Security Assessment in Future Power Systems

submitted by

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Summary

The penetration of unscheduleable generation will increase due to legislation and eventually saving on fuel cost. This will cause an increase in uncertainty of power-flow and drive up balancing market costs, the safety margin for N-1 will have to increase. i.e. N-1 will not accurately represent the state of the system. A security assessment scheme (SAS) that considers probabilistic uncertainty could give financial savings and/or better security of supply.

In other words a power system with a high penetration of renewables is likely to require a new type of security assessment scheme. Before that is done we must be able to compare and evaluate existing and proposed schemes.

This thesis has two goals. Firstly, to be able to compare two security assessment schemes to determine which is better for the current system. The work details a computer program that combines a two stage Monte Carlo Sampler and a power system simulator to generate a level of security. The number of simulations that fail to converge within limits in N-1 and N-2 was compared to the calculated level of security and found to not be a good predictor.

The second goal is to see how the level of security changes as the uncertainties of renewable generation get added into a given power system. In doing this, the effect of adding renewables can be quantified. The work found that if 15% of the generation power comes from generators the are unscheduleable or stochastic the security of supply does not greatly change. Whereas if the penetration is increased to 30% the security level become significantly worse in almost all tested scenarios.

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Nomenclature

$\underline{x}$ denotes a vector

x_n denotes the value of x at the current time-step

x_{n+1} denotes the value of x at the next time-step

x_n System state

u_n System inputs

y_n System outputs

h Time-step duration, seconds

λ Largest eigenvalue in a matrix

τ Smallest time constant in a matrix

$\mathbb{I}$ The identity matrix

P Real power

Q Reactive power

V Voltage magnitude

θ Voltage angle

Glossary

ANN	Artificial Neural Network
Brownouts	Poor power quality, specifically a low voltage
Cascading Outages	A fault, leading to further faults.
GA	Genetic Algorithm
GPGPU	General Purpose Graphics Processing Unit
IEEE-RTS	The IEEE Reliability Test System (see Section 8.1.1)
Islanded	A power system that has been separated into two or more parts
Memoization	A computing optimisation used to speed up computer programs. It does this by storing a table of previously-processed inputs so that they do not have to be re-calculated.
MCP	Measure, Correlate, Predict
MCS	Monte Carlo Sampling (see Section 7.2)
MTTF	Mean Time To Fail
MTTR	Mean Time To Repair
NWP	Numerical Weather Prediction
N-1	A deterministic SAS where only single component outages are considered
N-x	A deterministic SAS where only ‘x’ simultaneous failures are considered

ODE	Ordinary Differential Equation
Safety Margin	A margin of error given to SAS to account for inaccuracies
SAS	Security assessment scheme (see Chapter 6)
SO	System Operator (e.g. National Grid in the UK)
Unacceptable System	A power system with a generator/load imbalance, components out of limits and, depending on the situation security constraints.
Unscheduleable	A generator whose power output can not be controlled (e.g Wind Turbines)
Wind Penetration	The ratio of wind turbine installed capacity to total generator installed capacity

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Chapter 1

Introduction

1.1 Context

1.1.1 What People Expect

Electrical Power Systems are ubiquitous; they effect every aspect of our everyday lives. We rely on them to provide us with as much power as we demand at any time without notice and failure is treated harshly. It is simply assumed that we have affordable, flexible power.

This is highlighted by the London black-out on 28th August 2003 affecting an estimated 500,000 people. London Mayor Ken Livingstone declared the situation a *"catastrophic failure"*, CNN reported *"Power cut cripples London"*, BBC news' description is equally panic stricken:

> *"Thousands of passengers were left stranded during the evening rush hour by the black-out, which halted 1,800 trains and closed 60% of the Tube network . . . Pubs lit candles as people left work to seek refuge, many staying late into the night as crammed buses and taxis tried to*

help thousands of people to get home. " [11]

Surprisingly, this black-out directly affected only about 10% of the population of London and power was restored to most users within 30 minutes. A black-out in north-east America in the same year cost an estimated $6 billion USD. Evidently any failure in the supply of electricity has serious social and financial consequences.

1.1.2 The Technical Difficulty

Behind the scenes we have one of the largest man-made devices ever created. It is hard to think of something other than the Internet taking up so much space and requiring such cooperation, coordination and control.

To maintain supply is not a simple task. Electricity cannot be easily stored in the required quantities and therefore production must match demand at every moment. This supply of power mostly comes from either fuel shipments (often from unstable countries) or from weather dependent sources, which cannot be relied upon.

As well as matching the prediction in demand, the selection of generators is important. Different generators have different times for starting up or varying the power output and the economics of generation cost have to be considered. This is not the only concern to the system operator: transmission lines have thermal limits; lightning strikes cause temporary faults; end users are unpredictable etc. (other factors are discussed later in Section 6.1). In spite of these difficulties energy use is on the rise.

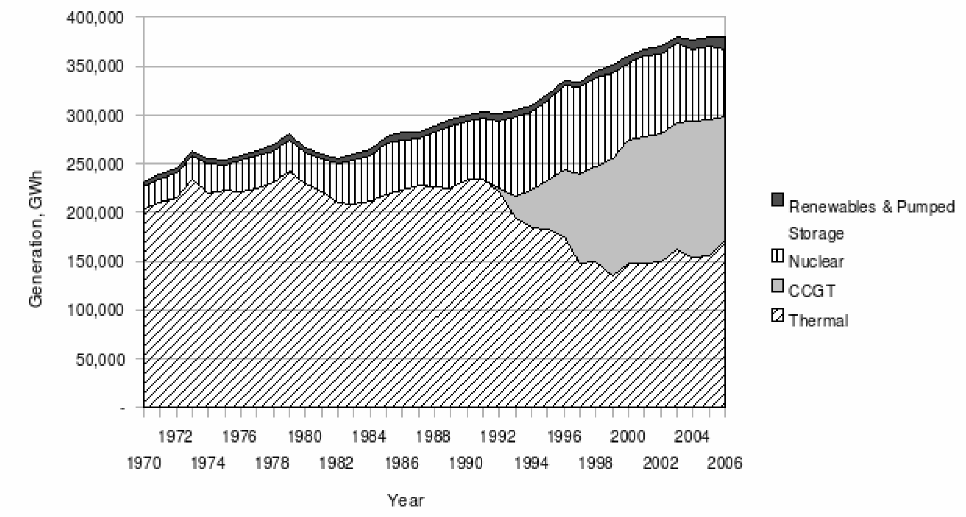


Figure 1-1: Historic Power Use

1.1.3 The Environmental Factor

We are living in a world in flux. Climatic cycles brought on by natural occurrences cause ice to cover much of the globe then retreat flooding massive areas and killing entire species. It appears that our own actions have put us on the brink of another change. Regardless of the cause, melting of the ice caps and a massive increase in tropical storms and tidal waves are a bad thing for the human race. Life itself is likely to survive any changes we cause but there will be mass extinction, huge uninhabitable areas, and a new landscape. If it occurred it would be at least the sixth similar mass extinction on the planet. Life will go on, what we want is to keep the status quo.

As it looks now the main changes we need to make include keeping or expanding the rainforest and other havens of biodiversity and stopping the release of greenhouse gasses. A large part of the greenhouse gasses are from electrical power systems. This means that the choice of components will likely be skewed toward those which are environmentally friendly, or at least more friendly than alternatives. The change to renewable power will also come from a financial point of view as well. Once the price of installation drops, there are massive savings to be had in running costs due to the freedom from fuel.

The UK government have performed a review of climatic change from an economic standpoint. Even ignoring ethical issues it advocated action to prevent global warming as the quotes below indicate.

> *"The scientific evidence is now overwhelming: climate change is a serious global threat, and it demands an urgent global response. This Review has assessed a wide range of evidence on the impacts of climate change and on the economic costs, and has used a number of different techniques to assess costs and risks. From all of these perspectives, the evidence gathered by the Review leads to a simple conclusion: the benefits of strong and early action far outweigh the economic costs of not acting.*
>
> *Climate change will affect the basic elements of life for people around the world: access to water, food production, health, and the environment. Hundreds of millions of people could suffer hunger, water shortages and coastal flooding as the world warms.*
>
> *Using the results from formal economic models, the Review estimates that if we don't act, the overall costs and risks of climate change will be equivalent to losing at least 5% of global GDP each year, now and forever. If a wider range of risks and impacts is taken into account, the estimates of damage could rise to 20% of GDP or more."* [92]

1.1.4 The Future

We can imagine a future when we have much less reliance on fossil fuels. Where our power is generated by nuclear fission, producing no nuclear waste or by massive solar banks in the world's deserts using solar power to charge hydrogen fuel cells which are shipped around the world. Once electricity can be stored in large quantities it gets easier to manage. We can rely much less on the pylons and lines.

1.1.5 The Present

This future is a long way off; the technologies needs to advance. Nuclear fission, solar photovoltaic cells and hydrogen storage need to be much more efficient before they become viable alternatives. Our attitudes need to change as well. We need to recognise that a change is needed and allow for it. Deliberation about the causes of climate change are a pointless blame game that detracts from the goal.

Sources such as the British Wind Energy Association (BWEA) and National Grid indicate that wind power will supply the major constituent of the UK 2010 target [29, 66]. This is because the technology involved is relatively well established, with a long lifetime and positive public opinion, however the problems arise because of the random nature of generation, the quality of the power produced by wind, and instabilities it imposes on the grid. With this change we need a new way to analyse power systems to cope with the uncertainty that dealing with the weather brings.

Some issues are addressed by the BWEA, The Carbon Trust, Department of Trade and Industry (DTI), National Grid, and The Office of Gas and Electricity

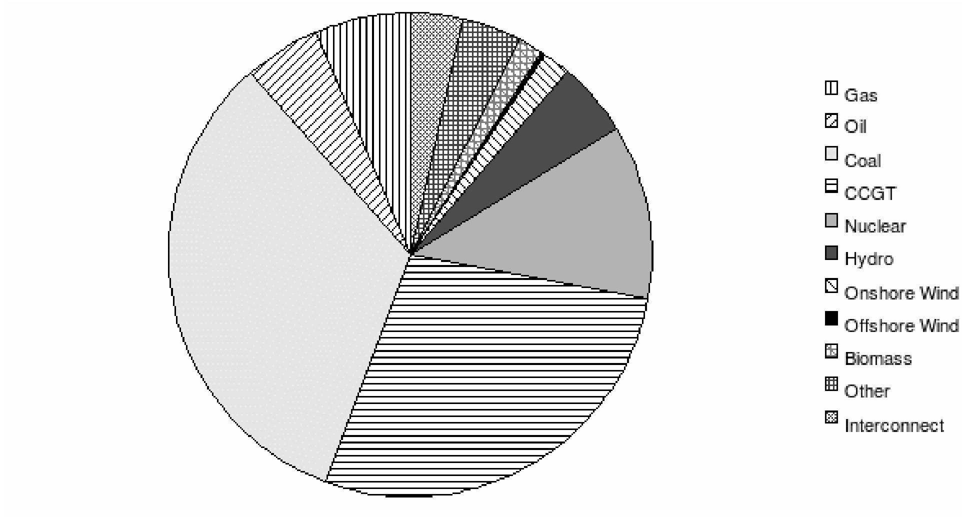


Figure 1-2: Installed Capacity

Markets (Ofgem) but the general consensus is, that as of now, renewable power is not causing a significant enough impact to necessitate a change in the tools or practises. As can be seen from (Fig 1-2) installed capacity of renewables is currently low. This will, however, change in part due to the UK target of having 20% of supplied electricity from renewable sources with most of this (70-80%) coming from wind power.

A key publication on this subject is the 'Renewable Network Impact Study' by the Carbon Trust & DTI [30], it states that:

> *"At the current target levels, intermittency is not a significant issue affecting the development of renewable generation. However, system balancing costs will increase as the penetration of intermittent renewables increases, and balancing costs could increase substantially with regard to meeting the 2020 aspirational target."* [30]

It is not only intermittency that will become a problem. Other factors such as stability and scheduling will have to be addressed as well. Consequently there is now a real need to develop a new tool to more accurately assess current and future electrical networks. This will enable the system to be operated closer to its limits enabling large savings.

UK energy policy aims to cut carbon dioxide emissions by ten percent from 1990 levels by the year 2010 and 20% by the year 2010 as part of 'The Kyoto Protocol to the United Nations Framework Convention on Climate Change' [98]. As well as the longer term plan of a 50 percent decrease by the year 2050 [38]. It is encouraging low emissions in electricity generation through schemes such as Renewable Obligation Certificates and the Climate Change Levy.

This will direct the changing face of electricity generation and transmission. These systems have their own intricacies and problems. Renewable generation will be the mainstay of the industry. One can already see the impact of such schemes, wind farms currently have an installed capacity of 2.3 GW in the UK with a massive 15 GW in planning, approved, or in construction [25]. Traditional generator output can be controlled but that is not the case with new generation like wind turbines or photovoltaics. These are not only unable to be controlled but cannot be accurately predicted either. The focus of these concerns and actions can be seen from Government publications such as the 2007 white-paper [38] and its follow-up from the DTI [39].

1.1.6 This Work

This work is an intermediate step, at a time when there is a large number of unpredictable generators and a reliance on a power grid of lines and pylons. It is intended as a comprehensive account of how to look at power system security in such a system. It aims to show how the current method of analysing power systems will not be the most effective, and provides a scheme to compare methods of security assessment.

The system operator has the overall responsibility for ensuring the system is in an acceptable state, that is, everyone receives enough power. They can make predictions but only receive details on generation and demand half an hour before power is to be delivered. In this time they must perform simulation and analysis, then if required contact the generators telling them to change their output to make the system acceptable.

The current method to do this does not consider intermittent generation and hence will not be optimal in a system with a high penetration of renewables.

Before a new security assessment schemes is used it must be tested. The primary goal of this thesis is to create a method to compare security assessment schemes. This require significant computer power and an advanced power system simulator hence this thesis details work that has been done in modifying simulation tools to increase their speed.

1.2 Aims & Objectives

This thesis can be broken down into a few main areas of research. These inevitably lead to other required areas of work. The following list highlights these main aims and objectives:

- To see how unscheduleable generation, such as wind farms, effect system wide *security of supply*.

- To see how the *security assessment scheme*, *N-1*[1], is affected by a high penetration of *unscheduleable generation.*

- To do this requires the ability to compare different security assessment schemes, which is a useful tool in its own right.

1.3 Contribution

This work has four main areas of contribution in the area of power system security assessment. This contribution is mainly from the point of view of a system operator. It aims to:

- Highlight the need for a change in security assessment,

- Develop a new way to assess a security assessment scheme,

- See if N-1 is a good predictor of system security,

- Create a novel method for comparing security assessment schemes, and

- Compare the security of power systems with differing penetrations of wind power.

The software that was created to achieve the aims has a number of other potential uses. In addition to being able to compare different SAS it is itself a security assessment scheme. In it's current form it would have to be used more like a planning tool but with enough computing power it could become a powerful tool for the control room.

[1]Although N-1 is used throughout this thesis to mean only single outages are considered in reality system operators are more likely to use a modified form of N-1 or N-2. A better example is the requirements laid out in National Grid's SQSS document.

Another facet of the computer program is to aid in planning decisions. If there is a proposed change to the network the program can be used to show how that change will affect the security of supply. This was done in this thesis to compare a system with and without wind generation but could just as easily be used to look at changes such as the addition of a new transmission line or an analysis of how storage should improve security of supply. In Section 7.5.2 further applications of the computer program are discussed.

One final feature of the program is to locate components of the network that are likely to cause security problems. In the large number of simulations that are run certain components will invariably cause problems more often than others, this data could be very useful for network planners.

1.4 Structure of This Thesis

Following this introductory chapter, the thesis first describes current power systems in Chapter 2. This is followed by security issues that can arise with power systems (Chapter 3). Next, the future of power system is introduced focusing on two areas: generation, and demand (Chapter 4). At this point the reader should understand the relevant factors in power systems and the challenges posed to a system operator in the future.

The next part looks at how one assesses security. Chapter 5 looks in detail at two simulation methods for power systems as well as issues to consider when including wind power generation. This includes the authors extensive modifications to both dynamic and static simulators.

Following that, in Chapter 6, SAS are introduced looking at both how they are currently implemented as well as proposed modifications in the literature.

The chapter ends by highlighting the limitations of deterministic methods for systems with a high wind penetration. The method of analysis in this chapter leads to the creation of a tool for comparing SAS which is introduced in Chapter 7. Chapter 7 ends by listing limitations to the proposed method as well as possible applications.

Chapter 8 details the computer software used to form the results. It also contains details of various test procedures used to verify the accuracy of the work. The next chapter, Chapter 9, contains the results and discussion of various experiments that use the previously discussed computer program. It includes an analysis to see if N-1 or N-2 is a good predictor of overall system security and a study into the effect of the introduction wind generation into a system.

The thesis ends with a conclusion and proposed further work.

1.5 Exemplary Background Texts

- Sustainable Energy - without the hot air: David J C MacKay [62]
- Operating in 2020: National Grid [67]
- Power System Stability and Control: Kundur [59]
- Future Electricity Technologies and Systems: Jamasb [52]
- The Economics of Climate Change: Nicholas Stern [92]
- Renewable Network Impact Study: Carbon Trust & DTI [30]
- Reliability Evaluation of Power Systems: Roy Billinton [19]
- Reliability Assessment of Power Systems using Monte Carlo Methods: Roy Billinton [17]
- Seven Year Statement: National Grid [66]
- Wind Power in Power Systems: Ackerman [1]

Chapter 2

Power Systems Operation

This chapter introduces the main players in electrical power systems. It talks about their roles and how they operate in the market. It then goes on to look at some physical components and discusses their use and control, possible considerations for the market, system operator, environment; and how this might change as we move to the future.

2.1 Structure

The privatisation of the UK power system, has organised the network into different sectors. Some are physical divisions, others trade electricity as a commodity without ownership of any part of the network. This section provides background information about the current UK electricity market, its main market participants and their roles.

The *regulator*, OFGEM in the UK, promotes competition by enforcing regulations on the monopoly companies which run gas and electricity networks, paid for by an annual license fee from the regulated companies [72]. The *transmission*

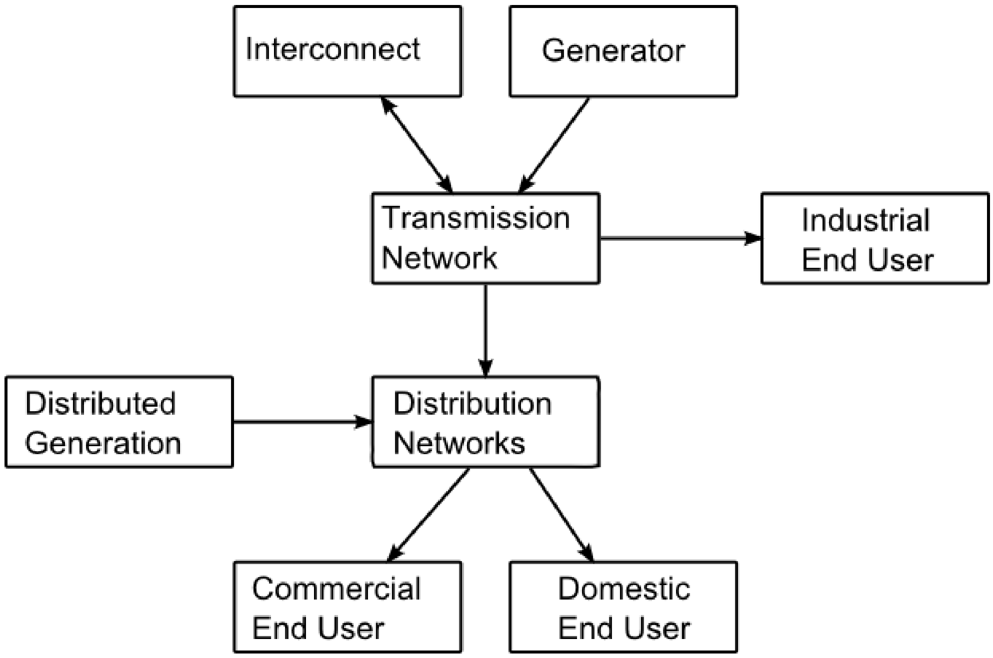


Figure 2-1: Physical Structure of an electric power system

system and *distribution systems*, both monopolies, make up the physical network of lines, transformers and *busbars* that transport electricity to the end-users. The *Transmission System Owner* (TSO) in England and Wales is National Grid Transco, which is also the UK *System Operator* (SO); responsible for maintaining a constant and consistent supply to the end-users.

Historically, all power generation was connected to the transmission system, which in turn was connected to one of the 12 distribution systems at *grid supply points*. The distribution system supplies electricity to the end-user at a lower voltage.

New generation, particularly renewables are being connected directly to the distribution system. The transmission system owner and *Distribution System Owners* (DSO) are paid through connection charges and use-of-system charges from the generators and suppliers. Adjacent networks are connected together

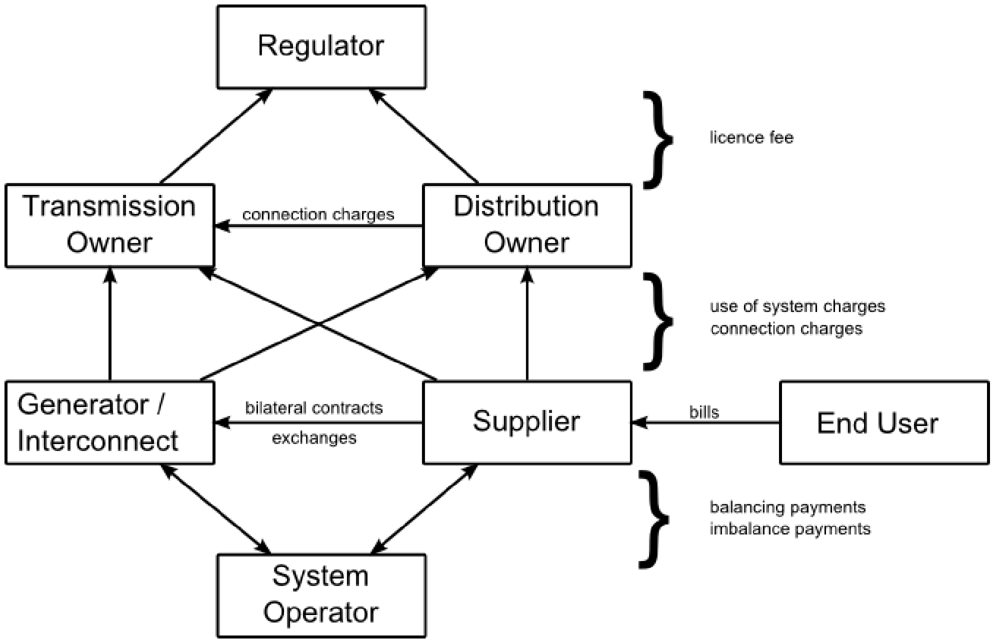


Figure 2-2: The UK electricity market

through interconnects. These allow the transmission of power across most of Western Europe. This structure is shown in Fig 2-1.

Suppliers buy electricity from generators and sell to end-users. This simplifies the process for the end-users and enables competition by promoting market liquidity. The generators, which supply electricity, form deals with suppliers and end-users in a number of ways. *Bilateral contracts* are a two-way deal between suppliers and generators stating the quantity of power traded, the price, and the time over which that power is to be delivered. This is done in half hour blocks, often months in advance. *Exchanges*, similar to stock exchanges, allow anonymous trading of power in a real time market closer to the time that the energy is to be used. This enables suppliers to fine tune their purchased power to match their predicted demand using more accurate load forecasts close to the *Final Physical Notification* (FPN). The FPN is the point, one hour ahead of real-time, at which

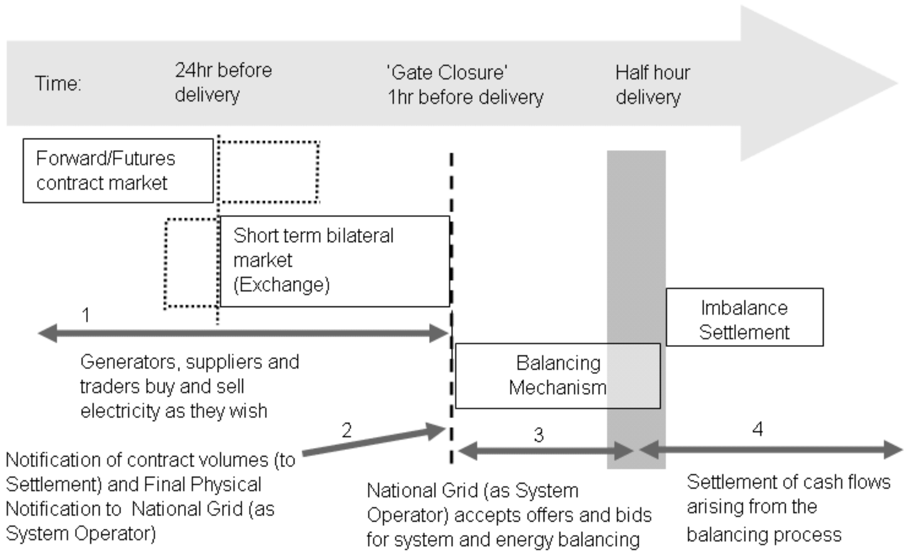


Figure 2-3: Overview of market structure

all generators and suppliers must inform the system operator, who is also the transmission system owner in England and Wales, of the electricity inputs and outputs to the system. Fig 2-2 shows the transfer of money between players and Fig 2-3 shows the timescale under which the market operates.

The trading process up to this point has been entirely market-driven but this can violate *transmission constraints.* Constraints make sure that lines are not overloaded and there are no inter-area oscillations or other such stability problems. The system operator is able to make additional trades so the system operates in a secure way. This is called the *balancing mechanism.* Any trader or generator can bid into the balancing market with a list of prices to increase or decrease their power use by various quantities; these bid and offer prices are what the system operator uses to stabilise the network.

A system operator can decide to tell a generator to *back off* and another

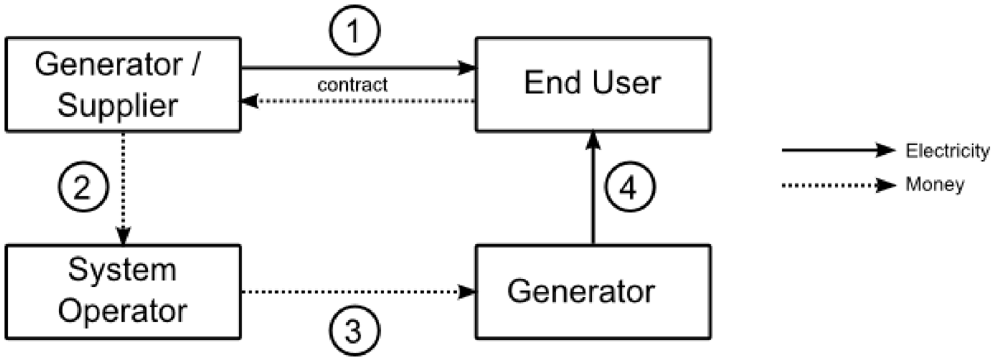


Figure 2-4: Balancing Market Operation

to increase power output for either stability or financial reasons. The system operator will get paid by a generator for telling them to back off generation. The system operator uses this money to pay another generator to supply the electricity to the end-user. This is illustrated in Fig 2-4.

The generator who is being backed off still gets the contracted money from the end-user but generates less, saving fuel and money. The generator who has increased output, profits by setting their price higher than their fuel costs. The end-user simply pays his contracted fee and receives the requested power, without being aware of these transactions.

The price that the system operator has to pay to increase energy is called the *System Buy Price* (SBP) and the price of telling a generator to back off its generation, the *System Sell Price* (SSP). The system operator can actually make a profit from the balancing mechanism by backing off, i.e. reducing generation output of expensive generators and using cheaper generation instead. But sometime they will lose money if they need to use an expensive generator for stability reasons.

If there is a weak network, i.e. one with stability issues, there will need to be a lot of rescheduling of generation. This will require more expensive generation to be used, causing higher balancing market prices. Certain generators may forgo making bilateral contracts hoping they will get a higher price in the balancing market.

If a generator knows that it has a stabilising influence on the network they may deliberately set their price higher knowing that the system operator will have to use them. Extra uncertainty in the network means that more generation needs to be kept in the balancing market, again driving up costs. Accurate predictions of the load and stability are a way of reducing the balancing market costs.

The system operator has to consider cost and stability when deciding which generators to back off and which to request more generation from. Deciding the best combination is known as the problem of *economic dispatch* and it is a relatively straight-forward process of ranking all generators by price and selecting all the cheapest ones to run at full power. Unfortunately it is not that simple in practise.

It is complicated by the fact that losses in the lines must be taken into account. These losses change with each mix of generation. A *load-flow* (power-flow) must be done to find the losses. Hence the solution to economic dispatch is often known as *optimal power flow*. Other factors, such as voltage limits and constraints, should be taken into account to find the optimal power flow. Constraints are most often taken as fixed (steady-state) guidelines to stop stability or power quality problems. In reality these may be too constrictive given the specific generators and loads used at that time. A more accurate idea of stability can be obtained by performing a more detailed simulation and hence the system can be operated more economically. Zhang gives a detailed description of optimal power flow and

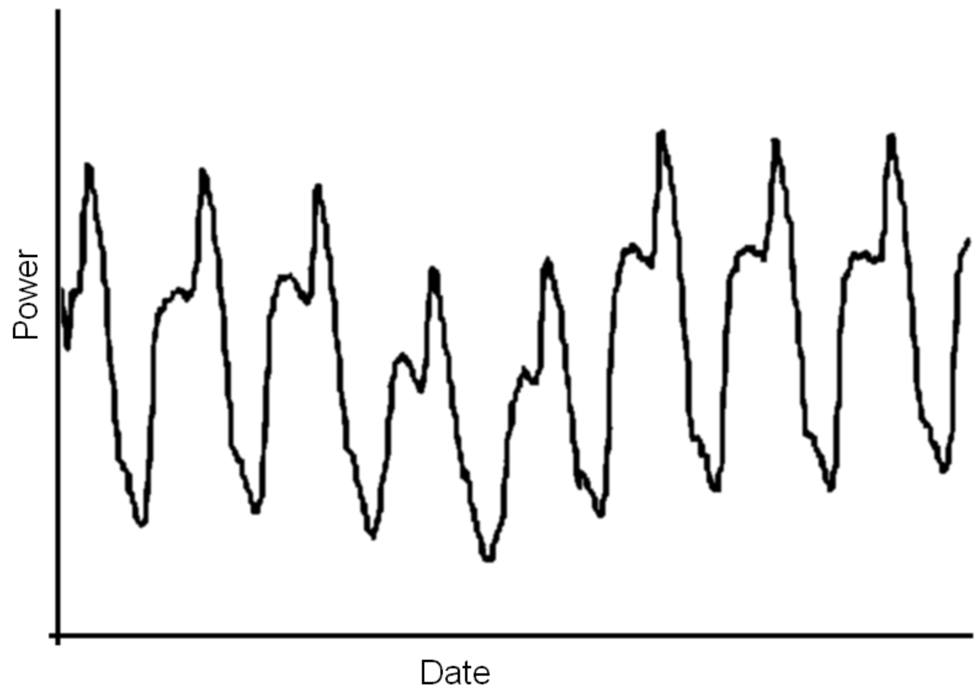


Figure 2-5: Weekly Demand for UK

using dynamic simulation to improve optimal power flow [107].

If any generators or loads deviate from the contracted trades or a fault occurs during delivery of power then the system operator must pay for this discrepancy as the generation/demand balance must be maintained. The use of extra generation is paid at the SBP. This is illustrated in Fig 2-3; on chapter ten of National Grid's Seven Year Statement [66]; or on Elexon's information sheets [42].

The system operator forecasts the load to assist in maintaining equilibrium and stability. This relies on the fact that although individual consumption by end-users is erratic, when aggregated together the load is predictable. For instance, there is a certain cyclic pattern based upon on work hours, but this will change with seasonal and temperature fluctuations. A typical weekly demand profile can be seen in Fig 2-5. As unpredictable generation, such as wind power becomes more popular *load forecasting* will become more difficult requiring more advanced tools for the assessment of power system operation. Wind forecasting has to be combined with normal load forecasting, adding to uncertainty.

2.2 Control

End-users expect power to be both constant and consistent, i.e. the power should always be available and not vary from what is expected both in terms of voltage and frequency. For domestic users in the UK this expected value is 240V at 50 Hz. Maintaining a consistent connection requires the *generation-load balance* to be equal and for the system to remain in synchronous operation. The balance of generation and demand to some extent is maintained by the market but not all load or generation can be predicted accurately; line losses, faults and outages cause addition discontinuities. This imbalance must be corrected by the system operator in real-time. Most systems aim to operate at *N-1 security*, meaning that if any one *contingency* occurs the system will remain stable and there will be no system-wide problems. Contingencies include user error, faults in the equipment and environmental effects such as lightning and freezing rain.

The challenges of supplying power can categorised as follows:

- Maintaining good *power quality*. This relates to making sure that the power delivered is constantly at the correct voltage and frequency, i.e. there are no sags or swells, the voltage does not flicker, no under/over voltage, and no deviations from a perfect sine wave at 50Hz.

- Keeping system *synchronism* i.e. ensuring that every generator turbine is approximately the same frequency and phase.

- Requested power being delivered to most loads i.e *no load shedding*
- Keeping each component *within limits* for voltage/current/power most of the time (i.e. no components that are overloaded or experiencing voltage collapse)
- Making the system reasonably *fault tolerant*
- Supplying energy at *minimum cost* with *minimum environmental impact*

Obviously there are many trade-offs involved for the SO. These challenges are compounded by the fact that in the UK this optimisation must be done one hour before the power is to be delivered. To do this optimisation the main control method is to trade electricity, as described before, to change the output of certain generators. It is also possible that certain loads will be disconnected for short periods of time.

To allow the system operator to control the power system a number of services are required. One service is the *system reserve*. The need for the system reserve arises from the fact that the start-up time for generators is too long to maintain balance and the system inertia is small, hence some generators must be kept on as a *spinning reserve*, ready to supply extra power should it be needed. Other control mechanisms include AVR, Governors and SVC, which give the ability to control reactive power, frequency, and voltage.

Defining the overall stability of an entire system is not an easy task but it is one extensively studied. A system that looks like it is on the boundary of stability may in-fact be able to be pushed further due to complex power electronics keeping it stable, whereas one that looks to be completely stable may be teetering on the edge. This will be covered in more depth in Section 3.4.

2.3 Generation

The basic means of generation has not changed since Edison's time. Some external power source, generally known as the *prime mover*, rotates a section of a generator called the *rotor*. This causes a voltage drop across the stationery part of the generator, conveniently called the *stator*, forcing a current to flow in the wires in the same way a motor uses electrical energy to convert back to kinetic energy.

The source of the prime mover's energy, i.e. what drives the rotating turbines, is most often steam. This is created by boiling water using one of the following methods:

- Nuclear fission,
- Nuclear fusion,
- Heat from the earth's core (geothermal),
- Using focused sunlight (solar parabolic trough),
- Burning fossil fuels (coal, oil, gas, diesel).

All of these generation methods use a large amount of heat, which is mostly wasted. *Combined heat and power* (CHP), uses the excess heat from power stations in nearby homes, shops or factories greatly increasing efficiency.

Not all methods of moving the turbines use steam, other methods include: using wind power, the movement of waves or tidal flow.

Photovoltaic cells, more commonly known as solar panels, do not use turbines at all. The direct conversion of sunlight to electricity is performed by an electrical process.

All of these different types of generators have pros and cons to their use.

2.3.1 Scheduling

Most generators can produce a requested quantity of energy up to a maximum value. To change the power output takes different times in different types of generation. A faster time is better from the point of view of system stability, and these will be more likely to operate in the balancing market. Invariably the easier they are to change, the greater their variable costs.

Nuclear is not generally varied and is run at full power due to its low cost and slow speed to change output. CCGT, a type of gas turbine, is more expensive but can change its output quickly hence it is used in the balancing market where the power is requested shortly before supply. Generators that cannot be scheduled include wind power, which only generates when the wind is blowing. If there are more *unscheduleable generators* then more uncertainty is introduced causing an increase in the number of expensive gas turbines that are needed to run. To some extent this cancels out the carbon saving.

2.3.2 Predictability

Those generators that cannot be scheduled have to be predicted and the accuracy of these predictions is an important factor. If the accuracy of the prediction is high enough they can be treated the same as a normal generator. It is also desirable if times of high power output correlate to the times of high power use.

Photovoltaics do not have this correlation because they do not generate on an overcast winter's day, which is when power use is highest.

If predictions become more accurate then extra balancing market costs decrease. This could happen by improving the prediction techniques themselves, or it could come from having more dispersed wind farms. The greater the geographical distance the less correlation of wind speeds and hence the more likely that they will average out to a more predictable number.

2.3.3 Power Output

Obviously different generators will have different abilities to produce power. Larger traditional power stations, for example, are often more efficient. Tidal or hydroelectric stations have a power output limited by the quantity of water stored or flowing but can produce a lot of power when water is available.

The efficiencies of plants are increasing, though many types are effected by economies of scale. The larger they are the more efficient. This does present a problem if you start to rely on a few large power stations and they break. One of the major road blocks to the introduction of nuclear fusion is the economies of scale. Renewables often do not have the same problem. For instance, wind power comes from many small turbines hence wind farms can be built of any size.

2.3.4 Fuel Type

It is not wise for a network to rely too heavily on one fuel, particularly if that fuel has to be imported. Fluctuating prices, political uncertainty and dwindling supplies mean that a good *fuel mix* is expedient. Many renewables have the advantage of not needing any fuel deriving their power from natural processes like the sun, tides, or the earth's heat. Nuclear Fission has the problem of the toxic waste it produces, fossil fuels cause greenhouse gasses and are increasingly taxed for that reason. Biomass can use waste or cleared foliage; in either case you are initially increasing the carbon in the atmosphere but there is a great improvement from then on as the same quantity will be cycled through rather than the continuous increase of fossil fuelled generators.

2.3.5 Efficiency

Certain types of generation produce more power with the same quantity of fuel and are therefore favourable. CHP schemes gain very high efficiencies if all the heat can be put to good use. Efficiency will drop if the location is not ideal. If the generator is connected to a low voltage or weak part of the grid it will have greater losses. Obviously generators that do not require fuel do not have this problem.

2.3.6 Emissions

Aside from the ethical issues, it is financially efficient for a generator to have low emissions. Government directives like the 'climate change levy' or ROC [39] provide definite incentives for carbon capture schemes and increased fuel efficiency. Nuclear power produces no greenhouse gasses but does generate radioactive waste. It is difficult to provide a direct comparison between the two.

When looking at the emissions of a generator it is important to consider emissions during construction and deconstruction as well as while running and the utilisation. A gas plant that is run at half its installed capacity will be less efficient than running at full capacity although, due to the nature of gas plants, it may be a good idea for security reasons to keep some reserve to deal with uncertainty. A wind farm that has a large initial carbon cost might be installed but unless it is fully utilised it will never regain that initial deficit.

2.3.7 Stability

Certain generation has a better ability to deal with faults in other parts of the system or may be able to supply more reactive power. Generators that can change their power output rapidly generally have a stabilising effect by being able to compensate for faults on other parts of the system quickly. It is not only the physical generator that determines the effect on stability but its location. Connections near the load centres or at higher voltage are more stable than low voltage or electrically distant connections. Due to the requirements of wind power they often have to be on electrically distant connections as shown by Swisher et al.:

> *"Perhaps the most significant barrier is transmission simply because the wind resource is typically found at a distance from load centres."* [95]

2.3.8 Location

Generators have many different requirements for their physical location. This impacts both on their power output and stability. The location may be affected by public opinion as well as optimum location for generation. As stated before the voltage level they are connected at is important, as is the distance from the main load centres. Though it is unlikely that larger generating stations will be built near load centres as these are often in an area of high population density.

2.3.9 Technology

If the technology has not been proved commercially it will lack investment and hence widespread development. Nuclear Fission suffers from a lack of research into toxic waste. More research is needed to find how to properly dispose of the waste. This will not happen until there are new nuclear generators, but the new generators will not be built until we have a better waste management strategy.

Governments seem to be imposing new restrictions and targets on a yearly basis. The kind of long-term planning that is needed when deciding to invest in a new technology become very difficult when governments keeps moving the goalposts. This can hinder the uptake of new technologies, even if the new laws are meant to help them.

2.3.10 Lifetime

A longer life means more time to recoup investment costs; giving a larger profit over the life of the project. The first generation of photovoltaics degraded to an unusable point in a few years. This made them an unsound investment, although their lifetime is increasing through new research.

Many generators in the UK are coming to the end of their planned lifetimes. We will see an influx of new generators and revamps of old generators to cope with this change. It is important to consider the generators that we install now are likely to still be running for the next 40 years. This must be considered with respect to our long-term plans.

2.3.11 Set-up Cost

A large set-up cost can be offset if there is high power output and a long lifetime but it is still a major factor in finding investors. Renewables tend to have a high installation cost, as well as being an unproven technology. It is quite a large risk, though with low running costs and an expected increase in fuel costs and emissions taxes, there could be a large reward.

2.3.12 Generation Cost

Staff costs, maintenance and fuel costs are major factors in the profitability of a power station. At certain times it might be more profitable to not run your generator at all. Wind power has very few overheads, so is a very attractive option from this point of view. But despite having very few overheads unscheduleable generation has very little purchasing power. There is no advantage in not selling, regardless of how low the price is; and wind generators do not have the ability to make long-term contracts without making some contingency in-case the wind is not blowing. One way in which a gas generator can lower costs is by buying wind power to reduce the fuel costs of gas turbines.

2.3.13 Distance from load

Due to the constraints imposed by the type of generation, they may have to be placed far from the end-user. This causes large power loss in the lines resulting in extra infrastructure having to be developed. Wind farms are best located offshore or in remote areas. There is then a trade-off between connecting the power to the nearest point on the Grid or installing new lines, giving a higher installation cost but better operational efficiencies.

The connection of large power stations to remote parts of the Grid can cause stability problems, such as when where one area starts to oscillate against another.

2.3.14 Electricity Cost

A number of these factors come together to produce a cost for the power generated. High power output, low emissions and high predictability mean that the generator should make bilateral contracts for all its generation; this is exactly what nuclear power does. CCGT are very quick at varying their power, hence will only contract for a fraction of their installed capacity. They will instead bid in the balancing market. The decision whether to sign bilateral contracts or bid into the balancing market becomes more complicated with hydroelectric or wind power. Hydroelectric dams cannot generate continuously, in-fact it uses electricity to store energy by pumping water back into a higher reservoir. Their decision of when to generate and when to recharge requires an intimate knowledge of the market. There is a risk attached to signing bilateral contracts with unpredictable generation because there is no guarantee that they will be able to produce the contracted power.

2.4 Demand

The demand is the sum total of power requirements across the Grid. On a small scale it is unpredictable, because there is no way of knowing when someone will turn their TV on. Yet aggregated across the country it becomes much more manageable a cyclic patterns emerge.

Climate plays a major role in demand: Hot countries experiencing a peak in the summer daytime when air-conditioners are running; cold countries are more affected by heating in the winter. There are daily cycles caused by industry, down to one-off occurrences like the final episode of a popular TV programme. All these factors must all be taken into account and this calculation is usually done with an error of less than 5%.

Demand has seen constant growth throughout the lifetime of the Grid and this is likely to continue. This growth is likely to increase as we move away from using fossil fuels directly in homes and rely on Grid supplied power for things like heating and cooking.

There is a trend to reduce the demand on Grid power by local supply. If a large number of end users have installed small renewable energy generators in their home their power demand, as seen from the Grid, will be significantly reduced. It remains to be seen which of these factors dominate but regardless the impact of a large scale change in power demand should be examined.

2.5 Storage

Other than demand side management (DSM), storage is currently inefficient. It is not easy to store large quantities of electrical power for long periods. This results in a careful balancing act of deciding how much energy will be lost in storage and if that is worth the savings of not using an expensive generator. Jamasb [52] provides a good introduction to possible storage technologies and their uses.

One storage method that does not suffer the problems of power loss for long-term storage is pumped hydroelectric. Unfortunately there are only a limited number of sites where this is a viable option and many of them are already in use.

Flywheels are a good storage system for their specific niche. They basically consist of large spinning platters to store the power. Electricity can be transferred extremely rapidly; i.e. a fully charged flywheel can be discharged in a matter of minutes whereas a battery of equivalent size may take many hours. Flywheels do not hold charge well meaning they are not suited to long-term storage but as they require little maintenance and have relatively high energy density they are good for short term averaging of power fluctuations such as averaging output of a wind farm or to smooth the peaks in demand when electric trains start moving.

Super-capacitors store energy as electric charge. Like flywheels they do not hold their charge for long periods of time and require little maintenance over their long lifetime. But they are good for short term averaging or can be used with a battery to prevent unnecessary use, which will increase the batteries lifespan. In about one month they may lose half their stored power, whereas a conventional battery may only lose 10%.

Hydrogen is probably the most promising technology for long-term energy storage. When power is stored it can remain in that state for long periods of time without causing power loss. It can be used inside modified combustion engines as well as fuel cells. Hydrogen could become a direct replacement for fossil fuels if efficiencies can be improved. This could include generating energy from renewable sources where it is cheap, storing that power, and transporting the hydrogen in cargo ships across the world.

If this was to happen it would have the effect of removing the need for peaking generators. A base load of generators would generate at full power, for efficiency, all the time. Any excess power would be stored and used when needed. Unscheduleable generation would either be used or stored in the same way. This would make the task of the system operator easier but significantly different from how it is now. Unfortunately this will not happen until either the efficiencies of hydrogen get far above 50% or a new long-term mass energy store is found.

2.6 Network

Power networks are likely to see greater interconnection in the future. There is already plans for greater links between the UK and mainland Europe. Interconnection allows both countries to import energy during peak time, which tend to differ between countries. This results in less use of expensive peaking generation but it comes at a cost. Larger systems are more complex, particularly if there is more than one SO. Additionally there is the problem of over reliance. Italy has become dependent on its interconnections, it does not have enough capacity to supply itself with power at peak times.

2.7 Chapter Summary

This chapter provides background information relating to electrical power systems and how electricity markets operate. It does this in preparation for a more detailed discussion on likely changes in future powers systems in a later chapter.

After briefly discussing some of the main issues that face electrical power systems the factors that affect generators are discussed. These are looked at further in the chapters on the future of power systems and simulation techniques.

Chapter 3

Power System Security

3.1 Reliability

A power system must be *reliable*, that is, it must be able to supply power at an acceptable quality to those that demand it without damaging system components. A reliable system is one they can stay secure long-term.

Power System Reliability can be seen as having two components: adequacy and security. The NERC Planning standards [69] provide a commonly cited definition for these terms. They are basically split by time-frame. Adequacy is long-term planning reliability and security is short-term operational reliability.

For a broad overview of the methods used within power system reliability refer to the three books by Billinton, Li, and Allen [19, 17, 18]

3.2 Adequacy

Adequacy looks at power system reliability from a long-term planning point of view and determines if there is sufficient generation and network capacity in place to deal with all likely scenarios. This may involve physical changes to the system such as reinforcing transmission lines or building new components.

3.3 Security

Security deals with the day-to-day operation of ensuring the system is acceptable. It must be able to maintain this acceptable state given changes in the system (known as contingencies) and environment (weather, customer demands, etc.) [9].

A secure system is one that is stable and within operating limits following any credible disturbance. It therefore depends on both the likelihood of a disturbance occurring and its consequence.

Anything outside of this list of contingencies is considered too unlikely to take into account. Power System control is the actions and administration required to maintain, as far as possible, secure and safe operation.

3.4 Stability

> *"Power System Stability may be broadly defined as that property of power system that enables it to remain in a state of operating equilibrium under normal operating conditions and to regain an acceptable state of equilibrium after being subjected to a disturbance."* [59]

> *"Power system stability is the ability of an electric power system for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains*

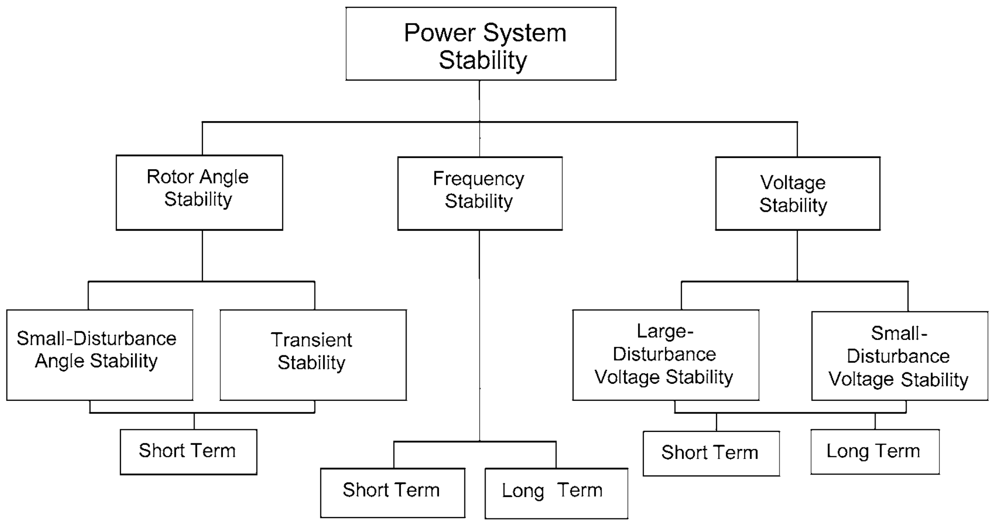


Figure 3-1: Classification of Power System Stability [60]

intact." [60]

Although stability is essentially a single problem it can help analysis to categorise stability as in Fig 3-1. This allows simplifying assumptions which are essential for meaningful analysis. The highly non-linear nature of power systems can lead to various forms of instability interacting. One form of instability may inevitability cause another. Stability can be categorised number of ways:

1. Size of disturbance (small, large)

2. Variable affected (frequency, voltage, rotor angle)

3. Nature of effect (dynamic or static)

3.5 Disturbances

Any change to a power systems operating condition is know as a disturbance. These are categorised as either small or large. *Small disturbances* in the form of load changes occur continually and due to their size can often be analysed using linearisation. Whereas, *large disturbances*, such as the loss of a transmission line, cause a system-wide transient response. A line loss can be though of as a transient followed by a change in the system topology.

Machine rotor speeds will change due to the difference between created mechanical and electrical torque giving rise to different busbar voltages. This results in voltage regulators and governors responding to the changes. Any number of further actions may take place where the system either stabilises at a new operating point or causes a *cascading outage* leading to total black-out.

3.6 Frequency Stability

This is the ability of the system to keep an acceptable frequency following a disturbance. It is essentially an issue of maintaining generator load balance and indeed a lack of generation reserve is often a factor in frequency instability. It can become a factor if a poorly coupled system becomes *islanded*; one island may not have sufficient reserve to cope with generation causing an unacceptable drop in frequency.

3.7 Voltage Stability

Voltage stability refers to the ability for each busbar on the system to maintain an acceptable voltage. It is essentially a local phenomena which can lead to widespread impact. It is mainly due to an inability for the power system to meet the demand for reactive power. In fact, a system with an unstable voltage is defines as one where a busbar whose voltage decreases as reactive power increases

[59]. *Voltage collapse* is a severe drop in voltage across an area.

3.8 Rotor Angle Stability

This is the ability of generators to remain *synchronised* following a fault. A fault will cause a change in the electrical torque leading to a change in speed of the rotor in the generators. If great enough some generators may then lose synchronism or *pole-slip*. In the same way that a generator that has lost synchronism will be disconnected by its protection system, a group of generators can become islanded if they are no longer in-step with the rest.

It is usefully to categorise rotor angle stability by the type of disturbance. Small disturbances relate to *small signal angle stability* and large refer to *transient stability*. Any increase in speed of one generator will cause an increase in electrical torque on the generator and a subsequent decrease in electrical torque of the surrounding generators. In turn, this causes the other generators to increase in speed and the original one to slow down. If at any point the difference in rotor angle becomes too great the rotor will skip a rotation causing huge strain on the components - this is known as a pole-slip. The protection system of a generator will attempt to disconnect it before this occurs.

The strength of the force that keeps generators rotating together is known as *synchronising torque*. If there is not enough synchronising torque a generators rotor angle can gradually drift away from the rest. This is known an *aperiodic drift* and can be seen in Fig 3-2. It has been largely negated by a piece of control electronics known as an *automatic voltage regulator* (AVR), the AVR increases the synchronising torque such that aperiodic drift should not occur [14].

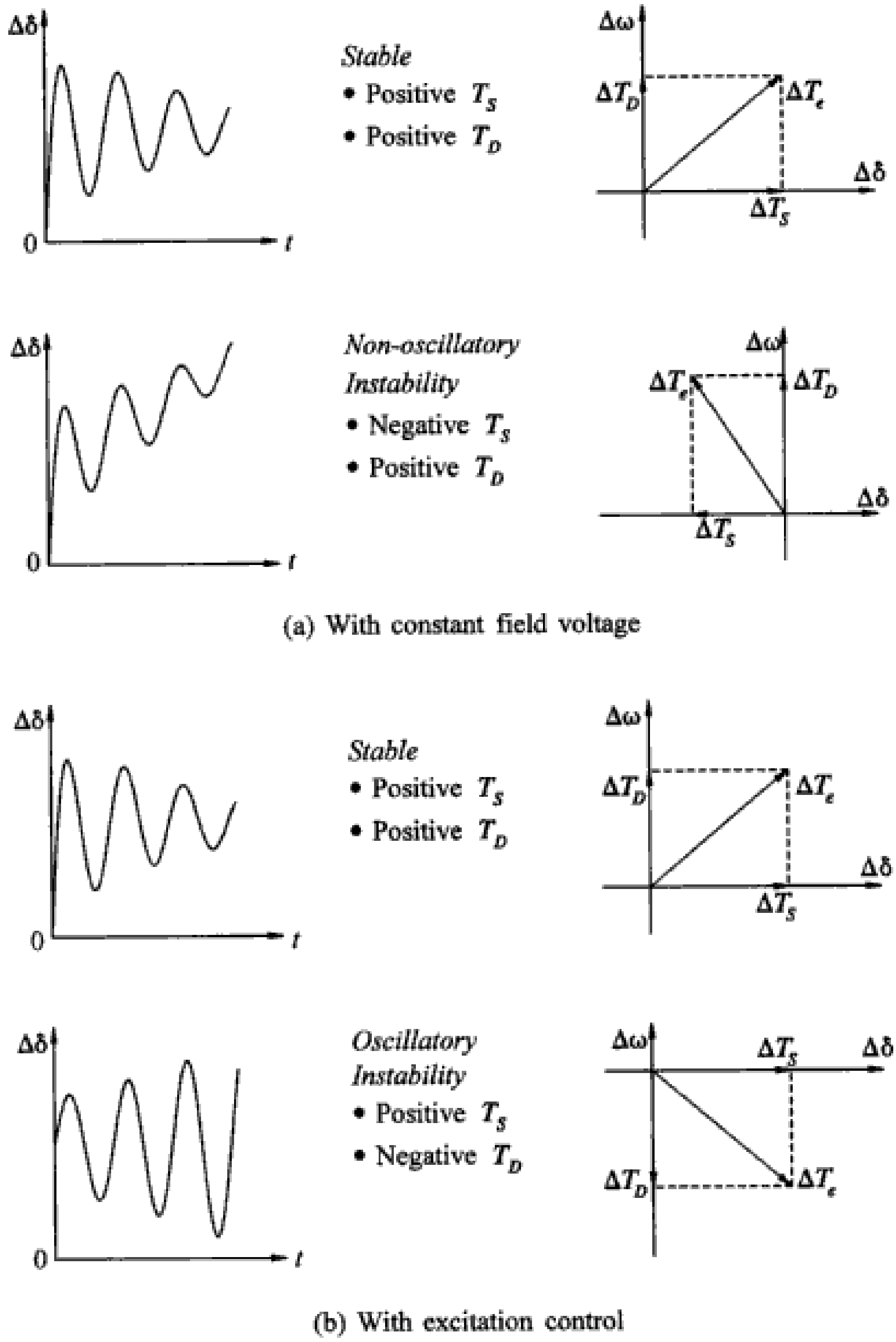
If the synchronising torque is too strong then the perturbed generator will oscillate against the others like a caravan snaking as it is pulled down a motorway. If these oscillations are not sufficiently damped, by another piece of power electronics known as *power system stabilisers* (PSS), then they will increase in magnitude leading to *oscillatory instability*. Properly set controllers will have enough *damping torque* to mitigate many instances of oscillatory instability.

3.8.1 Small Signal Angle Stability

Aperiodic drift, shown in Fig 3-2 as *non-oscillatory instability*, can be caused by a small disturbance though this is unlikely in a system with adequate AVRs. Therefore, small signal angle stability is generally an issue of oscillatory instability and mitigated by providing enough damping torque through properly configured PSS and a sufficiently well connected network. You can see in the diagram how oscillations build up until the machine is no longer synchronous.

3.8.2 Transient Stability

The three cases shown in Fig 3-3 categorise the types of transient stability issues. A transiently stable generator, Case 1, oscillates against the other generators but the synchronising torque is enough to stop it initially de-synchronising and the damping torque is strong enough to reduce the oscillations. In Case 2, the disturbance is large enough to overcome the synchronising torque and the rotor angle increases until synchronism is lost, this is known as *first swing* instability. Case 3 has enough synchronising torque but not enough damping torque; the fault has effectively moved the system into a small signal unstable state.



(a) With constant field voltage

(b) With excitation control

Figure 3-2: Rotor angle response to a small disturbance [59]

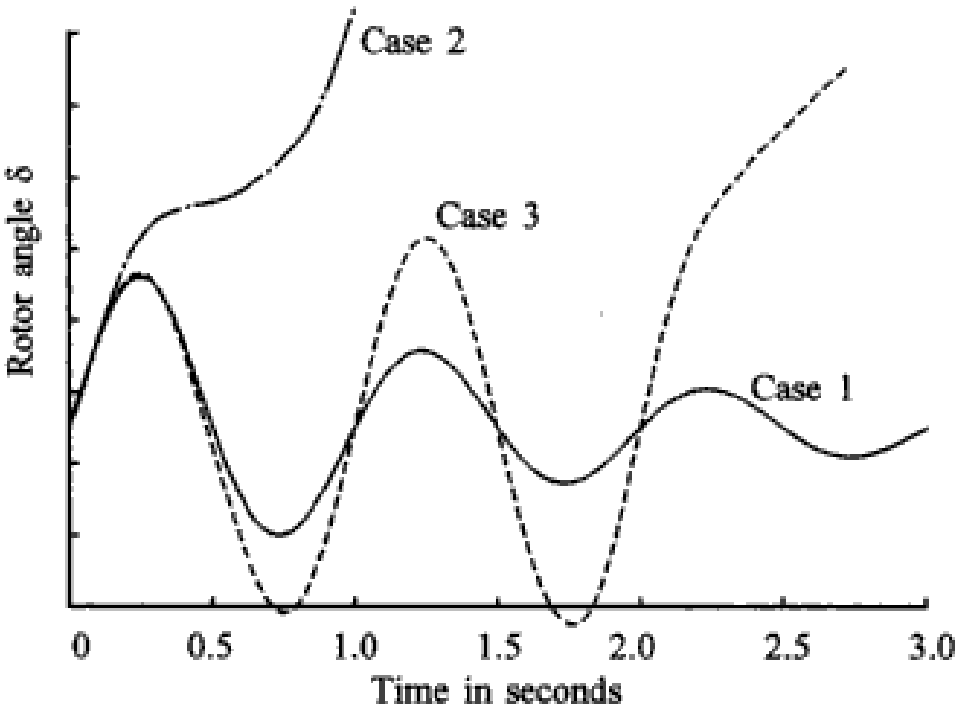


Figure 3-3: Rotor angle response to a transient disturbance [59]

3.9 Inter-Area Oscillations

Rotor angle instability can occur with groups of generators. Often these are connected by weak tie lines and the two areas act as single machines oscillating against each other. This can either be small signal or can be set off by a large disturbance. A more through review is given in [57]. This is a large and complex problem with many contributing factors, hence it is an area of intense research.

3.10 Security Assessment

3.10.1 Dynamic Security Assessment

A transmission line that is subject to a fault will experience a dynamic transient as the initial wave propagates down the line. This will either converge to a final value or diverge causing further action, such as another line automatically tripping. Dynamic security looks only at the short-term transient state of the line whereas static security concerns itself with the steady state value.

3.10.2 Static Security Assessment

Static Security concerns the system when voltage, rotor angle and frequency are in steady-state i.e can assumed to be constant. For this reason many of the nuances of the fault can be missed but this is still an important factor to consider as there are static limits imposed on components such as thermal limits on line flows.

3.11 Chapter Summary

There is a lot of confusion surrounding definitions in the area of power system reliability and security. This chapter defines all the related terms and provides examples related to the work carried out. It also helps define the scope of the work. This work looks at security, hence, while adequacy is important, it is not a central theme of this work. Finally two different types of security assessment are defined; this will be revisited in detail in the chapter on simulation.

Chapter 4

Future Power Systems

The future of power systems is well summarised in the work of Jamasb [52], this includes a looks at the likely future components from a economic basis and how these could fit into six different scenarios for 2050. These scenarios are drawn from four factors:

- Economic Growth
- Technological Growth
- Environmental Attitudes
- Political and Regulator Environment

Additionally the reports by such as the National Grid's "Operating in 2020" [67] and Renewable Network Impact Study by Carbon Trust & DTI [30] give a more up to date account of the expected problems in the near future. This section briefly highlights the changes that are likely to bee seen and some of the issues that though changes will bring.

4.1 Power Generation

There are three main renewable resources that are likely to have significant installation in the UK: wind farms, photovoltaic power and pumped-hydro power. Of these three wind is not only going to have the largest increase but represent the biggest challenge to the system operator.

4.1.1 Wind Power

Wind power is likely to be the largest area of growth in installed capacity for generation. In the UK there are a total of 274 generators over 1MW of which 76 are wind farms/turbines [15]. This ignores 527 MW of smaller wind farms.

As with conventional generation it is driven by a turbine which allows existing knowledge to be leveraged to aid design and operation. Although each turbine has a relatively small power output (see Fig 4-1 for the rapid growth in turbine sizes) the total power from a wind farm can be considerable due to the number of turbines that can be situated together. Obviously wind is unscheduleable - that is we cannot tell the generator to produce a certain quantity of power at a given time. This is a major change from conventional generation but in most parts of the world the penetration of wind is too small for this to make a difference.

The introduction of this intermittent and unscheduleable resource will have a number of effects. The impact of these effects will depend on the type, installed capacity, climate and geographic distribution of the installed turbines. The inherent intermittency of renewable generation means that it cannot displace conventional generation on a "megawatt for megawatt" basis [93], it will however tend to increase balancing market costs [45]. This is not currently a large problem but as penetration increases there will need to be larger reserves

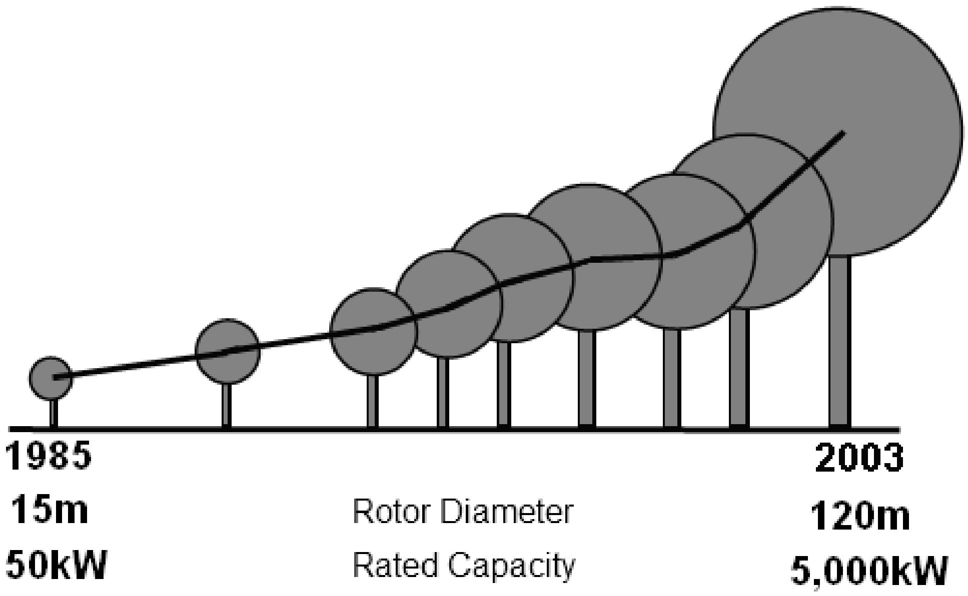


Figure 4-1: Growth in size of wind turbines [28]

or a change in market.

It was the case that wind farms were simply not made to ride-through faults, disconnecting until normal operation resumed. This has a detrimental effect on the system by amplifying the consequence of any fault. They have this feature due to the lack of reactive power control on older SCIG based turbines, in fault conditions they would consume large amounts of reactive power, possibly leading to voltage collapse. The effects of wind power on system dynamics are covered by a series of papers by Slootweg and Kling including [87]. This shows how newer DFIG cope better with faults and due to advance control electronics can have a stabilising effect post-fault. A comprehensive review of the effects of integrating wind by Ackermann [1] highlight the danger of cut-off in turbines:

> *"Wind power reductions due to the cutoff wind speed can, in extreme situations, lead to vary large power deviations."* [1]

These effects can be observed in the system currently but they are not at a level to cause concern. Presently they masked by the margin of error in load forecasting. It has been shown that in simple single machine cases or cases where the penetration is less than 20% there is no significant impact on transient stability. However, wind power does increase balancing market costs and will increasingly do so as penetration levels rise. The BWEA states that operational data from wind plants in Denmark and Germany show that the maximum power swings within an hour never exceed about 20% of the installed wind capacity [27].

Work has been done to try and determine the most financially efficient way of trading wind power [10]. This includes a table of expected generation variation between 0.5 and 4 hours after a forecast.

4.1.2 Pumped Hydro-Power

Pumped Hydro-Power is a fantastic but scarce resource. To a certain extent it is able to be scheduled and change power output more rapidly than any other generator of that size. In effect it can act as a highly efficient form of long-term energy storage. Its disadvantage from a power system point of view is its limited ability to generate for sustained periods of time and the fact that it can only be built at certain sites. In England there are very few potential places that could house such a generator but Wales and Scotland still have such places. Most notably in Britain is the Severn Estuary, which if dammed could act as a huge hydro generator and provide a significant portion of balancing power electrically close to the UK's load centre, London.

4.1.3 Solar Power

Photovoltaic power is unusual in that it does not use any form of turbine to create electricity. The process is the direct conversion of solar radiation into electricity. It could provide significant power if situated in equatorial regions but most demand is in the northern hemisphere so transfer of power, as well as political issues mean this is problematic. In the UK they are not likely to be a significant proportion of the total generation as the available resource is low.

Solar power can also come in other forms. The Stirling engine and the solar parabolic trough use heat to power a turbine which then drives a generator as per conventional generation. This resource is again promising but only in areas that receive strong sunlight though most of the year.

4.1.4 Other Renewable Generation Types

There are other renewable generation options but they are unlikely to represent a significant proportion of the plant mix and hence are not considered in this project.

Wave power has a huge potential due to the large forces at work but an efficient means of extracting that power is yet to be devised. The Pelamis wave energy converter [49], in Scotland, is one of a few attempts to harness the power of the waves. It uses a segmented snake like structure that oscillates with the waves. If an efficient scheme for extracting power could be devised the UK would be an ideal place to use it.

Geothermal power is driven by a steam turbine generating power by heat taken from the earth's core. It provides a significant proportion of power in Iceland, though many place would not have the necessary conditions. The UK does have a capability for Geothermal power but it is not likely to become significant.

4.1.5 Nuclear

Unless it is defeated on the political stage nuclear is likely to see significant growth in the future despite its shortcomings. Its disadvantages include a very high initial cost, coupled with very long start-up and ramp rates and the complex issue of disposal of the toxic waste created by the process. That said it provides high power with low fuel cost and, assuming we can perfect sea water extraction of uranium, will provide sufficient power for millions of years, billions if fusion become viable.

4.1.6 Fossil Fuels

Until we run out of fuel it is likely that fossil fuelled generators will continue to be used. They are, however, likely to change. This change will be either incremental improvements or the addition of features to reduce the environmental impact. These changes are unlikely to be significant as regards to the requirements of this project and hence will not be considered.

4.1.7 Future of Generation

In the long-term, assuming our demand for power is constant, the only sources that look viable for producing the bulk of our energy generation is nuclear and desert-based solar power [62]. That is not to say they will be our only sources but the available resource from other generators is significantly lower than nuclear and solar. This work looks to the medium term where many fossil & nuclear generators are assumed to still be operating with the rest being made up of large wind farms. The main types of generator are shown in Fig 4-2. Highlighting the ones that are to be considered in this project.

4.2 Demand Side Management & Storage

4.2.1 Interruptable Supply

Up until now most end-users expect their power to be delivered regardless of the situation. That is, with the exception of certain large factories, such as steel mills. They can have an agreement with the system operator to be disconnected for a certain price. The SO can then use this as a control action to reduce demand in an area following a disturbance. The factory will set the price so that they earn more money than they would have by producing goods, hence both parties benefit. Actions of this sort are known collectively as *demand side management* (DSM). DSM could be used increasingly in the future.

4.2.2 Smart Appliances

There are many more resources that could act as demand management without inconveniencing the end users. Cooling and Heating systems account for a large proportion of demand yet they do not need to be on constantly. If the SO had the ability to turn off everyone's fridges, freezers, heaters and hot water for one hour every day there would be a great reduction in peak power leading to financial savings as well as the ability to instantly reduce disturbances. Due to the inertia in these systems the end user is unlikely to notice the action but should still be reimbursed for the service they are providing to the Grid.

For this system to work there needs to be some form of control system attached

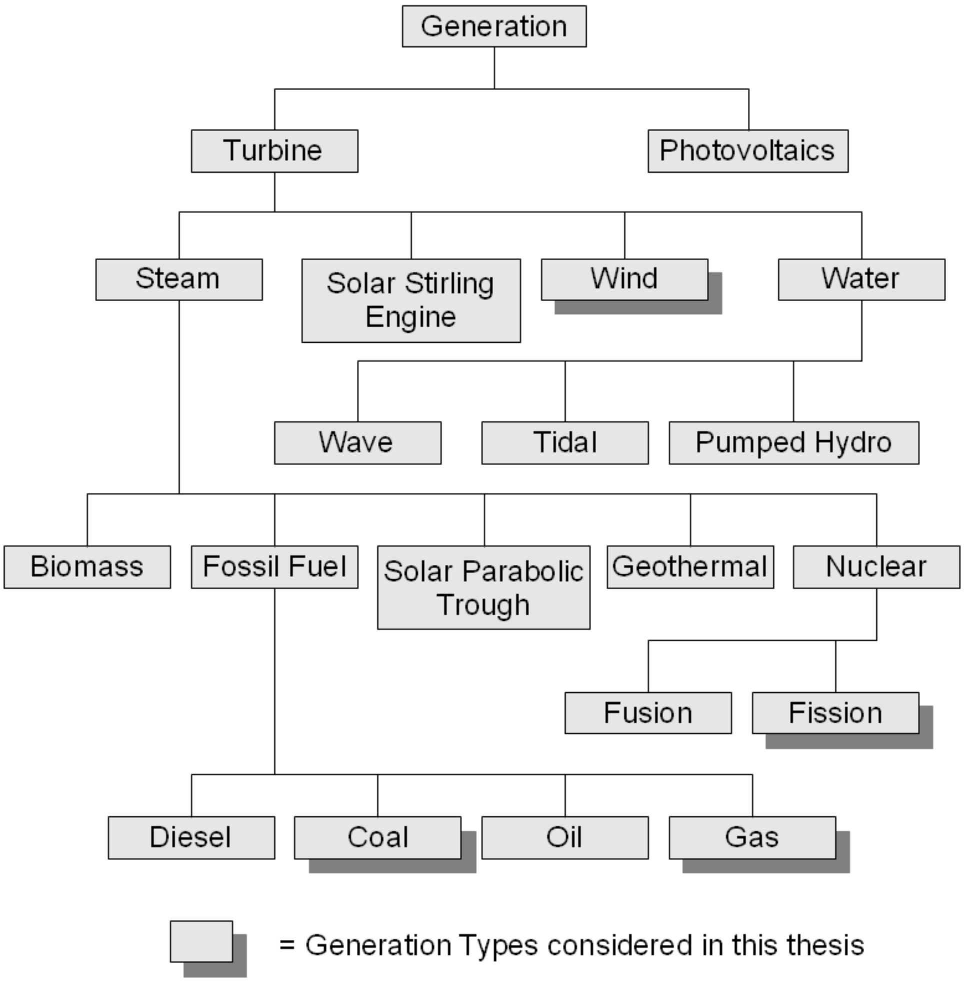


Figure 4-2: Types of Generators

to each device. The term for devices which have this feature is *smart appliances*. In effect these smart appliances are acting like a form of storage, utilising the stored heat in a boiler rather than a battery.

4.2.3 Electric Cars

Electric cars may become more widespread over the coming years. They allow much higher efficiencies to be achieved as long as the Grid increases its usage of renewable power. With them they will bring a massive increase in demand causing extra strain on the network but also a possible practical means of large scale storage. The cars must be charged regularly but for most of the time cars are parked. If the operator had the authority and means to delay charging thousands of cars for one hour the effect would be a simple means of mass energy storage. The impact on the car owner would be the minor inconvenience of having the car take longer to charge. The saving SO would make on not having to use expensive generators can go to reimbursing the owner of electric cars.

4.2.4 Storage

Batteries, flywheels, and super-capacitors seem unlikely to provide the kinds of power that will effect a system operator; they are simply not cost effective. They have been used successfully in specific scenarios but will not be considered for this work for this reason.

4.2.5 Future use of DSM

DSM is likely to be a large component of a future power system and it is likely to improve security not reduce it. It does have significant barriers to entry but these are mostly political rather than technical. This project does not consider DSM but further work could use the tools provided by this project to see how the use of large scale DSM changes the reliability of a power system.

4.3 Network, Operation & Control

4.3.1 Smart-Grid

The term smart-Grid is not firmly defined but has been used to describe how the power system will look in the future. It is really an extension of many of the things we are already seeing in power systems: demand side management, smart appliances, smart metering, computer automation, artificial intelligence, and interconnection. When these come together we get an image of a huge, highly complex system that aids the SO.

4.3.2 Artificial Intelligence

As computers become faster their use in the power system has increased. They are used both in on-line operation for such things as auto-generation control and SCADA as well as off-line planning studies. This trend can only be expect to increase with the growth in size and complexity of power systems. No longer are we in a situation where a few highly skilled individuals can intuitively optimise the generation; modern power systems require a huge amount of computation power. If this trend does continue the logical extension is for automation to extend to other parts of power system control. Even partial automation of something as complex and non-linear as a power system requires advanced artificial intelligence. It is for this reason that artificial intelligence and power systems have been linked over many years [103].

4.3.3 Interconnection

Not only is the individual demand for power causing an increase in the size of the power system but so to is the increase in interconnection. National Grid are looking into increasing its connection into mainland Europe with links to the Netherlands and Norway. This brings both advantages and disadvantages.

As the countries are in different time zones their peak loads are at different times. By connecting them together the peak demand gets averaged across both countries meaning that cheaper generators can be utilised. In the case of countries with a high penetration of pumped hydroelectricity they can further utilise this as storage for neighbouring countries.

Its disadvantages are twofold. Firstly, there is an increase in complexity of the power system. If a neighbouring country experiences faults then the impact of these will be felt by interconnected systems. As there are more total components the likelihood of one of the components in fault increases meaning the system will have to be more stable. It is not only post fault that the increased size may cause problems, the two countries may experience inter-area oscillations and as there is more than one SO involved communication becomes an added challenge.

4.3.4 Distributed Generation

The power system was designed to be top-down; generators made electricity which was passed through the high voltage transmission network to Grid supply points where it would enter the distribution system for use. This paradigm is slowly changing with the advent of distributed generation; put simply the connection of generators at lower voltage levels. Although there is no reason why the system cannot work like this, it is simply not how it was designed hence some are wary of its impact.

Distributed generation can come in a few forms. It may be very small micro generation attached to peoples homes, this includes CHP, wind turbines and solar photovoltaics. As each element is so small it does not currently require control from the SO but if a large percentage of the country had wind farms the fluctuations caused by changing weather might have to be taken into account. As it is micro generation looks to be an interesting area but of little impact to a system operator, who will only see a reduction in demand and use of the transmission network.

The other form of distributed generation is small commercial wind farms connected to remote parts of the Grid. Remote Grid elements are often weak Grid elements and the effect of generation at such a distance should be explored but is outside the scope of this project.

4.4 Chapter Summary

This chapter aims to provide the reader with a good understanding of the components of a future electrical power system. These are split into three areas: generation, demand side management, and network & operation. After looking at these components it is decided that large scale wind farms are the most interesting area of study both for their likelihood of being installed in large numbers, and the new challenges that they will bring. Smart appliances, including electrical vehicles, were identified as an interesting area of study but are beyond the scope of this work.

Chapter 5

Power System Simulation

This section introduces the different options for modelling power systems: details the parts of a dynamic simulator; discusses how to model wind power before highlighting the changes made to the load-flow program CPF to make it suitable for later experiments.

5.1 Simulation Types

5.1.1 Why Simulation is Needed

An accurate simulation is the best way to understand the operation of full electrical power networks given their size, cost and complexity. Each component in the system can be described mathematically by their electro-mechanical or electro-magnetic equations. By giving a sensible initial condition, any eventuality can be tested as long as the simulator describes the models in sufficient detail.

As performing tests on a real system is impracticable some form of simulation must be used to determine system stability. Depending on the level of detail required different types of simulation can be performed. The simplest of these is the *load-flow*, or power-flow. It only looks at static flows across the network treating the machines as static power injections. Obviously this means that certain phenomena are masked including all issues of rotor angle. It is assumed that all machines are perfectly synchronous and the frequency is exactly as desired. Despite its shortcomings it provides valuable information on voltage and overloads. Indeed, if the phenomena to be examined can be seen with a load-flow then that is the tool that should be used:

> *"It should be stressed that the simplest representation should always be used, consistent with the accuracy of the information available. There is no merit in using very complicated machine and line models when the load and other data are only known to a limited accuracy."* [104]

A load-flow is an order of magnitude faster than the *dynamic simulation*, the next most complicated simulation type. The dynamic simulation treats each machine as a set of ODEs. These model such things as the rotor, inertia and control electronics which provides much greater detail than a load-flow. The ODEs can be as complex as required and vary depending on which computer program used.

PSAT [65] is one such simulation program with the ability to do both load-flow and dynamic simulation. Its model of a basic generator can be anywhere between 3rd and 7th order depending on the level of complexity required.

The third type of simulation is the *transient simulation*. It typically operates on a very small timescale looking at electromagnetic effects. This might include lightning over-voltage studies, and protective device testing. The most common program for simulating transients is Electro Magnetic Transients Pro-

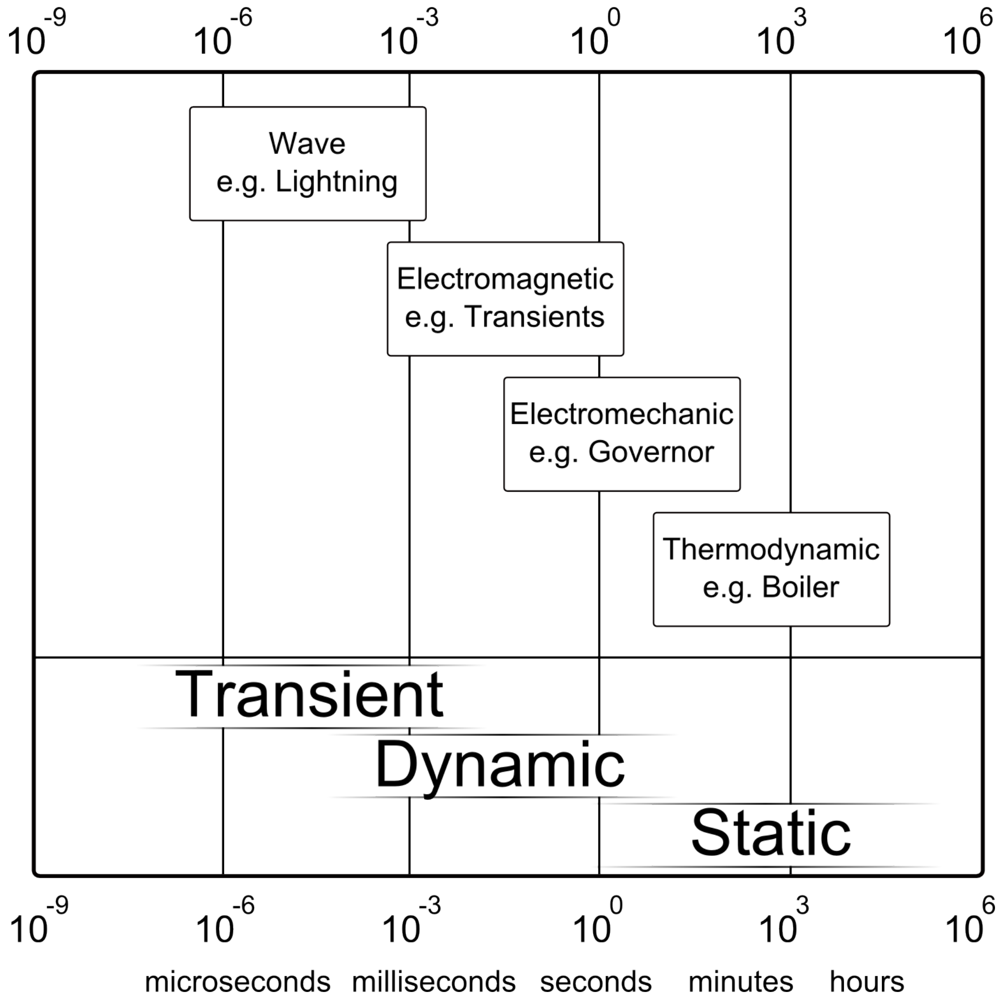


Figure 5-1: Simulator Timescales

gram - Alternative Transients Program (EMPT-ATP) [36]. The timescale that these simulation deal with is given in Fig 5-1 this is expanded in [14].

Power system simulation is not a new process. Early work by Blondel on synchronous machines at the turn of the last century [22] paved the way for Park's mathematical transform from 3-phase to the conceptually and numerically simpler direct & quadrature components [74, 75]. The detail and speed of simulations has progressed immensely with the dramatic increase in computational power. Work by researchers such as Dandeno and Kundur [50] have allowed simulations to show different types of instability, allowing them to be better understood. A full system, the size of the UK, can now be simulated to a reasonable accuracy ten times faster than real-time. A good introduction to these simulation techniques is given by Arrillaga [7].

Transient simulation is not really suitable for the work in this thesis due to the simulation time and the level of detail required on components It is for this reason that it will not be included. Both dynamic and load-flow simulators will be discussed in detail later.

In terms of introductory books on the subject of modelling power system: Meier [102] provides a good introduction to basic power systems; Kundur [59] gives a detailed introduction to all aspects of stability; Arrillaga [6, 7] details the basics of different types of modelling for power systems; Brenan [23] looks in depth at the mathematics behind work used by Arrillaga; and the IEEE Std 1110-2002 [50] updates the work by Arrillaga focusing on real-time modelling. PSAT [65] and PSS/E [83] are two industry standard real-time modelling programs.

5.1.2 Other Analysis Methods

Given a mathematical description of a system it should be possible to mathematically determine certain properties, such as stability. These methods do not guarantee a perfect solution as there are many ways to mathematically describe all the components in a system as well as the inaccuracies of measuring system parameters. The transient energy function [106] aims to calculate the synchronising torque and hence determine the size of disturbance that the system can withstand. Analytical methods are a very useful alternative to numerical simulation but will not be used for this work as they are best suited to steady state problems on a relatively small system.

5.1.3 Components

There are only a few types of components that have to be mode led. These can generally be grouped into generators and associated electronics, loads, and network components. It may be useful to simulate the main control electronic parts of a generator, depending on the situation. These are the AVR, governor and the PSS as well as the actual turbine. Loads can either be static or dynamic; in the case of dynamic loads they can be treated as an induction generator/motor. The network components include SVC, capacitor banks, transmission lines, transformers, as well as HVDC and FACTS links.

Most generators (Coal, Oil, Gas, Nuclear, CHP, Biomass, Tidal, Hydroelectric) behave in a similar way from a modelling point of view, as such they can all be treated as a generic synchronous generator, each with different settings and power electronics. Photovoltaics are connected through a DC link removing most of the problems associated with stability, but there is still the issue of intermittent supply. Wind turbines do behave differently. They also come in a number of forms. They can either operate at one or more fixed speeds, or they can vary their speed continuously with the wind. They have varying amounts of power electronics that connect them to the Grid. Ackermann [1] provides a good introduction to the different types of wind turbine configurations. Many of these wind turbines are often connected together as a wind park or wind farm. This has been shown to reduce the total fluctuations in power output over a single turbine. A problems that may surface with wind turbines is *tower-shadow*. This is caused by the drop in energy from a blade passing the tower, this drop is not significant on its own but if it synchronises in an entire wind farm it may cause oscillatory instability. There has also been problems with the lack of reactive power control of older wind turbines, this has been compensated through the use of expensive power electronics. Further information on modelling wind power is given in Section 5.4.

5.2 Design of a Dynamic Simulator

The most suitable type of simulator for looking at faults across a system is the dynamic simulator. Unfortunately most dynamic simulator programs focus on detail rather than speed. As speed is a limiting factor in the types of studies being looked at work was undertaken to develop a simple dynamic simulator that operates very quickly. This section contains the result of the research into dynamic simulation.

Before completion the project was dropped as it became apparent that it would not be possible to complete in the required time-frame. Research into load-flow simulation indicated that it would be possible to get initial results without the detail, and time, of a full dynamic simulation. Hence PSAT, a Matlab toolbox, and CPF, a program written at the University of Bath as part of their dynamic simulator were used instead.

Much of the work on this chapter is from the work done on PSSENG. PSSENG is a dynamic simulation program developed at the University of Bath by Dale [35], Berry [16] and Chan [32]. It is been used my many postgraduate students at University of Bath, mainly for automated security assessment using artificial intelligence [40, 71, 107, 12]. While it was a very fast simulator it was inflexible. It had no capability to include wind turbines hence it was not suitable for this work.

A dynamic simulator is based around a *numerical integrator*. Each dynamic component, such as a generator or large induction motor, is modelled as a set of non-linear ordinary differential equations (ODEs). The result of this is passed into the network solver which performs a load-flow. The load-flow results are then passed back into the integrator to be solved again. This repeats until the results from the network equation and the numerical integrator match. This gives us out first time-step. The same process is repeated to get subsequent time-steps after taking into account any external events. Before any of this can happen the initial state of the machines must be worked out from the known values. This entire process is shown in Fig 5-2. Machine ODE also require iteration to find a valid solution. For each machine the integrable and non-integrable parts of the ODE are separated so that simpler linear techniques can be used to solve the applicable parts. Different simulators use different methods and improvements but this is the most common [83, 65].

The mathematical model is broken down in a number of ways to speed up the running of the simulation program:

- The simulation time is broken down into discreet steps, normally of the order of 10ms. The time step can be varied such that during a fault a low value is used for accuracy while a large one is used to increase simulation speed.

- Each generators' dynamics are calculated separately from the others; this is then put into a load-flow to determine the voltages on the transmission system.

- The system is reduced from three phase to direct & quadrature using Park's

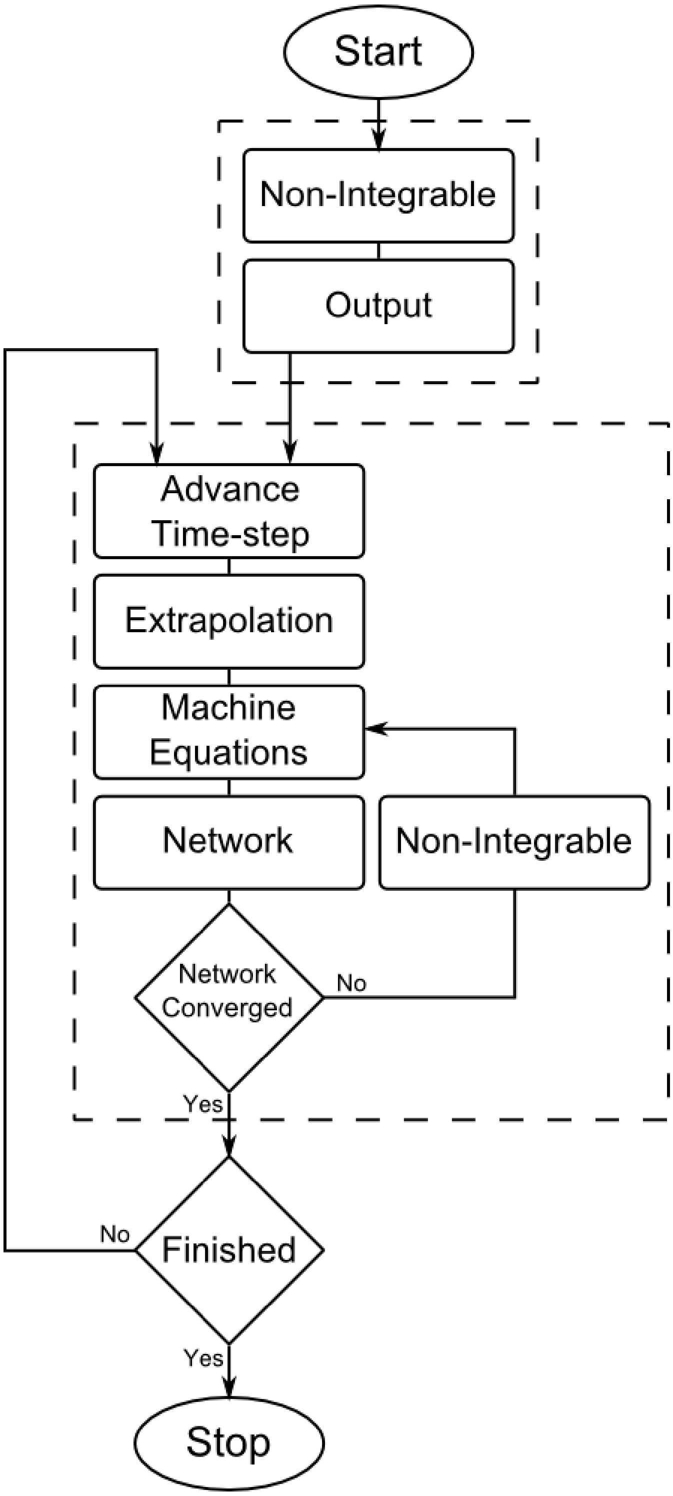


Figure 5-2: Dynamic Simulator Flow Diagram

transformation [74, 75].

- Within each generator's calculation, the linear and non-linear elements of the equations are solved separately. This allows the use of well established and fast methods for solving linear equations [23].

The choice of algorithm for solving the linear part of the generator's equations is an important one. An incorrect algorithm will produce erroneous results, often without indication that they are wrong or it may simply take an inordinate amount of time to solve. The problem of producing erroneous results is exacerbated by the fact that the controllers in power systems often contain both small and large constants, which causes many methods for solving the equations to become unstable, regardless of whether the system you are simulating is unstable or not.

Systems that have both small and large constants are known as *stiff systems*. Unfortunately the class of algorithms that provides the best results in terms of accuracy/time falls foul to this problem, having to use a very small time-step to overcome it. The small time-step means that more steps are needed to simulate the same amount of time, hence the simulation takes longer removing the previous advantage. One way to overcome this is to modify the equations by removing the small time-constants. However this is not a simple task. Wheatley [46] and Ascher [8] provide good comparisons of the different types of algorithm.

For transient stability modelling programs, such as the one being considered, the best algorithm is a trapezoidal integration algorithm, it is *a-stable*, meaning it responds well to stiff systems. By repeatedly feeding the answer back in to the algorithm an estimate for the error can be obtained and used to alter the step-size or iterate to improve the answer.

There are different ways of mathematically describing a synchronous machine, and within that there are different levels of detail that can be considered. Milano [65] gives a comparison of the different levels of detail for the *voltage behind sub-transient method*; Dandeno [50] gives a comparison of the more popular *flux-linkage* models. Both methods can work but to ensure correct results are obtained, a suitable level of detail within the models must be used.

5.2.1 Numerical Integration

A good numerical integrator is key to having a realistic simulator. In general a numerical integrator takes a set of equations describing a system, along with an initial condition, and calculates the state of the system at any point in time. In power systems the numerical integrator is used to find the solution to the linear components of the ODE.

The general form is where the integral ($\dot{x}_n$) can be calculated from the system state (x_n) and the inputs (u_n) for any value of time Eqn 5.1. It also requires that the initial system states and inputs are known Eqn 5.4. The outputs (y_n) are simply a function of the states at that time: the inputs are a function of both states and outputs.

The objective is to be able to accurately predict the outputs at any given time given only this information [33]. Sometimes the input changes based upon external factors but this does not change the calculation.

$$\dot{x}_n = f(x_n, u_n) \tag{5.1}$$

$$y_n = g(x_n) \tag{5.2}$$

$$u_n = h(x_n, y_n) \tag{5.3}$$

$$x(0) = x_0, u(0) = u_0 \tag{5.4}$$

Euler's Method

The most basic form of numerical integration uses a linear extrapolation from the current point using the slope known from Eqn 5.1 to provide a rather crude estimate for the next system state. This only uses the known values of states, input and the time step duration: h (i.e. the amount of time between two time steps) [61].

$$x_{n+1} \approx x_n + [f(x_n, u_n)] \tag{5.5}$$

The error in each iteration is proportional to the square of the time step duration h. This is known as the *local error*. Over a number of iterations the error is proportional to the time step duration and is known as the *global error* [46].

$$localerror \propto O(h^2) \tag{5.6}$$

$$globalerror \propto O(h) \tag{5.7}$$

Heun's Method

We know that Euler's method will always underestimate the correct value for lines whose slope is positive over the time-step in question. We can use the approximation for the system's states, x'_{n+1}, can be used to make another estimate, this time using the derivative from the new value. This will be an overestimate and hence by averaging we get a closer approximation to the real value.

$$x_{n+1} = x_n + \frac{k_1 + k_2}{2} \tag{5.8}$$

$$k_1 = h \times f(x_n, u_n) \tag{5.9}$$

$$k_2 = h \times f\left(x_n + h, u_n + k_1\right) \tag{5.10}$$

Runge Kutta

This method takes the idea in the previous section further and makes multiple predictions and averages them together. The most common of these is RK4. It uses four weighted predictions using the derivative at each and the middle of the time-step.

$$x_{n+1} = x_n + \frac{h}{6}\left(k_1 + 2k_2 + 2k_3 + k_4\right) \tag{5.11}$$

$$k_1 = f\left(x_n, u_n\right) \tag{5.12}$$

$$k_2 = f\left(x_n + \frac{h}{2}, u_n + \frac{h}{2}k_1\right) \tag{5.13}$$

$$k_3 = f\left(x_n + \frac{h}{2}, u_n + \frac{h}{2}k_2\right) \tag{5.14}$$

$$k_4 = f\left(x_n + h, u_n + hk_3\right) \tag{5.15}$$

Multi-step Methods

The last three methods are all single step, that is, they all only use the current state to work out the next one. A more accurate estimate can be made for continuous curves if previously calculated steps are used. This will only work on systems that have the first few time steps specified, though these could be worked out using other methods. Other method include using higher order integrals of the system states. A summary of numerical methods for ODEs is given in Table 5.1.

Stability

Although RK4 or multi-step methods provide great advantages in terms of speed and accuracy, they only useful if the solution is stable. This has nothing to do with the stability of the power system that is being modelled. Very stiff systems require very small time steps to give a correct answer, this cancels out any advantage gained by the superior method.

For any explicit integration method to be stable its time-step must satisfy the following relationship (where λ is the largest eigenvalue and τ is the smallest time constant):

$$h < \frac{2}{|\lambda|} \tag{5.16}$$

$$h < 2\tau \tag{5.17}$$

Certain integration methods are A-stable meaning they do not depend on the size of the time step. Linear implicit Euler (backward Euler) and *trapezoidal*

Table 5.1: Comparison of Numerical Methods for ODEs

Method	**Type**	**Local Error**	**Global Error**	**Stability**	**Variable step-size**	**Ref.**
Euler	single-step	$O(h^2)$	$O(h)$	good	good	Lengyel p.448
Improved Euler	single-step	$O(h^3)$	$O(h^2)$	good	good	Lengyel p.448
Modified Euler	single-step	$O(h^3)$	$O(h^2)$	good	good	Wheatley p.303
Taylor Series	multi-step					Wheatley p.301
Runge-Kutta 4	multi-step	$O(h^5)$	$O(h^4)$	good	good	Wheatley p.306
Milne	multi-step	$O(h^5)$	$O(h^4)$	poor	poor	Wheatley p.314
Adams-Moulton	multi-step	$O(h^5)$	$O(h^4)$	good	poor	Wheatley p.318

integration both have this property. Small time constants are simply not visible in the output rather than making the system unstable. As stated before the trapezoidal integration is the best method for such problems owing to its stability.

Linear and Pseudo-Linear Systems

Linear systems allow simplifications to increase the speed of calculation. Although power systems are highly non-linear they can be rewritten so that the non-linear components form algebraic equations giving new inputs to the system. In this way the advantage of linear systems can be utilised while only sacrificing a higher iteration number on highly non-linear parts.

$$\underline{\dot{x}_n} = [A]\underline{x_n} + [B]\underline{u_n} \tag{5.18}$$

$$\underline{\dot{y}_n} = [C]\underline{x_n} \tag{5.19}$$

By substituting the above equations into the trapezoidal method a simplified form can be obtained that depends only on three constant matrices. To assist the costly matrix inversion the decomposition of one matrix into lower and upper triangular form can be performed. This *LU decomposition*, as it is known, preconditions the calculated matrices. As these matrices stay constant in a power system a huge time saving can be achieved. The process of LU decomposition can be improved by pivoting. This changes the order of rows in the matrix to either reduce the error or keep the matrix as sparse as possible.

This is shown in Eqn 5.20.

$$x_{n+1} \approx x_n + \frac{h}{2}\left[f(x_n, u_n) + f(x_{n+1}, u_{n+1})\right] \tag{5.20}$$

$$x_{n+1} \approx x_n[M] + [N]\left(u_n + u_{n+1})\right) \tag{5.21}$$

$$M = \left(\mathbb{I} + \frac{h[A]}{2}\right)\left(\mathbb{I} - \frac{h[A]}{2}\right)^{-1} \tag{5.22}$$

$$N = \left(\frac{h[B]}{2}\right)\left(\mathbb{I} - \frac{h[A]}{2}\right)^{-1} \tag{5.23}$$

A further advantage of the trapezoidal method is that it is possible to iterate to improve the accuracy of the solution.

$$(L.U)^{-1}x_{n+1} \approx x_n\left(\mathbb{I} + \frac{h[A]}{2}\right) \tag{5.24}$$

5.2.2 Optimising Run-time Speed

In addition to the method described above there are many less frequently used techniques available to increase the execution speed of dynamic simulations.

Power systems will give rise to *sparse matrices*, that is most of the matrix will be filled with zeros. This can be exploited so that only the non zero sections of the matrices get calculated. Unfortunately other techniques can change the sparsity of the matrices giving the technique less impact. The matrices can be *partitioned* so that larger areas are sparse or even so that different computing cores can calculate the result in parallel. There are many format for sparse matrices. After comparing a number of them (dense, linked list, CSR, CSC, coordinate format [82] the vector of linked lists used in PSSENG was deemed to be best owing to the speed of both calculation and initialisation.

The reordering required for partitioning has a tendency to make one area of the matrix dense removing some of the aforementioned advantage. Chan [32] worked extensively on matrix partitioning for an old version of PSSENG.

Rather than try to execute parts of the matrices in parallel a simpler method is to separate the execution by generator. As the simulator already separates generators for calculation and as they already have a low input and output they are ideal for *parallel execution*. Managing the threads of execution would be difficult to do at the required speed but as multi-core chips are increasingly common it could provide significant advantages.

If the generators ODE calculations are being passed to another computation unit it would be worthwhile finding the best type of chip to use. Obviously the calculations will work on a general purpose CPU but the type of calculations involved mean that fast floating point arithmetic is advantageous. *SIMD* is an extension to x86 instruction sets in most common computers. It is made specifically for pipelining floating point arithmetic for quick solutions.

Even more specialised is the GPU, or graphics card, is made for computer games. It excels at just the task required for power system simulation. Only recently have developers been able to use graphics cards for general purpose calculations (this is known as *GPGPU* [34]). This would require a major rethink due to the idiosyncrasies of the device but the advantage should be large.

As the majority of the ODE calculations are fixed throughout the life of the simulation a possibility if to use a *FPGA* set for the specific system. This programmable computer is a halfway house between hardware and software and could be used to give huge speedups in execution at the expense of a large set-up time.

Another possible improvement proposed by Rod Dunn of the University of Bath is to somehow separate the network equations by taking into account the speed of light. As nothing can move faster than light a fault on one area of a network has zero impact on far away components in the next time step. This separation should mean that arbitrarily large systems could be simulated with only a linear slowdown rather than the current exponential cost.

Finally optimisations can be done at the top most level; the entire simulation. Edwards [40] trained an *Artificial Neural Network* (ANN) to recognise systems that would become unstable using only the first second of a dynamic simulation. That system decided if the system was definitely stable, the rest had a full 30 seconds of dynamic simulation to see the actual result. This filtered out the need for a huge number of simulations to be run and gave time for a simple SCOPF based upon a Genetic Algorithm (GA) to be run.

If many simulations need to be run on the same basic system then the problem is trivially parallelizable. Each simulation can be added to a queue to tasks. When a computer is free it simply grabs the next task off the queue. If there is a change that the exact system state will be asked to simulate repeatedly the result can be saved in a database rather than calculated again. This is called *memoization*.

As with any optimisation careful profiling is necessary to determine if the proposed changes are worth the effort. At the rate computing power is increasing these methods, while advantageous, may fall short of the more pragmatic method of simply buying faster computers as they become available.

5.3 Load-Flow

5.3.1 Load-Flow (Power-Flow)

> *"The object of load-flow calculations is to determine the steady-state operating characteristics of the power generation/transmission system for a given set of busbar loads... The solution is expected to provide information of voltage magnitudes and angles, active and reactive power flows in the individual transmission units, losses and the reactive power generated or absorbed at voltage-controlled busbars... constraints make the problem non-linear and the numerical solution must therefore be iterative in nature."* [6]

A load-flow is one of the most common forms of simulation owing to its simplicity and speed. To perform a load-flow we require knowledge of certain parameters on each busbar. There are three types of busbar depending on the components attached:

1. PV - Voltage controlled busbar - Generator. Assumes P & V held constant by power electronics.
2. PQ - Von-voltage controlled busbar - Load. Assumes that P & Q is not affected by small voltage changes.
3. $V\theta$ - Slack (swing) busbar. Corresponds to the one busbar that does frequency control.

The PV busbar represents a generator where we assume governor action holds the real power P at a given value, hence it is specified and an AVR fixes the voltage in the same way. A PQ is used for busbars without control from an AVR. These are mainly load centres without an accompanying generator, hence the complex power is known. It is assumed that the power will not be affected by small changes in voltage, a reasonable simplifying assumption in most instances.

One busbar is needed to take up the slack as the load-flow requires matched generator-demand balance and the line losses are unknown. This slack busbar has its voltage fully specified in both phase and magnitude. In most instances a phase balanced operation is assumed hence only one phase is modelled but it is possible to have a three-phase load-flow [7].

Initial conditions are supplied to start the iterative equation assuming that the phase is zero and voltage is one for busbars where it is not known. The iteration continues until the mismatch between power and/or voltage is below a certain threshold.

A power-flow calculates complex power flow and losses on each power line as well as the following data for every busbar on the system:

1. P – Real (active) power
2. Q – Reactive (quadrature) power
3. V – Voltage magnitude
4. θ – Voltage phase angle

A load-flow is an invaluable tool but it has its limitations. Most of these come from its inability to simulate dynamics which results in many stability effects being masked. It also has limits on its ability to accurately show the steady state effect of large disturbances.

A load-flow can be used in conjunction with a dynamic simulation to partly overcome these limitations . A dynamic simulation can determine a set of load-flow conditions that cause problematic transient phenomena. These conditions form *constraints* that can be used with a load-flow to detect possible stability issues that it normally would not be capable of detecting.

A dynamic simulation and a real system will respond to a line outage in a complex way, whereas a load-flow can only compensate for the change by either changing the reactive power profile or changing the power of the slack bus. Because of this, a poorly designed load-flow simulation can become more a test of the capabilities of a slack busbar rather than the system as a whole.

Every generator will experience a slight change in power following a line fault on a real system. This relationship is non-linear but depends on network topology, prime mover inertia and generator droop characteristics.

A distributed slack busbar compensates for this shortcoming in the load-flow by having more than one slack bus. At its logical extreme, if every busbar acts like a slack busbar the load-flow will behave more like a dynamic simulation. It obviously will not be able to simulate dynamics but it is more likely to end up at a similar steady state solution.

This requires an equation stating how to split power between the slack busbars. This basically is a simplified simulation of inertia, control electronics and droop characteristics. The simplest possible way to achieve this is to assign the mismatched power to be made up by the slack generators according to their current power output. Pseudo-code for this mismatch fixing is given in Appendix C.

Work was done to modify CPF to allow a load-flow to more accurately deal with faulted systems by using this special form of distributed slack bus.

5.3.2 Optimal Power Flow (OPF)

Owing to their rapid simulation speed, load-flow programs can be embedded inside optimisation programs. There is a variety of things that can be optimised, as well as a variety of techniques for the optimisation [107]. PSAT includes an optimal power flow (OPF) program which selects the lowest cost generation that has a load-flow solution without overloads.

This kind of OPF can be seen as an incredibly simplified simulated SO in that one of the roles of the SO is to run the cheapest generation available. The SO's other main operational role is to ensure security; there has been work done on creating automatic security constrained OPF programs but there is still much to be done in that field.

5.4 Modelling Wind Power

Wind turbine output is unscheduleable it therefore needs to be predicted unlike conventional generation. Modelling wind farm output is a complex task. Not only do the electromechanics of the machinery need to be considered but so to does the weather.

There are different methods required, depending on the data available and the type of task. If, as in the case of this thesis, an artificial system is used then there is not going to be any real data. It is therefore a task of matching a realistic set of data onto the system.

In a real system there is likely to be some form of historic wind speed database. These speeds can be taken at face value but it is unlikely that there will be a large data-set available at the wind turbine sites themselves. Most data is from weather stations. The task then becomes a case of finding how different the turbine site is to the nearest weather station. This task is known as MCP analysis (Measure Correlate Predict) [97, 81].

Synthetic data may be preferable [94] even if a real system is used as the basis for study. The main advantage is that synthetic data does not suffer from a limited number of data points to draw upon – more samples can be taken at will.

5.4.1 Wind Speeds

The wind speeds are chaotic and dependent on a number of factors. They are both spatially and temporally correlated. This spatial correlation is not just a function of distance but is effect by terrain including valleys, vegetation and buildings. Work by the University of Bath separated the UK into 20 zones, further split by terrain type (lowland, highland, coastal, offshore) to ensure a more accurate model [99].

The time correlation has many periodic cycles, most notably diurnal and seasonal effects as well as short term gusting. Weather fronts will show a change of wind speed moving across a region over a period of time. There is even a correlation with demand level through temperature; a low temperature will affect wind speed as well as causing an increase in demand. This means wind speed prediction is highly complex; luckily there are synthetic models as well as historic data available.

5.4.2 Wind Farms and Turbines

Aside from the wind speed the design of individual turbines as well as the wind farm needs to be accounted for.

The altitude that wind speed is measured at a weather station is often 10m. This is well below the hub height of a wind turbine and hence the speed needs to be altered to reflect this. The term for the way wind speed changes at altitude is wind sheer. This is often a significant effect especially with the hub height of newer turbines reaching over 100m.

The layout of a wind farm will cause two significant effects. One is that there will be wake losses caused by having many wind turbines in one area. Careful planning can reduce this but in [77] wake losses account for an 8% reduction. There will also be the positive effect of spatial smoothing. A wind farm will have the effects of gusting averaged out across each turbine leading to less dramatic changes in power when compared to single turbines. This averaging effect also takes place across the country but this effect should automatically come out of the wind speed model.

Early research by the author involved looking into so called '3p' effects. This included the drop in power as each of the three blades passed the tower. On its own the magnitude would not be great but if blades were to synchronise, either from electromechanical effects or wind movements, the effect could be significant. A literature review, shown in the next section, indicated that this effect was negligible and that wind farms could be modelled as a single turbine for system-wide studies.

There are standard equations [1] for converting a wind speed into a generator output power for certain types of turbine and blades. There is four parts to

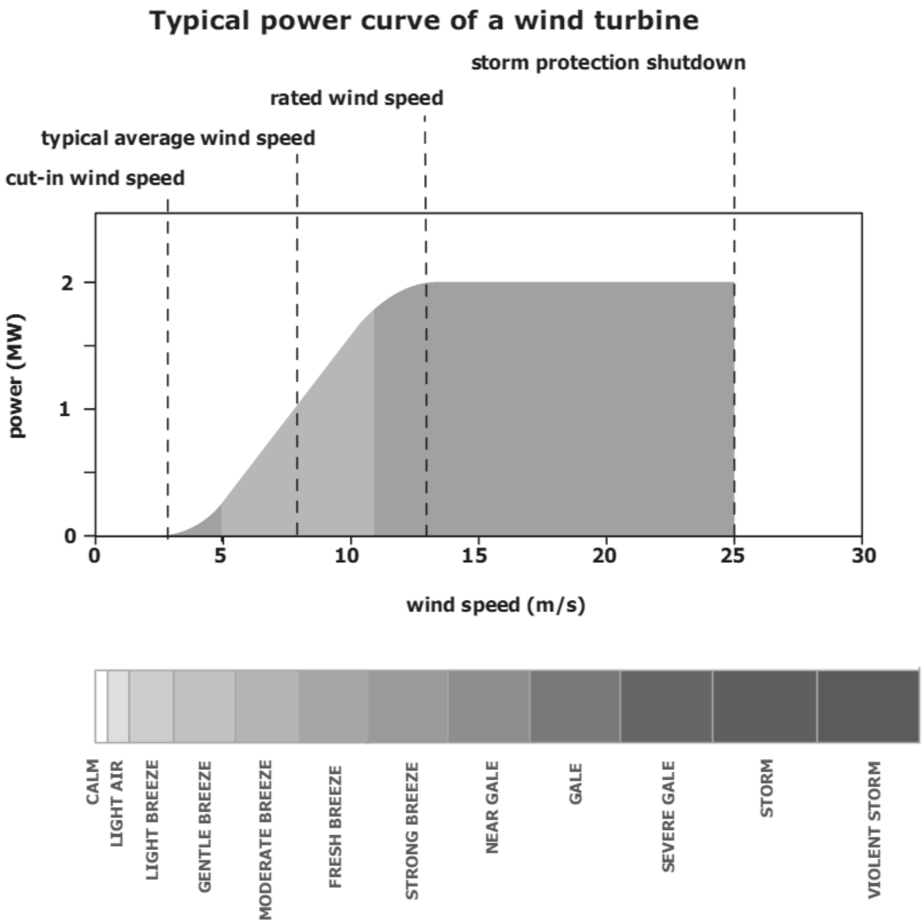


Figure 5-3: Wind Power Curve [28]

this curve Fig 5-3. The first is where the wind speed is insufficient to cause any generated power at all. Next the power ramps up almost linearly to a maximum before reaching a cut-off where the blades are forced to stop moving to prevent damage to the machinery.

The cut-off region is of great interest as there is a large change in power for a very small change in wind speed. It is not hard to imagine a situation where all wind farms are running at full capacity allowing conventional generators to be switched off. If then wind speed was to increase across the country many wind farms could suddenly stop generating due to this safety cut-off. Because of this a larger amount of spinning reserve is required.

5.4.3 Dynamics and Power Electronics

There has been much work done in the area of wind power generation modelling. The Electrical Power Systems Group, Delft University of Technology, Netherlands provides great detail on dynamic modelling of wind turbines, especially the work by W. L. Kling, J.G. Slootweg, H. Polinder. The most relevant of their work is on initialisation of wind turbine models [89], and two papers on the modelling [90, 84] culminating in a General Model for Representing Variable Speed Wind Turbines in Power System Dynamics Simulations [86].

Their work progresses in two directions.

1. In creating an aggregated model for wind farms [88], where it is found that their combined model accurately reflects the detailed model they had created before, even during fault conditions, confirmed by other studies [31].

2. They look at the stability effects of distributed generation [80, 79, 85, 101] and find that, due to the inability for induction generators to control reactive power, they are a destabilising influence on the network as a whole, whereas double fed induction generators (DFIG) are much more stable.

This is reflected in work by other Institutes which say that normal induction generators can cause voltage sags [48], which can lead to voltage collapse, and that double-fed induction generators are not only better than normal induction generators, they are better than synchronous machines due to their power electronics [100]. By having a generator that causes voltage collapse during faults they must be tripped. This adds to the severity of the fault [43]. Luckily most recently installed generators are of the variable speed DFIG type.

Reactive compensation can overcome the destabilising effect of fixed speed wind turbines as shown by Palsson et al. [73] but these are expensive components.

It is also possible that power storage devices, like flywheels, could average out fluctuations but this technology is not widely exploited and is expensive. Nick Jenkins at Electrical Energy and Power Systems, The University of Manchester, UK takes a higher level approach by looking at the stability aspects of large wind farms on the transmission network [53].

The paper by Thomas Ackerman et al., at Royal Institute of Technology, Sweden, covers many aspects of wind power security [43].

> *"The TSO had been unable to assess the impact of wind generation on system stability due to the lack of suitable dynamic models.*
>
> *With increasing wind capacity, the TSOs became concerned about the impact of high levels of wind generation on system stability. The integration of wind power has been hampered by the lack of suitable dynamic models for use in transient stability studies."* [43]

Although they go on to say *"Wind Turbines do not cause transient stability or any dynamic oscillation issues"*, they do agree that scheduling can become problematic. *"High wind power penetration levels require a rethinking of the power system operation method because wind power cannot be scheduled with the same certainty as conventional power plants."* In terms of variability the paper says, *"large turbines with variable speed operations tend to absorb gusts"* and short term fluctuations may become a problem when large off-shore farms are installed. Wind power reductions due to the cut-off can, in extreme situations lead to very large power deviations.

Finally, they state that increasing wind power penetration usually requires more frequent usage of long-term reserves, which would increase balancing market prices, and that wind output may have to be curtailed for stability reasons.

5.5 Chapter Summary

There are different techniques for reasoning about a power system. This chapter compares different methods. Two in particular, load-flow and dynamic simulations, are explored in detail. This is due to the fact that simulation accuracy and speed are vitally important to the success of the proposed work. There was extensive work done to try and create a very fast dynamic power system simulator. This presented a few promising areas of future work. The chapter ends with a detailed look at the specifics of modelling wind farms.

Chapter 6

Security Assessment Schemes

This chapter introduces the problem of security assessment from the point of view of a system operator (SO). After detailing the problem it goes on to compare the traditional deterministic schemes with the less used probabilistic method.

6.1 The Role of the System Operator (SO)

The task in security control is to keep the system in the normal state. The normal state is defined as having all system variables within normal range with no overloads; that the system operates securely and is able to withstand a contingency without violating the constraints [59]. Security assessment is the analysis of data from security monitoring. The decentralisation of power markets has caused power systems to be driven closer to their operation limits, trading off security for cost. The optimal way to do this trade-off is by having the most accurate security assessment schemes available.

If a sub-optimal security assessment scheme is used it may lead to costly over-securing in certain conditions and dangerously low security in others. This will mean that higher safety margins must be put on poor security schemes which will lead to an unnecessarily high cost.

An accurate scheme should take into account both likelihood and consequence of every possible event. In fact a security assessment scheme should accurately represent the risk of running the system in the current state where risk is a function of both likelihood and consequence for every possible event [21].

$$R = \sum_i L(e_i) \times C(e_i) \tag{6.1}$$

Where R is Risk, e is an event, L is likelihood, and C is consequence. This equation is used in a number of fields in different ways. In event planning consequence and likelihood are rated on a five point scale. In the financial industry likelihood can be seen as a probability and consequence financial (i.e. lost income in dollars). Power systems can also use the equation in this way alternatively consequence could be treated as MW of lost load.

A further definition of security [9] gives further insight into the problem:

> *"Security may be defined as the probability of the system's operating point remaining in a viable state, given the probabilities of changes in the system (contingencies) and its environment (weather, customer demands, etc.)."* [9]

A perfect system is infeasible in practise due to time constraints. In the UK, system operators have only one hour to perform final balancing actions between the FPN - the point when they are supplied with the final load/generator data, and the point of delivery. Though the balancing market lasts only one hour, the system operator is likely to make predictions on generator bids beforehand for use in preliminary calculations. Power system security is all about coping with likely changes. Kirschen [54] provides a good overview to some of the challenges involved.

Security cannot easily be defined in absolute terms; there are many trade-offs to be made. The goal is to achieve an acceptable level of security, at the least cost. To deal with the massive complexity involved in this calculation many simplifying assumptions are made and the use of computer simulations are invaluable.

6.2 Security Assessment Schemes (SAS)

The term Security Assessment Scheme (SAS) means a set of rules that are required for a power system to be called secure. For instance N-1 is a SAS which states that a system can be called N-1 secure if, and only if, any single component outage still leaves the system in an acceptable state. Obviously for this scheme to be used in practise the set of components to be considered needs to be more accurately defined as well as the term ‘acceptable‘ in this context. SAS are used to ensure a system remains reasonably secure. If the system fails the SAS then further operator action must be taken to ensure it passes. This necessitates simulation to verify the contingencies that are considered.

A SAS in the context of this work does not match wholly with reality. In the UK the SO, National Grid, has a team of engineers creating predictions, contingencies and constraints months in advance of delivery. The predictions are based upon expert knowledge aided by scores of specialist programs and simulations. These are handed down to other teams to refine and update based upon better predictions. These form a set of likely events which are tuned, not only to the specific system, but to the weather, time of day, and even the schedule of TV. Finally, when the FPN (final physical notification) is received, only minor tweaks *should* be needed to be made. Then, as power is delivered, automatic actions as well as constant manual tuning keep the system in check.

This thesis uses a more simplified idea of security assessment. It assumes that one program is given the task of assessing whether the state the power system is in is acceptable. It is therefore the purpose of a security assessment scheme to return either a pass or fail for a system in a given state. The system operator then makes balancing actions which change the system state until it has passed the SAS.

If the SAS reports too many operating conditions as passes then costly emergency operator action will be regularly required. If it reports too little passes then the system is being needlessly over-secured at additional cost. Therefore there is an optimal level of security for the system, henceforth known as the security threshold. There is a direct trade-off between security and cost, which must be managed.

6.3 Designing Goals of a SAS

There are five criteria that a SAS should be measured against. It should be:

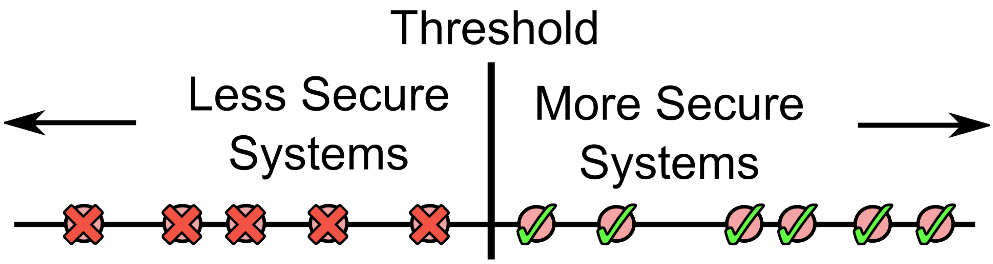
- Economic,
- Secure,
- Fast,
- Verifiable, and
- Fair.

The role in designing a SAS is not only to pick the best level of security for the system but also to make sure the SAS accurately represents the security level. The problem arises because we cannot accurately determine the security of a power system in a given state. The assumptions made in designing a SAS may lead to certain conditions being over-secured and others under-secured. The more accurately the SAS can be designed, the lower the margin of error and the greater the financial savings.

In this context we use the definition of security given in [60] - that security is the ability of a power system to remain stable and within operational limits following any likely disturbance. In this way security is a function of both the current state of the system and any changes that occur during delivery. It is for this reason that weather can effect the security of all power systems, even ones without renewable generation.

Given this definition it not easy to quantify the security not only due to the number of unknowns but also due to its multi-faceted nature. For the purpose of this discussion let us assume the security level of a power system in a given state can be calculated as a number. Further, let us assume that we have a large number of likely system states. A perfect security assessment scheme would report a pass to all systems that have a security level above the security threshold and a fail to all those below.

This can be visualised as follows: Assume that the security level of a power system in a given state can be represented by a probability that the system will, due to the unexpected changes during delivery, be in an unacceptable state such as a blackout. Further, let us assume that the security threshold is set to 'less than one blackout every 25 years' . If there were more than this there would



System ID	Security	Desired SAS Result
1	20	✗
2	53	✓
3	75	✓
4	46	✗
5	25	✗
6	67	✓
7	40	✗
8	...	...

Figure 6-1: Example of a Perfect SAS

be severe financial penalties from the regulator, less and the operator could be paying more than is necessary to secure the system. An ideal SAS would report a pass for all systems with a probability of blackout being less than one in 25 years. This is shown in Fig 6-1.

Fig 6-2 shows a number of different theoretical SAS marked against the same set of system operating conditions. We can see that 6-2-a is perfectly accurate and precise. It only ever reports a pass to those over 50. This is impossible to achieve in practise due to time constraints.

6-2-b is equally precise but the additional passes mean it has low accuracy and is under-secured. If this was used as a real SAS we would expect emergency operator action to be regularly required.

6-2-c is again precise with low-accuracy but this time it is over-secure. The downside to this option is cost. As stated for 6-2-a it is not possible to have a perfectly precise SAS; 6-2-d shows a lower precision SAS with high accuracy. This is more like what would be expected from a real SAS.

If we have a very low precision SAS then it would have to be altered to be over secure. The reason for this is that only a certain frequency of interruption will be accepted. To ensure that a low precision SAS will have this low frequency of interruption it must have a built-in safety margin. This safety margin is costly.

In addition to the precision and accuracy of the SAS, which give rise to cost and outage rate, there are other criteria that must be addressed. Firstly, the results must be verifiable; that is following an incident such as cascading outages or brown-outs it must be possible to determine who, if anyone, is at fault. The SO has a responsibility to maintain an acceptable reliability and if it had used an inadequate SAS or the SAS is not being used correctly then they should be

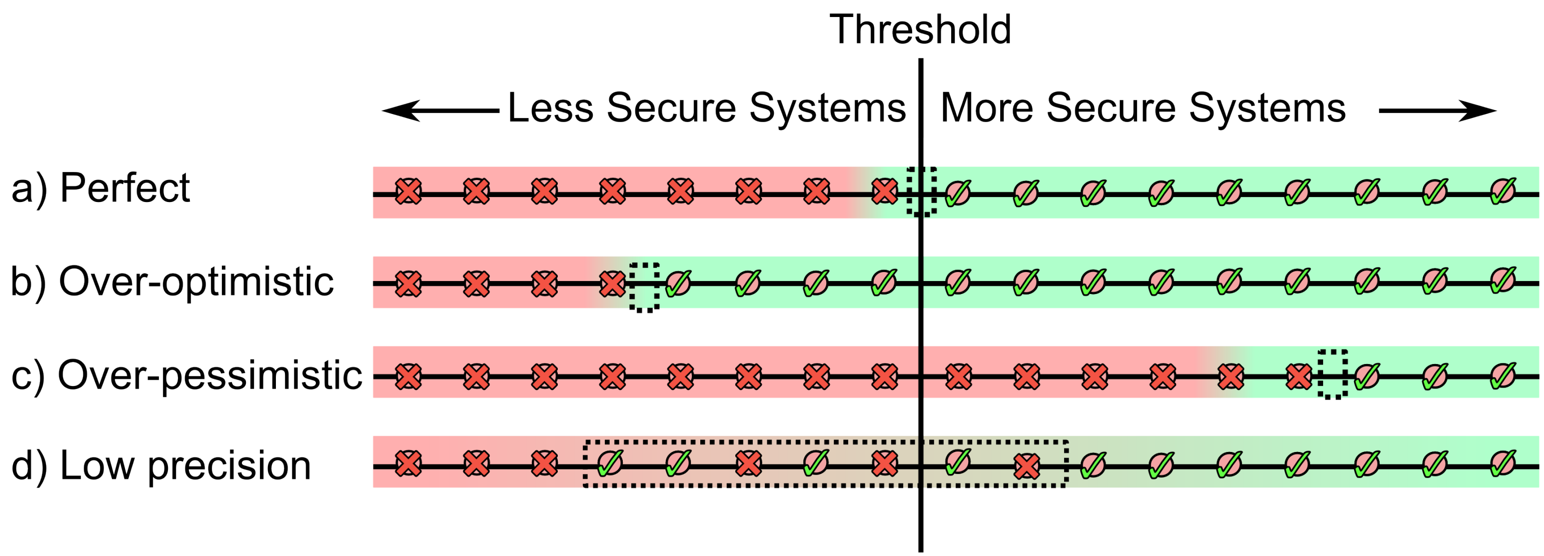


Figure 6-2: Comparison of SAS

held accountable. But as stated above there is an optimum level of security and therefore an optimal number of cascading outages, brown-outs and loss of load. If the SAS is deemed adequate and was followed correctly then a certain number of faults should be expected as part of the benefit of having cheaper electricity.

A further requirement is that it does not disadvantage any particular generator and ideally should allow for environmentally friendly operation by rarely curtailing renewables. It has been the case in the UK that wind generations have had to be curtailed for stability reasons.

This must all be able to be run fast enough for the SO to make an necessary modifications and rerun the SAS until the system is adequate.

6.4 Deterministic Power System Security

Traditionally, security assessment schemes manage this complexity by using a set of credible contingencies. These are meant to represent all likely events with a severe consequence – they should be events with the largest product of likelihood and consequence. There has been significant work in determining which events to include [9, 64, 37]. These contingencies are often different for each half-hour delivery period and vary based upon weather and season.

The set of normal contingencies that are considered is given in [59]; a sub-set of this is known as *N-1*. N-1 is a security assessment scheme that considers the failure of one component (line, generator or transformer) at a time. In other words, the simultaneous failure of two components is considered too unlikely to count. There have been various modifications to N-1, including the addition of correlated failures, such as the failure of two lines on a common right-of-way.

The UK SO does consider a sub-set of N-2 contingencies where two simultaneous failures are considered but not all possible double failures are checked. This traditional contingency screening has worked well for many years but with the paradigm shift in generation, that is coming in the form of local, unscheduleable generation, it is time to review this idea.

The problem with all such N-x methods (N-1, N-2, etc.) is that they treat likelihood in such a crude way; it assumes all contingencies to be equally likely.

Another disadvantage of any deterministic security assessment scheme is that it can lead to problems if something outside of the expected set happens.

In the UK, the simultaneous failure of two generators was considered non-credible; hence, after it occurred during 2008, emergency operator action was needed. This is far from the only incident of its kind. 2003 saw more than its fair share of major incidents with North America, Libya, London and Italy [41] all experiencing widespread black-outs.

The credible disturbances are no longer best represented by discrete events. The change in wind power over a one hour period is significant, spatially correlated and continuous. It is possible to treat wind power as a contingency by quantisation at a large resolution into a small number of likely states. In performing this method one must be careful to have enough possible wind states to accurately represent everything that could happen.

If wind farms continue to be built at the current rate wind power will become a major component of the UK's plant mix. Unless the market changes this is likely to disadvantage wind farms due to their uncertainty [26]. Some may say that their cost will accurately reflect their difficult of incorporating such uncertainty in a power system but there is no point in building wind turbines if they are not to be fully utilised. Renewable power should be encouraged from an environmental point of view. However the technical challenges must be overcome. In reality the likelihood is that the wind resource as a whole will not fluctuate drastically, especially if turbines are distributed over a large geographical area. But the risk must be quantified and verifiable before new security assessment methods can be implemented.

6.5 Probabilistic Power System Security

Risk-based, probabilistic, security assessment uses probability much more directly. It is not a new idea, it has been used in other industries since the 1960's; and has been studied in power systems since the 1970's [76]. But it is computationally expensive and often harder to produce a verifiable result. As the disadvantages of deterministic methods impacts financially, the focus has begun to turn towards probabilistic methods [64, 54]. This is already happening as balancing market prices have been driven up by wind power [26].

Sobajic et. al. [91] provides a brief overview of four different approaches to the problem of stability assessment. The paper then discusses one such pattern recognition method after highlighting the works of Patton, Billinton, and Wu as contributing significantly to probabilistic methods.

After an extensive literature review, including the mention of Monte Carlo methods, McCalley [63] goes on to determine a set of deterministic rules based upon risk-based methods.

Monte Carlo methods are a type of algorithm used commonly in risk assessment where a system with uncertainty is repeatedly sampled. In this way Monte Carlo Methods lend themselves well to the task of probabilistic risk assessment. A comparison of different modifications to standard Monte Carlo Methods is given in [13], there a financial value is placed upon outages to give an absolute level of comparison.

For an up-to-date review of the work in risk-based security assessment see [56]. It also provides a good conceptual representation which shows how risk-based security assessment will more accurately reflect the actual level of security. Xiao [105] shows graphically how traditional SCOPF can produce a more risky solution due to its fixed constraints.

By assigning a severity to each type of disturbance Ni [70] created a system for aiding control room decisions based on risk.

6.6 Limitations of N-1 Security

The list of contingencies to be simulated has traditionally been where each line, transformer, and generator are individually taken out of service [56]. This generates a set known as N-1, where N represents the number of system components; to be N-1 secure is to have a system which remains stable after any N-1 contingency occurs. The UK operates somewhere between N-1 and N-2 security (the set of all possible failures on any two components); that is, any single component fault and credible double fault should not cause the system to enter an emergency state.

In this way N-x security treats the probability of failure in a simplistic way; it assumes all contingencies to be equally likely. It fails to recognise that intermittent non-scheduleable generators have a quite inaccurate prediction of their output power [10]. It also fails to take into account correlated failure caused by common right of way, common structure or extreme weather conditions.

Additionally, the set of credible disturbances is no longer discrete. This means the contingency analysis itself is losing some of its past merit. In the case of wind generation the output is stochastically variable, by treating it as a contingency you ignore the fact that the output can vary continuously between its rated capacity and zero power output. Using traditional security assessment will increasingly disadvantage renewable generation as penetration grows [29]. The treatment of variable load or supply under N-1 would be one of three cases:

1. It is treated as an insignificant variation and hence taken at its expected value. This is how variation in load is currently treated.

2. The worst case of possible values is used for testing against each contingency. For wind this would be either no output or maximum output.

3. The variation is treated as a separate contingency, meaning it would not be tested in conjunction with other faults.

To treat the curtailment of wind power as a separate contingency means that it will not be considered in conjunction with other faults in a N-1 security analysis, this will cause an over estimation of system security. Whereas, if it is treated as a unknown variable and hence put at its worst case, i.e. either full or no power generation, then wind will be the cause of an under estimation in system stability. For an individual generator there is only a 29% chance that the output will remain within 5% of what it currently is; but there is an almost negligible chance of it changing across its entire installed capacity. For this reason wind cannot be treated as an insignificant variation.

In reality there is a certain probability that the output will be at any particular value. This probability density function can be constructed from historic wind data. These have to be considered with each contingency. For instance the stability must be assessed while the wind is doing X with contingency Y.

6.7 Chapter Summary

This chapter sets out exactly what is required in a security assessment scheme. It then performs a thorough literature review of security assessment focusing on comparisons between deterministic and probabilistic methods. This leads to an analysis that forms the basis of the novel work presented in later chapters. The chapter finishes by detailing the problems faced by using deterministic N-1 security.

Chapter 7

Criteria for Security Assessment Schemes

This chapter covers how security assessment schemes are assessed and compared then proceeds to detail the creation of a new method for comparing security assessment schemes. Finally, results are presented showing the novel method in action.

The work is based around a two stage Monte Carlo Sampler which uses a load-flow simulation of the IEEE-RTS Area 1. The first stage generates *scenarios*, representing possible states the power system could be in. The second stage is used to create the probability that each of the scenarios from the first stage are acceptable. In this context acceptable means that no emergency operator action is required during the half-hour delivery period. This data is then tabulated to form an overall picture of how secure the system is in a number of cases. This can be useful in its own right but it can be further used to compare security assessment schemes as described below. The outline for this process is given in Fig 7-1.

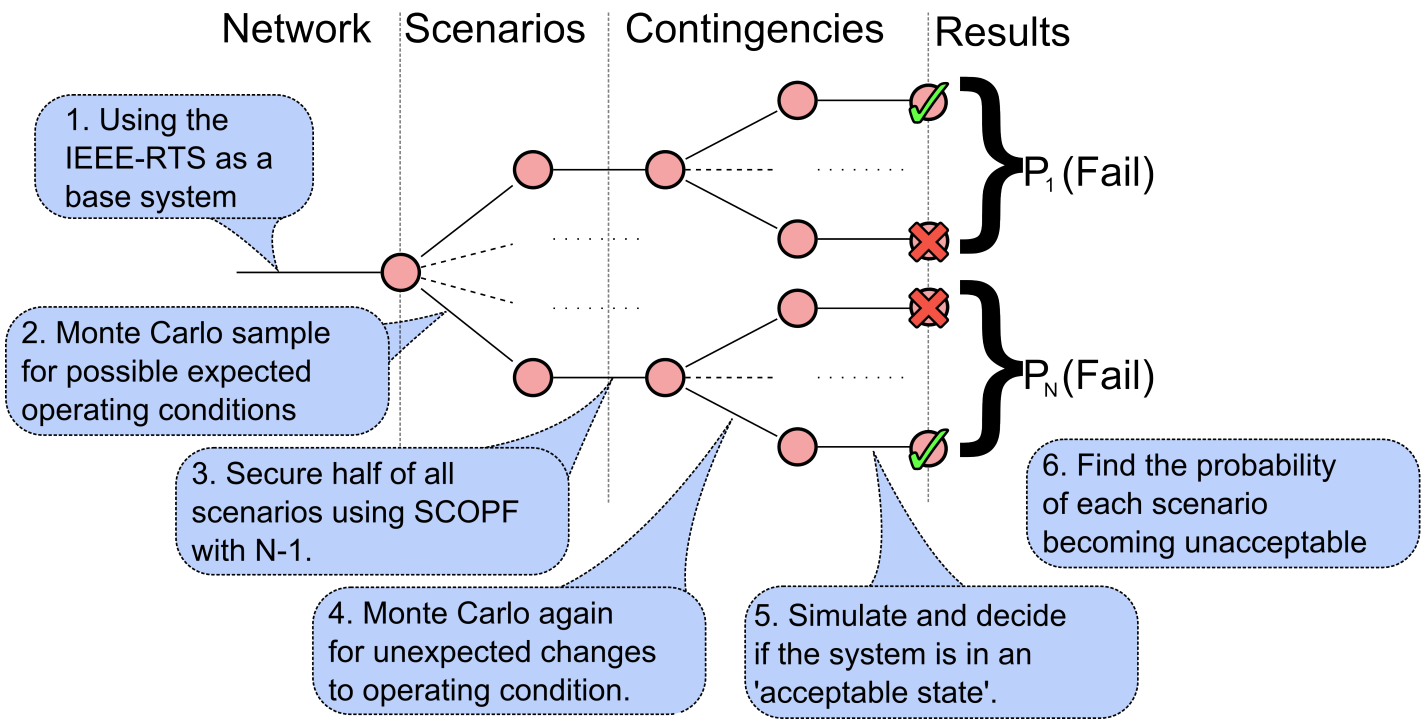


Figure 7-1: Structure of Comparison Program

7.1 Method of Comparison

Although there is significant work on different types of security assessment scheme and how well they perform there is relatively little work performing a direct comparison between two such schemes.

Lets say we have a SAS such as N-1. In other words the system is said to pass N-1 if the failure of any one component does not leave the system in an unacceptable state. We can test N-1 against each of our many operating conditions and see if it passes or fails. This can be shown graphically as in Img 6-2 above. We can take a number of factors from the results that this gives us. Firstly we known for this specific set of operating conditions how many times our SAS under test differs from the perfect SAS described above. Obviously we want a low number of cases where they are in error.

We can also see whether the operating conditions that were in disagreement were false-positives or false-negatives. A false positive means a pass on the left of the security threshold; this is a system more likely to cause a problem than has been planned for. It is an under secure system. A false negative, a fail to the right of the threshold, represents an over secure system. It is likely that a SO would consider a false positive (under-secure) worse than a false negative (over-secure).

By looking at the specific operating conditions that were in disagreement it may be possible to determine whether the SAS is lacking in some respects. It may, for instance, misrepresent only systems where the wind variability is high.

We can also gather information by looking at the difference between each of the points in disagreement and the threshold. This gives an indication of how badly the SAS performs when errors do occur. If a very insecure system, where a blackout has a one in a thousand change of occurring, is reported as a success by a SAS then this is a larger problem than one with a chance of one in ten thousand. In other words it would be a very poor SAS if it reported that a few very insecure scenarios were actually acceptable.

If we allow such a system to run in that state then we are open to the financial cost of whatever stability or limit violations that occur. We can sum up the difference between each operating condition in disagreement and the threshold to come up with a value for the severity of error in the SAS. It should be noted that this number is not meant to represent anything in reality but is simply an indication of how well the SAS is for those operating conditions tested on that specific system. It can however be compared to another SAS run over the same operating conditions on the same system, to see which is best.

7.2 Monte Carlo Sampling

Monte Carlo Sampling (MCS) is simply the term given to the random sampling of events by their probability. If enough samples are taken properties of the underline system can be understood. The alternative to MCS is analytical techniques these, rather then performing sampling, use the probability data itself to gain knowledge of the underlining system.

For instance if we want to know the probability of a fair coin landing on heads three times in a row we can either use the analytical technique which simply gives $0.5^3 = 0.125$ or we can perform MCS. For this a computer program would be set up so that a pseudo-random number generator (PRNG) produces uniformly distributed numbers between 0 and 1. If the random number is above 0.5 the result is a head, otherwise it is a tail. After performing many samples we can see how many had three heads in a row as a percentage of the total.

This should approximately match the analytical value but as MCS is a random approximation it cannot be expected to get the result perfectly.

Obviously in this example the analytical technique is far simpler but in other applications, such as the one needed for this thesis, analytical techniques become more complicated than MCS. To cope with that complexity large simplifications must be made in the analytical techniques meaning that for complex problems MCS is preferable.

The only caveat for creating a good MCS program is to ensure that the PRNG is suitable. Many programming languages come with random number functions by default but often these are not suitable for MCS. Pudaruth [77] provides a good comparison of random number generators. He concluded that the Mersenne Twister is the best suited, having both fast execution speed and a colossal period. Further discussion on the generation of random numbers is covered in the classic computer science monograph The Art of Computer Programming [58].

The work detailed later was created in Python which used the Mersenne Twister as its default PRNG:

> *"Almost all module functions depend on the basic function random(), which generates a random float uniformly in the semi-open range [0.0, 1.0). Python uses the Mersenne Twister as the core generator. It produces 53-bit precision floats and has a period of* $2^{19937} - 1$*. The underlying implementation in C is both fast and thread-safe. The Mersenne Twister is one of the most extensively tested random number generators in existence. However, being completely deterministic, it is not suitable for all purposes, and is completely unsuitable for cryptographic purposes."* [78]

There are two ways MCS can be used: sequential and random. Sequential sampling builds up a time history of events through sampling whereas random MCS takes independent samples with no time history. Both are equally accurate and must be chosen on their other merits. Due to its faster execution random MCS should be chosen unless a time history is required.

One case where sequential MCS is preferable, as highlighted in [19], is the modelling of pumped hydro storage. The current stored water depends on the power generated in previous samples, hence is best modelled sequentially. This is true of any component with storage that lasts longer than the period of one sample. It may be possible to model the level of storage as a partly random parameter if sequential analysis had shown that it would be accurate enough. In that way even pumped hydro storage could be modelled by random MCS but the extra work, as well as loss of accuracy, means that is rarely done.

Another case where sequential sampling may be required is if the failure rate of a component depends on when it last failed. This is best modelled sequentially because of the time history but if analysis has shown it would be acceptable this could be converted for use in random MCS.

Random sampling is used for the work in this thesis as there are no components that have a significant time dependency.

7.3 Modelling of Monte Carlo Parameters

For a Monte Carlo Sampling program to work well it must have good input probabilities. This sections details some of the possible factors that could be taken into account when creating a MCS program for this purpose.

7.3.1 Wind Power Forecasting

This has been discussed previously in Section 5.4. The simplest method of adding wind into the IEEE-RTS is to fit an existing historic model, such as the UK data available from the MET Office, over the geographic topology given in [47]. A more accurate method would be to create a synthetic model which would allow many more samples to be taken without repeating.

7.3.2 Wind Forecast Error

If historic data was used for forecast, then finding the forecast error is simply a case of taking the difference between two successive samples. Persistence forecasting is the name given to the assumption that the wind will stay the same over the time period. At such a short timescale, persistence forecasting is not far behind numerical weather prediction (NWP) methods and is far simpler.

If synthetic wind data was used, then a method such as the one proposed in [10] could be used. This creates a statistical model of the change in wind speed. Table 7.1 is taken from that paper and shows how likely it is that wind power will deviate from it's current value. The report 'Operating in 2020' by National Grid [67] shows that there is a correlation between time of day and wind forecast error, though this may be more due to the difference in load level at those times.

7.3.3 Load Forecasting & Load Forecast Error

At its minimum the load forecast should have diurnal, weekly, and seasonal cycles. The model in the IEEE-RTS covers all these. There are likely to be much more accurate models available but the supplied data is suitable for the studies required.

Table 7.1: Probability of Various Expected Energy Generation with Increasing Forecast Delay [10]

	Forecast Delay (hours)							
Expected Energy	**0.5h**	**1h**	**1.5h**	**2h**	**2.5h**	**3h**	**3.5h**	**4h**
0.00-0.05	-	-	-	1	2	2	2	3
0.05-0.15	-	1	2	3	4	5	5	6
0.15-0.25	2	4	5	6	6	6	10	10
0.25-0.35	7	10	12	13	13	14	14	13
0.35-0.45	24	22	20	19	18	16	14	14
0.45-0.55	40	29	25	20	19	19	18	17
0.55-0.65	21	19	17	16	15	14	12	12
0.65-0.75	21	19	17	16	15	14	12	12
0.75-0.85	5	10	10	11	11	9	11	10
0.85-0.95	1	4	5	5	6	6	7	7
0.95-1.05	-	-	-	1	1	1	2	2

7.3.4 Component Outages, Maintenance and Correlated Failures

Component outages can be modelling in many ways, the simplest of which is based around the mean-time-to-fail (MTTF) and mean-time-to-restore (MTTR). Often a two state model is made where separate MTTF and MTTR values are given for good and adverse weather. Line faults are more common during adverse weather hence using separate values is more realistic.

There is also correlated failures to consider. If a single external event can cause the loss of more than one component then this should be considered. One example of this is where two separate transmission lines are located on the same physical tower. Damage to one line can cause damage to the other.

Maintenance is a more complex issue. A generator will only be scheduled for maintenance if it will not cause a problem. This in itself requires extensive testing hence is not included in this work.

7.4 Method

7.4.1 Stage 1: Scenario Generation

Stage one is the creation of scenarios. These scenarios are meant to represent a snapshot of a power system at a given time. They are therefore based upon:

- Date and Time
- Weather Forecast
- Components on outage (either for planned maintenance or a previous unplanned outage that is yet to be repaired)
- Demand forecast
- Output power forecast of renewable generation
- The effects of sympathetic tripping
- Bid and offer prices for all scheduleable generators

These are complex and interdependent, hence simplifying assumptions must be made. Once the above data is gathered, it must be processed to turn it into a testable power system simulation. To do this requires a simulated SO as well as some form of SAS.

Unfortunately, the SAS that is being tested by the entire process can not be used in this stage. Luckily, it is not necessary to have a very good SAS; in fact the method requires a range of security levels, including some that have very poor security, hence it would be advantageous if certain scenarios were better secured than others.

One form of simplified SO that could be used is an OPF that optimises generator cost while maintaining a system that has no overloaded components.

This simulated SO will need to be tweaked to produce a suitable range of outputs.

7.4.2 Stage 2: Contingency Generation

The second stage takes each scenario through another round of Monte Carlo Sampling. This time it samples for unplanned changes, these include:

- Load forecast error
- Weather forecast error, hence generator power mismatch
- Component faults during current operation period (of 0.5 hour)

The purpose of this stage is to see what realistically might happen to a power system in such a state. By simulating each of these samples we can obtain a measure of how likely it is that the given scenario will need emergency operator action and hence one measure of security level.

The simulation of the second stage is less involved than the first. Because we are looking for systems where emergency operator action is not needed we do not have to simulate a SO for this stage. This means only automatic actions need to be modelled. The ideal method is to do a full dynamic simulation.

As millions of simulations are likely to be required either distributed computing or a change to the simulator will be required. A load-flow simulation is an order of magnitude faster than a dynamic simulation but does not have the ability to model outages and mismatches in the same way.

Once the simulations are performed and acceptable systems are marked as such we can then move on to the analysis stage.

7.4.3 Stage 3: Analysis

The analysis phase takes the results from the first two stages and determines the best SAS. It does this using the method described in Section 6.3 and Section 7.1 but it will be paraphrased here.

Each scenario is tested with each SAS to find whether they pass or fail. A security threshold is determined by policy where a perfect SAS would pass all scenarios one side of the threshold and fail the others. The SAS that has the most results in agreement with this theoretical perfect SAS is determined to be better for the tested power system under the specified scenarios.

7.4.4 Determining the Security Threshold

The security threshold is an important factor in the success of the proposed scheme. More work needs to be done to determine the actual tolerable level of security as it is defined by the method above.

To find the ideal level of the threshold a cost benefit analysis could be performed. There has been work done on finding the cost of security [13, 55] and this can be used to determine the optimum level. In other words, if the security level was set at X what would be the direct cost and what would be the cost of emergency action and disturbances.

7.5 Limitations and Applications

7.5.1 Limitations

As with any method this one suffers from limitations. These should not be seen as detracting from the central point of the thesis, namely that by using a Monte Carlo simulation we can learn a lot about the security of a power system and by using these results we can compare how different SAS will fare. Instead the limitations should be taken as further work or a set of considerations which must be checked if this method is to be taken forward.

1. There is a significant data requirement. Some power systems will not have sufficient data to create the Monte Carlo model.

2. There is a significant computational requirement. Many millions of power system simulations are required.

3. Counting unlikely events means things that were not included in the Monte Carlo could have a greater affect.

4. The method does not distinguish between severity of failure. Both a small overload on a line and a system-wide black-out are considered the same.

5. The proposed method requires a simulated system operator. This is very difficult to accurately achieve.

6. The security threshold needs to be specified but as yet it is an unknown quantity. A poorly chosen value could have severe consequences.

7. Any non-deterministic simulation has a chance of giving misleading results through insufficient samples.

8. This method does not aim to make general claims about the ability of different security assessment schemes.

1. Data

Failure rates of components, even in such a simple form as MTTF & MTTR, are not readily available yet are required for this method to work. System operators do not supply such data but if it were available it would be interesting to perform a study on a real system where system operators already have first hand experience on the quality of their SAS.

Because of the large number of samples that are used the accuracy of the input data will have a massive effect on the result. Real failure rates are correlated with weather, usage and component age. It would be interesting to see how much of a difference a more detailed failure model would have no the results but it is outside the scope of this work.

Wind speed data is often available in some form but is rarely as required. Missing entries are common but the least of the problem. Historic wind data is rarely available at the specific sites where wind farms are built. The main tool for assessing the wind resource at a site is "measure, correlate, predict" (MCP) analysis [96]. This involves matching a short-term sample of wind data from the site to longer term data nearby. But this method is fraught with inaccuracy as the article states. Sensitivity to the shape of the landscape as well as nearby forests and the change in wind speed with altitude (the height of the wind hub) mean that there may be little correlation. Techniques do exist to mitigate some of these issues including using NWP (numerical weather prediction methods) or ANN (artificial neural networks) to effectively fill in the gaps in the data.

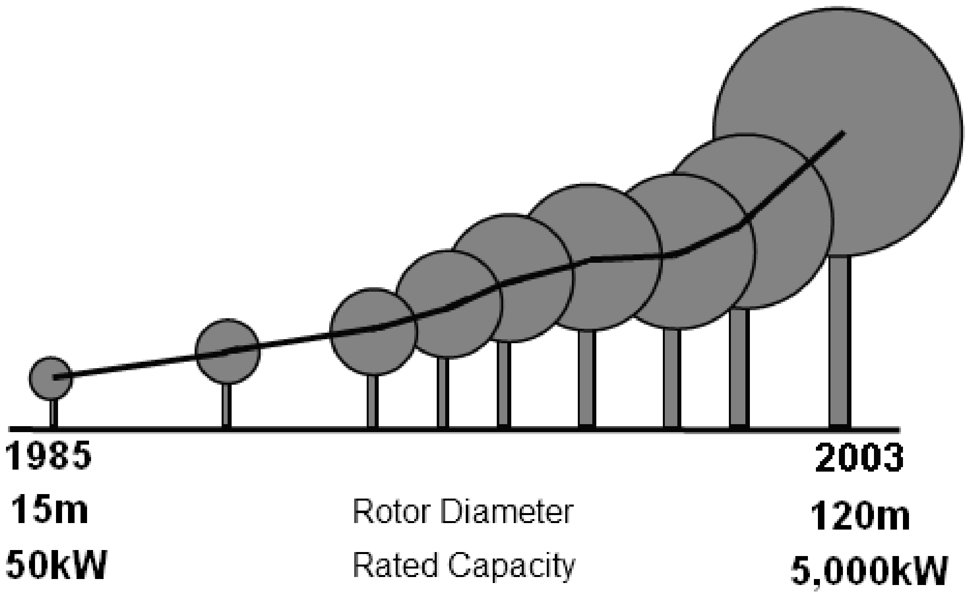


Figure 7-2: Wind Turbine Hub Heights [28]

Weather stations take the wind at a relatively low altitude, the calculations for 'wind shear' aim to account for the difference but these can be far from accurate and even a change of four kph results in a 15% change in turbine output. This resulted from an altitude change of 50 meters but modern turbines can have a hub height of over 100 meters (see Figure 7-2). The new estimates for wind resource by National Renewable Energy Laboratory [68] are three times what previous studies have estimated based upon these new larger, taller wind turbines.

All this means that although wind data may be available, converting it into a form that can be used for taking millions of samples is not simple. There is work at the University of Edinburgh under the EPSRC SuperGen project (see `http://www.see.ed.ac.uk/research/IES/supergen`) to develop a computer program that generates a sample-able set of data given the historic power of the area. This would be a perfect compliment for the work here as even 20 years of data, which is available from many sites in the UK, is not enough if we realise that we have to sample by day or year and hour of day. This leaves only 20 samples. This limitation could be partly mitigated by quantisation at larger intervals. By taking the months or even quarters of a year and splitting the day into three hours rather than single hour blocks we have many more samples available to select from.

2. Computing Power

Although the work has not been done to determine the minimum number of simulations required it is expected to be in the millions. This is a very large computational load. Reducing the samples at either stage will introduce errors and therefore is not an option. Luckily time is not a main factor in the proposed method. Unlike a SAS itself the method for comparing them is only limited by patience. A SAS must be quick enough for a SO to make balancing changes then re-run the SAS until the result is satisfactory. The comparison procedure does not need to be regularly run hence it can be left to process for many weeks if necessary.

As each sample is independent the problem is trivially parallelizable. A block of samples can be sent off to a computer for it to process and the result sent back when it is done. The very small input and output required by each sample combined with its high computation cost means it is a perfect application for parallel execution.

A second speed-up can be obtained by memoization combined with careful quantisation of the Monte Carlo outputs. Many of the samples will be the same to a certain degree of accuracy. Initial results show that some 98% of all stage 2 samples do not have any failed components. In addition, there are less than a hundred values of load forecast meaning that 98% of all stage 2 samples can be calculated in 100 simulations regardless of how many actual samples are required. The introduction of wind variation makes this effect less pronounced but it is still an important factor in reducing the computation load.

Finally the choice of simulator is also relevant. A load-flow will simply not represent certain stability issues but is far faster than the more detailed dynamic simulation. As previously discussed, modifications can be done to the load-flow which will allow it to give a more realistic result.

3. The Long Tail

The objective is to find a SAS that is better that N-1 hence, the most important Stage 2 samples are the ones that have either multiple outages or large forecast errors. This means the important samples are from very unlikely events. The less likely the event the more a small change in input probability or input distribution will affect it.

There comes a point where accuracy of data is more important than number of samples. This can be tested by sensitivity analysis. By changing the inputs slightly, one at a time, we can see how they effect the final result. If any data causes a massive change in results from a small change input then we must be sure that we have the most accurate possible measure of that data. This further goes to highlight the importance of having accurate data.

4. Severity

The method shown makes no distinction between an overloaded line and total system black-out. They are both marked as unacceptable. In reality, temporary small overload is not an issue. Certain other states that are unacceptable may be trivial to fix requiring only straightforward operation action.

Ideally we consider the operator action required to stabilise the system. This could be in the form of the amount of power that has to be shed [55]. This adds another layer of complexity to an already complex method and is not considered here but is a very useful addition. If the modification were made it would not be trivial to add it to the rest of the stages.

The idea of a single stability value would have to be rejected in exchange for a probability that the required load to be shed is less than X. This probability density function would make further calculations more difficult as well as the problem of interpreting the results but it would be a great advantage to the system.

5. Simulated System Operator

A system operator (SO) is not an individual, it is a company with a team of people planning years ahead and refining those plans to create specific knowledge about how the system will run. All this cannot be replaced by a simple computer program. There is simply too many unknowns.

As we must accept this situation then we must realise that we are limited by the accuracy at which we choose to model the SO. An overly simplified SO will lead to unrealistic scenarios. Luckily we do not need a greatly accurate SO. We want the system to fail in certain instances as we want to compare the number of times a system is unacceptable. This means a large part of a system operator's action, namely the on-line action, can be greatly reduced or removed entirely.

Even if we could simply all operator action down to a computer program it could not be used here. We cannot use a specific SAS as part of the method when testing that SAS. If all scenarios were secured to N-1, then in the analysis phase all scenarios would pass N-1 by definition. This means we would not have any failure data with which to compare the effectiveness of different results. It is possible that wind forecast errors alone could create problems leading to failed scenarios but it would be far more effective if there were a wide range of security levels.

That said the less the simulated SO represents reality, the less applicable the results are. Remembering that the SAS will be applied to both unsecured systems and secured ones leads us to the idea that some of the scenarios should be secured and others simply stable.

6. The Security Threshold

The security threshold is the minimum level of security that we can have which we want to pass our perfect SAS. Although the idea has existed before, here it is used as a concrete value. It is vital to the success of the scheme that this value is chosen correctly. There is no research available on the optimal value for the security threshold because it has not been used in this way before. This work does not aim to address it.

7. Statistical Anomaly

As with any non-deterministic simulation this one also has a chance of giving misleading results through insufficient samples.

8. Limits of Claims

This method does not aim to make general claims about the ability of different security assessment schemes.

7.5.2 Applications

This method gives us one measure of security of a number of possible scenarios. From this a number of useful applications can be envisaged. Secondly, the method creates a database of likely consequences of certain system states. Below is a few possible applications that the method could be used for. Note that some of these will require changes and would require further testing.

1. Comparing SAS
2. Aid in developing a new SAS
3. Locating weakness in an electrical power system
4. Identifying weakness in a SAS
5. Testing the effect of network changes on security

1. Comparing SAS

As described above we can use the idea of a perfect SAS to find the number of mismatched results in two sets of data.

2. Aid in developing a new SAS

Once we have data from the analysis phase of the proposed method we can quickly test modifications to a SAS. This allows improvements to be made quickly. If weakness are found then the SAS can be modified to overcome these.

If we had infinite computational power we could simply run stage 2 as a SAS. It would come up with the probability that the current system state will lead to an unacceptable system. Sadly we are far from having enough computational power to do a representative Monte Carlo. Hence what is required is a fast SAS that gives the same results as using stage 2 as a SAS. In other words, it is finding a mapping between the system state and its security level.

The problem of mapping is ideal for ANN but it is yet to be seen if they can cope with the complexity of security assessment. Human neural networks still make mistakes more often than we would like and ANN is a long way off having human intellect.

3. Locating weakness in an electrical power system

As it is necessary for such a large number of simulations to be performed we can get a feel for which components are likely to cause problems. For instance, in the RTS the underground cable may be a source of reactive power issues or there may be certain components that are likely to lead to unacceptable systems than others.

This set of likely problems would be a fantastic resource for operator training. Not only are they realistic scenarios but they would be the kinds of problems likely to occur.

4. Identifying weakness in a SAS

The results of testing can be valuable even if the decision is made to not change the SAS . By analysing the false positive and false negatives, weakness in the

SAS can be identified. This can either result in modification to the SAS to better deal with those types of events or prepare the SO better to notice and react accordingly.

5. Testing the effect of network changes on security

It may be possible to test the effect of small network changes although it is far beyond the scope of this work. This could be done by re-running the scheme with the same samples to see if it causes any changes in output.

7.6 Chapter Summary

This chapter covers how security assessment schemes are themselves assessed. It then proceeds to detail the creation of a new method for comparing security assessment schemes. The possible applications and limitations are explored in detail.

Chapter 8

Computer Program

The aim of this chapter is to detail the development of a computer program made to test and compare SAS. It is then tested using approximate analytical calculations.

8.1 Program Data Sources

Here the sources of data used in the final program, as well as external tools, are discussed. They are broken down into three areas:

- The Power System Network
- The Network Simulator
- The Probabilities for the Monte Carlo Sampler

8.1.1 Network - The IEEE Reliability Test System 96

The IEEE Reliability Test System 96 (IEEE-RTS) [47] is a sample power system with a thorough set of data for operation, emissions, and reliability. It was for this reason that it was chosen as the test system for this work. For the bulk of the simulation the three area version was used, which is composed of 99 generating units, 73 busbars, 120 lines, 51 loads and two voltage levels. The network diagram is shown in Figure 8-1.

It was not meant to be representative of any particular power system but aimed to represent all the different technologies and requirements that could be encountered. Because of this it has been updated to include new technologies as the sector advances. The first version of this system was developed in 1979 [51] it was then updated in 1986 [3] and once again in 1996 [47].

In addition to new data the system has increased in size to incorporate three almost identical areas. As they are almost identical only the details of the components in the first area are shown in the following tables, a full listing is given in Appendix A.

There have been many changes to power systems in the last 14 years and it would be good if the IEEE-RTS could be updated to incorporate these changes. The largest of the changes is the increase in penetration of renewable generation. As it stands the IEEE-RTS includes no renewable generators. Although the literature is showing examples of individuals who have added wind turbines there is no consensus or standard forming on where and how much renewable power should be added.

As this paper is used extensively in this work it is included for reference in Appendix A.

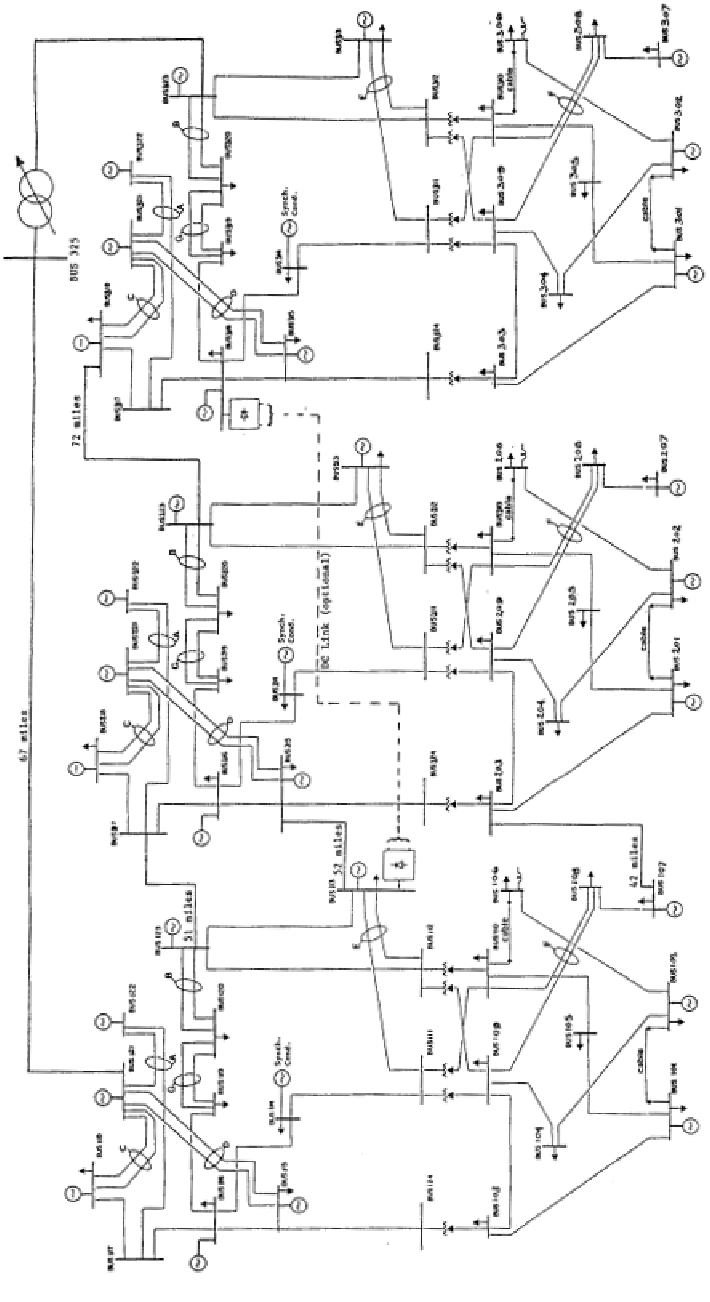


Figure 8-1: Network Diagram for IEEE-RTS-96 [47]

Table 8.1: Line Probabilities

Line ID	From	To	Fail Rate	MTTR
A1	1	2	0.24	16
A2	1	3	0.51	10
A3	1	5	0.33	10
A4	2	4	0.39	10
A5	2	6	0.48	10
A6	3	9	0.38	10
A7	3	24	0.02	768
A8	4	9	0.36	10
A9	5	10	0.34	10
A10	6	10	0.33	35
A11	7	8	0.30	10
A12-1 *1	8	9	0.44	10
A13-2 *1	8	10	0.44	10
A14	9	11	0.02	768
A15	9	12	0.02	768
A16	10	11	0.02	768
A17	10	12	0.02	768
A18*2	11	13	0.40	11
A19	11	14	0.39	11
A20*2	12	13	0.40	11
A21	12	23	0.52	11
A22	13	23	0.49	11
A23	14	16	0.38	11
A24	15	16	0.33	11
A25-1*3	15	21	0.41	11
A25-2*3	15	21	0.41	11
A26	15	24	0.41	11
A27	16	17	0.35	11
A28	16	19	0.34	11
A29	17	18	0.32	11
A30*4	17	22	0.54	11
A31-1*5	18	21	0.35	11
A31-2*5	18	21	0.35	11
A32-1*6	19	20	0.38	11
A32-2*6	19	20	0.38	11
A33-1*7	20	23	0.34	11
A33-2*7	20	23	0.34	11
A34*4	21	22	0.45	11

* starred lines are on a common right of way with those of the same number if one fails the other will also fail with a probability 0.08

Table 8.2: Generator Probabilities

Generator ID	Busbar	MTTF	MTTR
G1	1	450	50
G2	1	450	50
G3	1	1960	40
G4	1	1960	40
G5	2	450	50
G6	2	450	50
G7	2	1960	40
G8	2	1960	40
G9	7	1200	50
G10	7	1200	50
G11	7	1200	50
G12	13	950	50
G13	13	950	50
G14	13	950	50
G15	14	-1	-1
G16	15	2940	60
G17	15	2940	60
G18	15	2940	60
G19	15	2940	60
G20	15	2940	60
G21	15	960	40
G22	16	960	40
G23	18	1100	150
G24	21	1100	150
G25	22	1980	20
G26	22	1980	20
G27	22	1980	20
G28	22	1980	20
G29	22	1980	20
G30	22	1980	20
G31	23	960	40
G32	23	960	40
G33	23	1150	100

8.1.2 Load-flow Simulator - CPF

A detailed discussion of simulation techniques and tools in general is covered in Chapter 5; this section discusses the specific requirements and decisions for this particular application.

Requirements

The requirements of the simulator were as follows. It must have:

- The ability to simulate the chosen network using either a load-flow or dynamic simulation.
- The ability to be run from command line without user interaction.
- A fast simulation speed.
- Results that are easily analysed by another computer program.
- The ability to remove individual lines, busbars and generators. To simulate planned outages or failures during operation.
- The ability to easily change the load level of busbars in the input file.

Niceties

In an ideal world both stages of the program would have different simulation parameters. The first stage needs to represent a random snapshot in time of the power system as a system operator might see it. It would be a useful extension to the project to add an OPF to the first stage.

The second feature that was non-essential but would have improved accuracy would be an ability to simulate in multiple stages. After the OPF of the first stage it would have been good to feed the results into a load flow simulator after applying contingency changes.

PSAT

The two niceties must both be present in the same program for it to work as a whole. A number of different simulation tools were reviewed, the closest match was PSAT, a Matlab toolbox. Although it appeared to fit all the criteria, problems were found during testing and couldn't be resolved. Ultimately this was because PSAT is not meant to be used in such a way. The output file is meant to be read by humans not a computer and as such was very difficult to parse (get the computer to read an interpret the results).

Another significant challenge was communicating between PSAT and the Monte Carlo Simulator which had already been written in another programming language. Communicating directly with PSAT inside Matlab proved too complex. Hence to run a simulation, the output of the Monte Carlo Sampler is saved to disk. Matlab is run as an external program using those stored results as it's input. This process, although complex and slow worked. It would make more sense to use a program that properly supported data streams to avoid the slow hard drive access and one that was meant to be run from a command line.

Due to the very slow start-up and shutdown time of Matlab, simulations were done in batches. For example, 100 simulations were written to file to be processed in one go. By grouping simulations this way Matlab could process many simulations each time it was started. This enabled the program to be trivial to parallelise if multiple computer or multiple cores were available.

In the flow diagram (Image 8-2) the process for Stage 1 is detailed. Here it

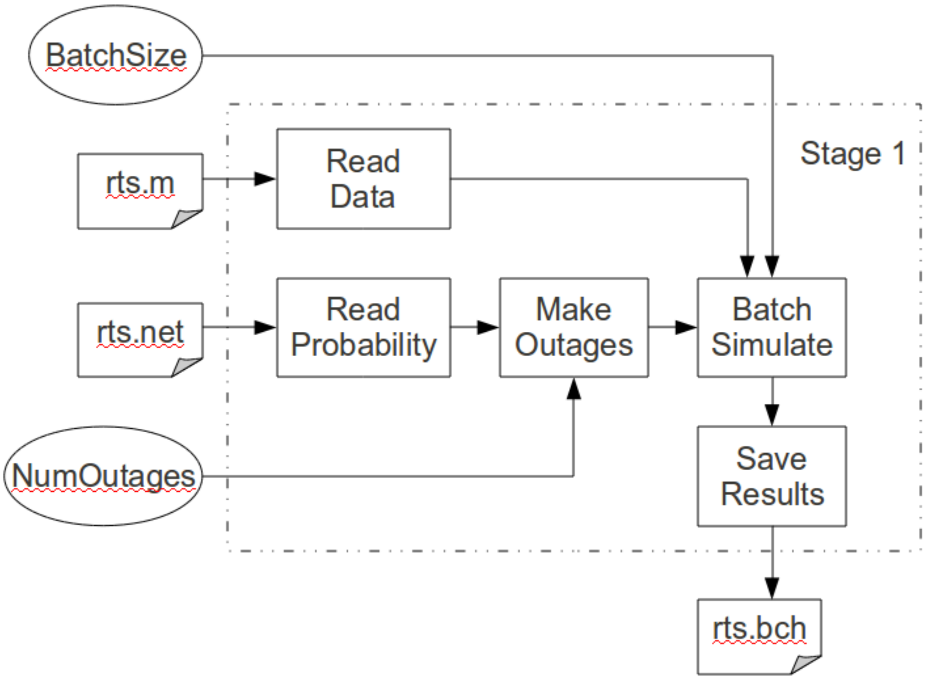


Figure 8-2: Flow Diagram for PSAT Stage 1 Sampling

includes simulation but that is not necessary. In addition to the batch file it was possible to gather statistics about the samples and simulations. These statistics are analysed later.

The sampling program is based around four main data types, each associated with a file type. These are created and modified with a number of scripts.

- The PsatData type is a Matlab file containing information for PSAT about a specific scenario to be simulated. This file is used by Matlab to produce a simulation report. The files end in .m. More information on this can be obtained from the PSAT documentation.

- PsatReport is the report produced my Matlab after a simulation is run. It contains power flows, losses and bus bar voltages. It is meant to be analysed by hand and hence it requires parsing to be interpreted by a computer. Report files end in _XX.txt where XX is an incrementing number.

- NetworkProbability is a data file containing the probability of failure of various components as well as joint failure of different components. It creates scenarios from a network probability data file. Probability files end in .net.

- SimulationBatch files hold a list of scenarios. Each scenario contains the changes that have occurred such as a line outage or a change in demand. Batch files can optionally contain simplified simulation results. Batch files end in .bch.

Ultimately, PSAT was dropped as the power system simulator and a simpler, faster tool was used. The software that used PSAT was never fully finished, but a number of parts are complete and available at `http:\\github.com\kerspoon\`

`laos`. This could be used as a starting point for further work using PSAT for security analysis.

CPF

CPF is part of PSSENG, a Dynamic Power System Simulator developed at the University of Bath by Dale [35], Berry [16] and Chan [32]. CPF was originally used to work out the initial load-flow conditions before a full dynamic simulation. As it was written as part of a dynamic simulator, the core algorithm is very fast. It actually matched all requirements by design and was an easy fit for the simulation.

Unlike PSAT it also had a very fast start-up time meaning the complicated and complex batch processing, including constantly writing large files to disk, was not needed.

There were some modifications needed. Firstly, to remove components easily they had to be placed on their own line of the input file. These were joined to the original bus by a line of zero impedance so as to make no difference to the simulation results. This meant that removing a component was as simple as deleting a few lines. No calculations were needed. Changing the load level was relativity straight forward as each power was a single number in the file. The modified output could be piped directly into CPF from the Python-based Monte Carlo Simulator

For these reasons CPF was selected as the simulator for this program.

8.1.3 System Probabilities - Monte Carlo Sampler Program

The core of the computer program is the two-stage Monte Carlo Sampler; the general points to consider are covered in Section 7.2. The specifics relating to this application are detailed in this section.

Implementation

Stage one consists of sampling to generate a range of realistic operating conditions. Outages of lines, busbars and generators are calculated from their mean time to fail (MTTF) and mean time to repair (MTTR) as per Eqn 8.1. For components that have a failure rate specified, instead of a MTTF, a simple conversion was performed. Busbar failure rate is not included in the original paper so a value of 0.025 was chosen to be consistent with values in the literature [2, 20, 24, 44]. Failure rate is given in failures per year and MTTF and MTTR is given in hours. Included in the paper is the probability that the tripping of certain lines will cause tripping of others. This effect was also taken into account in this work.

$$P_o = \frac{MTTF}{(MTTF + MTTR)} \tag{8.1}$$

The second stage takes each scenario through another round of Monte Carlo sampling; this time it samples for unplanned changes. Load forecast error is considered but only in the most basic form, a normally distributed random number with mean 1 and s.d. 0.05 is multiplied by the forecast given in stage one.

A more realistic measure should take better account of the correlation between time and load forecast error as well as weather impacts. Component faults are

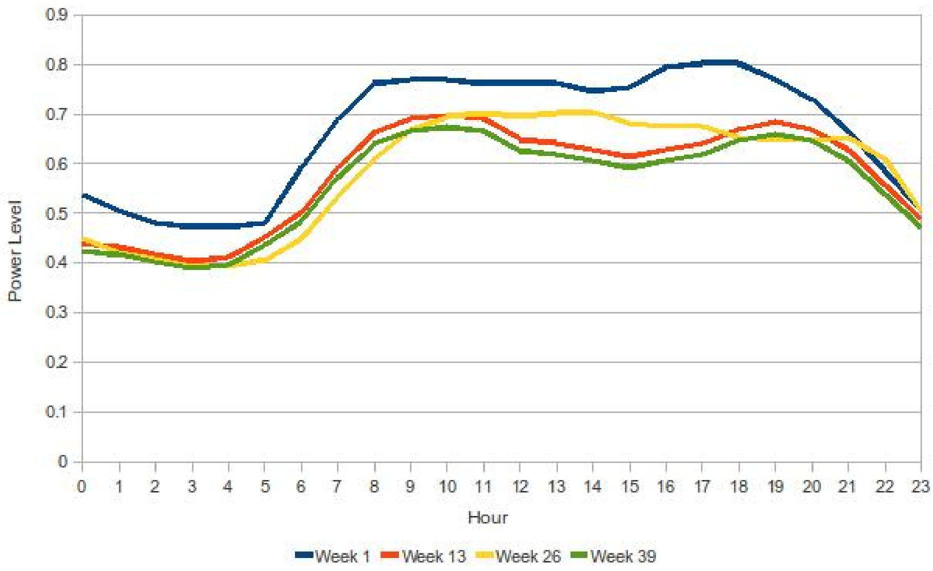


Figure 8-3: Demand Level per Hour of Day

taken by converting line, generator and busbar value, from the original paper, into the probability that they will fail during the half-hour delivery period. This calculation uses Eqn 8.2. A weather forecast is unnecessary in this part of the work as the IEEE-RTS does not have renewable generators.

$$P_f = 1 - e^{-\lambda t} \tag{8.2}$$

Demand Forecast Analysis

The IEEE-RTS supplied data for demand level is based upon the season, hour and week. This section looks at how the load level fluctuates then uses the MCS to form aggregate data.

As can be seen in Figure 8-3 the power use is much lower during the night, it ramps up rapidly from 5am reaching its first peak around 9am, then depending on the specific week observed it either tails off or holds steady until the evening

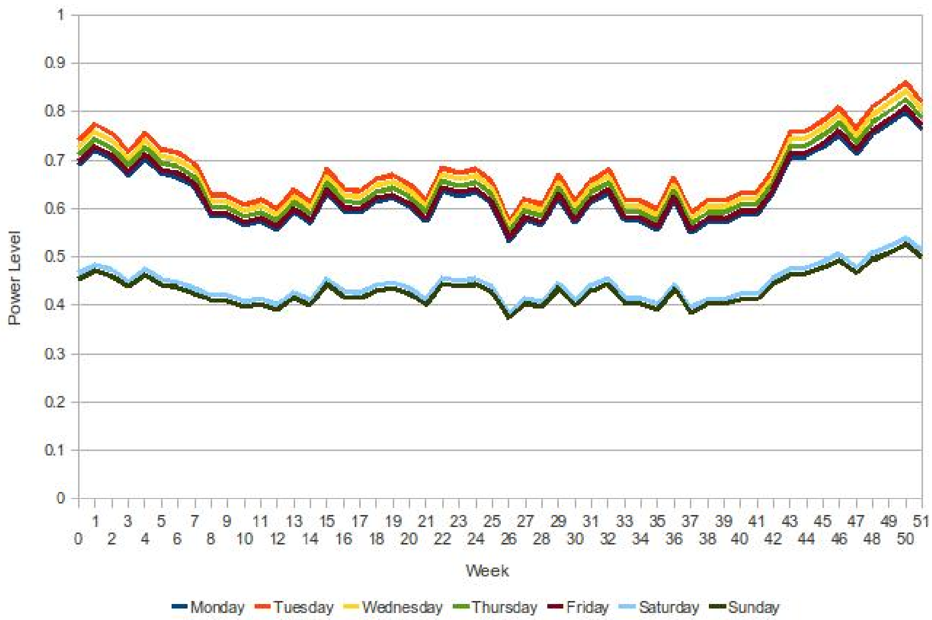


Figure 8-4: Demand Level per Week of Year

peak between 6pm and 8pm. Week 1, being the start of January, is notably higher than other weeks due to extra energy usage for space heating and, in the evening, lights.

The yearly changes appear much more stochastic (Figure 8-5). The most notable trends are a much lower energy usage at weekends as well as the seasonal variation of higher energy use in winter.

When sampled this data-set gives the probability density as shown in Image 8-5. In this graph the demand forecast has been quantised to the nearest 0.05. Note that only a very small percentage of samples are at the full demand level (only 603 out of one million samples in the run shown in the graph). Also note that there is a reasonable high probability that the system will be running at 35% of its maximum. It is not unreasonable to expect wind power alone to meet this demand level which could cause significant problems if not enough spinning

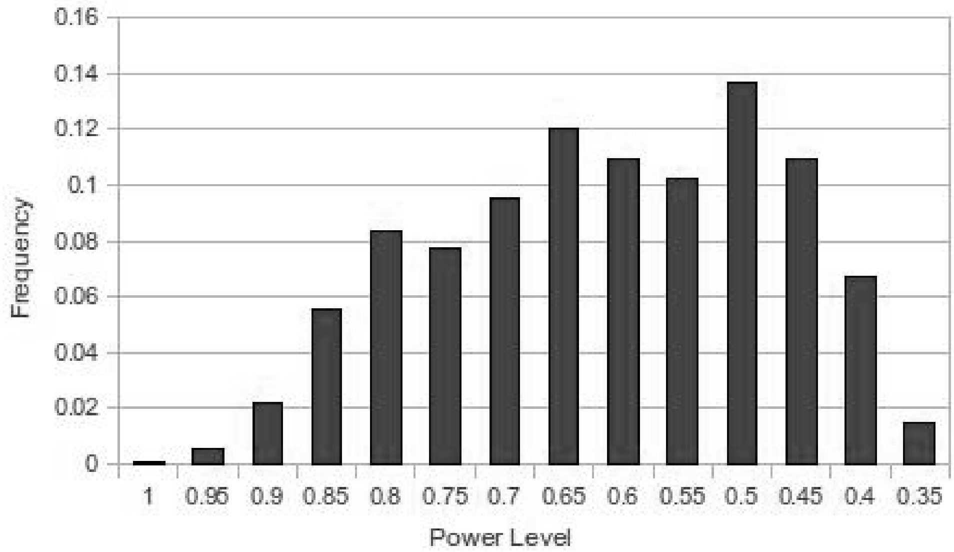


Figure 8-5: Aggregated Load Forecast

reserve was available. As this graph shows the fraction of samples of a given power level it also serves as a good approximation to the probability of a base-case having the given load forecast.

The second stage of Monte Carlo Sampling took the load forecast and created a forecast error. This was simply taken as a normal distribution. The results of quantisation are shown in Figure 8-6. It has a relatively small effect when compared to the forecast itself but a 10% increase in power demand is significant both in its frequency and effect.

Outage Frequencies

The number of components that have failed or are on outage in each sample are illustrated in Figure 8-7 and Figure 8-8. Rather unexpectedly it shows that up to eight simultaneous component outages can occur in one million samples. This would seriously weaken the network. There is a 77% change of at least one

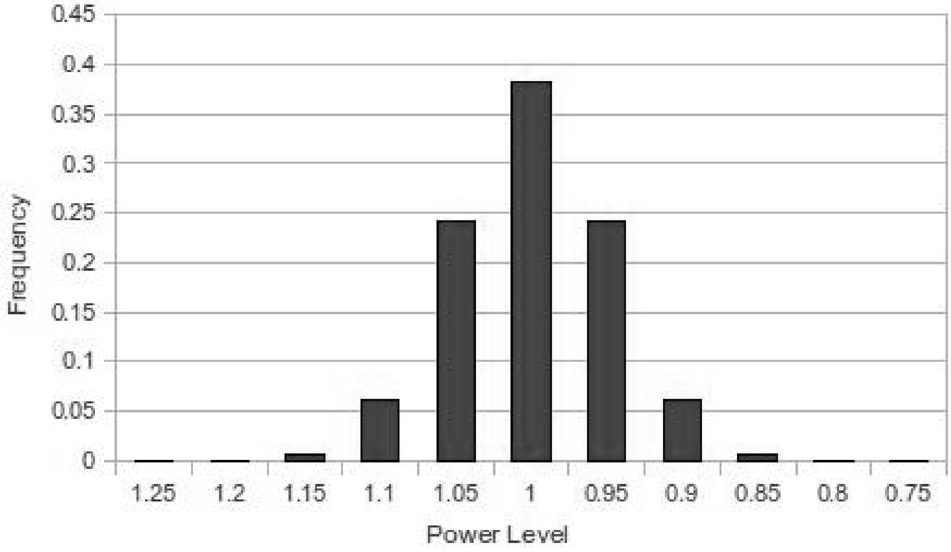


Figure 8-6: Aggregated Load Forecast Error

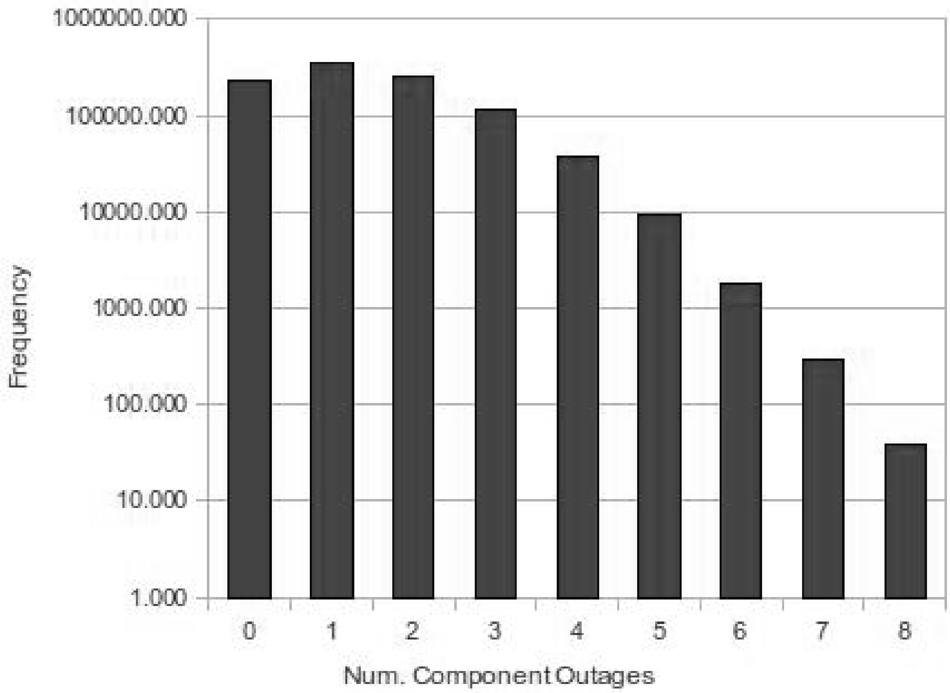


Figure 8-7: Component Outage (Stage 1) Frequencies

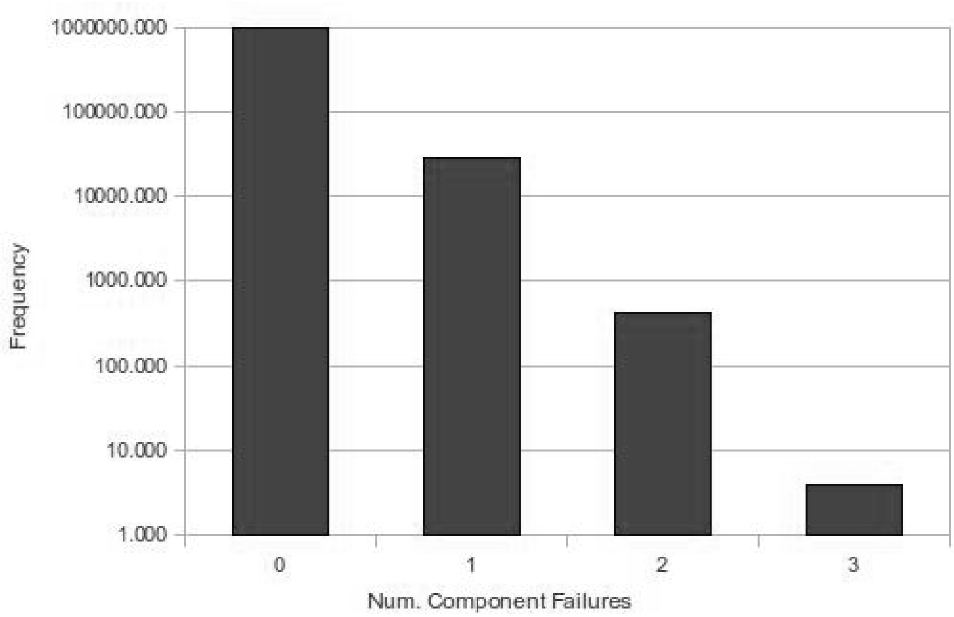


Figure 8-8: Component Failure (Stage 2) Frequencies

component outage, hence it is much more likely that the system is not at it's full generating capacity. Generator failures accounted for most of these outages with only 3% of samples having at least one line failure and only 0.1% of samples having any busbar failures.

Components failures (Figure 8-8), tell a similar story on a much smaller scale. These represent problems that occur to the system during delivery. This means that in four samples out of a million, three unrelated failures all occurred within the same half hour period. This will cause extreme stress to the system but it is an unlikely event. Though independent samples should not be thought of as a time series, one million half-hour samples represents a time period of about 60 years. Taken in the context that Edison set up the first ever power system about 130 years ago this million samples is bound to include some very unlikely events.

8.2 Program Structure

The program itself was written mostly in Python and is available on-line at `http://github.com/kerspoon/kiribati`.

It has a number of functions which all take input from the command line. This allows it to be combined together easily and intermediate parts written out to file for debugging or analysis.

Each heading below denotes a separate use of the computer program developed.

Generate Base Cases

```
# generate 10 unique base cases and save to file.
python main.py base-case 10 > base.csv
```

This option outputs a list of base-cases to the command line. The base cases are generated using Monte Carlo Sampling as described in Section 7.2, taking in to account MTTF, MTTR, CROW failures, and load-level.

The parameter is the number of unique base cases to output. For instance, if this was set to 1000 there would be 1000 lines in the files, each representing a different base-case. There would probably be some samples that have already been included in the output and hence are not shown. If two base cases, for example, had a bus bar level of 0.55 and only G23 on outage then it would output a single line.

The advantage of this is that it will cause only one simulation to be run. This has a very dramatic effect on the speed of computation with no loss of accuracy. In one run of 256 billion samples there were only 100,000 simulations required.

The output is a comma separated value file (CSV), meaning it can be opened in any spreadsheet program or text editor. Here is an example output.

```
1, outage, None, , 0.75, G22, G23, G86, G71, G16, G65
1, outage, None, , 0.7, G62, G23, G91, C30
1, outage, None, , 0.55, G80, G99, G65
1, outage, None, , 0.5, G6
1, outage, None, , 0.65, G39, G35, G1, G90
1, outage, None, , 0.45, G84, G68, G71, G78
1, outage, None, , 0.65, G30, G5, G3, G68, G44, G66, G98
1, outage, None, , 0.5, G80, G57
```

Each line is one base case. The first column is the number of base-cases that had the following result. So in the example above the line produced would be:

```
2, outage, None, , 0.55, G23
```

The second column is the type of the sample. For base-cases it is always "outage" but it will change for contingencies or n-x runs.

The third and fourth detail the results of simulation which are not defined until a simulation is run on the file.

The fifth column is the load level. This number is the percentage of the peak that all loads will be scaled to. For instance, if the load for a particular bus was 6.2 before the sample was applied and the load-level was 0.5 the resulting bus level would be 3.1, this is applied equally across the busbars.

The rest of the columns list the names of components that are not to be included in the simulation. In base-cases this represents maintenance or previously failed components that are not available during the delivery period. In contingencies it represents components that will fail during the current delivery period.

Obviously the base-cases it produces are dependent on the input files which specify the components and probabilities. As the only power system considered in this thesis is IEEE-RTS the file names are hard-coded into the program.

Generate Monte Carlo Contingencies

```
# generate 1000 unique contingencies
# using the base cases in base.csv and save to file.
python main.py contingency 1000 < base.csv > contingency.csv
```

This option first generates contingencies based upon the probabilistic changes during the delivery period. It then combines the contingencies produced with the base cases given on the standard input.

For example, if there were only two base cases given:

```
1, outage, None, , 0.5, G1
1, outage, None, , 1.0, G2
```

Then it may output something like the following:

```
0, base, None, , 1.0
1, failure, None, , 0.95, A1
1, failure, None, , 1.05, A2
1, outage, None, , 0.5, G1
1, combined, None, , 0.475, G1, A1
1, combined, None, , 0.525, G1, A2
1, outage, None, , 1.0, G2
```

```
1, combined, None, , 0.95, G2, A1
1, combined, None, , 1.05, G2, A2
```

The output here is in sections. First is the raw base case with no changes, then the contingencies not combined with a base-case. Next is the first base case in the input followed by that base case combined with each contingency given before in turn. This is repeated for all base cases. This means there will be: $x = (B+1)*(C+1)$ samples in the output file, and hence that many simulations to perform.

Note that the same samples are used for each base case. This does not necessarily represent reality but as long as there are enough samples it is not a limiting factor to the accuracy of the results.

Just the failures are put into the output and any base-cases are ignored if the command line option `noInput` is given.

Generate N-x Contingencies

```
# generate all single component failures
# using the base cases in base.csv and save to file.
python main.py n-x 1 < base.csv > n-1.csv
```

This option generates contingencies but this time they are not from Monte Carlo. The parameter specifies the number of simultaneous outages to consider. If the parameter is one, for example, then only single component outages are considered. This would cause one contingency per system component. In the IEEE-RTS this would cause 289 contingencies to be created, as there are 289 components.

If the parameter is two using the IEEE-RTS as the input file there will be 41,616 contingencies.

Like the `contingency` option it combines the set of contingencies with each base case ready for simulation.

Simulate

```
# generate all single component failures
# using the base cases in base.csv and save to file.
python main.py simulate < base.csv > results.csv
```

This takes base cases or contingencies and simulates each one in turn using CPF. The results from each simulation are categorised as either acceptable or unacceptable. Unacceptable means there was: divergence, islanding, or a component out of static limits. This represents whether a system operator would have to perform emergency action to keep the system running acceptably.

The output file is of the same format as the input, the only change is to the third and fourth column to set the results.

The file is processed one line at a time, rather than waiting until the entire program is complete before producing any output. This meant that if there was a problem with the simulator it could be checked while it was still running. It was also possible to stop the simulation part way through without losing all the results.

It is possible to specify all steps in one go, eliminating intermediate files. Unfortunately, this gives no feedback as to progress. It also means that all steps have to be run again if a change is needed.

Analyse

```
# summarize the results of a block of simulations
python main.py analyse < results.csv > analysis.csv
```

The final stage of the program takes the output from a simulation of contingencies combined with base cases and condenses them down. It doesn't matter whether the contingencies were generated using Monte Carlo or n-x.

For each base case it counts the total number of unacceptable samples. This gives the probability of acceptability, which is used in the final assessment.

For example if the input file was:

```
0, base, True, ok, 1.0
1, failure, True, ok, 0.95, A1
4, failure, True, ok, 1.05, A2
1, outage, True, ok, 0.5, G1
1, combined, True, ok, 0.475, G1, A1
4, combined, False, ok, 0.525, G1, A2
1, outage, True, ok, 1.0, G2
1, combined, False, ok, 0.95, G2, A1
4, combined, False, ok, 1.05, G2, A2
```

Then the analysis would produce:

```
0, base, True, ok, 1.0
0, 5
1, outage, True, ok, 0.5, G1
4, 5
```

```
1, outage, True, ok, 1.0, G2
5, 5
```

It alternates between printing out the base-case and printing the number of acceptable cases. Note that it does not simply count the number of lines as certain lines represent more than one sample, as can be seen in the example.

Utilities

In addition to the main use of the program it also has two utility functions.

The command `test` prints out the results of simulating a number of interesting base-cases that stress the program in different ways. It also prints the file that is used as an input for CPF. This is a file that if normally never seen but is useful in checking the behaviour of the program. This is to ensure that it is being produced properly for a number of edge cases. The cases selected also make sure that the simulator is tested on those edge cases as well.

Finally the command `clear` deletes all files from previous runs so that the working directory is clear to start again.

Flow Diagram

The connection between each different use of the program is shown in Figure 8-9. For instance you can see that the results of the base case generation feeds directly into the simulation function. The diagram shows a complete run from the creation of bases cases down to the analysis of both N-x and Monte Carlo contingencies. The same process is shown programatically in Section 8.4.

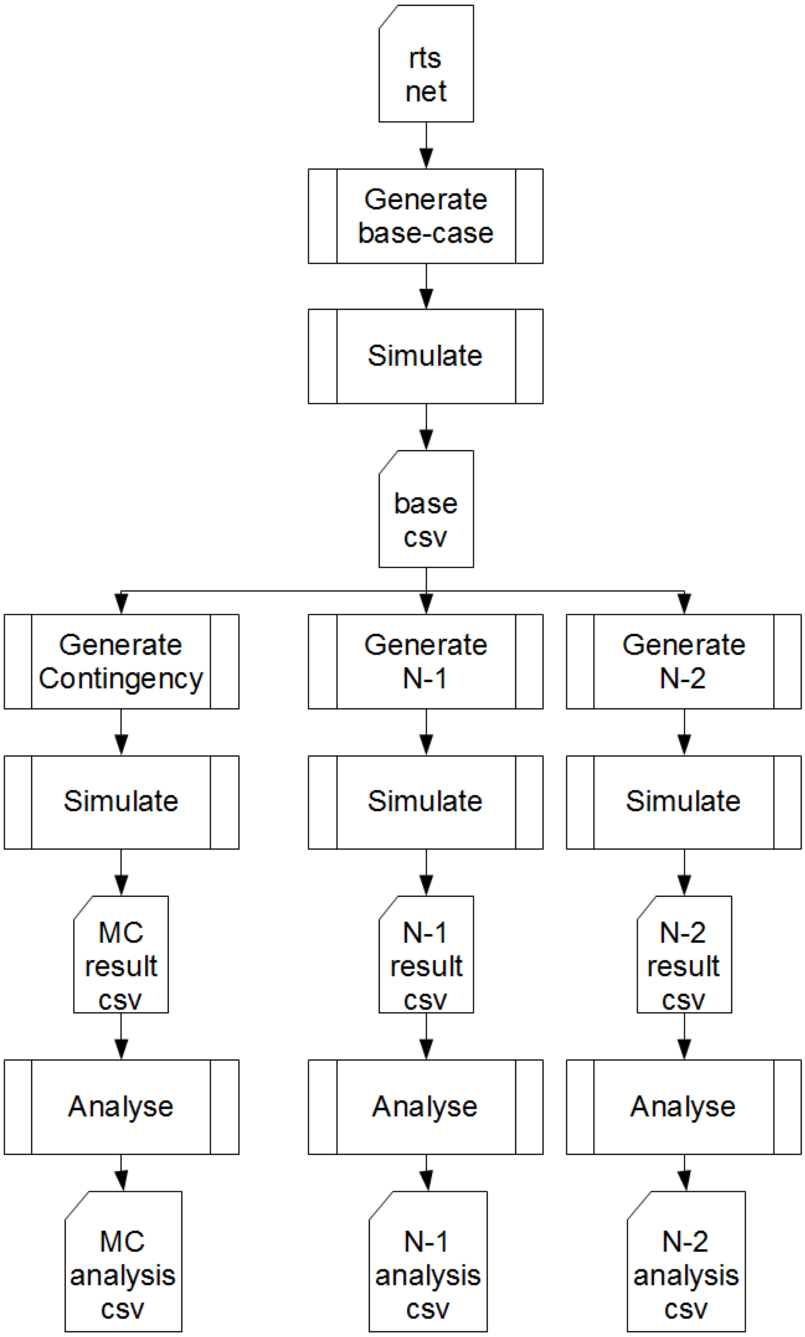


Figure 8-9: Flow Diagram

8.3 Testing

To ensure the proper operation of the program there were various tests performed. These ranged from: quick checks of individual functions; checking simulation output with hand worked examples; to an analysis of how many samples were actually needed to ensure that it was not the limiting factor.

Unit Tests

The simplest of these checks are the small unit tests. These are best described by David Thomas et al. in Pragmatic Unit Testing [5]:

> *"A unit test is a piece of code written by a developer which exercises a very small, specific area of functionality in the code being tested."* [5]

While the program was being developed unit-tests were programmed to run every time the code was run. If any change caused the unit-tests to fail the feedback would be immediate. The extract of code below shows one of these tests. It makes sure that the individual function `quantised_01` does what is expected on a few hand worked examples.

```
class Tester_quantised(ModifiedTestCase):
    def test_01(self):
        self.assertEqual(quantised_01(0.00), 0.00)
        self.assertEqual(quantised_01(0.005), 0.01)
        self.assertEqual(quantised_01(0.0049), 0.00)
        self.assertEqual(quantised_01(0.0149), 0.01)
        self.assertEqual(quantised_01(0.9999), 1.00)
```

These functions, although not individually useful in calculating anything to do with power systems, form the building blocks that make a useful program and the unit tests are there to make sure the foundation is solid.

Module Tests

Module tests are the next logical level up from unit tests and could probably be considered unit tests in, and of, themselves. They test the boundaries of modules as seen externally. This makes sure that the interaction of the modules class and its helper functions all work together properly.

The `buslevel` module has two main functions exported for other modules to use. If we ensure that these two functions work then no further testing of the internals should be necessary. One of the functions takes as an input the week of the year, day of the week and hour of the day to produce a single forecast load figure. These can easily be hand worked. The first hour of the year (01/Jan at 00:00), for example, should give a load forecast of 0.537 times the base level. This is what is checked in the first assertion in the code below:

```
def test_peak_load(self):
    self.assertAlmostEqual(forecast_load(0, "Monday", 0), 0.537, 3)
    self.assertAlmostEqual(forecast_load(0, "Sunday", 0), 0.504, 3)
    self.assertAlmostEqual(forecast_load(51, "Sunday", 23), 0.578, 3)
    self.assertAlmostEqual(forecast_load(37, "Tuesday", 12), 0.646, 3)
```

Another example ensures that the samples which form the basis of all input and output of the program are able to be read and printed properly. It does this by reading in some test cases then printing then back out and checking they match the original file.

```
def util_readwrite_match(self, inp):
    batch = list(input_scenario(StringIO(inp)))
    stream = StringIO()
    output_scenario(batch, stream)
    self.assertEqual(stream.getvalue(), inp)


def test_1(self):
    self.util_readwrite_match("""
    1, outage, False, bad, 0.55, G49, G32, G22, G12
""")
    self.util_readwrite_match("""
    999, failure, True, ok, 1.0
""")
    self.util_readwrite_match("""
    999, combined, None, ok, 0.01, A1
""")
    self.util_readwrite_match("""
    1, combined, False, message here, 0.525, G31, G66
""")
```

Fix Power Mismatch

This is another example of a module test but is a special case as it changed the functionality of the load-flow program used for all simulations, hence it is worth documenting.

Load-flow programs cannot be run with any mismatch. This is by design. If there is a mismatch it will be cancelled out during calculation by the slack-bus. If there are significant mismatches, such as from the removal of certain generators, it can lead to problems. The simulation may end up testing the ability of the slack-bus to cope with changing power levels rather than the entire system. For this reason the expected mismatch is averaged across all suitable generators according to their current power levels.

The code ensures that generators power limits are observed so that if a generator was to hit a limit it is simply set at full power and the rest of the power distributed among the other generators.

The code for this is given in Appendix C.

Certain generators are not suitable for variation. These are the ones where power output is not controllable, for example, wind turbines. In these cases they are taken to be of a fixed value and the rest of the generators must make up the difference.

Sometimes the power requirement is too high to be met by the available generation. This is a problem of adequacy and as such the particular case can be marked as unsuitable even before a simulation is run. This did occasionally happen during simulation but it was rare. It required either the power to be over 15% higher than the forecast maximum or that the power was still very high and large generating units were out of service. As this could happen in a real power system it is not a problem with the simulation but accurately represents a problem in the system.

The following piece of code is an example of one of the tests for the mismatch fixing code. It checks that a mismatch is evenly split when applied to two generators whose power equal.

Note that it would not always be split equally. If one generator had a limit of less than 1.5 p.u. or the initial powers of the generator differed from each other the resulting power on each generating unit would be different.

```
def test_2(self):
    current_power = [1, 1]
    max_limits = [2, 2]
    min_limits = [-2, -2]

    res = fix_mismatch(1.0, current_power, max_limit, min_limit)
    self.assertAlmostEqualList(res, [1.5, 1.5])
```

Integration Testing of Monte Carlo Simulation

The Monte Carlo simulation spanned a number of modules. It had code to read in the input files, generate random numbers in various distributions, and output the results. As such the testing involved is no longer known as unit tests and becomes integration testing:

> *"Integration testing shows that the major subsystems that make up the project work and play well with each other."* [4]

If the Monte Carlo simulation was working correctly it should have an output that almost matches the theoretical results. For example, the theoretical result of tossing a coin 1000 times would be 500 head and 500 tails. A working Monte Carlo sampler will give results similar to this.

The exact analytical solution to the problem we are simulating is complex involving failures that change the probability of other events occurring such as

Table 8.3: Theoretical Results

Name	**No.**	**Min**	**Max**	**Average**
Bus P_o	24	3.70×10^{-005}	3.70×10^{-005}	3.70×10^{-005}
Bus P_f	24	3.00×10^{-006}	3.00×10^{-006}	3.00×10^{-006}
Line P_o	38	3.42×10^{-004}	1.75×10^{-003}	6.69×10^{-004}
Line P_f	38	2.00×10^{-006}	6.20×10^{-005}	3.90×10^{-005}
Generator P_o	32	1.00×10^{-002}	1.20×10^{-001}	4.34×10^{-002}
Generator P_f	32	3.40×10^{-004}	2.22×10^{-003}	8.80×10^{-004}

CROW failures (see Section 8.1.3). These effects should be dwarfed by the overall probabilities and as such are ignored.

Theoretical Results A simple calculation of the expected number of failures per component was performed as a test for the Monte Carlo sampling. This simply uses the average outage probability multiplied by the number of components. The expected number of failures given in Table 8.3 should approximately match the results obtained from the Monte Carlo Sampling in the next section.

Monte Carlo Results and Comparison One million samples were run and it can be seen from Table 8.4 that the theoretical and Monte Carlo results match to within a few per cent. It should be noted that lines can also fail because of correlated common right of way failures. For this reason, the line outages are expected to differ more than the other components. It is likely due to the low probability of this tripping type that it is not noticed in the final results. The error is likely to be even smaller if individual probabilities are used instead of averages.

Table 8.4: Comparison of Theoretical and Monte Carlo Results in 1,000,000 samples

Name	Theoretical	Monte Carlo	% Error	Abs Error
Bus P_o	888	861	3.0	27
Bus P_f	72	65	9.7	7
Line P_o	25110	25117	0.0	7
Line P_f	1481	1441	2.7	40
Generator P_o	758554	764102	0.7	5548
Generator P_f	27779	27657	0.4	122

Testing The Simulator

Although the simulator has been used before and has formed an important part of other Ph.D. theses [35, 16, 32] it was important to ensure it worked in the context of what was done for this work. There was also additional code that needed to be checked.

14 test cases were generated that tested a variety of code paths and covered a range of edge cases. These are given in the code below.

```
def main_test(out_stream):
    """print the results and the intermediate file for
       a number of interesting scenarios, so we can check
       by hand if the intermediate file generator and the
       simulator are doing the correct thing.
    """
    batch_string = ""
    # base - as normal
    batch_string += "1, base, None, , 1.0\n"
    # half load power
```

```
batch_string += "1, half, None, , 0.5\n"
# tenth load power
batch_string += "1, tenth, None, , 0.1\n"
# island
batch_string += "1, island, None, , 1.0, B11\n"
# removed 1 slack bus
batch_string += "1, slack, None, , 1.0, G12\n"
# removed all slack busses
batch_string += "1, slack-all, None, , 1.0, G12, G13, G14\n"
# remove 1 line
batch_string += "1, line, None, , 1.0, A2\n"
# remove 1 generator
batch_string += "1, gen, None, , 1.0, G24\n"
# remove 1 bus without generators
batch_string += "1, bus, None, , 1.0, 104\n"
# remove 1 bus with generators attached
batch_string += "1, bus-gen, None, , 1.0, 101\n"
# remove slack bus and all slack generators
batch_string += "1, bus-slack, None, , 1.0, 113\n"
# remove bus that causes island
batch_string += "1, bus-island, None, , 1.0, 208\n"
# load power high
batch_string += "1, high-load, None, , 1.10\n"
# load power above max gen power
batch_string += "1, over-max, None, , 1.15\n"
```

These were tested and simulated. The results of the simulation as well as the intermediate file were checked by hand to make sure the program was working correctly.

The intermediate file is the combination of the sample and the base load-flow file that forms the input to the load-flow program. There were various things that could be checked. The most important was checking that the correct components had been removed and that the load and generator power totals were correct. The base load-flow file has 172 busbars and 222 branches with result in a file with a total of 397 lines. If no components have been removed this should remain the same. The removal of a generating unit should *not* cause a change in the total power output as it should be counteracted by the mismatch fixing code described earlier, but there should be a reduction in the number of busbars and branches to reflect that change.

Once the intermediate files were checked the results of the simulation were checked as well. The removal of line B11, for example, causes the system to be islanded which should result in a result of "false" coming back from the simulator.

Table 8.5 and Table 8.6 shows the summary of the results and forms a quick reference for future checking. Creating such checks means that the program itself can be changed easily for reasons of speed or clarity without worrying that it may have broken some part of the program. Changes such as this are discussed in the next section.

Improving Simulator Performance

It was possible to improve the program to make it run faster, once the program was working and the tests were largely automatic. The largest improvement was

Table 8.5: Simulation Test Checklist - Intermediate File

Test Name	**# Busbars**	**# Branches**	**Lines in File**
base	172	222	397
half	172	222	397
tenth	172	222	397
island	172	221	396
slack	171	221	395
slack-all	169	219	391
line	172	221	396
gen	171	221	395
bus	171	220	394
bus-gen	167	215	385
bus-slack	168	215	386
bus-island	171	219	393
high-load	172	222	397

Table 8.6: Simulation Test Checklist - Results File

Test Name	**Result**	**Δ Load Power**	**Δ Generator Power**
base	True		
half		-4275	-4275
tenth		-7695	-7695
island	Island		
slack	True		(95.1-95.1)
slack-all	Slack		(172-172)
line			
gen			(400-400)
bus		74	-74
bus-gen		-108	-108+(172-172)
bus-slack	Slack	-265	-265+(285.3-285.3)
bus-island	Island	-171	-171
high-load	True	855	855

built in to the design of the program, namely to only simulate samples that were different from each other. This saved many orders of magnitude of time enabling testing to be done on one computer rather than hundreds.

Manually improving the speed of code is notoriously difficult. Optimisations that seem logical can slow down execution due to cache sizing issues and compiler optimisation. The key tool in reducing the run-time of a program is the use of a profiler. Python, the language this program is written in, comes with it's own profiler which is thankfully easy to set up.

If the following code `-m cProfile -o profile.prof` is added to any python run it creates a file containing profile information. This can be analysed in various ways but the easiest is to do the following:

```
elif args[0] == 'profile':
    if len(args) != 2:
        p = pstats.Stats('profile.prof')
    else:
        p = pstats.Stats(args[1])
    p.strip_dirs().sort_stats('time').print_stats()
```

This produces a text-based output of the profile, which makes it easy to see which parts of the program are the slowest. The focus of optimisation can then be directed to the most important part.

The program used for this work is actually made of a number of almost completely separate code paths and hence the results of profiling are completely different depending on the options given to it. This meant that the profiler had to be run on each stage of the programs operation and the results of it analysed separately.

On one run of the program there were 355 functions included in the output in total. Of these only 39 functions actually spend more than 0.01 seconds executing. It seems obvious that the focus of the optimisation should focus on just those 39. Of those 39, 12 functions spent more than 15 seconds executing and three actually took longer than a minute. Table 8.7 shows the results of this run but the exponential decay is more easily seen in Figure 8-10. Note that most of the functions are internal functions which I cannot optimise but I may be able to reduce the number of times they are called.

Table 8.8 and its corresponding graph in Figure 8-11 show that although there is the same drop-off rate in function execution time the different task causes various different functions to be the main cause of slowdown.

In Table 8.8 the function called `Ensure` takes a fair amount of the execution time but its only purpose is to check the program is working properly, it performs no useful calculation. As long as the program has been well tested this function could be removed saving over 6 mins from the execution time without changing the output at all.

Required Number of Simulation Samples

Tests were performed, as detailed below, to ensure that enough samples were taken. If there were not enough samples results could be spurious. This is discussed in Section 7.5.1 as point 7. Performing too many samples wastes time; time which could be spent improving the accuracy of the simulation in other ways.

The number of required simulations was determined in the simplest fashion that works well. If the result is stable in repeated runs then the number of

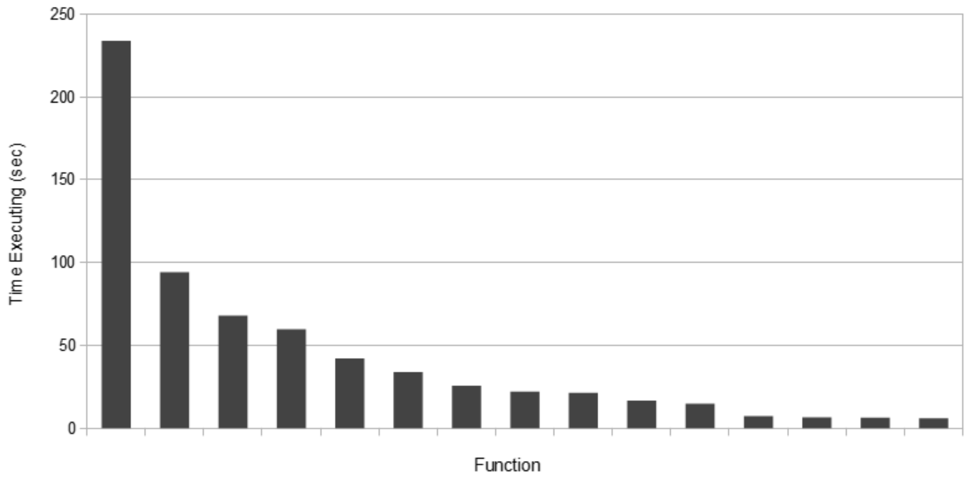


Figure 8-10: Execution Time of Slowest Monte Carlo Functions

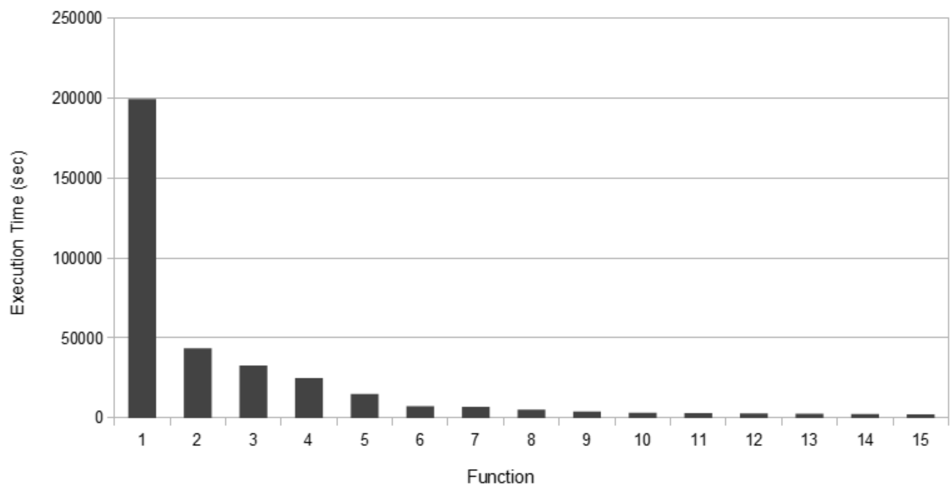


Figure 8-11: Execution Time of Slowest Simulation Functions

Table 8.7: Profiler Output for Monte Carlo Generation

# calls	time	function
3125914	233.799	sample_failures
911953657	94.213	random
124417069	67.913	as_csv
12997901	59.788	str.join
1	42.152	main_failure
12996899	33.858	Scenario.str
9860000	25.726	combine_scenarios
12996899	22.045	as_csv
9870987	21.325	file.write
3125921	16.555	dict.items
12996914	14.743	Scenario
1	7.376	generate_n_unique
3125915	6.463	failure_scenario_generator
3125914	6.452	random.normal
3125914	5.938	get_crow
3125914	5.891	round
3125915	4.452	make_sample_generator
3125914	2.724	actual_load2
3125914	2.529	crow_failures
4279242	2.095	math.log
3125914	1.924	quantised_05
3127096	0.629	len
11000	0.111	scenario_from_csv
1001	0.076	stream_scenario_generator
1	0.034	output_scenario
12008	0.023	str.split
68501	0.014	str.strip
6031	0.005	rnd_random
1	0.003	main.py
10265	0.002	list.append
1	0.001	Sampler.read
1	0.001	modifiedtestcase.py
1	0.001	loadflow.py
2	0.001	collections.py
1	0.001	__init__.py
1	0.001	main.py
120	0.001	read_branch
1	0.001	__init__.py

Table 8.8: Profiler Output for Simulation

# calls	**time**	**function**
156309881	199616.866	poll
3786873971	43658.848	scsv.writerow
156561165	32776.221	posix.read
9870987	25062.888	lfgenerator
9751366	15107.11	cleanup_output
3814361971	7376.932	readline
13730243660	6967.25	str.strip
9866241	5251.293	fix_mismatch
3765844391	4033.054	str.split
9870987	3268.428	posix.fork
2105257643	3070.346	lineinlimit
3746102409	2754.014	string.split
9870987	2696.547	_execute_child
3814361989	2547.835	str.find
7356139055	2333.641	list.append
9751366	2248.675	limits.check
1697809764	2191.069	is_slack_bus
9059008903	2138.692	len
9870987	1916.243	_communicate_with_poll
3814361971	1193.221	_complain_ifclosed
9870987	1169.734	simulate
1621342034	1068.585	businlimit
9870989	891.71	filter
95573879	890.89	sum
4210515286	871.37	abs
2105257643	856.336	max
1939278531	737.549	find_total_gen
19741974	512.453	dict.keys
9870987	496.926	subprocess.py
1	491.271	main_simulate
9870987	453.826	_communicate
157935792	444.363	fcntl
39451985	439.006	dict.items
19741974	434.167	_eintr_retry_call
29612961	422.776	posix.fdopen
1003352127	382.654	Ensure
39497561	377.3	str.join
9751366	374.08	check_limits
9601860	332.461	find_limit_min
29612961	296.08	file.close

samples is not the limiting factor hence it is unlikely the result will change simply by running more simulations.

First, a set of 100 base-cases were generated to form the basis of the test. Next, contingencies were generated using the Monte Carlo Sampler. This was done repeatedly starting with 1 unique sample going up an order of magnitude each time until 100,000 unique samples had been tested. These results were analysed to find the probability of acceptability in each case.

If the probability of acceptability for each base case is the same for any two sets of sample sizes then we know that the smaller of the two has enough samples. For example if 1,000 and 10,000 both had the same results to a certain number of significant figures then running more samples is not likely to change that number.

The results for one such test on a particular base-case are shown in Table 8.9 and Figure 8-12. The change tapers off as the number of samples increases. The difference in the results with 10,000 and 100,000 samples is very small meaning it is not worth doing more than 10,000 samples.

Table 8.9: Finding the Required Number of Samples

# Unique	# Unacceptable	# Actual	P(Acceptable)
1	0	1	0.0000
5	0	14	0.0000
10	0	34	0.0000
50	2	580	0.3448
100	8	1347	0.5939
500	98	14213	0.6895
1000	522	67813	0.7698
5000	7539	1078238	0.6992
10000	21832	3150946	0.6929
50000	448340	64421520	0.6959
100000	1794430	257651817	0.6965

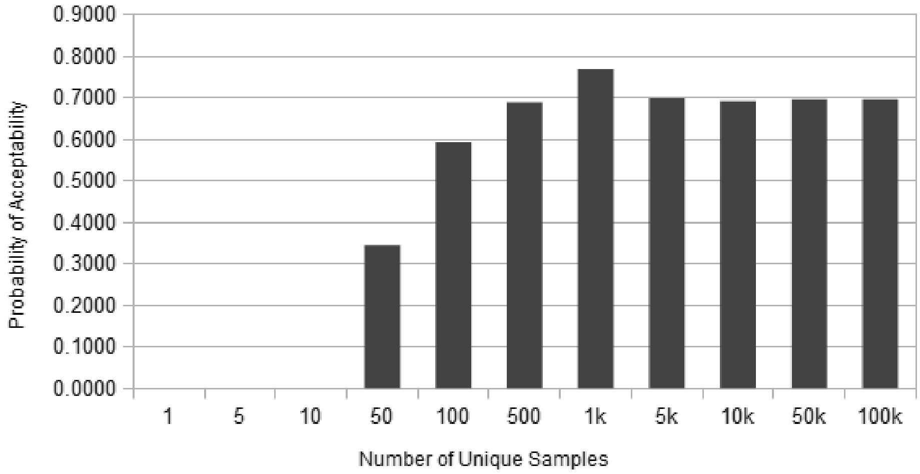


Figure 8-12: Finding the Required Number of Samples

8.4 Using the Program

The following piece of code is the shell script that does each stage of simulation in order to produce the final analysis. First, it removes old files, then generates base cases and simulates them. Then it generates contingencies and simulates the combination of both. Finally analysis is done on the results of the simulation.

```
#!/bin/sh
echo "start", $1, $2
python2 main.py clean


python2 main.py base-case $1 > base-case.csv
python2 main.py simulate < base-case.csv > base-case-result.csv
echo "base-cases done"


python2 main.py contingency $2 < base-case-result.csv > combi.csv
```

```
echo "generate contingencies done"


python2 main.py simulate < combi.csv > result.csv
echo "simulate contingencies done"


python2 main.py analyse < result.csv > analysis.csv
echo "analysis done"
```

8.5 Chapter Summary

This chapter details the software used to form the results of this thesis. It details decisions made during its construction, such as why a particular network was chosen. It also discusses and analyses some of the tests created as part of the program to ensure its correct operation.

Chapter 9

Results

This chapter contains the results gained from the computer program detailed in the previous chapter. It is broken down into a number of sections. First the results are gathered after creating the contingencies from Monte Carlo Sampling. The next two sections have results created from single (N-1) then double (N-2) component failures. This allows a comparison of how well N-1 and N-2 are predictors of the Monte Carlo sampling.

After that the program is modified to begin incorporating unscheduleable generation and then modified again to look at unpredictable power output. The aim is to determine how the level of security changes with unpredictable generation such as wind.

9.1 Base Cases

The script given in Section 8.4 was run producing 1000 base cases and 10,000 unique contingencies all generated from Monte Carlo Sampling. This section looks at the base-cases generated.

Table 9.1: First 20 Base-Cases Tested Using Basic Monte Carlo

# Unacceptable	**# Samples**	**P(Acceptable)**	**Load Level**	**Outaged Components**
981	3125913	0.000313	0.85	G80, G45, G46, G10
1151	3125913	0.000368	0.35	
1303	3125913	0.000416	0.65	G13, G67
1126	3125913	0.000360	0.35	G52, G44
8277	3125913	0.002647	0.7	G39, G87, G2, G1, G72
1301	3125913	0.000416	0.55	G26, A25-1
1651	3125913	0.000528	0.85	G7, G30
13308	3125913	0.004257	0.8	G38, G65, G71, G78, G6
1402	3125913	0.000448	0.5	G52, G44, G56
1242	3125913	0.000397	0.45	G6, G33, G23, G1, G68, G57, G56, G72, G17
1303	3125913	0.000416	0.55	G31, G24, G68
1296	3125913	0.000414	0.45	G34, G40, G85, G87, G56, G99
1323	3125913	0.000423	0.5	G13, G86, G22, G66, G38
1430	3125913	0.000457	0.5	G2, G76, G89, G1, G87
10363	3125913	0.003315	0.75	G39, G71
3086	3125913	0.000987	0.8	G79, G40, G77, G19, G17, G66
1261	3125913	0.000403	0.45	G31, G5, G37, G90
1362	3125913	0.000435	0.55	G74, G42
1119	3125913	0.000357	0.45	G1, G21, G8, G80, G70, G72, G14, G78, G56
1304	3125913	0.000417	0.75	G16, G1, G11

It is not necessary or helpful to give all 1000 base cases in the text. Table 9.1 shows the summary of 20 base cases selected at random to give an idea of the sort of output the computer program produced.

The column that is of most interest is the third one. This is the number of unacceptable contingencies divided by the total number. It is this number that aims to represent the overall security of that base case. Taking the first row as an example, in around 3 million contingencies about 1000 were unacceptable and would need emergency operator action. If the number of unacceptable cases were higher it would mean it was more likely that the system operator would need to perform emergency action. This is discussed further in the next section. This section focuses on the fourth and fifth column which describe the make up of a base-case.

An intuitive feel for the normal state of system operation can be gained from Table 9.1. In most of the cases there were a number of components out of service; these were almost all generators. This is what was expected from the probabilities these are based upon but by viewing it this way it becomes easier to visualise.

9.1.1 Load Level Forecast

The load level mostly hovers at around half the maximum output, indeed it is the modal value with between 14 and 16% of base-cases having a power level of 0.5 times the maximum. The range of powers spanned from 0.35 at the lowest to 1 at the highest. It is interesting to note that the median value was around 0.6 meaning that on average 40% of installed capacity was unused. This is shown in Table 9.2. It is shown graphically in Figure 8-5 in an earlier chapter.

Interestingly if the forecast was high in the base-case, a contingency may cause

Table 9.2: Frequency of Load Levels in Base-Cases

Power Level	**Frequency (%)**
0.35	1.8
0.4	5.9
0.45	11.0
0.5	15.4
0.55	11.4
0.6	11.2
0.65	8.6
0.7	7.5
0.75	8.8
0.8	8.5
0.85	6.9
0.9	2.3
0.95	0.4
1	0.1

the power required to be higher than the power available. This is a clear example of an adequacy issue. Not very surprising as the system in question is used in a lot of adequacy studies.

9.1.2 Number of Components on Outage in Base Cases

The number of components that are out for repair or maintenance in each base case ranges from 0 to 13, the exact frequencies are shown in Figure 9-1 and Table 9.3. One surprising result is that in one base-case 13 separate components were unavailable. This does not take into account the fact that the loss of a single busbar may remove a number of generating units, which could make that result higher. The modal value of component outages was 4 with 5 coming in a close second. The median was also between 4 and 5 meaning, for this system, at any given time one would expect 4 components to be non-functioning.

97.5% of all failures were of generating units making up 4123 of the total 4229

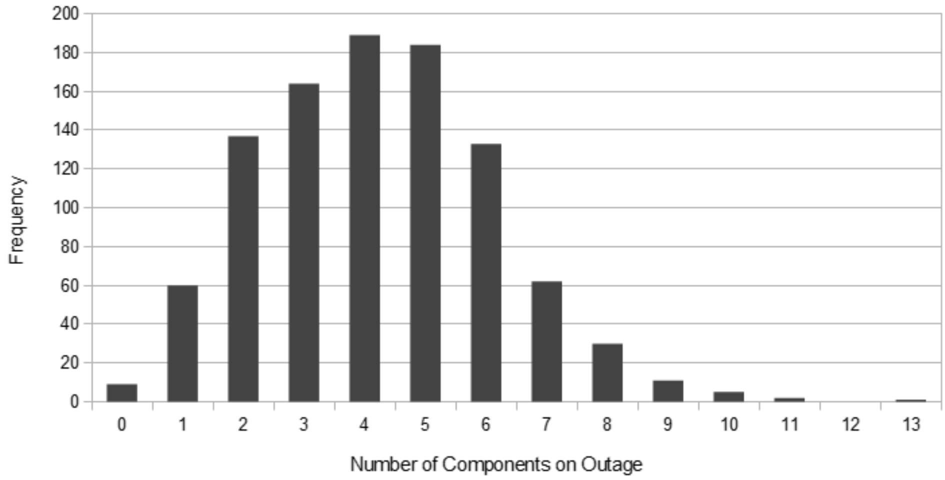


Figure 9-1: Component Outage Frequencies in Base Cases

components that were on outage in all the 1000 bases-cases. There were 100 line outages in the base cases corresponding to a total of 2.4%. The final 0.1% of outages were caused by a fault on a busbar, there were only 4 of these in all the base-cases.

9.1.3 Excluded Base Cases

There were 13 bases cases that were excluded from further analysis (see Table 9.4). These were ones that were not stable or they had limit violations even before contingencies were applied. For example, there is no reason to run all the contingency tests on a base case that is already islanded. Unless random failures manage to remove all but the main island it will never have any acceptable cases and will simply skew the results without adding to them.

It would have been possible to manually re-balance the failed system, this is what would happen in reality; unfortunately it opens more questions than it solves. If the system were to have been balanced for the failed cases; why not

Table 9.3: Frequency of Outages in Base-Cases

Outaged Components	**Number of Base Cases**	**Percentage of Total**
0	9	0.9
1	60	6.1
2	137	13.9
3	164	16.6
4	189	19.1
5	184	18.6
6	133	13.5
7	62	6.3
8	30	3.0
9	11	1.1
10	5	0.5
11	2	0.2
12	0	0.0
13	1	0.1

balance all of them to the same degree. If that is done then analysis would depend heavily on the type of stability/security constrained optimal power flow that was used. For this reason it was decided that all base-cases that fail an initial simulation would not be included in the rest of the analysis.

Given more time it would be interesting to study the failed base-cases. They are likely to be of interest to a system operator and excluding them is not ideal.

9.2 Contingencies from Monte Carlo Sampler

This section looks at the contingencies generated by Monte Carlo Sampling. There were a total of 10,000 unique sample which resulted in an actual total of 3,125,913 samples. A selection of these is given in Table 9.5. The same set of contingencies were used against each base-case to find the number of acceptable cases, hence only one set of Monte Carlo Sampled contingencies were generated.

Table 9.6 shows that certain contingencies occurred very often. Over a million

Table 9.4: Unacceptable Base Cases

Failure Reason	**Load Level**	**Outages Components**
limits	0.8	G71, G6, G35, G72
limits	0.8	G24, A10, G34, G89, G70, A12-1, G67, G56, A32-1
limits	0.75	G22, B24, G71, G45, G72, G63
divergence	0.6	G74, G90, G13, C5, G47
islanded	0.85	C11, G35, G23, G72
limits	0.9	G24, G39, G74, G45, B10, G98
limits	0.85	G31, G23, G97, G96, G57, G55, G47, G13, G64
limits	0.4	G33, B15, G89, G19, G90
limits	0.7	G71, G24, G3, G72
islanded	0.65	G41, C11, G83, G72
limits	0.55	G31, G5, C10, G12
limits	0.7	G76, B10, G1
divergence	0.8	G57, G66, G56, G90
limits	0.65	G6, G5, G67, G99

Table 9.5: First 20 Contingencies Generated using Monte Carlo Sampling

Repeat	**Simulation Result**	**Load Level**	**Outages Components**
3	islanded	0.9	C34, C30
24	ok	0.95	C12-1
1	ok	0.95	G94, B21
1	ok	1	G97, G72
1	ok	1	G97, G73
3	ok	0.95	G50, G99
1	ok	0.95	G62, A30
1	ok	0.95	G50, G93
1	ok	1	G7, G55
1	ok	0.95	G50, G94
1	ok	1	G94, G57
2	ok	1.05	G67, G10
1	ok	1.05	G67, G18
1	ok	1.1	G77, G1
1	mismatch	1.2	G3
1	mismatch	1.2	G5, G55
1	ok	0.9	G67, G10
25	ok	0.85	G79
21	ok	0.85	G78
13	ok	0.85	G75

samples had no change to the base case as can be seen in the first line. It is also interesting to note how quickly the number of repeated contingencies drops off, with an order of magnitude decrease from the 5th to the 6th most frequent contingency.

The result in the 7th row (where the Simulation Result is "mismatch") means the simulation failed as there was a mismatch between the supply and demand, i.e. there was not enough generator capacity.

Table 9.6: Excerpt of Most Frequent Contingencies

Repeat	Simulation Result	Load Level	Outages Components
1092920	ok	1	
692195	ok	1.05	
691647	ok	0.95	
173354	ok	0.9	
172965	ok	1.1	
17200	ok	0.85	
16850	mismatch	1.15	
2508	ok	1	G6
2494	ok	1	G5
2491	ok	1	G39
2478	ok	1	G71
2477	ok	1	G38
2464	ok	1	G35
2463	ok	1	G2
2452	ok	1	G34
2447	ok	1	G68
2413	ok	1	G67
2398	ok	1	G1
2371	ok	1	G72
1602	ok	0.95	G34

9.2.1 Load Forecast Error

The load forecast error (shown in Table 9.7 and Figure 9-2) is rather simple as it is just a Monte Carlo sampled normal distribution with a mean value of 1. At

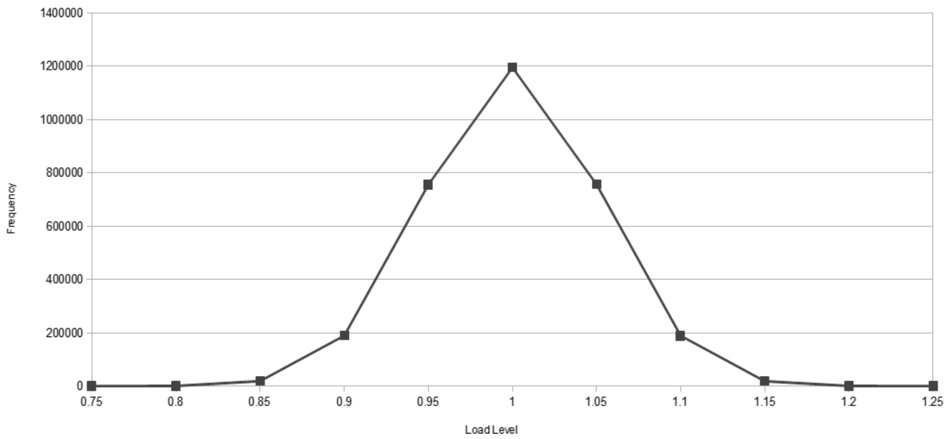


Figure 9-2: Frequency of Given Load Level

the upper power levels demand actually starts to become greater than the system can supply as can bee seen on the 7th row of Table 9.6.

Table 9.7: Frequency of Given Load Level

Load Level	**Frequency**
0.75	9
0.8	722
0.85	18,866
0.9	18,9425
0.95	756,143
1	1,195,666
1.05	756,986
1.1	188,946
1.15	18,429
1.2	715
1.25	6

9.2.2 Component Failures

Table 9.8 and Figure 9-3 shows the number of contingencies that had exactly X component failures. Obviously these fall at an exponential rate showing how

Table 9.8: Frequency of Component Failures

Number of Failed Components	**Frequency**
0	2,858,453
1	255,453
2	11,606
3	390
4	11

unlikely it is to have multiple components fail within an hour of each other without an external factor causing all the effects.

Interestingly there were 11 cases where 4 components failed at the same time. This is a hugely unlikely event but it did happen so it is worth looking at. To give a vague idea of this likelihood we can assume that all the one hour samples follow one another. There were over 3 million samples each representing 1 hour and 11 of them have 4 simultaneous failures, this corresponds to 4 simultaneous failures every 32 years. This is however, stretching what is realistic with the statistics, and is used just to form a mental model of how unlikely the event is. To give another comparison, some form of component failure occurred in one in every 12 samples, meaning about twice a day one would expect some sort of malfunction somewhere on the system.

The total number of failed components in all simulations is 279,879 of these 264,025 were of generating units (94.3%); 15,190 were lines (5.4%); the other 664 were busbar failures (0.3%).

9.2.3 Probability of System Becoming Unacceptable

From the graph in Figure 9-4 it is easy to see that the number of failed contingencies is highly non-linear and that there are a few outliers with a very high probability of failure. These are outliers in the sense of being outside the main

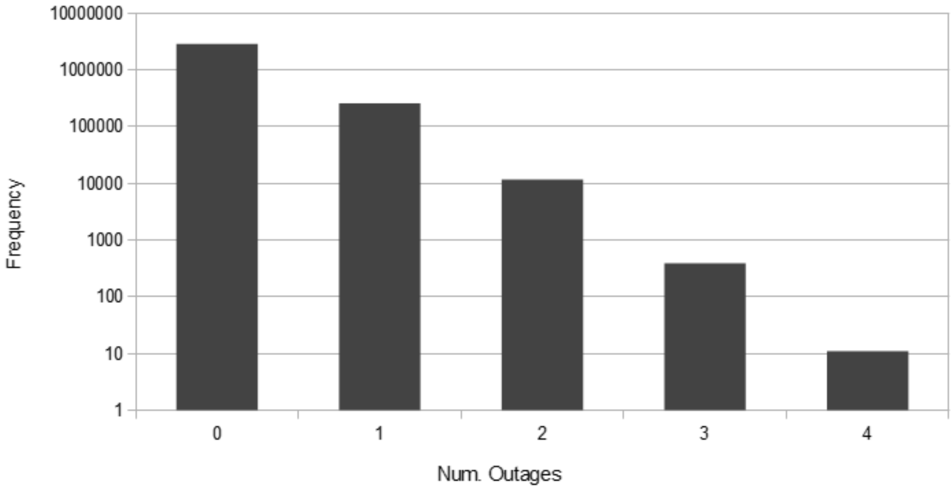


Figure 9-3: Frequency of Component Failures

grouping of results but not such that should be removed. These are interesting cases where a system operator should know that the system is in a precarious state and should be re-balanced to a new and more stable operating point.

Table 9.10 shows 20 of these cases. Even in that selection the number of unacceptable cases goes up two orders of magnitude. The least secure base case on this run actually had more chance of being unacceptable than not. Clearly not a system that an operator would consider running.

By looking at these cases a few things should be obvious. There is not an unusual number of components on outage. The load-power is higher than average but this cannot be the sole determinant as there are many non-problematic cases with a large number of components on outage and a high load forecast level for example the 5th row from the bottom of Table 9.1. There are some patterns to which generator are included in this set, for example 90 and G71 seem to turn up a lot but this could be due to a statistical anomaly rather than a pertinent feature.

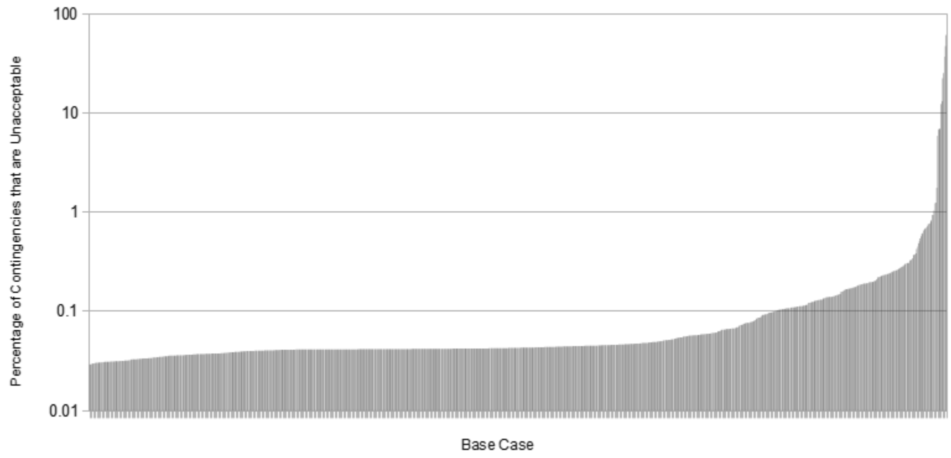


Figure 9-4: Percentage of Contingencies that are Unacceptable with no Unscheduleable Generation

Figure 9-4 shows the percentage of unacceptable contingencies. The average percentage of unacceptable contingencies for all base-cases is 0.3% which works out to be 10,419. This is clearly skewed by a few base-cases. Most cases fall between 1,000 and 10,000 unacceptable contingencies. The base-cases with the fewest unacceptable cases is shown in Table 9.11, the lowest having a percentage of 0.03%. The largest percentage of unacceptable base-cases was 60% and is shown in Table 9.10.

There were a variety of reason why a simulation might fail to find an acceptable solution, these are shown below:

ok There were no problems found in the simulation.

component out of limits Line limits were exceeded.

divergence Failed to find stable solution.

islanded System split into multiple parts.

failed to find a replacement slackbus All available slack buses removed.

mismatch The fix-mismatch function found that demand outstripped supply.

Table 9.9 lists the frequency of these events for the base case. This varied massively depending on which base case was selected, as is to be expected. The reason the number of power mismatches was so high in the base case was that it has a power level of one which is very close to the maximum amount of load the system can support. A more realistic figure would be the average power level, which is half that of the base case.

Table 9.9: Reasons for Unacceptable System States

Result of Simulation	**Frequency**
ok	3104289
component out of limits	868
divergence	249
islanded	184
failed to find a replacement slackbus	7
mismatch	20316

9.3 Contingencies from N-1 & N-2

9.3.1 N-1

Each base case was again tested against a set of contingencies. Unlike the previous section the contingencies were not generated randomly. These were generated by assuming one component fails at a time. As there are 289 components (lines, generating units, busbars) in the system there are the same number of contingencies to test.

Monte Carlo Sampling required 10,000 contingencies to be generated, hence if N-1 provides a suitable approximation of the full Monte Carlo sampling then

Table 9.10: Base-Cases With Fewest Acceptable Contingencies

# Unacceptable	# Samples	P(Acceptable)	Load Level	Outaged Components
23972	3125913	0.0076687995	0.75	G24, G12, G89, G77, G87, G73, G47, G14, G78
24212	3125913	0.0077455771	0.85	G90, G93, G78, B25-1, G89
25191	3125913	0.0080587656	0.75	A7, G97, G57, G46, G90, G49, G79, G99
25962	3125913	0.0083054135	0.9	G71, G57, G23, G21
29263	3125913	0.009361425	0.75	G51, B28, G90
29295	3125913	0.009371662	0.45	G39, B15, G79, G36, G87
32364	3125913	0.0103534551	0.75	G17, C16, G47
38629	3125913	0.0123576696	0.8	G24, G23, G97, G68, G69, G57, G89
39178	3125913	0.0125332983	0.85	G39, G77, G79, G89
55172	3125913	0.0176498834	0.45	G75, B17, G80, G45, G36
183875	3125913	0.0588228143	0.7	G34, G1, G77, G58, G67, G99
214245	3125913	0.0685383758	0.95	G57, G45, G99
216475	3125913	0.0692517674	0.35	G71, C16, G9
216574	3125913	0.0692834382	0.85	G24, G32, G23, G33, G45, G90
386576	3125913	0.1236681891	0.8	G6, G24, G35, G1, G5, G71, G13, G12
412692	3125913	0.1320228682	0.9	G39, G38, G47, G78, G90
699206	3125913	0.2236805695	0.6	G74, G67
788947	3125913	0.2523893019	0.7	G6, G5, G35, G34, G38, G66
1159364	3125913	0.3708881213	0.95	G39, G72, G71, G90, G47, G66
1473545	3125913	0.4713966767	0.7	G6, G24, G80, G5
1916405	3125913	0.6130704853	0.75	G38, G71, G72, G44, G59, G79

Table 9.11: Base-Cases With Fewest Unacceptable Contingencies

# Unacceptable	# Samples	P(Acceptable)	Load Level	Outaged Components
911	3125913	0.000291	0.85	G31, G35, G1
914	3125913	0.000292	0.85	
925	3125913	0.000296	0.85	G57, G29
928	3125913	0.000297	0.85	G46
933	3125913	0.000298	0.85	G62, G51, G13
936	3125913	0.000299	0.85	G24, G54, G2, G34
946	3125913	0.000303	0.85	G42, G67
947	3125913	0.000303	0.85	G10
952	3125913	0.000305	0.85	G44, G45, G29
953	3125913	0.000305	0.35	G2, G57, G45, G47, G49, G79
953	3125913	0.000305	0.85	G42, G57
955	3125913	0.000306	0.80	G35
957	3125913	0.000306	0.80	G85, G24, G22, G56, G54
958	3125913	0.000306	0.80	G35, G20
958	3125913	0.000306	0.85	G30, G14, G88
962	3125913	0.000308	0.85	G24, G57, G1
966	3125913	0.000309	0.85	G4
967	3125913	0.000309	0.80	G35, G46
969	3125913	0.000310	0.80	G53, G68, G57, G10
969	3125913	0.000310	0.80	G40, G68, G45

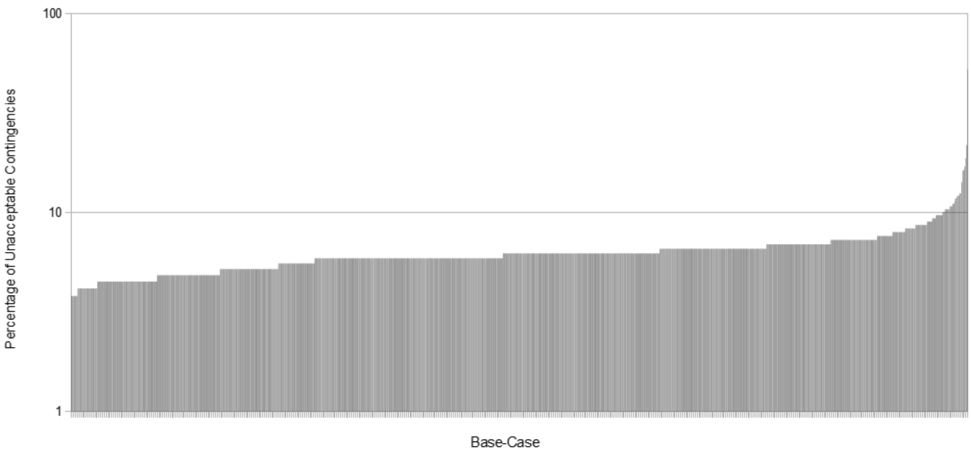


Figure 9-5: Percentage of Failed N-1 Contingencies (Logarithmic)

we can greatly reduce the computational load required to analyse the security of the system. This will be a great advantage to system operators who want to optimise the system for stability.

Monte Carlo Sampling should give results which match reality closer, i.e. more accurately than N-1. This is because the probabilities of certain events are explicitly taken into account. N-1 is a sort of approximation of the full Monte Carlo Sampling which considers only a certain subset of comparatively likely events. It does fall down in some aspects, for example, the simultaneous loss of generating units G71 and G72 is twice as likely to happen as the loss of line A7. These sort of differences are not taken in to account in N-1.

Between 11 and 151 out of 289 contingencies failed on the different base-cases. The median value was 18 again showing a high skew, there were a small number of base-cases where a large number of contingencies failed. The results can be seen in Figure 9-5.

Table 9.12 shows the reasons for failures occurring in all N-1 contingencies across all base cases.

Table 9.12: Reasons for Unacceptable System States in N-1

Result of Simulation	Frequency
ok	268249
component out of limits	11332
divergence	3508
islanded	2120
failed to find a replacement slackbus	994
mismatch	27

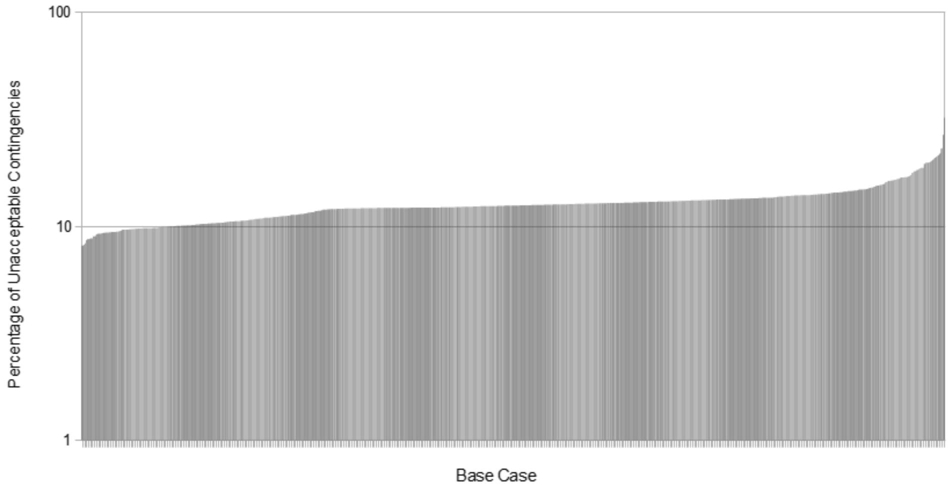


Figure 9-6: Percentage of Failed N-2 Contingencies (Logarithmic)

9.3.2 N-2

The contingencies from this section were generated by selecting each combination of two components as the ones that will fail. This gave a total of 41,616 contingencies, far more than is needed using Monte Carlo sampling. On average 5200 contingencies resulted in unacceptable system states with the minimum being 3385 and the maximum 13,407. The percentage of failed contingencies is shown in Figure 9-6.

9.4 Comparing N-1, N-2 and Monte Carlo Sampling

It would be very useful to see if N-1 or N-2 is a good predictor of the results gained from Monte Carlo Sampling. It is also interesting to see how N-1 and N-2 differ. Figure 9-7 shows a scatter plot of the percentage of failed contingencies in both N-1 and N-2. It is easy to see a high correlation between these two sets of results, this is to be expected, N-1 and N-2 are very similar sorts of tests. This is in contrast to Figure 9-8 which does not have such a high correlation. This figure compares the results gained from N-2 to those from Monte Carlo Sampling. It shows that the number of failed base cases in N-2 (and by their high degree of correlation in N-1) is not a good predictor of the results gained through Monte Carlo Sampling. As those results are meant to represent the overall system security it means that the number of contingencies that fail N-1 is not a good predictor of system security.

Another way of looking at the data is to plot the percentage of failed contingencies for each base case. This is done in Figure 9-9, in this figure the base cases are sorted by the percentage of Monte Carlo sampled contingencies that failed. If N-1 was a good predictor of the Monte Carlo results it would in some way match the curve of the Monte Carlo results. This doesn't happen enough for N-1 to become a useful predictor. There is some change in the N-1 data point in the right of the figure, although it seems just to be a higher variance.

These results bring in to question the value of performing a full N-2 simulation. It can highlight problematic areas of a system but it will not take into account the probabilities enough, potentially leading to securing the wrong parts

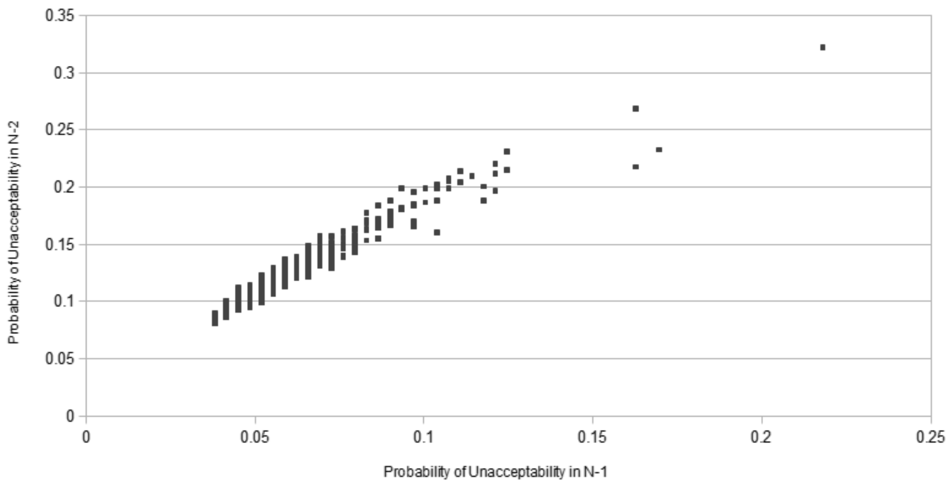


Figure 9-7: Scatter Plot of Percentage of Failed Contingencies using N-1 and N-2

of the system. Risk is likelihood times consequence and N-2 doesn't consider the likelihood accurately enough. A probabilistic model such as the one used here can give more accurate results in less simulation time.

It can even be used to find problematic areas of the system. The current results tell you for a given system what the likelihood is that it will become problematic. This can be inverted by counting the number of times a component is in an unacceptable system verses an acceptable one. This will give a measure of which components are problematic. To use the software in such a way requires simply running a large MCS and simulating each contingency. Then, for each unacceptable contingency, mark each component that failed. The total number of marks that a component has across all contingencies tell a system planner how often that component is problematic.

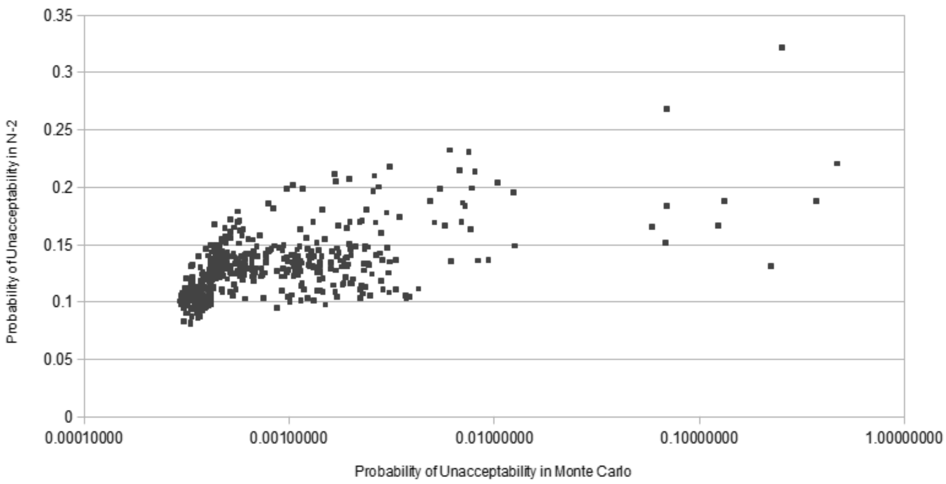


Figure 9-8: Scatter Plot of Percentage of Failed Contingencies using N-1 and Monte Carlo

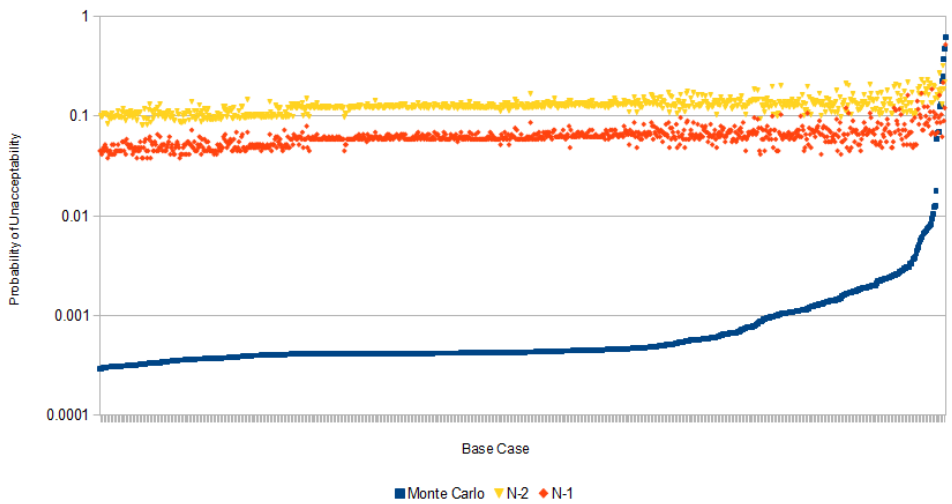


Figure 9-9: Percentage of Failed Contingencies using N-1, N-2 and Monte Carlo

9.5 Unscheduleable Generators and Wind Power

In the following two sections renewable energy is added in to the equation, specifically wind power. There are two things notably different about wind power that matters to this application. Firstly the power output of wind cannot be set like it can with a conventional generator i.e. it is *unscheduleable*. Secondly the wind forecast is often wrong by some extent meaning the predicted value will be partly wrong i.e. it is *stochastic*.

One would expect that when the added uncertainty of wind power gets added to a network the security would decrease. However, as this is a complex system with many interacting parts, what is expected can be quite different from what is experienced.

9.5.1 Wind Modelling Requirements

Wind power is not easy to model in the general case. For the purposes of this work a greatly simplified model can be used as long as it exhibits the two factors discussed above. There are still problems to be overcome, specifically:

- where on the network should wind power be added,
- what installed capacity should each wind farm be given,
- how is the power level for each wind farm determined in the base-cases,
- how does the wind forecast error get determined in the contingencies,
- what should the be total penetration of wind generation.

9.5.2 Adding Wind To The IEEE-RTS-96

The first two points will be addressed at the same time as they are related. If new generation was added to the network it would change the adequacy of the system, this would greatly reduce the validity of the comparison between a system with no wind turbines and one with. It would mean that the total installed capacity was greatly increased but that lines were more likely to be overloaded. This is the installed capacity at the busbars with new generating units would be higher.

Another option is to replace certain generating units with the same installed capacity of wind generation. But wind power cannot replace conventional generation on a megawatt by megawatt basis [93]. It therefore makes more sense to put in wind turbines such that when it is at the average load factor it produces the same amount of generation as the unit it is replacing. Unfortunately this changes the adequacy of the lines. By having the same power after the load factor is taking into account the new wind generator must have an installed capacity much higher than the conventional generator it replaced; if the wind generator ever happens to produce near its installed capacity the line will surely be overloaded.

It is not the purpose of this work to see how the power profiles of very similar electrical networks cause differences in security. The aim is to find out how the same network is affected by having the added uncertainty of wind turbines.

The easiest way to do this is to not change the network or base-cases at all. Simply take the assumption that some generating units behave like wind generation, in-that their output cannot change to smooth out errors in the load-forecast or take up slack following faults on other components.

The changes that are required only modify the Monte Carlo Generation of contingencies and they are as follows:

1. Make some generators *unscheduleable* by excluding each them from the `fix-mismatch` function. This means that those generators will not be able to change power in response to changes in the network.

2. Make the designated generators' power vary *stochastic*ally. Change the power output of each generating unit that is designated as renewable by an amount correlated with the probabilities in Table 7.1 from [10]. This represents the error in wind forecasting. Although to some extent the errors for each site will cancel out in terms of the total power generated the difference will have to be made up by the conventional generators[1].

This allow easy comparison between the results in previous sections with those that include wind generation. It also enables the two parts to be computed separately to determine which has a bigger role in security.

9.5.3 Location of Wind Generation

Although wind power is not currently included in the IEEE-RTS a number of published papers have done so. Most of these papers have added wind in addition to the current generating units which is not ideal for the current application as discussed previously. Because of this, wind has to be added based on other criteria. As the IEEE-RTS does not represent a real system the location cannot be chosen on factors such as wind availability as it would in reality. All that is required is to adequately mimic what one might see. It is neither possible or desirable to place all wind generation at one busbar, the desired wind penetration is too high to allow that. It also does not makes sense to evenly distribute the

[1]Given a real power network it would be preferable to model the covariance of geographically close wind farms

wind to all busbars, a real system is likely to have a number of busbars that contain just conventional generation.

The possible location is further reduced by the desired penetration level.

9.5.4 Choosing Wind Penetration

As discussed in the introductory chapters many studies have looked at a penetration of wind such that on average 20 % of the power comes from renewable generators. Because of this 2 different penetration levels were chosen. One just below at 15%, and one above at 30%. Having the one penetration level to be exactly double the other allows a better comparison. There are certain generating units that are identical on some busbars. The location of the wind generators was chosen such that changin the penetration level did not change which busbars contained wind generation. This was done by selecting only busbars where there were two identical units on the same busbar.

By further restricting the selection of wind location to be around the desired penetration level there were only a few options available. The one that matched the desired penetration levels the closest was chosen. There were 12 generating units that made up the 15% penetration level selection. These are shown in Table 9.13. The 30% penetration level consisted of converting another generating unit of the same type on each of the busbars listed.

9.5.5 Simulation Results

The same scenarios are used here as in the experiment with only conventional generators. Because of this, there is only one interesting column in the output file for this experiment - the number of unacceptable contingencies. As was done

Table 9.13: Unschedulable Generators at 15 % penetration

Gen	**Bus**	**Unit Type**
G3	101	U76
G7	102	U76
G9	107	U100
G16	115	U12
G25	122	U50
G31	123	U155
G67	201	U76
G73	202	U76
G75	207	U100
G82	215	U12
G91	222	U50
G97	223	U155

in the earlier experiment 10,000 contingencies were generated using Monte Carlo sampling. Unlike the scenarios, which are the same for each experiment the contingencies differ. It would have been possible to use the same contingencies in this experiment but in the latter experiment, when a wind forecast error is present in the contingencies, they need to be different.

There were a number of base-cases that failed to simulate properly. These were excluded from further analysis as was done at the end of Section 9.1.3. This meant that some experiments had more base cases than others, to keep the results consistent only the bases cases that weren't problematic in any experiment were included in the final analysis. For example, if a base case had failed to simulate when there was 30 % unscheduleable generation then it would be excluded from the analysis of all other experiments including 15 % unscheduleable where it might have actually passed the simulation. This reduction left a total of 795 base cases that could be analysed in all experiments.

The percentage of contingencies that are unacceptable in each scenario is plotted in Figure 9-10 and 9-11 for penetrations of 15% and 30% respectively. To

Table 9.14: Summary of Failure Rates in Unscheduleable Experiments

	Absolute Value			Probability		
	Min	**Median**	**Max**	**Min**	**Median**	**Max**
Conventional	911	9372	1473545	0.03	0.30	47.14
15% Unscheduleable	903	6326	1199363	0.03	0.20	37.80
30% Unscheduleable	934	80950	1958134	0.03	2.55	61.71

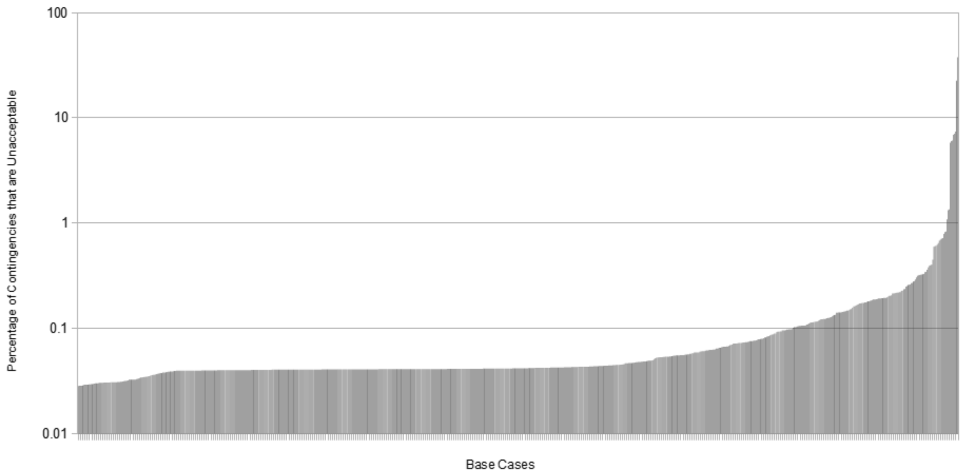


Figure 9-10: Percentage of Contingencies that Failed with 15% Unscheduleable Generation

make the graphs clearer the scenarios are sorted by the percentage of contingencies that are unacceptable. For comparison this was done the same way for conventional generators in Figure 9-4.

The shape of the graph for the 15% penetration level is very similar to the one with no unscheduleable generation, curiously it is also of a similar magnitude; the modal value appears to be the same in both figures. Looking at the summary table for this data Table 9.14 [2] shows that the system actually becomes more secure with small number of unscheduleable generators. This is counter-intuitive and if not for the further analysis might be put down to an artefact of the few

[2]The same data is also shown along with the other experiments in Table 9.17

cases with a very low security happening to skew the results. The clearer finding is in the graphs; adding a moderate amount of unscheduleable generation does not adversely affect the security of the system in this experiment.

Table 9.15: Relative Failure Rates in Unscheduleable Experiments

	Conventional	**Unscheduleable**	
		15%	**30%**
Conventional	-	195	574
15% Unscheduleable	600	-	635
30% Unscheduleable	221	160	-

Table 9.16: Relative Failure Rates in Unscheduleable Experiments (as percentage of base cases)

	Conventional	**Unscheduleable**	
		15%	**30%**
Conventional	-	25	72
15% Unscheduleable	75	-	80
30% Unscheduleable	28	20	-

As the scenarios and network remained constant between experiments and the number of simulations produces a consistent result another form of comparison can be used. Table 9.15 and Table 9.16 compare the number of scenarios that are more secure in each experiment; if there were no differences between the experiments the results would be around 50:50. It is more easily seen in the second table where the number is expressed as a percentage of the number of scenarios tested.

For example, 75% of the scenarios were more secure with 15% of the generation coming from unscheduleable generation when compared to the case of all conventional generation. This again gives further weight to the finding that under these specific conditions having a reduced number of generators that change their output in response to the network is actually a stabilising factor. This may

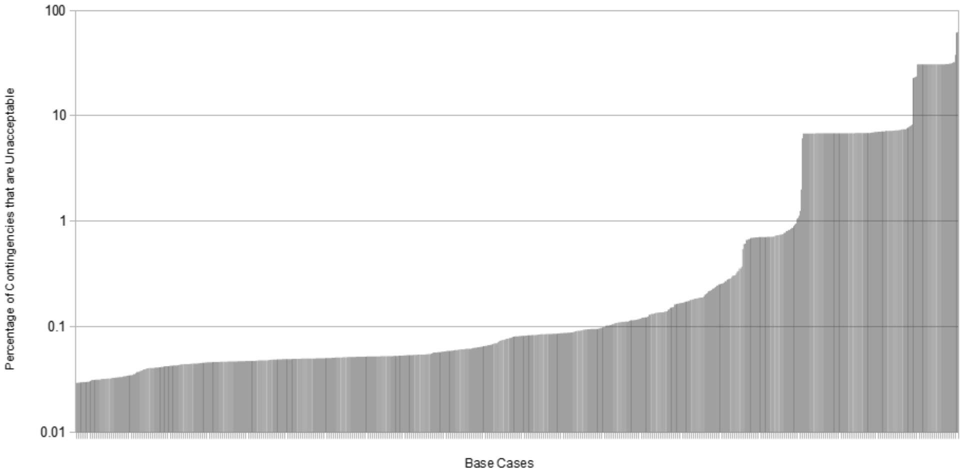


Figure 9-11: Percentage of Contingencies that Failed with 30% Unscheduleable Generation

however be due to a factor of the simulation method or of the simplified way in which the pick-up of power mismatch is modelled.

When the penetration level was doubled there was a noticeable difference in the resulting output. Figure 9-11 shows the profile of security across scenarios as it did for the four experiments to come before it.

With the most secure contingencies the result is comparable to the two previous experiments. This can also be seen in Table 9.14 where the minimum probability is the same to two decimal places (at a level of 0.03%). However the graph becomes quite different in the less secure cases. There are many more cases that are less secure and the least secure scenarios are considerably less secure than those in the other experiments so far. For this system at least having 30% of the system unable to react to power changes results is a much less secure system. In Table 9.16 it shows that 72% of the scenarios were less secure than a system with all conventional generation and 80% were less secure than a system with a small number of unscheduleable generators.

9.6 Wind Variability

The final stage is to take into account the stochastic nature of wind. Again the bases cases were not changed, only the contingencies were modified. The power output of the selected generators was randomly perturbed based on the figures in the one hour forecast delay of Table 7.1.

This additional variability changed the number of samples that were duplicates, in the case of 30 % stochastic generators 10011 samples resulted in only 11 that were duplicated. This does mean that results are not quite as accurate as in earlier experiments but based upon the analysis in the tests of the previous chapter they should be enough to draw conclusions from. The number of contingencies sampled in each scenario is shown in Table 9.17.

Table 9.17: Summary of Failure Rates in all Experiments

		Failure Rate		
	Number Contingencies	**Min**	**Median**	**Max**
Conventional	3125913	911	9372	1473545
15% Unscheduleable	3172811	903	6326	1199363
30% Unscheduleable	3172925	934	80950	1958134
15% Stochastic	23353	4	146	10590
30% Stochastic	10011	4	1007	6236

Table 9.18: Summary of Percentage Failure Rates in all Experiments

	Min	**Median**	**Max**
Conventional	0.03	0.30	47.14
15% Unscheduleable	0.03	0.20	37.80
30% Unscheduleable	0.03	2.55	61.71
15% Stochastic	0.02	0.62	45.35
30% Stochastic	0.04	10.06	62.29

As with the experiments with unscheduleable generation the results are shown in three forms: as a graph of the number of unacceptable contingencies for each scenarios Figure 9-12 and Figure 9-13; as a table summarising the percentage of unacceptable contingencies in Table 9.17 and as percentages in Table 9.18; and finally as a comparison showing which scenarios were more stable in which experiment, again shown as raw values in Table 9.19 and as percentages in Table 9.20.

Curiously the case with 15% penetration again seems to be more secure in some ways than the system with all conventional generation. There are two points to this, firstly the modal level of unacceptable scenarios is lower as can be seen from Figure 9-12, secondly the number of scenarios in which it was more secure was higher than in any other experiment, this is shown in the fourth row of Table 9.20. Given more time it would be interesting to see if this artefact holds true with a different underlying network or a more accurate simulation model is used. While it is not strong enough evidence to conclude that having wind power makes the system more secure it does at least show that at low penetrations the addition of renewable power is unlikely to case a problem to the security of the network.

Table 9.19: Relative Failure Rates

	Conventional	**Unscheduleable**		**Stochastic**	
		15%	**30%**	**15%**	**30%**
Conventional	-	195	574	271	744
15% Unscheduleable	600	-	635	290	752
30% Unscheduleable	221	160	-	208	758
15% Stochastic	522	505	587	-	727
30% Stochastic	51	43	37	68	-

The clearest finding of all the experiments is the one with 30% of the generation being stochastic in nature. Figure 9-13 shows that it is significantly less secure. It also does not level of to a clear modal value like the others experiment.

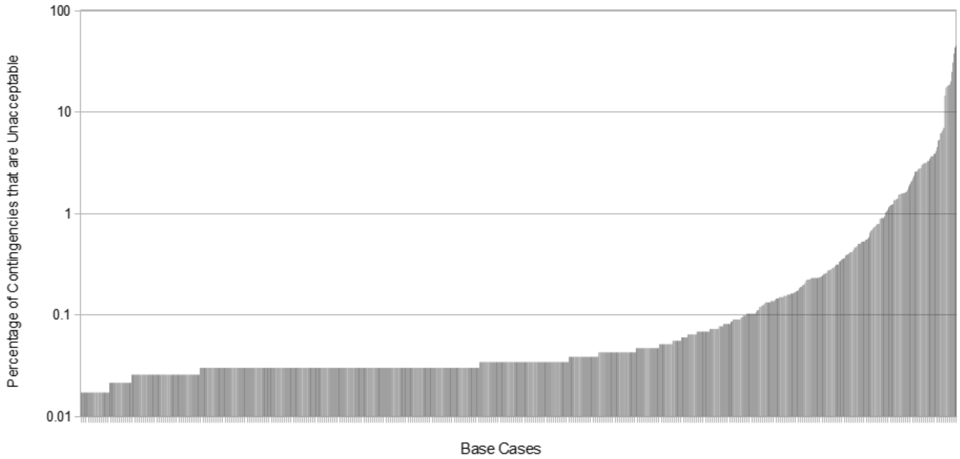


Figure 9-12: Percentage of Contingencies that Failed with 15% Stochastic Generation

Table 9.20: Relative Failure Rates (as percentage of base cases)

	Conventional	Unscheduleable		Stochastic	
		15%	30%	15%	30%
Conventional	-	25	72	34	94
15% Unscheduleable	75	-	80	36	95
30% Unscheduleable	28	20	-	26	95
15% Stochastic	66	64	74	-	91
30% Stochastic	6	5	5	9	-

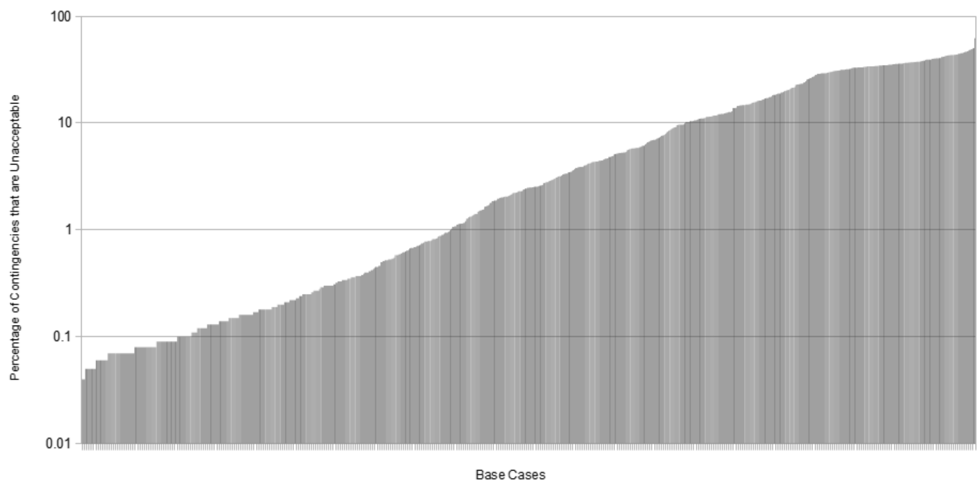


Figure 9-13: Percentage of Contingencies that Failed with 30% Stochastic Generation

This is reflected in Table 9.20 where over 90% of scenarios were less stable under these conditions. The average percentage of scenarios that were problematic was four times higher than the next worse as shown in Table 9.18.

9.7 Chapter Summary

Scenarios (or base-cases) were generated and analysed by simulating them under a number of different conditions. The conditions for generating contingencies and analysing scenarios were:

1. N-1: All single component failures

2. N-2: All combinations of two components failing

3. MCS (Monte Carlo Sampling) where all supply is conventional

4. MCS where 15% of supply came from unscheduleable generators

5. MCS where 30% of supply came from unscheduleable generators

6. MCS where 15% of supply came from stochastic generators

7. MCS where 30% of supply came from stochastic generators

The first three conditions assumed all generation was conventional i.e. it could be scheduled to produce a given amount of power and would produces that unless the component completely failed. Under these conditions three experiments were run, the first two tested all single and double component failures, the third used Monte Carlo Sampling (MCS) to generate the contingencies. It was shown that there was not a high degree of correlation between the number of contingencies that failed with MCS and the number that failed with N-2.

The next two conditions assumed a certain percentage of the supply could no longer be scheduled i.e. the unit would not respond to changes in the system and simply had a set power output. This was run at 15% and 30% of supply. At 15% there was not much change in the output compared to conventional whereas at 30% many more scenarios had a high number of problematic contingencies.

The remaining two conditions modified the same generators again to simulate errors in the power level expected. This represents how wind has to be forecast and that the forecast can be wrong. Again this was run at 15% and 30% of supply. At 15%-stochastic the results were relatively similar to the 15%-unscheduleable, whereas almost all contingencies were significantly less secure when 30% of their power came from stochastic generation.

Chapter 10

Conclusion

This thesis aims to show that the introduction of renewable power will adversely effect the security of a power system at high levels of penetration. It also aims to show the inadequacy of N-1 in a system with a high penetration of renewables.

Before that question was posed a literature review of future power systems determined that wind farms will make up a large proportion of the system mix in the future. Due to their inherent inability to be scheduled and their stochastic generation they are also significantly different in operation to conventional generation. This brought about the more specific question of how the introduction of wind power will change the security of the system.

To analyse the security of the system, current simulation techniques were reviewed based upon the requirements of the work. A number of avenues for further work were identified to increase the speed of the simulations. A load-flow simulator was chosen and integrated into a suite of tools that can be used to analyse security or compare security assessment schemes.

These computer programs were extensively tested to ensure their correct and fast operation. Experiments were also done to determine the number of samples required in each scenario to ensure reliable results.

The program works by taking a probabilistic model of the network including failure rate of various types of components as well as load forecasting and models of error rates in wind forecasts. This data is fed into a Monte Carlo sampler to produce a number of contingencies. These represent likely changes to the system in the one hour delivery period. By simulating these contingencies and categorising them as acceptable or unacceptable a measure of the level of security is obtained. For instance if one scenario had 100/1,000,000 contingencies that were unacceptable then it would be more secure than a scenario with 500/1,000,000 unacceptable scenarios.

The scenarios themselves were also generated through Monte Carlo simulation, in total 1000 scenarios were generated, of which over 700 were used in the final analysis.

This program was used in two ways:

1. Each scenario was tested with N-1 and N-2 and the results of the simulations were again categorised as acceptable or unacceptable. If N-1 was a good predictor of system security then there would be a high degree of correlation between the level of security calculated earlier and the number of N-1 contingencies that were unacceptable. This was found not to be the case. N-1 and N-2 do however have a high degree of correlation between each other.

2. The underlying system and scenarios were modified to gradually introduce renewable generation. This was done in two ways. Firstly a certain set of generators that account for 15% of total generation had their output power fixed, i.e. they became unscheduleable. The next stage was to take the same

generators and vary their power stochastically based upon normal error levels in wind forecasts. Both parts were run again at double the penetration (30%) to see how that changed the security level. If the introduction of renewables has no effect on the security then the results from each of the four tests should be the same as the first set of test where all generators were conventional. In fact there were significant differences found between the experiments.

When the penetration was low the introduction of renewables had a small stabilising effect. This was true both in the form of unscheduleable and stochastic generation. This is highly counter-intuitive and good cause for further study. That further study is a significant undertaking given that each experiment requires millions of simulations to be run. It may be that this counter-intuitive effect disappears when the network is changed to be based upon a real system.

Although most scenarios were fairly comparable between the experiment with 15% unscheduleable generation and the one with 30% unscheduleable generation there were some noticeable differences. Certain scenarios are inherently less secure than others, looking only at the least secure the difference seems to be much larger in the experiment with higher penetration. In other words if the power system is already weakened then having fewer generators that can be called upon to pick-up the mismatch causes a them to become even worse.

The most noticeable effect of all experiments comes from the one where 30% of generators vary stochastically. Almost all scenarios were significantly less secure than in any of the other experiments.

This work echoes the findings discussed in the first chapter of the thesis, that at low penetrations the introduction of renewable generation is not likely to pose a significant problem to the security of the system, but as the penetration increases the number of problems will too, especially if the wind forecasts are inaccurate.

Chapter 11

Further Work

As with all research this work opens up many avenues for further work. This chapter expands on a few of those ideas to present possible avenues of research. In general the literature review on power system simulation identified a number of areas where potential improvements were possible. The computer program also provides two areas for expansion. Firstly the computer program itself can be improved to provide a more accurate simulation. Secondly, the program can be used for a number of additional areas of study. These were introduced in the relevant chapters but will be re-examined here. One final area for further work comes from the conclusions themselves. The findings discussed naturally open up more questions as to the nature of power system security analysis.

11.1 Improvements to Power System Simulation

11.1.1 GPGPU ODE Solver

The proposed work demands a large number of simulations to be performed quickly. It was for this reason that so much energy was spent on creating a dynamic simulator that has a faster execution speed than those currently available. There are still great advances to be made in this area and the one that looked the most promising is moving the ODE solver to the graphics cards (GPU). Huge increases in speed have been reported using this method but, as the GPGPU programming is very new, it is an underdeveloped area. It not only allows the speedup to come from the specialised hardware but it will require a redesign that would necessitate being able to calculate different machine equations in parallel. This should have a near linear speed-up due to the low overheads involved.

11.1.2 New Simulation Software

While it was not possible in this body of work due to the simulation time, it should be possible to replace the load-flow program with a dynamic simulator. This would enable the work to take into account a much wider range of issues which can not be represented by a load-flow.

11.2 Improvements to the Developed Computer Software

11.2.1 Parallelisiation

As each simulation is independent of any other it should be possible to compute many different simulations at the same time. This would result in a linear speed-up of execution time allowing many more experiments to be run. For example, if five computers each with two processor cores were set-up to perform the simulation then it should operate at nearly 10 times the speed. This would have enabled the work to contain 50 different experiments rather than five. If this was possible it would be interesting to increase the penetration level in small steps of around 5% to see exactly how the results differed.

11.2.2 Better Accounting for Consequence in the Comparison Program

One of the limitations of this work is its poor treatment of consequence. A line overload is treated as equally bad as system collapse. This is simply unrealistic. One way to overcome this was briefly mentioned in Section 7.5.1. This scheme involves tripping loads until the system is stable and in-limit. The amount of load that needs to be shed is a measure of how severe that scenario was.

11.3 Other uses for the Developed Computer Software

11.3.1 Testing of Planned Network Changes

If a new piece of power system plant is about to be introduced it is vital to know how it will effect the security level. The tools used in this thesis are already suitable for this work without modification. For instance it might be interesting to see how a HVDC line running down the centre of the UK would change the security.

11.3.2 Catalogue of Problematic Network Sections

If every simulation performed on a network was saved to a database there are a number of interested queries that can be answered by it. The most obvious, and potentially useful, is to find the components that are good predictors of a unstable scenario. One might find that when a certain component is on outage it greatly reduces the overall security of the system. This would be valuable information for the system planner.

Appendices

Appendix A

The IEEE Reliability Test System

The IEEE Reliability Test System - 1996

A report prepared by the Reliability Test System Task Force* of the Application of Probability Methods Subcommittee

ABSTRACT

This report describes an enhanced test system (RTS-96) for use in bulk power system reliability evaluation studies. The value of the test system is that it will permit comparative and benchmark studies to be performed on new and existing reliability evaluation techniques. The test system was developed by modifying and updating the original IEEE RTS (referred to as RTS-79 hereafter) to reflect changes in evaluation methodologies and to overcome perceived deficiencies.

INTRODUCTION

The first version of the IEEE Reliability Test System (RTS-79) was developed and published in 1979 [1] by the Application of Probability Methods (APM) Subcommittee of the Power System Engineering Committee. It was developed to satisfy the need for a standardized data base to test and compare results from different power system reliability evaluation methodologies. As such, RTS-79 was designed to be a reference system that contains the core data and system parameters necessary for composite reliability evaluation methods. It was recognized at that time that enhancements to RTS-79 may be required for particular applications. However, it was felt that additional data needs could be supplemented by individual authors and or addressed in future extensions to the RTS-79.

In 1986 a second version of the RTS was developed (RTS-86) and published [2] with the objective of making the RTS more useful in assessing different reliability modeling and evaluation methodologies. Experience with RTS-79 helped to identify the critical additional data requirements and the need to include the reliability indices of the test system. RTS-86 expanded the data system primarily relating to the generation system. The revision not only extended the number of generating units in the RTS-79 data base but also included unit derated states, unit scheduled maintenance, load forecast uncertainty and the effect of interconnection. The advantage of RTS-86 lies in the fact that it presented the system reliability indices derived through the use of rigorous solution techniques without any approximations in the evaluation process. These exact indices serve to compare with results obtained from other methods.

Since the publication of RTS-79, several authors have reported the results of their research in the IEEE Journals and many international journals using this system. Several changes in the electric utility industry have taken place since the publication of RTS-79, e.g. transmission access, emission caps, etc. These changes along with certain perceived enhancements to RTS-79 motivated this task force to suggest a multi-area RTS incorporating additional data.

* Co-Chairmen: C. Grigg and P.Wong; P. Albrecht, R. Allan, M. Bhavaraju, R. Billinton, Q. Chen, C. Fong, S. Haddad, S. Kuruganty, W. Li, R. Mukerji, D. Patton, N. Rau, D. Reppen, A. Schneider, M. Shahidehpour, C. Singh. See Biographies for affiliations.

96 WM 326-9 PWRS A paper recommended and approved by the IEEE Power System Engineering Committee of the IEEE Power Engineering Society for presentation at the 1996 IEEE/PES Winter Meeting, January 21-25, 1996, Baltimore, MD. Manuscript submitted August 1, 1995; made available for printing January 15, 1996.

It should be noted that in developing and adopting the various parameters for RTS-96, there was no intention to develop a test system which was representative of any specific or typical power system. Forcing such a requirement on RTS-96 would result in a system with less universal characteristics and therefore would be less useful as a reference for testing the impact of different evaluation techniques on diverse applications and technologies. One of the important requirements of a good test system is that it should represent, as much as possible, all the different technologies and configurations that could be encountered on any system. RTS-96 therefore has to be a hybrid and atypical system.

SYSTEM TOPOLOGY

The topology for RTS-79 is shown in Figure 1 and is labeled "Area A." Since the demand for methodologies that can analyze multi-area power systems has been increasing lately due to increases in interregional transactions and advances in available computing power, the task force decided to develop a multi-area reliability test system by linking various single RTS-79 areas. Figure 2 shows a two-area system developed by merging two single areas - - "Area A" and "Area B" through three interconnections. As shown the two areas are interconnected by the following new interconnections:

- 51 mile 230 kV line connecting bus # 123 and bus # 217
- 52 mile 230 kV line connecting bus # 113 and bus # 215
- 42 mile 138 kV line connecting bus # 107 and bus # 203.

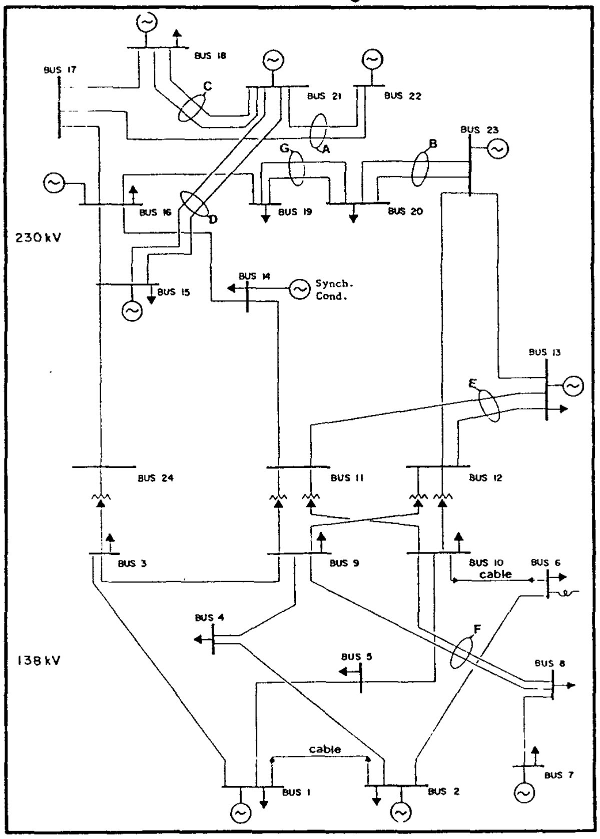


Figure 1 - IEEE One Area RTS-96

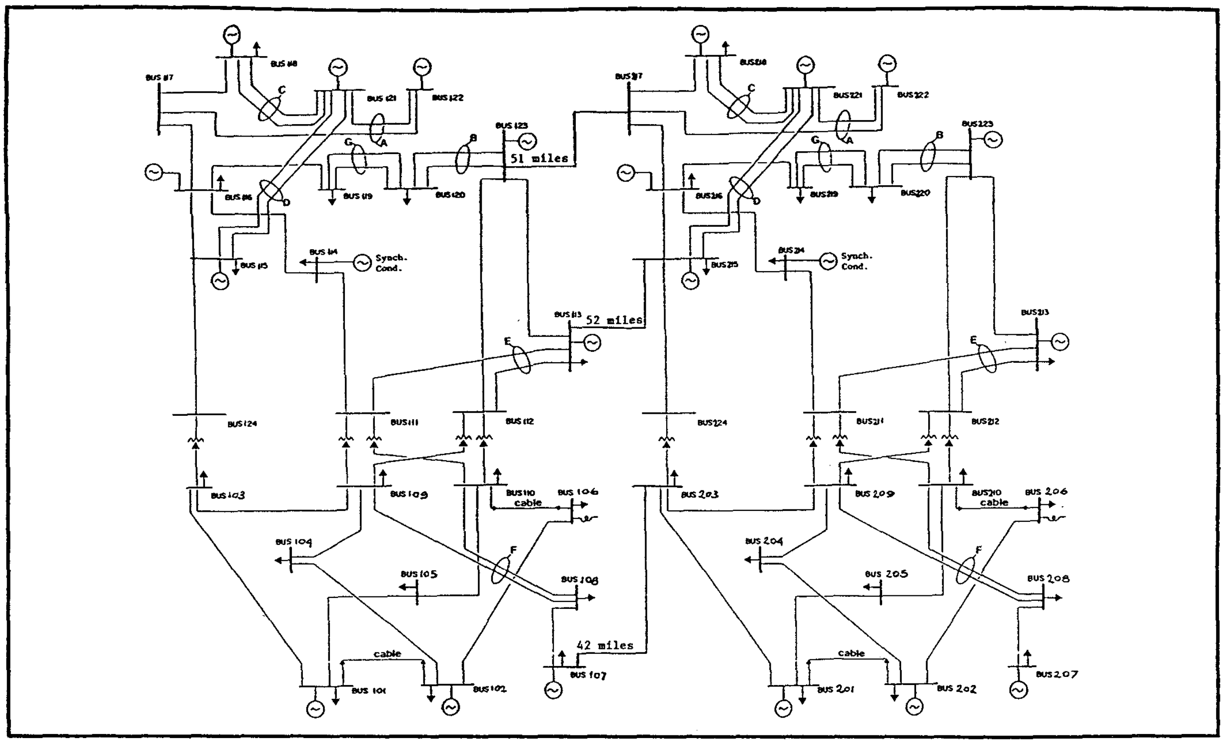


Figure 2 - IEEE Two Area RTS-96

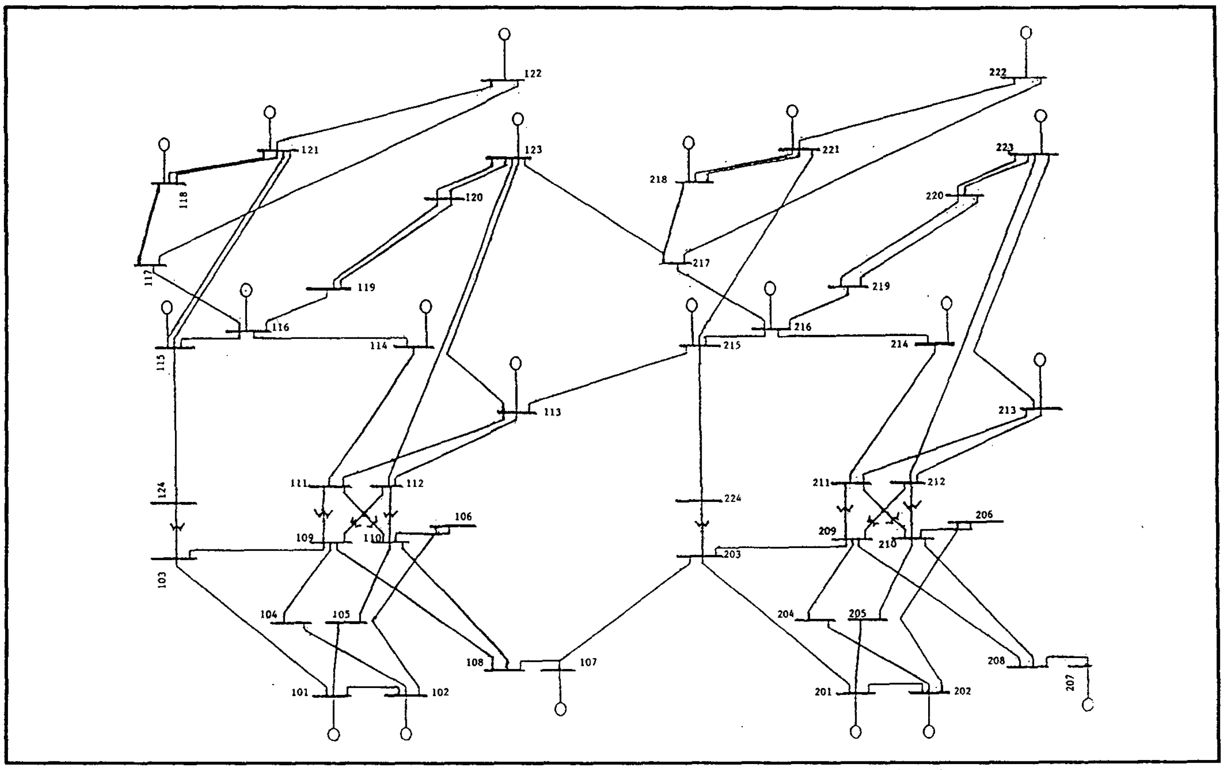


Figure 3 - IEEE Two Area RTS-96 with Geographic Scale

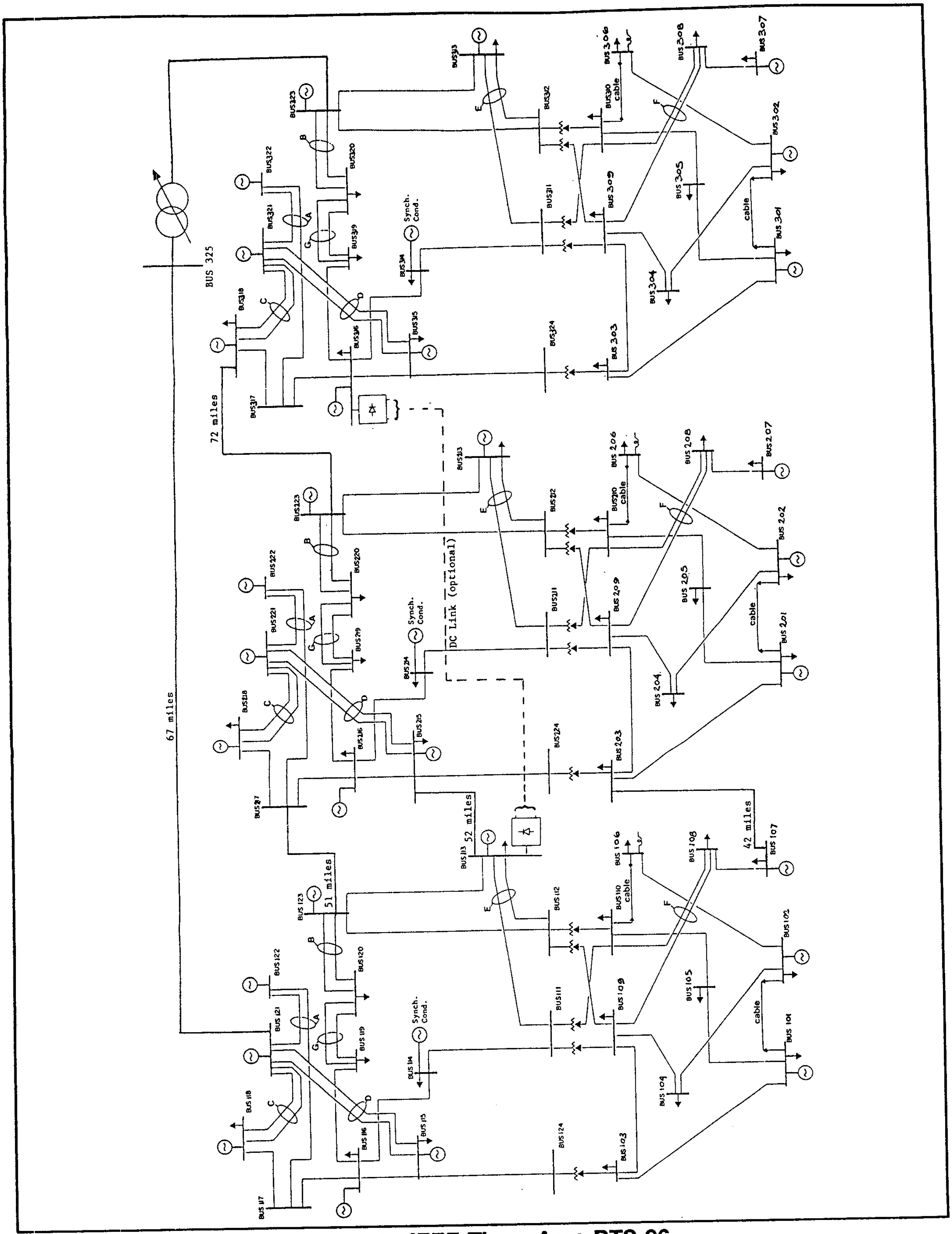


Figure 4 - IEEE Three Area RTS-96

Figure 3 shows relative geographic positions for the two-area system. Figure 4 shows a three-area system formed by adding a third single area "Area C" to the two-area system through two interconnections. A 72 mile 230 kV line connects "Area B" at bus 223 to "Area C" at bus # 318 and a 67 mile 230 kV line connects "Area A" at bus # 121 to "Area C" at bus # 325. A phase shift transformer has been added between buses # 325 and 323 in "Area C". An optional DC link connects "Area A" at bus # 113 to "Area C" at bus # 316.

BUS DATA

Except for the bus numbering system, the bus data has not changed from the RTS-79 data. Table 1 lists the bus data for the three areas. The buses for each area are numbered with a preassigned numbering system. For "Area A" the buses are labeled with numbers ranging from 101 through 124. For "Area B", the buses are labeled with numbers ranging from 201 through 224. While for "Area C" the buses are labeled with numbers ranging from 301 through 325. In addition, the three areas' buses are divided into subareas and zones. The bus load is assigned based on assumptions shown in Table 5.

Table 1 - IEEE RTS-96 Bus Data (3 Areas)

BUS #	BUS NAME	BUS TYPE	MW LOAD	MVAR LOAD	GL	BL	Sub Area	Base kV	Zone #
101	Abel	2	108	22	0	0	11	138	11
102	Adams	2	97	20	0	0	11	138	12
103	Adler	1	180	37	0	0	11	138	11
104	Agricola	1	74	15	0	0	11	138	11
105	Aiken	1	71	14	0	0	11	138	11
106	Alber	1	136	28	0	1.0	11	138	12
107	Alder	2	125	25	0	0	11	138	12
108	Alger	1	171	35	0	0	11	138	12
109	Ali	1	175	36	0	0	11	138	13
110	Allen	1	195	40	0	0	11	138	13
111	Anna	1	0	0	0	0	11	230	13
112	Archer	1	0	0	0	0	11	230	13
113	Arne	3	265	54	0	0	12	230	14
114	Arnold	2	194	39	0	0	12	230	16
115	Arthur	2	317	64	0	0	12	230	16
116	Asser	2	100	20	0	0	12	230	16
117	Aston	1	0	0	0	0	12	230	17
118	Astor	2	333	68	0	0	12	230	17
119	Attar	1	181	37	0	0	12	230	15
120	Attila	1	128	26	0	0	12	230	15
121	Attlee	2	0	0	0	0	12	230	17
122	Aubrey	2	0	0	0	0	12	230	17
123	Austen	2	0	0	0	0	12	230	15
124	Avery	1	0	0	0	0	12	230	16
201	Bach	2	108	22	0	0	21	138	21
202	Bacon	2	97	20	0	0	21	138	22
203	Baffin	1	180	37	0	0	21	138	21
204	Bailey	1	74	15	0	0	21	138	21
205	Bain	1	71	14	0	0	21	138	21
206	Bajer	1	136	28	0	1.0	21	138	22
207	Baker	2	125	25	0	0	21	138	22
208	Balch	1	171	35	0	0	21	138	22
209	Balzac	1	175	36	0	0	21	138	23
210	Banks	1	195	40	0	0	21	138	23
211	Bardeen	1	0	0	0	0	21	230	23
212	Barkla	1	0	0	0	0	21	230	23
213	Barlow	2	265	54	0	0	22	230	24
214	Barry	2	194	39	0	0	22	230	26
215	Barton	2	317	64	0	0	22	230	26
216	Basov	2	100	20	0	0	22	230	26
217	Bates	1	0	0	0	0	22	230	27
218	Bayle	2	333	68	0	0	22	230	27
219	Bede	1	181	37	0	0	22	230	25
220	Beethoven	1	128	26	0	0	22	230	25
221	Behring	2	0	0	0	0	22	230	27
222	Bell	2	0	0	0	0	22	230	27
223	Bloch	2	0	0	0	0	22	230	25
224	Bordet	1	0	0	0	0	22	230	26
301	Cabell	2	108	22	0	0	31	138	31
302	Cabot	2	97	20	0	0	31	138	32
303	Caesar	1	180	37	0	0	31	138	31
304	Caine	1	74	15	0	0	31	138	31
305	Calvin	1	71	14	0	0	31	138	31
306	Camus	1	136	28	0	1.0	31	138	32
307	Carew	2	125	25	0	0	31	138	32
308	Carrel	1	171	35	0	0	31	138	32
309	Carter	1	175	36	0	0	31	138	33
310	Caruso	1	195	40	0	0	31	138	33
311	Cary	1	0	0	0	0	31	230	33
312	Caxton	1	0	0	0	0	31	230	33
313	Cecil	2	265	54	0	0	32	230	34
314	Chain	2	194	39	0	0	32	230	36
315	Chase	2	317	64	0	0	32	230	36
316	Chifa	2	100	20	0	0	32	230	36
317	Chuhsi	1	0	0	0	0	32	230	37
318	Clark	2	333	68	0	0	32	230	37
319	Clay	1	181	37	0	0	32	230	35
320	Clive	1	128	26	0	0	32	230	35
321	Cobb	2	0	0	0	0	32	230	37
322	Cole	2	0	0	0	0	32	230	37
323	Comte	2	0	0	0	0	32	230	35
324	Curie	1	0	0	0	0	32	230	36
325	Curtiss	1	0	0	0	0	32	230	35

Bus Type: 1 - Load Bus (no generation).
2- generator or plant bus.
3- swing bus.

MW Load: load real power to be held constant.

MVAR Load: load reactive power to be held constant.

GL: real component of shunt admittance to ground.

BL: imaginary component of shunt admittance to ground.

SYSTEM LOADS

Table 2 shows the weekly peak loads in percent of the annual peak. This seasonal load profile can be used to adapt to any system peaking season one desires to model. For example, if week number 1 is assumed to be the first week of the calendar year, then table 2 shows a winter peaking system with the peak occurring in the week prior to Christmas. If week number one is assumed to be the first week of August, then table 2 shows a summer peaking system with an assumed peak occurring in the month of July.

Table 3 shows the assumed daily peak load in percent of the weekly peak; while Table 4 shows the hourly load in percent of the daily peak (note that the week numbers corresponding to the seasons of the year can be reassigned depending on the climate zone that one wishes to model.)

Table 5 shows the assumed load for each bus of the three-area system.

Table 2 - Weekly Peak Load in Percent of Annual Peak

Week	Peak Load	Week	Peak Load
1	86.2	27	75.5
2	90.0	28	81.6
3	87.8	29	80.1
4	83.4	30	88.0
5	88.0	31	72.2
6	84.1	32	77.6
7	83.2	33	80.0
8	80.6	34	72.9
9	74.0	35	72.6
10	73.7	36	70.5
11	71.5	37	78.0
12	72.7	38	69.5
13	70.4	39	72.4
14	75.0	40	72.4
15	72.1	41	74.3
16	80.0	42	74.4
17	75.4	43	80.0
18	83.7	44	88.1
19	87.0	45	88.5
20	88.0	46	90.9
21	85.6	47	94.0
22	81.1	48	89.0
23	90.0	49	94.2
24	88.7	50	97.0
25	89.6	51	100.0
26	86.1	52	95.2

Table 3 - Daily Load in Percent of Weekly Peak

Day	Peak Load
Monday	93
Tuesday	100
Wednesday	98
Thursday	96
Friday	94
Saturday	77
Sunday	75

Table 4 - Hourly Peak Load in Percent of Daily Peak

	winter weeks 1 -8 & 44 - 52		summer weeks 18 -30		spring/fall weeks 9-17 & 31 - 43	
Hour	Wkdy	Wknd	Wkdy	Wknd	wkdy	wknd
12-1 am	67	78	64	74	63	75
1-2	63	72	60	70	62	73
2-3	60	68	58	66	60	69
3-4	59	66	56	65	58	66
4-5	59	64	56	64	59	65
5-6	60	65	58	62	65	65
6-7	74	66	64	62	72	68
7-8	86	70	76	66	85	74
8-9	95	80	87	81	95	83
9-10	96	88	95	86	99	89
10-11	96	90	99	91	100	92
11-noon	95	91	100	93	99	94
noon-1pm	95	90	99	93	93	91
1-2	95	88	100	92	92	90
2-3	93	87	100	91	90	90
3-4	94	87	97	91	88	86
4-5	99	91	96	92	90	85
5-6	100	100	96	94	92	88
6-7	100	99	93	95	96	92
7-8	96	97	92	95	98	100
8-9	91	94	92	100	96	97
9-10	83	92	93	93	90	95
10-11	73	87	87	88	80	90
11-12	63	81	72	80	70	85

Table 5 - Bus Load Data

Bus number	Bus load	Load		If peak load 10% higher	
	% of System Load	MW	MVar	MW	MVar
101,201,301	3.8	108	22	118.8	24.2
102,202,302	3.4	97	20	106.7	22.0
103,203,303	6.3	180	37	198.0	40.7
104,204,304	2.6	74	15	81.4	16.5
105,205,305	2.5	71	14	78.1	15.4
106,206,306	4.8	136	28	149.6	30.8
107,207,307	4.4	125	25	137.5	27.5
108,208,308	6.0	171	35	188.1	38.5
109,209,309	6.1	175	36	192.5	39.6
110,210,310	6.8	195	40	214.5	44.0
113,213,313	9.3	265	54	291.5	59.4
114,214,314	6.8	194	39	213.4	42.9
115,215,315	11.1	317	64	348.7	70.4
116,216,316	3.5	100	20	110.0	22.0
118,218,318	11.7	333	68	366.3	74.8
119,219,319	6.4	181	37	199.1	40.7
120,220,320	4.5	128	26	140.8	28.6
	Total 100.0	2850	580	3135	638

GENERATING UNITS

The major addition to this revision is the inclusion of production cost related data for the generating units. Unit start-up (hot and cold start) heat input, net plant incremental heat rates, unit cycling restrictions and ramping rates and unit emissions data have been included to facilitate system production cost calculations and emissions analysis. Table 6 shows the unit availability assumptions. Table 7 shows unit active and reactive power quantities used in the base-case load flow. Table 8 shows unit start-up heat input requirements. Table 9 shows the generating unit heat rates. Table 10 tabulates the unit's cycling restrictions and ramp rates while Table 11 shows the assumed unit emissions.

Table 6 - Generator Data

Unit group	Unit Size (MW)	Unit Type	Force Outage Rate	MTTF (Hour)	MTTR (Hour)	Scheduled Maint. wks/year
U12	12	Oil/Steam	0.02	2940	60	2
U20	20	Oil/CT	0.10	450	50	2
U50	50	Hydro	0.01	1980	20	2
U76	76	Coal/Steam	0.02	1960	40	3
U100	100	Oil/Steam	0.04	1200	50	3
U155	155	Coal/Steam	0.04	960	40	4
U197	197	Oil/Steam	0.05	950	50	4
U350	350	Coal/Steam	0.08	1150	100	5
U400	400	Nuclear	0.12	1100	150	6

Table 7 - Data of Generators at Each Bus

Bus ID	Unit Type	ID #	PG MW	QG MVAR	Q^{max} MVAR	Q^{min} MVAR	V_S pu
101	U20	1	10	0	10	0	1.035
101	U20	2	10	0	10	0	1.035
101	U76	3	76	14.1	30	-25	1.035
101	U76	4	76	14.1	30	-25	1.035
102	U20	1	10	0	10	0	1.035
102	U20	2	10	0	10	0	1.035
102	U76	3	76	7.0	30	-25	1.035
102	U76	4	76	7.0	30	-25	1.035
107	U100	1	80	17.2	60	0	1.025
107	U100	2	80	17.2	60	0	1.025
107	U100	3	80	17.2	60	0	1.025
113	U197	1	95.1	40.7	80	0	1.020
113	U197	2	95.1	40.7	80	0	1.020
113	U197	3	95.1	40.7	80	0	1.020
114	Sync Cond	1	0	13.7	200	-50	0.980
115	U12	1	12	0	6	0	1.014
115	U12	2	12	0	6	0	1.014
115	U12	3	12	0	6	0	1.014
115	U12	4	12	0	6	0	1.014
115	U12	5	12	0	6	0	1.014
115	U155	6	155	0.05	80	-50	1.014
116	U155	1	155	25.22	80	-50	1.017
118	U400	1	400	137.4	200	-50	1.050
121	U400	1	400	108.2	200	-50	1.050
122	U50	1	50	-4.96	16	-10	1.050
122	U50	2	50	-4.96	16	-10	1.050
122	U50	3	50	-4.96	16	-10	1.050
122	U50	4	50	-4.96	16	-10	1.050
122	U50	5	50	-4.96	16	-10	1.050
122	U50	6	50	-4.96	16	-10	1.050
123	U155	1	155	31.79	80	-50	1.050
123	U155	2	155	31.79	80	-50	1.050
123	U350	3	350	71.78	150	-25	1.050
201	U20	1	10	0	10	0	1.035
201	U20	2	10	0	10	0	1.035
201	U76	3	76	14.1	30	-25	1.035
201	U76	4	76	14.1	30	-25	1.035
202	U20	1	10	0	10	0	1.035
202	U20	2	10	0	10	0	1.035
202	U76	3	76	7.0	30	-25	1.035
202	U76	4	76	7.0	30	-25	1.035
207	U100	1	80	17.2	60	0	1.025
207	U100	2	80	17.2	60	0	1.025
207	U100	3	80	17.2	60	0	1.025
213	U197	1	95.1	40.7	80	0	1.020
213	U197	2	95.1	40.7	80	0	1.020
213	U197	3	95.1	40.7	80	0	1.020
214	Sync Cond	1	0	13.68	200	-50	0.980
215	U12	1	12	0	6	0	1.014
215	U12	2	12	0	6	0	1.014
215	U12	3	12	0	6	0	1.014
215	U12	4	12	0	6	0	1.014
215	U12	5	12	0	6	0	1.014
215	U155	6	155	0.048	80	-50	1.014

Table 7 (Continued)

Bus ID	Unit Type	ID #	PG MW	QG MVAR	Q^{max} MVAR	Q^{min} MVAR	V_S pu
216	U155	1	155	25.22	80	-50	1.017
218	U400	1	400	137.4	200	-50	1.050
221	U400	1	400	108.2	200	-50	1.050
222	U50	1	50	-4.96	16	-10	1.050
222	U50	2	50	-4.96	16	-10	1.050
222	U50	3	50	-4.96	16	-10	1.050
222	U50	4	50	-4.96	16	-10	1.050
222	U50	5	50	-4.96	16	-10	1.050
222	U50	6	50	-4.96	16	-10	1.050
223	U155	1	155	31.79	80	-50	1.050
223	U155	2	155	31.79	80	-50	1.050
223	U350	3	350	71.78	150	-25	1.050
301	U20	1	10	0	10	0	1.035
301	U20	2	10	0	10	0	1.035
301	U76	3	76	14.1	30	-25	1.035
301	U76	4	76	14.1	30	-25	1.035
302	U20	1	10	0	10	0	1.035
302	U20	2	10	0	10	0	1.035
302	U76	3	76	7.0	30	-25	1.035
302	U76	4	76	7.0	30	-25	1.035
307	U100	1	80	17.2	60	0	1.025
307	U100	2	80	17.2	60	0	1.025
307	U100	3	80	17.2	60	0	1.025
313	U197	1	95.1	40.7	80	0	1.02
313	U197	2	95.1	40.7	80	0	1.02
313	U197	3	95.1	40.7	80	0	1.02
314	Sync Cond	1	0	13.68	200	-50	0.98
315	U12	1	12	0	6	0	1.014
315	U12	2	12	0	6	0	1.014
315	U12	3	12	0	6	0	1.014
315	U12	4	12	0	6	0	1.014
315	U12	5	12	0	6	0	1.014
315	U155	6	155	0.048	80	-50	1.014
316	U155	1	155	25.22	80	-50	1.017
318	U400	1	400	137.4	200	-50	1.05
321	U400	1	400	108.2	200	-50	1.05
322	U50	1	50	-4.96	16	-10	1.05
322	U50	2	50	-4.96	16	-10	1.05
322	U50	3	50	-4.96	16	-10	1.05
322	U50	4	50	-4.96	16	-10	1.05
322	U50	5	50	-4.96	16	-10	1.05
322	U50	6	50	-4.96	16	-10	1.05
323	U155	1	155	31.79	80	-50	1.05
323	U155	2	155	31.79	80	-50	1.05
323	U350	3	350	71.78	150	-25	1.05

PG & QG: are the generating unit's real & reactive power output.
Q^{max} & Q^{min}: are the limits of the unit's reactive power output.
V_S: is the unit's regulated voltage set-point.

Table 8 - Unit Start-up Heat Input

Unit group	Unit Size (MW)	Unit Type	Hot Start (MBTU)	Cold Start (MBTU)
U12	12	Oil/Steam	38	68
U20	20	Oil/CT	5	5
U50	50	Hydro	N/A	N/A
U76	76	Coal/Steam	596	596
U100	100	Oil/Steam	250	566
U155	155	Coal/Steam	260	953
U197	197	Oil/Steam	443	775
U350	350	Coal/Steam	1,915	4,468
U400	400	Nuclear	N/A	N/A

Table 9 - Heat Rate and Incremental Heat Rate

Size mw	Type	Fuel	Output %	MW	Net Plant Heat Rate Btu/kwh	Incremental Heat Rate Calculuted by continous function Btu/kwh
12	Fossil Steam	#6 oil	20	2.40	16017	10179
			50	6.00	12500	10330
			80	9.60	11900	11668
			100	12.00	12000	13219
20	Combustion Turbine	#2 oil	79	15.80	15063	9859
			80	16.00	15000	10139
			99	19.80	14500	14272
			100	20.00	14499	14427
50	Hydro		100	50.00	Not applicable	
76	Fossil Steam	Coal	20	15.20	17107	9548
			50	38.00	12637	9966
			80	60.80	11900	11576
			100	76.00	12000	13311
100	Fossil Steam	#6 oil	25	25.00	12999	8089
			50	50.00	10700	8708
			80	80.00	10087	9420
			100	100.00	10000	9877
155	Fossil Steam	Coal	35	54.25	11244	8265
			60	93.00	10053	8541
			80	124.00	9718	8900
			100	155.00	9600	9381
197	Fossil Steam	#6 oil	35	68.95	10750	8348
			60	118.20	9850	8833
			80	157.60	9644	9225
			100	197.00	9600	9620
350	Fossil Steam	Coal	40	140.00	10200	8402
			65	227.50	9600	8896
			80	280.00	9500	9244
			100	350.00	9500	9768
400	Nuclear Steam	LWR	25	100.00	12751	8848
			50	200.00	10825	8965
			80	320.00	10170	9210
			100	400.00	10000	9438

NOTE The hydro units have 100% capacity for the first half of the year and 90% capacity for the remainder. Their quarterly energy distribution is as follows: 35%, 35%, 10%, 20%, where 100% is 200 GWh.

Table 10 - Unit Cycling Restriction and Ramping Rates

Unit group	Unit Size (MW)	Unit Type	Min. Down Time (Hr)	Min. Up Time (Hr)	Start Time Hot (Hr)	Start Time Cold (Hr)	Warm Star Time (Hr)	Ramp Rate MW/Minute
U12	12	Oil/ Steam	2	4	2	4	12	1
U20	20	Oil/ CT	1	1	0	0	1	3
U50	50	Hydro	N/A					
U76	76	Coal/ Steam	4	8	3	12	10	2
U100	100	Oil/ Steam	8	8	2	7	60	7
U155	155	Coal/ Steam	8	8	3	11	60	3
U197	197	Oil/ Steam	10	12	4	7	24	3
U350	350	Coal/3 Steam	48	24	8	12	96	4
U400	400	Nuclear	1	1	N/A	N/A	N/A	20

Table 11 - Unit Emissions Data

IEEE-RTS unit group	U20	U12,U100,U197	U76,U155,U350
Unit type	GT	ST	ST
Fuel type	FO2	FO6	Bituminous Coal
Fuel sulfur content (%)	0.2	Unit-Specific	Unit-specific
Emissions Rate			
SO2 (Lbs/MMBTU)	0.2	Unit-specific	Unit-specific
NOX (Lbs/MMBTU)	0.5	0.5	Unit-specific
Part (Lbs/MMBTU)	0.036	0.1	Unit-specific
CO2 (Lbs/MMBTU)	160	170	210
CH4 (Lbs/MMBTU)	0.002	0.002	0.001
N2O(Lbs/MMBTU)	0.004	0.004	0.004
CO (Lbs/MMBTU)	0.11	0.04	0.02
VOCs (Lbs/MMBTU)	0.04	0.007	0.003

TRANSMISSION SYSTEM

The RTS-79 is expanded to include a phase shifter, a two terminal DC transmission line, and five inter-area ties. Table 12 shows the transmission branch data; this includes lines, cables, transformers, phase-shifter, and tie-lines. All pu quantities are on 100 MVA base. Areas A and B may be further interconnected by a DC link, based upon reference [3]. Table 13 shows the two-terminal DC transmission line data.

Table 12 - Branch Data

ID# = Branch identifier.
Inter area branches are indicated by double letter ID.
Circuits on a common tower have hyphenated ID#.
λp = Permanent Outage Rate (outages/year).
Dur = Permanent Outage Duration (Hours).
λt = Transient Outage Rate (outages/year).
Con = Continuous rating.
LTE = Long-time emergency rating (24 hour).
STE = Short-time emergency rating (15 minute).
Tr = Transformer off-nominal ratio.
Transformer branches are indicated by Tr ≠ 0.

ID #	From Bus	To Bus	L miles	- Perm - λp	Dur	Tran. λt	R pu	X pu	B pu	Con MVA	LTE MVA	STE MVA	Tr pu
A1	101	102	3	.24	16	0.0	0.003	0.014	0.461	175	193	200	0
A2	101	103	55	.51	10	2.9	0.055	0.211	0.057	175	208	220	0
A3	101	105	22	.33	10	1.2	0.022	0.085	0.023	175	208	220	0
A4	102	104	33	.39	10	1.7	0.033	0.127	0.034	175	208	220	0
A5	102	106	50	.48	10	2.6	0.050	0.192	0.052	175	208	220	0
A6	103	109	31	.38	10	1.6	0.031	0.119	0.032	175	208	220	0
A7	103	124	0	.02	768	0.0	0.002	0.084	0	400	510	600	1.015
A8	104	109	27	.36	10	1.4	0.027	0.104	0.028	175	208	220	0
A9	105	110	23	.34	10	1.2	0.023	0.088	0.024	175	208	220	0
A10	106	110	16	.33	35	0.0	0.014	0.061	2.459	175	193	200	0
A11	107	108	16	.30	10	0.8	0.016	0.061	0.017	175	208	220	0
AB1	107	203	42	.44	10	2.2	0.042	0.161	0.044	175	208	220	0
A12-1	108	109	43	.44	10	2.3	0.043	0.165	0.045	175	208	220	0
A13-2	108	110	43	.44	10	2.3	0.043	0.165	0.045	175	208	220	0
A14	109	111	0	.02	768	0.0	0.002	0.084	0	400	510	600	1.03
A15	109	112	0	.02	768	0.0	0.002	0.084	0	400	510	600	1.03
A16	110	111	0	.02	768	0.0	0.002	0.084	0	400	510	600	1.015
A17	110	112	0	.02	768	0.0	0.002	0.084	0	400	510	600	1.015
A18	111	113	33	.40	11	0.8	0.006	0.048	0.100	500	600	625	0
A19	111	114	29	.39	11	0.7	0.005	0.042	0.088	500	600	625	0
A20	112	113	33	.40	11	0.8	0.006	0.048	0.100	500	600	625	0
A21	112	123	67	.52	11	1.6	0.012	0.097	0.203	500	600	625	0
A22	113	123	60	.49	11	1.5	0.011	0.087	0.182	500	600	625	0
AB2	113	215	52	.47	11	1.3	0.010	0.075	0.158	500	600	625	0
A23	114	116	27	.38	11	0.7	0.005	0.059	0.082	500	600	625	0
A24	115	116	12	.33	11	0.3	0.002	0.017	0.036	500	600	625	0
A25-1	115	121	34	.41	11	0.8	0.006	0.049	0.103	500	600	625	0
A25-2	115	121	34	.41	11	0.8	0.006	0.049	0.103	500	600	625	0
A26	115	124	36	.41	11	0.9	0.007	0.052	0.109	500	600	625	0
A27	116	117	18	.35	11	0.4	0.003	0.026	0.055	500	600	625	0
A28	116	119	16	.34	11	0.4	0.003	0.023	0.049	500	600	625	0
A29	117	118	10	.32	11	0.2	0.002	0.014	0.030	500	600	625	0
A30	117	122	73	.54	11	1.8	0.014	0.105	0.221	500	600	625	0
A31-1	118	121	18	.35	11	0.4	0.003	0.026	0.055	500	600	625	0
A31-2	118	121	18	.35	11	0.4	0.003	0.026	0.055	500	600	625	0
A32-1	119	120	27.5	.38	11	0.7	0.005	0.040	0.083	500	600	625	0
A32-2	119	120	27.5	.38	11	0.7	0.005	0.040	0.083	500	600	625	0
A33-1	120	123	15	.34	11	0.4	0.003	0.022	0.046	500	600	625	0
A33-2	120	123	15	.34	11	0.4	0.003	0.022	0.046	500	600	625	0
A34	121	122	47	.45	11	1.2	0.009	0.068	0.142	500	600	625	0
AB3	123	217	51	.46	11	1.3	0.010	0.074	0.155	500	600	625	0
B1	201	202	3	.24	16	0.0	0.003	0.014	0.461	175	193	200	0
B2	201	203	55	.51	10	2.9	0.055	0.211	0.057	175	208	220	0
B3	201	205	22	.33	10	1.2	0.022	0.085	0.023	175	208	220	0
B4	202	204	33	.39	10	1.7	0.033	0.127	0.034	175	208	220	0
B5	202	206	50	.48	10	2.6	0.050	0.192	0.052	175	208	220	0
B6	203	209	31	.38	10	1.6	0.031	0.119	0.032	175	208	220	0
B7	203	224	0	.02	768	0.0	0.002	0.084	0	400	510	600	1.015
B8	204	209	27	.36	10	1.4	0.027	0.104	0.028	175	208	220	0
B9	205	210	23	.34	10	1.2	0.023	0.088	0.024	175	208	220	0
B10	206	210	16	.33	35	0.0	0.014	0.061	2.459	175	193	200	0
B11	207	208	16	.30	10	0.8	0.016	0.061	0.017	175	208	220	0
B12-1	208	209	43	.44	10	2.3	0.043	0.165	0.045	175	208	220	0
B13-2	208	210	43	.44	10	2.3	0.043	0.165	0.045	175	208	220	0
B14	209	211	0	.02	768	0.0	0.002	0.084	0	400	510	600	1.03
B15	209	212	0	.02	768	0.0	0.002	0.084	0	400	510	600	1.03
B16	210	211	0	.02	768	0.0	0.002	0.084	0	400	510	600	1.015
B17	210	212	0	.02	768	0.0	0.002	0.084	0	400	510	600	1.015
B18	211	213	33	.40	11	0.8	0.006	0.048	0.100	500	600	625	0
B19	211	214	29	.39	11	0.7	0.005	0.042	0.088	500	600	625	0
B20	212	213	33	.40	11	0.8	0.006	0.048	0.100	500	600	625	0
B21	212	223	67	.52	11	1.6	0.012	0.097	0.203	500	600	625	0
B22	213	223	60	.49	11	1.5	0.011	0.087	0.182	500	600	625	0
B23	214	216	27	.38	11	0.7	0.005	0.059	0.082	500	600	625	0
B24	215	216	12	.33	11	0.3	0.002	0.017	0.036	500	600	625	0
B25-1	215	221	34	.41	11	0.8	0.006	0.049	0.103	500	600	625	0
B25-2	215	221	34	.41	11	0.8	0.006	0.049	0.103	500	600	625	0
B26	215	224	36	.41	11	0.9	0.007	0.052	0.109	500	600	625	0
B27	216	217	18	.35	11	0.4	0.003	0.026	0.055	500	600	625	0
B28	216	219	16	.34	11	0.4	0.003	0.023	0.049	500	600	625	0
B29	217	218	10	.32	11	0.2	0.002	0.014	0.030	500	600	625	0
B30	217	222	73	.54	11	1.8	0.014	0.105	0.221	500	600	625	0
B31-1	218	221	18	.35	11	0.4	0.003	0.026	0.055	500	600	625	0
B31-2	218	221	18	.35	11	0.4	0.003	0.026	0.055	500	600	625	0
B32-1	219	220	27.5	.38	11	0.7	0.005	0.040	0.083	500	600	625	0
B32-2	219	220	27.5	.38	11	0.7	0.005	0.040	0.083	500	600	625	0
B33-1	220	223	15	.34	11	0.4	0.003	0.022	0.046	500	600	625	0
B33-2	220	223	15	.34	11	0.4	0.003	0.022	0.046	500	600	625	0
B34	221	222	47	.45	11	1.2	0.009	0.068	0.142	500	600	625	0

Table 12 (Continued)

ID #	From Bus	To Bus	L miles	- Perm - λp	Dur	Tran. λt	R pu	X pu	B pu	Con MVA	LTE MVA	STE MVA	Tr pu
C1	301	302	3	.24	16	0.0	0.003	0.014	0.461	175	193	200	0
C2	301	303	55	.51	10	2.9	0.055	0.211	0.057	175	208	220	0
C3	301	305	22	.33	10	1.2	0.022	0.085	0.023	175	208	220	0
C4	302	304	33	.39	10	1.7	0.033	0.127	0.034	175	208	220	0
C5	302	306	50	.48	10	2.6	0.050	0.192	0.052	175	208	220	0
C6	303	309	31	.38	10	1.6	0.031	0.119	0.032	175	208	220	0
C7	303	324	0	.02	768	0.0	0.002	0.084	0	400	510	600	1.015
C8	304	309	27	.36	10	1.4	0.027	0.104	0.028	175	208	220	0
C9	305	310	23	.34	10	1.2	0.023	0.088	0.024	175	208	220	0
C10	306	310	16	.33	35	0.0	0.014	0.061	2.459	175	193	200	0
C11	307	308	16	.30	10	0.8	0.016	0.061	0.017	175	208	220	0
C12-1	308	309	43	.44	10	2.3	0.043	0.165	0.045	175	208	220	0
C13-2	308	310	43	.44	10	2.3	0.043	0.165	0.045	175	208	220	0
C14	309	311	0	.02	768	0.0	0.002	0.084	0	400	510	600	1.03
C15	309	312	0	.02	768	0.0	0.002	0.084	0	400	510	600	1.03
C16	310	311	0	.02	768	0.0	0.002	0.084	0	400	510	600	1.015
C17	310	312	0	.02	768	0.0	0.002	0.084	0	400	510	600	1.015
C18	311	313	33	.40	11	0.8	0.006	0.048	0.100	500	600	625	0
C19	311	314	29	.39	11	0.7	0.005	0.042	0.088	500	600	625	0
C20	312	313	33	.40	11	0.8	0.006	0.048	0.100	500	600	625	0
C21	312	323	67	.52	11	1.6	0.012	0.097	0.203	500	600	625	0
C22	313	323	60	.49	11	1.5	0.011	0.087	0.182	500	600	625	0
C23	314	316	27	.38	11	0.7	0.005	0.059	0.082	500	600	625	0
C24	315	316	12	.33	11	0.3	0.002	0.017	0.036	500	600	625	0
C25-1	315	321	34	.41	11	0.8	0.006	0.049	0.103	500	600	625	0
C25-2	315	321	34	.41	11	0.8	0.006	0.049	0.103	500	600	625	0
C26	315	324	36	.41	11	0.9	0.007	0.052	0.109	500	600	625	0
C27	316	317	18	.35	11	0.4	0.003	0.026	0.055	500	600	625	0
C28	316	319	16	.34	11	0.4	0.003	0.023	0.049	500	600	625	0
C29	317	318	10	.32	11	0.2	0.002	0.014	0.030	500	600	625	0
C30	317	322	73	.54	11	1.8	0.014	0.105	0.221	500	600	625	0
C31-1	318	321	18	.35	11	0.4	0.003	0.026	0.055	500	600	625	0
C31-2	318	321	18	.35	11	0.4	0.003	0.026	0.055	500	600	625	0
C32-1	319	320	27.5	.38	11	0.7	0.005	0.040	0.083	500	600	625	0
C32-2	319	320	27.5	.38	11	0.7	0.005	0.040	0.083	500	600	625	0
C33-1	320	323	15	.34	11	0.4	0.003	0.022	0.046	500	600	625	0
C33-2	320	323	15	.34	11	0.4	0.003	0.022	0.046	500	600	625	0
C34	321	322	47	.45	11	1.2	0.009	0.068	0.142	500	600	625	0
CA-1	325	121	67	.52	11	1.6	0.012	0.097	0.203	500	600	625	0
CB-1	318	223	72	.53	11	1.8	0.013	0.104	0.218	500	600	625	0
C35	323	325	0	.02	768	0.0	0.000	0.009	0	722	893	893	1.00

The circuits which have common Right-Of-Way (ROW) or Common Structure (CS) are indicated by loops lettered A - G in the one-line diagrams, the common lengths (miles) are as follows: A - 45 (ROW), B - 15 (CS), C - 18 (CS), D - 34 (ROW), E - 33 (CS), F - 43 (CS), G - 19 (CS). It is recommended that common mode outages on CS circuits be assigned a frequency of 7.5% of the outage rates presented in table 12; this should be applied for both permanent and transient common mode outages. The time taken to restore one circuit is the same as the permanent outage duration given in table 12, while the second circuit will take as long again.

Table 13 - Two-Terminal DC Transmission Line Data (based on reference 3)

Control mode:	Power
DC line resistance (Ω):	5
Power demand (MW):	100
Scheduled DC voltage (kV):	500
Compounding resistance (Ω):	5
Margin in per unit of desired DC power:	0.1
Metered end:	Inverter
Line Outage Rates (Outages/yr): Permanent = 0.22 Transient = 0.7	
Permanent Outage Duration (hours):	10

	Rectifier	Inverter
Converter bus:	113	316
Number of bridges in series:	4	4
Nominal maximum firing angle:	15	16
Minimum steady state firing angle:	15	16
Commutating transformer resistance/bridge (Ω):	0.0180	0.0103
Commutating transformer reactance/bridge (Ω):	4.539	4.939
Primary base AC voltage (kV):	230	230
Transformer ratio:	0.46	0.46
Tap setting:	1.15452	0.97987
Max tap setting:	1.15452	1.17500
Min tap setting:	0.97996	0.97987
Rectifier tap step:	0.0050	0.0050

Table 13 (Continued)

The terminal equipment will have the following capacity table:

Capacity (%)	Prob	λ (event/yr)	Dur. (hr.)
0 ≤ capacity < 50	0.0179	6.03	26.00
50 ≤ capacity < 75	0.0747	54.97	11.90
75 ≤ capacity < 100	0.0007	1.08	5.77
Capacity = 100	0.9067	52.88	150.20

SUBSTATION

Substation data, based on reference [4], has been added to RTS-96. Figure 5 shows a single line diagram of the substations. Table 14 lists the failure rates and maintenance requirements of a substation breaker and switching time requirements for various components.

Table 14 - Data for Terminal Stations
(Based on reference 4)

Active failure rate of a breaker (failure/year)	=	0.0066
Passive failure rate of a breaker (failure/year)	=	0.0005
Maintenance rate of a breaker (outages/year)	=	0.2
Maintenance time of a breaker (hours)	=	108
Switching time - one or more components (hours)	=	1.0

SYSTEM DYNAMIC DATA

Table 15 contains the system dynamic data, which was taken from reference [5]. It is based on the following: a classical model is assumed for each generator, reactance and inertia data are typical of generators of the same type and the same size, reactance values are based on the given MVA base, and inertia values are based on the unit size in MW.

Table 15 - System Dynamic Data
(based on reference 5)

				Reactance			
Unit group	Unit size MW	Unit Type	MVA Base	Unit pu	Transformer pu	Inertia MJ/MW	Damping Ratio
U12	12	Oil/Steam	14	0.32	0.13	2.8	0.0
U20	20	Oil/CT	24	0.32	0.13	2.8	0.0
U50	50	Hydro	53	0.28	0.1	3.5	0.0
U76	76	Coal/Steam	89	0.3	0.13	3.0	0.0
U100	100	Oil/Steam	118	0.32	0.13	2.8	0.0
U155	155	Coal/Steam	182	0.3	0.13	3.0	0.0
U197	197	Oil/Steam	232	0.32	0.13	2.8	0.0
U350	350	Coal/Steam	412	0.3	0.13	3.0	0.0
U400	400	Nuclear	471	0.4	0.15	5.0	0.0

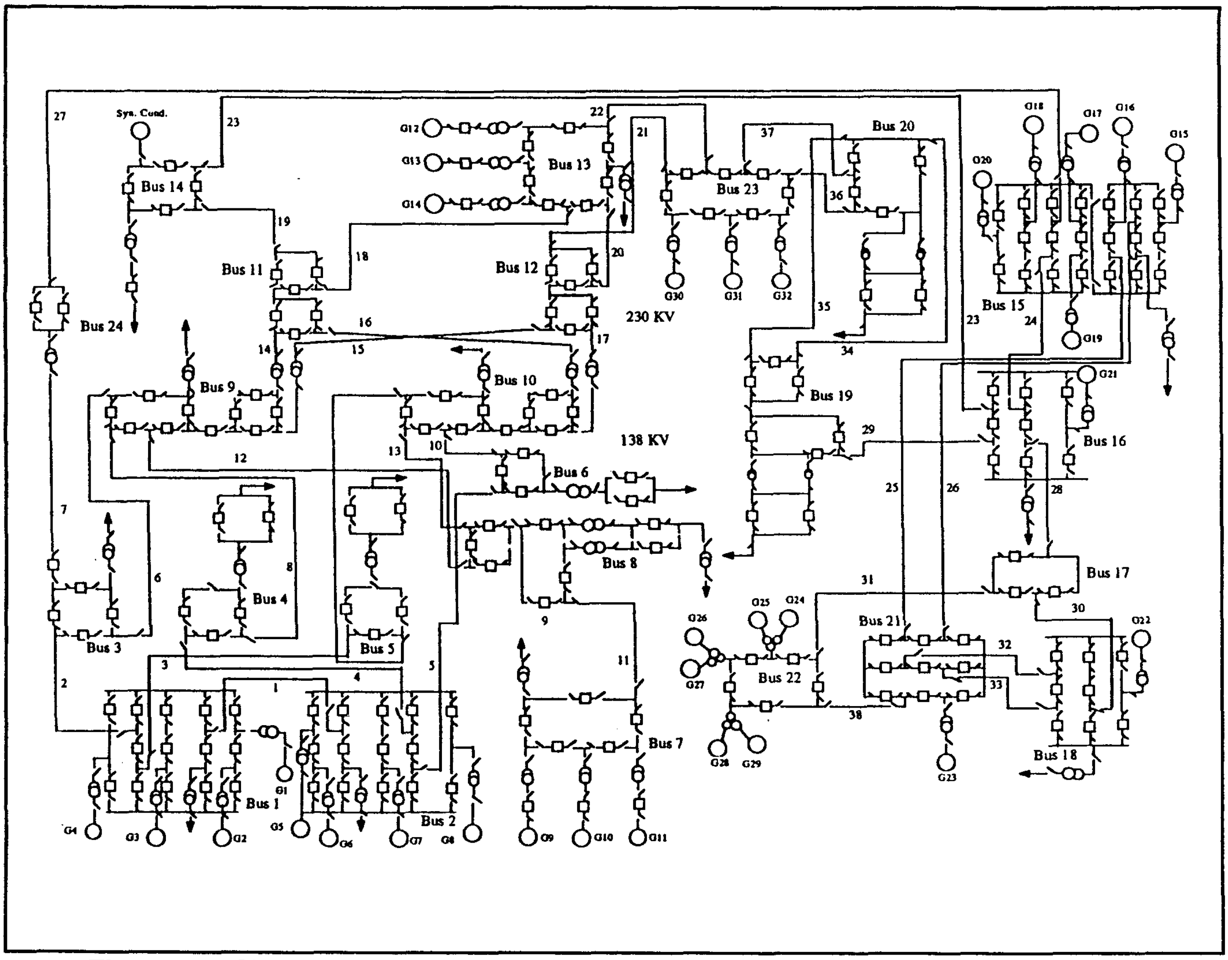


Figure 5 - Single Line Diagram of IEEE One Area RTS-96 Substation System

CONCLUSIONS

The Reliability Test System has been extended by adding a number of enhancements; these should be considered to be "optional" additions and no user should feel compelled to make use of them all. One-, Two-, and Three-Area systems have been presented, it is anticipated that one will be more suitable than the others for a particular application and it is up to the user to make a choice. Likewise, the inclusion of a DC link will not be appropriate for all applications.

Numerous load-flow configurations were reviewed during the development of RTS-96 and it is felt that the proposed systems present reasonable planning and operating scenarios. Loads are quite secure with all elements in service, but special operating strategies may be required when critical elements are removed.

This paper has presented data which is required by reliability models of power systems in use at the time of writing. It is expected that future models may require other parameters, and the authors of such future models are encouraged to choose values which are consistent with the values of parameters which are tabulated in this revision of the RTS.

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Discussion

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The effort to enhance and extend the IEEE Reliability Test System (RTS) has taken over six years and benefitted from the suggestions of numerous present and former members of the Application of Probability Methods subcommittee. As a member of the task force during the final year of this revision, I regret that the following points came to my attention too late for consideration in preparing the paper for submission. They are offered for three reasons: to eliminate changes from the 1979 RTS which would invalidate comparisons with applications of the latter, to insure that the new data presented will completely specify a base case load flow, and to suggest more economical and reliable bus configurations which will avoid distortions to the reliability indices of the RTS.

Unexplained Changes from the 1979 RTS to the Present Paper

1. Both fuel and O & M cost data have been deleted. A major objective of the current revision was to improve data concerning the generating units.

2. Changes have been made to the heat rate data (old Table 5, new Table 9) which will complicate comparisons based on the old and new RTS even if the analytical method under consideration does not depend on new features. Changes to data in the previous RTS should be made only if the former values are internally inconsistent, in which case an explicit statement should be made. A substitute Table 9, presented at the end of this discussion, is proposed to restore all heat rates shown in the 1979 RTS to their original values and to assume the incremental heat rate between the output values shown is constant. It should be noted that only two output levels, 80% and 100%, were shown for combustion turbines in the 1979 RTS. Values which have changed from those shown in Table 9 of the paper are italicized

Incomplete Data for Load Flow, Stability and/or Reliability Studies

1. For the phase shifter, the minimum and maximum shift and the desired MW flow (or the angle, if flow is not controlled) are essential data. I propose a range of +10 to -10 degrees. Since the generators at corresponding buses of different areas have identical watt and var generation, a net interchange of 0 for each area is implied. The flows specified for the phase shifter, and the optional DC line, if present, will determine whether the loads, generation and voltages shown in Tables 1 and 7 can all be achieved in a solved case.

2. The capacity of the optional DC line should be shown in Table 13.

3. The tap ratio of the generator stepup transformers should be specified in Table 15 or a footnote, even if unity is intended.

4. Figure 5 has two omissions which must be resolved to define a valid RTS configuration.

- The connection of the 100 MVAr reactor at bus 6 is not shown.
- The configurations of buses 3, 7, 13, 15, 17, 18, 21, and 23 make no provision for inter area tie line terminations, which do not appear in corresponding buses in every area.

5. No outage nor restoration rates are provided for the transformers supplying load, whether 230 kV or 138 kV. Specifying their impedances, tap ratios, and load tap changing characteristics would be a desirable addition.

Costly and/or unreliable bus configurations

Several of the substation configurations are more complex (hence, costly) than is needed and at the same time less reliable than simpler alternatives. While it need not be a goal of the RTS to present an optimum configuration at each bus, it is reasonable to avoid redundant breakers and unnecessary exposure to loss of all sources or all outlets to a bus from a single fault. Such exposure may distort the contribution to reliability indices of untypical failure modes.

- An unneeded line breaker connects line 7 to bus 3.
- Distribution system (under 138 kV) data is not generally provided by the RTS. A consistent technique of either showing transformers feeding load, as at but 15, or omitting them as at but 20, should be adopted. Paralleled breakers and/or transformers, as at buses 6 and 8, raise issues for which the RTS data is completely inadequate.
- The configurations of buses 9-12 are unnecessarily complex and unreliable. All these buses have the "supplies" grouped on one side of a critical element and the "loads" grouped on the other side. Loss of the common element will result in total interruption of supply from the 230 kV to the 138 kV system through the affected bus. Configuring each of these buses as a simple ring bus would be less costly and more reliable.
- Similarly, bus 8 has its sources from buses 9 and 10 grouped together and is susceptible to isolation by a single event.
- At bus 22, exchanging the connection of G26 and G27 with line 38 would eliminate the possibility of all generation at this station being lost from a single fault on a breaker.

Table 9 - Heat Rate and Incremental Heat Rate

Size MW	Type	Fuel	Output %	Output MW	Plant Heat Rate, BTU/kWh Net	Plant Heat Rate, BTU/kWh Incremental
12	Fossil Steam	#6 oil	20	2.4	*15600*	*11100*
			50	6.0	*12900*	*10233*
			80	9.6	11900	*12400*
			100	12.0	12000	
20	Combustion Turbine	#2 oil	*70*	14.0	*15250*	*13250*
			80	16.0	*15000*	*12750*
			90	18.0	*14750*	*12250*
			100	20.0	*14500*	
50	Hydro	Not applicable				
76	Fossil Steam	Coal	20	15.2	*15600*	*11100*
			50	38.0	*12900*	*10233*
			80	60.8	11900	*12400*
			100	76.0	12000	
100	Fossil Steam	#6 oil	25	25.0	*13000*	*8600*
			55	55.0	*10600*	*9000*
			80	80.0	*10100*	*9600*
			100	100.0	10000	
155	Fossil Steam	Coal	35	54.3	*11200*	*8560*
			60	93.0	*10100*	*8900*
			80	124.0	*9800*	*9300*
			100	155.0	*9700*	
197	Fossil Steam	#6 oil	35	69.0	10750	*8590*
			60	118.2	9850	*9810*
			80	157.6	*9840*	*8640*
			100	197.0	9600	
350	Fossil Steam	Coal	40	140.0	10200	*8640*
			65	227.5	9600	*9067*
			80	280.0	9500	*9500*
			100	350.0	9500	
400	Nuclear Steam	LWR	25	100.0	*12550*	*9100*
			50	200.0	10825	*9078*
			80	320.0	10170	*9320*
			100	400.0	10000	

Reliability Test System Task Force :

The task force thanks Mr. Schneider for his insightful comments and additions to the RTS.

The alternative table 9 will allow comparisions to be made with the former system while the "official" table 9 can be used for future studies.

The proposed range of ±10° for the phase shifter seems reasonable, as does a tap ratio of unity for the generator step-up transformers.

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Appendix B

Published Papers

1. Comparing Security Assessment Schemes Through Two-Stage Monte Carlo Sampling
2. Analyzing Security Assessment Schemes in Traditional Networks
3. An Optimized Defence Plan for a Power System
4. Controlled Islanding Scheme for Power Systems
5. Analysis of the National 8th November 2003 Libyan Blackout
6. Design of a Transient Stability Scheme to Prevent Cascading Blackouts

Paper 1

Comparing Security Assessment Schemes Through Two-Stage Monte Carlo Sampling

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Universities Power Engineering Conference, 2010. UPEC 2010. 45th International

Comparing Security Assessment Schemes Through Two-Stage Monte Carlo Sampling

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***Abstract*—The penetration of unscheduleable generation will increase due to legislation and eventually saving on fuel cost. This will cause an increase in uncertainty of power flow and drive up balancing market costs. A security assessment scheme that considers probabilistic uncertainty could give financial savings and better security of supply.**

Any change in security assessment scheme must be tested, compared, and verified. Though there has been a lot of work into probabilistic security assessment there has been far less on comparing security assessment schemes. This work uses two stage Monte Carlo sampling to generate a data set which can be used for easy comparison between different schemes.

In this paper numerical results are presented that show that this method can provide valuable information about how the system will cope with unexpected changes. This will allow security assessment schemes to be developed in the future that do not disadvantage a high penetration of variable renewable generation.

***Index Terms*—Monte Carlo methods, Power system reliability, Power system security, Power system simulation, IEEE Reliability Test System, Sustainable Power Generation**

I. Introduction

Reliable operation of electric power systems is taken for granted across most of the developed world. But this reliability is far from guaranteed; an electric power system can be seen of as one of the largest and most complicated machines ever created. The decentralisation of power markets has caused power system to be driven closer to their operation limits, trading off security for cost. The optimal way to do this trade-off is by having the most accurate security assessment schemes available.

If a sub-optimal security assessment scheme is used it may lead to costly over-securing in certain conditions and dangerously low security in others. This will mean that higher safety margins must be put on the poor security scheme which will lead to an unnecessarily high cost. An accurate scheme should take into account both likelihood and consequence of every possible event. In fact a security assessment scheme should accurately represent the risk of running the system in the current state where risk is a function of likelihood and consequence for every possible event [1].

$$R = \sum_i L(e_i) \times C(e_i) \tag{1}$$

Where R is Risk, e is an event, L is likelihood, and C is consequence.

A perfect system is infeasible in practice due to time constraints. In the UK, system operators have only one hour to perform final balancing actions between the FPN - the point when they are supplied with the final load/generator data, and the point of delivery. Though the balancing market lasts only one hour, the system operator is likely to make predictions on generator bids beforehand for use in preliminary calculations. Power system security is all about coping with likely changes, Kirschen [2] provides a good overview to some of the challenges involved these include:

- Maintaining good **power quality**, i.e. that the voltages/currents are approximately sine-waves at 50Hz.
- Keeping system **synchronism**, i.e. that every generator is approximately at the same frequency and phase.
- Requested power being delivered to most loads, i.e. **no load shedding**
- Keeping each component **within limits** for voltage/current/power most of the time (i.e. there are no components that are overloaded or experiencing voltage collapse).
- Making the system reasonably **fault tolerant**.
- Suppling energy at **minimum cost** with **minimum environmental impact**.

Obviously from the above list security cannot easily be defined in absolute terms; the trade-off between being fault tolerant and cost shows this. The goal is to achieve an acceptable level of security at least cost. To deal with the massive complexity involved in this calculation many simplifying assumptions are made and the use of computer simulations is invaluable.

Various types of computer simulation can be run to determine the behaviour of the system. These include a *load flow*, a *dynamic simulation* and a *transient simulation*. Each of these tests considers the system in increasing levels of complexity; the transient simulation is the most accurate but slowest test to run.

This paper uses the definition in [3] where reliability is the long term ability to safely and securely supply the demand for power. Secure operation is a power system's ability to remain stable and within operational limits following any likely disturbance. And stability refers to the whether the system can regain a state of operational equilibrium following a specific disturbance. For a broad overview of the method used within power system reliability refer to the works of Billinton and Allen [4].

A. Deterministic Power System Security

Traditionally, security assessment schemes manage this complexity by using a set of credible contingencies. These are meant to represent all likely events with a severe consequence. In other words they should be events with the largest product of likelihood and consequence. There has been significant work into determining which events to include [5] [6] [7]. These contingencies are often different for each half hour delivery period and vary based upon weather and season.

The set of normal contingencies that are considered is given in [8]; a subset of this is known as *N-1*. N-1 is a security assessment scheme that considers the failure of one component (line, generator or transformer) at a time. In other words, the simultaneous failure of two components is considered too unlikely to count. There have been various modifications to N-1 including the addition of correlated failures, such as the failure of two lines on a common right-of-way.

The UK system operator does consider a subset of N-2 contingencies where two simultaneous failures are considered but not all possible double failures are checked. This traditional contingency screening has worked well for many years but with the paradigm shift in generation that is coming in the form of local, unscheduleable generation it is time to review this idea.

The problem with all such N-x methods (N-1, N-2, etc.) is that they treat likelihood in such a crude way; it assumes all contingencies to be equally likely.

Another such disadvantage of any deterministic security assessment scheme is that it can lead to problems if something outside of the expected set happens. In the UK the simultaneous failure of two generators was considered non-credible; hence, after it occurred during 2008, emergency operator action was needed. This is far from the only incident of its kind. 2003 saw more than it's fair share of major incidents with North America, Libya, London and Italy [9] all experiencing widespread blackouts.

The credible disturbances are no longer best represented by discrete events. The change in wind power over a one hour period is significant, spatially correlated and continuous. It is possible to treat wind power as a contingency by quantizing it at a large resolution into a small number of likely states. In performing this method one must be careful to have enough possible wind states to accurately represent everything that could happen.

If wind farms continue to be built at the current rate wind power will become a major component of the UK's plant mix. Unless the market changes this is likely to disadvantage wind farms due to their uncertainty [10]. Some may say that their cost will accurately reflect their difficult of incorporating such uncertainty in a power system but there is no point in building wind turbines if they are not to be fully utilised. Renewable power should be encouraged from an environmental point of view however the technical challenges must be overcome. In reality the likelihood is that the wind resource as a whole will not fluctuate drastically, especially if turbines are distributed over a large geographical area. But the risk must be quantified and verifiable before new security assessment methods can be implemented.

B. Probabilistic Power System Security

Risk based (probabilistic) security assessment uses probability much more directly. It is not a new idea it has been used in other industries since the 1960's; and has been studied in power systems since the 1970's [11]. But it is computationally expensive and often harder to produce a verifiable result. As the disadvantages of deterministic methods impacts financially, the focus has begun to turn towards probabilistic methods [6] [2]. This is already happening as balancing market prices have been driven up by wind power [10].

Sobajic et. al. [12] provides a brief overview of four different approaches to the problem of stability assessment. The paper then discusses one such pattern recognition method after highlighting the works of Patton, Billinton, and Wu as contributing significantly to probabilistic methods.

After an extensive literature review, including the mention of Monte Carlo methods, McCalley [13] goes on to determine a set of deterministic rules based upon risk based methods.

Monte Carlo methods are a type of algorithm used commonly in risk assessment where a system with uncertainty is repeatedly sampled. In this way Monte Carlo Methods lend themselves well to the task of probabilistic risk assessment. A comparison of different modifications to standard Monte Carlo Methods is given in [14], there a financial value is placed upon outages to give an absolute level of comparison.

For an up-to-date review of the work in risk based security assessment see [15]. It also provides a good conceptual representation which shows how risk based security assessment will more accurately reflect the actual level of security. Xiao [16] shows graphically how traditional SCOPF can produce a more risky solution due to it's fixed constraints.

By assigning a severity to each type of disturbance Ni [17] created a system for aiding control room decisions based on risk.

C. Comparing Security Assessment Schemes

Although there is significant work on different types of security assessment scheme and how well they perform there is relatively little work performing a direct comparison between two such schemes. Any new scheme must fit a number of criteria most importantly it must not decrease the level of reliability or increase the cost. This is the main requirement of a security assessment scheme, but there are other criteria that must be considered. The scheme must be verifiable, that is, following an incident, it should be possible to determine who is at fault; the operator, the security assessment scheme or was it an anomalous event that requires no improvement to be made. It must be able to be used within the time-frame of 1 hour, remembering that this time includes making necessary modifications and re-running the test until the system is adequate. Finally it must not unfairly disadvantage any particular generator and ideally should allow for the most environmentally friendly operation (by not curtailing renewables).

D. The IEEE Reliability Test System 96

The IEEE-RTS is a sample power system with a thorough set of data for operation, emissions, and reliability. It was for this reason that it was chosen as the test system for this work. Only area A was used, which is composed of 32 generating units, 24 busbars, 38 lines, 17 loads and two voltage levels.

TABLE I
LINE PROBABILITIES

Line ID	From	To	Fail Rate	MTTR
A1	1	2	0.24	16
A2	1	3	0.51	10
A3	1	5	0.33	10
A4	2	4	0.39	10
A5	2	6	0.48	10
A6	3	9	0.38	10
A7	3	24	0.02	768
A8	4	9	0.36	10
A9	5	10	0.34	10
A10	6	10	0.33	35
A11	7	8	0.30	10
A12-1*1	8	9	0.44	10
A13-2*1	8	10	0.44	10
A14	9	11	0.02	768
A15	9	12	0.02	768
A16	10	11	0.02	768
A17	10	12	0.02	768
A18*2	11	13	0.40	11
A19	11	14	0.39	11
A20*2	12	13	0.40	11
A21	12	23	0.52	11
A22	13	23	0.49	11
A23	14	16	0.38	11
A24	15	16	0.33	11
A25-1*3	15	21	0.41	11
A25-2*3	15	21	0.41	11
A26	15	24	0.41	11
A27	16	17	0.35	11
A28	16	19	0.34	11
A29	17	18	0.32	11
A30*4	17	22	0.54	11
A31-1*5	18	21	0.35	11
A31-2*5	18	21	0.35	11
A32-1*6	19	20	0.38	11
A32-2*6	19	20	0.38	11
A33-1*7	20	23	0.34	11
A33-2*7	20	23	0.34	11
A34*4	21	22	0.45	11

* starred lines are on a common right of way with those of the same number if one fails the other will also fail with a probability 0.08

II. METHODOLOGY

The work is based around a two stage Monte Carlo Sampler which uses a Matlab PSAT simulation of the IEEE-RTS Area 1. The first stage generates *scenarios*, representing possible states the power system could be in. The second stage is used

TABLE II
GENERATOR PROBABILITIES

Generator ID	Bus	MTTF	MTTR
G1	1	450	50
G2	1	450	50
G3	1	1960	40
G4	1	1960	40
G5	2	450	50
G6	2	450	50
G7	2	1960	40
G8	2	1960	40
G9	7	1200	50
G10	7	1200	50
G11	7	1200	50
G12	13	950	50
G13	13	950	50
G14	13	950	50
G15	14	-1	-1
G16	15	2940	60
G17	15	2940	60
G18	15	2940	60
G19	15	2940	60
G20	15	2940	60
G21	15	960	40
G22	16	960	40
G23	18	1100	150
G24	21	1100	150
G25	22	1980	20
G26	22	1980	20
G27	22	1980	20
G28	22	1980	20
G29	22	1980	20
G30	22	1980	20
G31	23	960	40
G32	23	960	40
G33	23	1150	100

to create the probability that each of the scenarios from the first stage are acceptable. In this context acceptable means that no emergency operator action is required during the half-hour delivery period. This data is then tabulated to form an overall picture of how secure the system is in a number of cases. This can be useful in its own right but it can be further used to compare security assessment schemes as described below. The outline for this process is given in 1.

A. Monte Carlo Stage One

1) Rationale: Stage one consists of sampling to generate a range of realistic operating conditions. These are meant to be a representative sample of the possible states of the power system after the system operator has performed some balancing actions. If this method was applied to a real system, and the data was available, historic information for the system in question could be used, but as the RTS is a theoretical system no such data was available.

To represent the possible states: outages, forecasts and operator actions should all be considered. As these are correlated a realistic set of data is hard to come by, the RTS provides such data. Below is a list of some of the factors that could be considered:

- Faulted components on outage for repair
- A load forecast based upon date and time

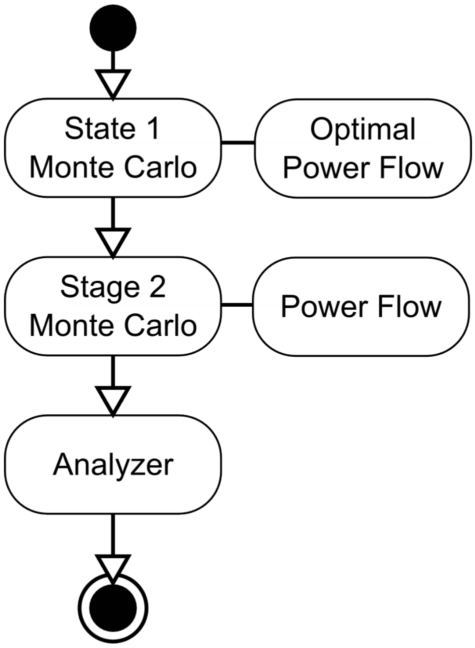

Fig. 1. Structure of Comparison Program

- A weather forecast giving the output power of renewable generators
- The effects of sympathetic tripping and common right of way failures
- Bid & offer prices for all scheduleable generators
- System operator balancing actions

2) Implementation: Not all factors are considered in this work, outages of lines busbars and generators are calculated from their mean time to fail (MTTF) and mean time to repair (MTTR) as per equation 2. For components that have a failure rate specified instead of a MTTF a simple conversion was performed. Busbar failure rate is not included in the original paper so a value of 0.025 was chosen to be consistent with values in the literature. Failure rate is given in failures per year and MTTF and MTTR is given in hours. Included in the paper is the probability that the tripping of certain lines will cause tripping of others, this effect was also taking into account in this work.

$$P_o = \frac{MTTF}{(MTTF + MTTR)} \tag{2}$$

3) Theoretical Results: As a test for the Monte Carlo sampling, shown later, a simple calculation of the expected number of failures per component was performed. This simply uses the average outage probability multiplied by the number of components. The expected number of failures given in III should approximately match the results obtained from the Monte Carlo Sampling in the next section.

4) Monte Carlo Results: One million samples were run and it can be seen that the theoretical and Monte Carlo results match to within a few percent. It should be noted that lines can also fail because of correlated common right of way failures.

TABLE III
THEORETICAL RESULTS

Name	No.	Min	Max	Average
Bus P_o	24	3.70E-005	3.70E-005	3.70E-005
Bus P_f	24	3.00E-006	3.00E-006	3.00E-006
Line P_o	38	3.42E-004	1.75E-003	6.69E-004
Line P_f	38	2.00E-006	6.20E-005	3.90E-005
Generator P_o	32	1.00E-002	1.20E-001	4.34E-002
Generator P_f	32	3.40E-004	2.22E-003	8.80E-004

TABLE IV
COMPARISON OF THEORETICAL AND MONTE CARLO RESULTS IN 1,000,000 SAMPLES

Name	Theoretical	Monte Carlo	% Error	Abs Error
Bus P_o	888	861	0.030	27
Bus P_f	72	65	0.097	7
Line P_o	25110	25117	0.000	7
Line P_f	1481	1441	0.027	40
Generator P_o	758554	764102	0.007	5548
Generator P_f	27779	27657	0.004	122

For this reason the line outages are expect to differ more than the other components. It is likely due to the low probability of this tripping type that it is not noticed in the final results.

5) Further work - system operator and power system simulation: Although the work completed to date does not include it, a simulated system operator is necessary to take the outages and forecasts into a viable system. In reality a system operator would have been planning constraints and contingencies for a long time before delivery. The full effect of a system operator is not something that can be modelled accurately by a computer. But at it's minimum a pool system can be assumed and generator outputs can be set to minimise cost. This will lead to overly unsecured systems but for the purposed of this work a wider range of security is of no disadvantage.

An enhancement to pool system economic dispatch is to consider the stability or even the security of the final system. This does lead to a problem: How can you compare different security schemes when you are using a security scheme as part of the testing procedure. The simplest way to overcome this is to use a range of different schemes. It is not required that each of the scenarios could be used under any particular security assessment scheme. What is required is that a wide range of possibilities are shown.

B. Monte Carlo Stage Two

1) Rationale: The second stage takes each scenario through another round of Monte Carlo sampling. This time it samples for unplanned changes, these include:

- Load forecast error
- Weather forecast error hence generator power mismatch
- Component faults during current operation period (of 0.5 hour)

The purpose of this stage is to see what realistically might happen to a power system in such a state. By simulating each of these samples we can obtain a measure of how likely it is that the given scenario will need emergency operator action and hence one measure of security level.

2) Implementation: Load forecast error is consider but only in the most basic form, a normally distributed random number with mean 1 and s.d. 0.05 is multiplied by the forecast given in stage one. A more realistic measure should take better account of the correlation between time and load forecast error as well as weather impacts. Component faults are taken by converting line, generator and busbar value (from the original paper), into the probability that they will fault during the half hour delivery period, this uses equation 3. As the IEEE-RTS does not have renewable generators a weather forecast is unnecessary.

$$P_f = 1 - e^{-\lambda t} \tag{3}$$

3) Results: Again theoretical results were calculated to verify the implementation of the Monte Carlo sampling program, these results are given in table IV. The result for the Monte Carlo and theoretical match up very well showing the implementation is correct.

4) Further Work - power system simulation and automatic actions: The simulation of the second stage is less involved than the first. Because we are looking for systems where emergency operator action is not needed we do not have to simulate a system operator for this stage. This means only automatic actions need to be modelled, the ideal method for this is to do a full dynamic simulation. Starting from the scenario and adding each of the changes when the previous changes' oscillations have damped down.

As millions of simulations are likely to be required either distributed computing or a change to the simulator will be required. A load flow simulation is an order of magnitude faster than a dynamic simulation but does not have the ability to model outages and mismatches in the same way.

Once the simulations are performed and acceptable systems are marked as such we can move on to the analysis stage.

C. Analysis Stage

This leads to the final section of the method, performing the comparison between different security assessment schemes. A perfect security assessment scheme would only pass those states where the probability of the system remaining acceptable was above a certain threshold. This threshold is a trade-off between the extra cost of securing the system and penalties caused by unsupplied load. It would be highly system dependent and it's calculation is not covered by this paper.

The first two parts of this work have given an approximation for the probability of acceptability for a number of different scenarios. If these are plotted as in 2 each security assessment scheme can simply be run with each of the scenarios to see if it agrees with the theoretical ideal. The sample data in 2shows that the top item was in error more then the bottom one. This means that the bottom one is a better security scheme for this system. It would also be interesting to know which cases are in error. If they are near to the threshold then it is less severe than if they are far away.

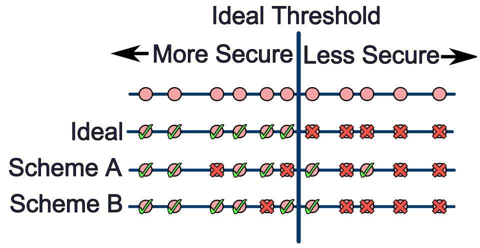

Fig. 2. Comparing Security Assessment Schemes

III. Limitations

This method allows two security assessment schemes to be compared but it does suffer from limitations. These limitations do not remove its merit but should be considered in future applications of this method.

- These is a significant data requirement. Some power systems will not have sufficient data to create the Monte Carlo model.
- These is a significant computational requirement. Many millions of power system simulations are required.
- The proposed method requires a simulated system operator, this is very difficult to accurately achieve.
- Any non-deterministic simulation has a chance of giving misleading results through insufficient samples.
- This method does not aim to make general claims about the ability of different security assessment schemes.
- Counting of unlikely events means things that were not included in the Monte Carlo could have a greater affect.
- The method does not distinguish between severity of failure. Both a small overload on a line and a system-wide blackout are considered the same.

It is the intention of the authors to further refine the proposed method to mitigate some of the limitations.

IV. Conclusion

In this paper a method for comparing security assessment schemes was introduced. Initial results test the implementation of the two stage Monte Carlo sampler showing a high correlation with expected results.

It is explained how this two stage Monte Carlo could be extended using simulation to provide a framework to easily compare security assessment schemes. Although there are many challenges and limitations to the method if these can be overcome it will provide a valuable tool to system operators.

Acknowledgement

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Paper 2

Analyzing Security Assessment Schemes in Traditional Networks

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Analyzing Security Assessment Schemes In Traditional Networks

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***Abstract*—The introduction of sustainable and renewable energy sources into traditional networks will be limited if we continue to use inappropriate methods for security analysis. The probabilistic nature of variable and non-schedulable renewable generation is not well represented in current on-line security assessment schemes.**

This paper presents a novel method of analyzing and comparing system security schemes and provides initial results of one such scheme. It does so by dynamic simulation of Monte Carlo samples on the IEEE Reliability Test System (IEEE-RTS). It aims to provide information on both how often and how badly the system security scheme fails.

After testing on the IEEE-RTS it can be shown that there are credible failures that N-1 does not consider. It highlights the need for a new security assessment scheme that goes beyond a small deterministic set of test cases.

***Index Terms*—Monte Carlo methods, Power system dynamic stability, Power system reliability, Power system security, Power system simulation, IEEE Reliability Test System, Sustainable Power Generation**

I. Introduction

The NERC Planning Standards [1] provide a commonly cited definition for security and adequacy. Security being the ability of the electric system to withstand disturbances. Whereas, adequacy is the ability to supply the total demand taking into account outages [2]. These are the two component parts of reliability: adequacy being a planning issue and security being an operational one.

The task in security control is to keep the system in the normal state. The normal state is defined as having all system variables within acceptable limits, that the system operates securely and it is able to withstand a contingency without violating the constraints [3]. Security assessment is the analysis of data from security monitoring. In this paper a method for comparing security assessment schemes is given.

Traditionally, security assessment schemes are based upon the simulation of a set of credible contingencies; The set of normal contingencies is given in [3]. This can lead to problems if something outside of the expected set happens. In the UK the simultaneous failure of two distant generators was considered non-credible; hence, after it occurred during 2008, emergency operator action was needed. With increasingly large and stressed systems the problem is intensified.

Additionally, the set of credible disturbances is no longer discrete. This means the contingency analysis itself is losing some of it's past merit. In the case of wind generation the output is stochastically variable, by treating it as a contingency you ignore the fact that the output can vary continuously between it's rate capacity and zero power output. Using traditional security assessment will increasingly disadvantage renewable generation as penetration grows [4]. In reality the likelihood is that national wind power as a whole will not fluctuate drastically, especially if turbines are distributed over a large geographical area [5]. But the risk must be quantified and verifiable before new security assessment methods can be implemented.

The definition of security in [6] gives further insight into the problem:

> Security may be defined as the probability of the system's operating point remaining in a viable state, given the probabilities of changes in the system (contingencies) and its environment (weather, customer demands, etc.). [6]

This begins to show that due to the increasing complexity as well as the introduction of non-schedulable generation, electric power systems will have to have a new scheme for security assessment. Weather will have an increasingly large effect on the system, and a larger system will be likely to experience more failures. This coupled with the dramatic increase in computing power and a reliance on grid supplied electricity means that new probabilistic methods are not only possible but likely.

For a broad overview of the methods used within power system reliability refer to the works of Billinton and Allen [7].

A. *Traditional Power System Security*

Power system security involves making sure the system is in an acceptable state, Kirschen [8] provides a good overview to this. In the UK the system operator has only one hour to achieve an acceptable level of security. This involves:

- Maintaining good **power quality**, i.e. that the voltages/currents are approximately sine-waves at 50Hz.
- Keeping system **synchronism**, i.e. that every generator is approximately at the same frequency and phase.

- Requested power being delivered to most loads, i.e. **no load shedding**.
- Keeping each component **within limits** for voltage/current/power most of the time (i.e. there are no components that are overloaded or experiencing voltage collapse).
- Making the system reasonably **fault tolerant**.
- Suppling energy at **minimum cost** with **minimum environmental impact**.

Obviously from the above list security cannot easily be defined in absolute terms. There are meant trade-offs involved; the goal is to achieve an acceptable level of security at least cost.

Various types of computer simulation can be run to determine the behavior of the system. These include a *load flow*, a *dynamic simulation* and a *transient simulation*. Each of these tests considers the system in increasing levels of complexity; the transient simulation is the most accurate but slowest test to run.

The list of contingencies to be simulated has traditionally been where each line, transformer, and generator are individually taken out of service [9]. This generates a set known as N-1, where N represents the number of system components; to be N-1 secure is to have a system which remains stable after any N-1 contingency occurs. The UK operates somewhere between N-1 and N-2 (the set of all possible failures on any two components) security; that is, any single component fault and credible double fault should not cause the system to enter an emergency state.

In this way N-x security treats the probability of failure in a simplistic way; it assumes all contingencies to be equally likely. It fails to recognize that intermittent/non-schedulable generators have a quite inaccurate prediction of their output power [10]. It also fails to take into account correlated failure caused by common right of way, common structure or extreme weather conditions.

That said, it remains a very popular scheme and there has been numerous methods to determine a least cost approach to maintaining N-1 security through stability constrained optimal power flow (SCOPF) [11].

To improve the deterministic security assessment there has been significant work to determine the optimal set of contingencies to consider [6] [2] [12]. They often consider external influences such as season or weather to change the working set. As the contingency selection becomes more complex it starts to introduce probability and risk.

B. Risk Based Methods

Risk based (i.e probabilistic) methods are categorized by their use of both probability and consequence. Billinton defines risk as the product of the probability of an event resulting in a security violation and the consequence of that violation [13].

Probabilistic risk assessment is nothing new, it has been used in other industries since the 1960's; and has been studied in power systems since the 1970's [14]. But due to the success of other techniques and the time constraints involved they have been slow to be adopted.

The disadvantage of using the deterministic approach will eventually start to impact financially. In some instances balancing market prices are already increased by the introduction of wind power [5]. For a further explanation on why the once adequate deterministic security assessment methods need to change see [2].

Sobajic et. al. [15] provides a brief overview of four different approaches to the problem of stability assessment:

- Numerical Integration,
- The Second Method of Lyapunov,
- Probabilistic Methods, and
- Pattern Recognition.

The paper then discussed one such pattern recognition method after highlighting the works of Patton, Billinton, and Wu as contributing significantly to probabilistic methods.

After an extensive literature review, including the mention of Monte Carlo methods, McCalley [16] goes on to determine a set of deterministic rules based upon risk based methods.

Monte Carlo methods are a type of algorithm used commonly in risk assessment where a system with uncertainty is repeatedly sampled. In this way Monte Carlo Methods lend themselves well to the task of probabilistic risk assessment. A comparison of different modifications to standard Monte Carlo Methods is given in [17] there a financial value is placed upon outages to give an absolute level of comparison.

For an up-to-date review of the work in risk based security assessment see [9]. It also provides a good conceptual representation which shows how risk based security assessment will more accurately reflect the actual level of security. Xiao shows graphically how traditional SCOPF can produce a more risky solution due to it's fixed constraints.

By assigning a severity to each type of disturbance Ni [18] created a system for aiding control room decisions based on risk.

C. The variability of wind

The introduction of intermittent and non-schedulable generation will have a number of effects. The impact of these effects will depend on the type, installed capacity, climate and geographic distribution of the installed turbines. The inherent intermittentcy of renewable generation means that it cannot displace conventional generation on a "megawatt for megawatt" basis [19], it will however tend to increase balancing market costs [20]. This is not currently a large problem but as penetration increases there will need to be larger reserves or a change in market.

It was the case that wind farms were simply not made to ride-through faults, disconnecting until normal operation resumed. This has a detrimental effect on the system by amplifying the consequence of any fault. They have this feature due to the lack of reactive power control on older SCIG based turbines, in fault conditions they would consume large amounts of reactive power, possibly leading to voltage collapse. The effects of wind power on system dynamics are

Unit group	Unit Size (MW)	Unit Type	Force Outage Rate	MTTF (Hour)	MTTR (Hour)	Scheduled Maint. wks/year
U12	12	Oil/Steam	0.02	2940	60	2
U20	20	Oil/CT	0.10	450	50	2
U50	50	Hydro	0.01	1980	20	2
U76	76	Coal/Steam	0.02	1960	40	3
U100	100	Oil/Steam	0.04	1200	50	3
U155	155	Coal/Steam	0.04	960	40	4
U197	197	Oil/Steam	0.05	950	50	4
U350	350	Coal/Steam	0.08	1150	100	5
U400	400	Nuclear	0.12	1100	150	6

Fig. 1. Generator Reliability Data [23]

covered by a series of papers by Slootweg and Kling including [21]. This shows how newer DFIG cope better with faults and due to advance control electronics can have a stabilizing effect post-fault. A comprehensive review of the effects of integrating wind by Ackermann [22] highlight the danger of cut-off in turbines:

> Wind power reductions due to the cutoff wind speed can, in extreme situations, lead to vary large power deviations. [22]

Work has been done to try and determine the most financially efficient way of trading wind power [10]. This includes a table of expected generation variation between 0.5 and 4 hours after a forecast.

D. Analyzing Security Assessment Methods

Any new security scheme will firstly need to have a set of easy to follow rules that can be determined quickly. it will need to provide a solution that doesn't disadvantage renewable generation while maintaining the same level of security all at least cost.

The security assessment method must also be verifiable, i.e they must be a way to see if the system operator or even the methodology were at fault following an event.

One problem with this is that there isn't really any measure of a level of security so comparing them between different schemes is difficult. That is the aim of this paper.

ID# = Branch identifier.
Inter area branches are indicated by double letter ID.
Circuits on a common tower have hyphenated ID#.
λp = Permanent Outage Rate (outages/year).
Dur = Permanent Outage Duration (Hours).
λt = Transient Outage Rate (outages/year).
Con = Continuous rating.
LTE = Long-time emergency rating (24 hour).
STE = Short-time emergency rating (15 minute).
Tr = Transformer off-nominal ratio.
Transformer branches are indicated by Tr $\neq$ 0.

ID #	From Bus	To Bus	L miles	-Perm- λp	Dur	Tran. λt	R pu	X pu	B pu	Con MVA	LTE MVA	STE MVA	Tr pu
A1	101	102	3	.24	16	0.0	0.003	0.014	0.461	175	193	200	0
A2	101	103	55	.51	10	2.9	0.055	0.211	0.057	175	208	220	0
A3	101	105	22	.33	10	1.2	0.022	0.085	0.023	175	208	220	0
A4	102	104	33	.39	10	1.7	0.033	0.127	0.034	175	208	220	0
A5	102	106	50	.48	10	2.6	0.050	0.192	0.052	175	208	220	0
A6	103	109	31	.38	10	1.6	0.031	0.119	0.032	175	208	220	0
A7	103	124	0	.02	768	0.0	0.002	0.084	0	400	510	600	1.015
A8	104	109	27	.36	10	1.4	0.027	0.104	0.028	175	208	220	0
A9	105	110	23	.34	10	1.2	0.023	0.088	0.024	175	208	220	0
A10	106	110	16	.33	35	0.0	0.014	0.061	2.459	175	193	200	0
A11	107	108	16	.30	10	0.8	0.016	0.061	0.017	175	208	220	0
AB1	107	203	42	.44	10	2.2	0.042	0.161	0.044	175	208	220	0
A12-1	108	109	43	.44	10	2.3	0.043	0.165	0.045	175	208	220	0
A13-2	108	110	43	.44	10	2.3	0.043	0.165	0.045	175	208	220	0
A14	109	111	0	.02	768	0.0	0.002	0.084	0	400	510	600	1.03
A15	109	112	0	.02	768	0.0	0.002	0.084	0	400	510	600	1.03
A16	110	111	0	.02	768	0.0	0.002	0.084	0	400	510	600	1.015
A17	110	112	0	.02	768	0.0	0.002	0.084	0	400	510	600	1.015
A18	111	113	33	.40	11	0.8	0.006	0.048	0.100	500	600	625	0
A19	111	114	29	.39	11	0.7	0.005	0.042	0.088	500	600	625	0
A20	112	113	33	.40	11	0.8	0.006	0.048	0.100	500	600	625	0
A21	112	123	67	.52	11	1.6	0.012	0.097	0.203	500	600	625	0
A22	113	123	60	.49	11	1.5	0.011	0.087	0.182	500	600	625	0
AB2	113	215	52	.47	11	1.3	0.010	0.075	0.158	500	600	625	0
A23	114	116	27	.38	11	0.7	0.005	0.059	0.082	500	600	625	0
A24	115	116	12	.33	11	0.3	0.002	0.017	0.036	500	600	625	0
A25-1	115	121	34	.41	11	0.8	0.006	0.049	0.103	500	600	625	0
A25-2	115	121	34	.41	11	0.8	0.006	0.049	0.103	500	600	625	0
A26	115	124	36	.41	11	0.9	0.007	0.052	0.109	500	600	625	0
A27	116	117	18	.35	11	0.4	0.003	0.026	0.055	500	600	625	0
A28	116	119	16	.34	11	0.4	0.003	0.023	0.049	500	600	625	0
A29	117	118	10	.32	11	0.2	0.002	0.014	0.030	500	600	625	0
A30	117	122	73	.54	11	1.8	0.014	0.105	0.221	500	600	625	0
A31-1	118	121	18	.35	11	0.4	0.003	0.026	0.055	500	600	625	0
A31-2	118	121	18	.35	11	0.4	0.003	0.026	0.055	500	600	625	0
A32-1	119	120	27.5	.38	11	0.7	0.005	0.040	0.083	500	600	625	0
A32-2	119	120	27.5	.38	11	0.7	0.005	0.040	0.083	500	600	625	0
A33-1	120	123	15	.34	11	0.4	0.003	0.022	0.046	500	600	625	0
A33-2	120	123	15	.34	11	0.4	0.003	0.022	0.046	500	600	625	0
A34	121	122	47	.45	11	1.2	0.009	0.068	0.142	500	600	625	0
AB3	123	217	51	.46	11	1.3	0.010	0.074	0.155	500	600	625	0
B1	201	202	3	.24	16	0.0	0.003	0.014	0.461	175	193	200	0
B2	201	203	55	.51	10	2.9	0.055	0.211	0.057	175	208	220	0
B3	201	205	22	.33	10	1.2	0.022	0.085	0.023	175	208	220	0
B4	202	204	33	.39	10	1.7	0.033	0.127	0.034	175	208	220	0
B5	202	206	50	.48	10	2.6	0.050	0.192	0.052	175	208	220	0
B6	203	209	31	.38	10	1.6	0.031	0.119	0.032	175	208	220	0
B7	203	224	0	.02	768	0.0	0.002	0.084	0	400	510	600	1.015
B8	204	209	27	.36	10	1.4	0.027	0.104	0.028	175	208	220	0
B9	205	210	23	.34	10	1.2	0.023	0.088	0.024	175	208	220	0
B10	206	210	16	.33	35	0.0	0.014	0.061	2.459	175	193	200	0
B11	207	208	16	.30	10	0.8	0.016	0.061	0.017	175	208	220	0
B12-1	208	209	43	.44	10	2.3	0.043	0.165	0.045	175	208	220	0
B13-2	208	210	43	.44	10	2.3	0.043	0.165	0.045	175	208	220	0
B14	209	211	0	.02	768	0.0	0.002	0.084	0	400	510	600	1.03
B15	209	212	0	.02	768	0.0	0.002	0.084	0	400	510	600	1.03
B16	210	211	0	.02	768	0.0	0.002	0.084	0	400	510	600	1.015
B17	210	212	0	.02	768	0.0	0.002	0.084	0	400	510	600	1.015
B18	211	213	33	.40	11	0.8	0.006	0.048	0.100	500	600	625	0
B19	211	214	29	.39	11	0.7	0.005	0.042	0.088	500	600	625	0
B20	212	213	33	.40	11	0.8	0.006	0.048	0.100	500	600	625	0
B21	212	223	67	.52	11	1.6	0.012	0.097	0.203	500	600	625	0
B22	213	223	60	.49	11	1.5	0.011	0.087	0.182	500	600	625	0
B23	214	216	27	.38	11	0.7	0.005	0.059	0.082	500	600	625	0
B24	215	216	12	.33	11	0.3	0.002	0.017	0.036	500	600	625	0
B25-1	215	221	34	.41	11	0.8	0.006	0.049	0.103	500	600	625	0
B25-2	215	221	34	.41	11	0.8	0.006	0.049	0.103	500	600	625	0
B26	215	224	36	.41	11	0.9	0.007	0.052	0.109	500	600	625	0
B27	216	217	18	.35	11	0.4	0.003	0.026	0.055	500	600	625	0
B28	216	219	16	.34	11	0.4	0.003	0.023	0.049	500	600	625	0
B29	217	218	10	.32	11	0.2	0.002	0.014	0.030	500	600	625	0
B30	217	222	73	.54	11	1.8	0.014	0.105	0.221	500	600	625	0
B31-1	218	221	18	.35	11	0.4	0.003	0.026	0.055	500	600	625	0
B31-2	218	221	18	.35	11	0.4	0.003	0.026	0.055	500	600	625	0
B32-1	219	220	27.5	.38	11	0.7	0.005	0.040	0.083	500	600	625	0
B32-2	219	220	27.5	.38	11	0.7	0.005	0.040	0.083	500	600	625	0
B33-1	220	223	15	.34	11	0.4	0.003	0.022	0.046	500	600	625	0
B33-2	220	223	15	.34	11	0.4	0.003	0.022	0.046	500	600	625	0
B34	221	222	47	.45	11	1.2	0.009	0.068	0.142	500	600	625	0

Fig. 2. Line Reliability Data [23]

E. IEEE-RTS

The IEEE-RTS was created to provide a common test-bed for study. It contains a wealth of information from three main papers culminating in [23]. For the purposes of this report a small subset of this will be initially considered:

- *Generator MTTF* (hours)
- *Generator MTTR* (hours)
- *Line fail rate* (outages/year)
- *Line fail duration* (hours)
- *Line transient fail rate* (outages/year)

The data shown comes from the tables in [23] these are included as Fig 1, 2, and 3.

II. Methodology

The method detailed in this project is a mix of completed and proposed work. The results of the completed work is detailed explicitly in the next section. The work is made up of a number of computer programs. These are shown in Fig 4 and described below. Basically it creates a set of initial states, sample each of them many times and simulate the samples; these results are then analyzed.

1) Initial State Generator: The initial state generator produces two parts, the load flow and the list of components on outage. In other words it creates a system in a working state as the system operator expects it to be. The load flow is made from the output at each generator and the demand at each busbar.

This information can either be created from a representative sample of historic data; or, as in this case, from the data files. The demand profile in the IEEE-RTS can be used to produce one half of the load flow with the other coming from basic fuel cost data. The fuel cost can determine the generator output through some sort of optimal power flow program. For renewable generators a statistical analysis of the wind resource for each site could produce a set of samples.

ID #	From Bus	To Bus	L miles	- Perm - λp	Dur	Tran. λt	R pu	X pu	B pu	Con MVA	LTE MVA	STE MVA	Tr pu
C1	301	302	3	.24	16	0.0	0.003	0.014	0.461	175	193	200	0
C2	301	303	55	.51	10	2.9	0.055	0.211	0.057	175	208	220	0
C3	301	305	22	.33	10	1.2	0.022	0.085	0.023	175	208	220	0
C4	302	304	33	.39	10	1.7	0.033	0.127	0.034	175	208	220	0
C5	302	306	50	.48	10	2.6	0.050	0.192	0.052	175	208	220	0
C6	303	309	31	.38	10	1.6	0.031	0.119	0.032	175	208	220	0
C7	303	324	0	.02	768	0.0	0.002	0.084	0	400	510	600	1.015
C8	304	309	27	.36	10	1.4	0.027	0.104	0.028	175	208	220	0
C9	305	310	23	.34	10	1.2	0.023	0.088	0.024	175	208	220	0
C10	306	310	16	.33	35	0.0	0.014	0.061	2.459	175	193	200	0
C11	307	308	16	.30	10	0.8	0.016	0.061	0.017	175	208	220	0
C12-1	308	309	43	.44	10	2.3	0.043	0.165	0.045	175	208	220	0
C13-2	308	310	43	.44	10	2.3	0.043	0.165	0.045	175	208	220	0
C14	309	311	0	.02	768	0.0	0.002	0.084	0	400	510	600	1.03
C15	309	312	0	.02	768	0.0	0.002	0.084	0	400	510	600	1.03
C16	310	311	0	.02	768	0.0	0.002	0.084	0	400	510	600	1.015
C17	310	312	0	.02	768	0.0	0.002	0.084	0	400	510	600	1.015
C18	311	313	33	.40	11	0.8	0.006	0.048	0.100	500	600	625	0
C19	311	314	29	.39	11	0.7	0.005	0.042	0.088	500	600	625	0
C20	312	313	33	.40	11	0.8	0.006	0.048	0.100	500	600	625	0
C21	312	323	67	.52	11	1.6	0.012	0.097	0.203	500	600	625	0
C22	313	323	60	.49	11	1.5	0.011	0.087	0.182	500	600	625	0
C23	314	316	27	.38	11	0.7	0.005	0.059	0.082	500	600	625	0
C24	315	316	12	.33	11	0.3	0.002	0.017	0.036	500	600	625	0
C25-1	315	321	34	.41	11	0.8	0.006	0.049	0.103	500	600	625	0
C25-2	315	321	34	.41	11	0.8	0.006	0.049	0.103	500	600	625	0
C26	315	324	36	.41	11	0.9	0.007	0.052	0.109	500	600	625	0
C27	316	317	18	.35	11	0.4	0.003	0.026	0.055	500	600	625	0
C28	316	319	16	.34	11	0.4	0.003	0.023	0.049	500	600	625	0
C29	317	318	10	.32	11	0.2	0.002	0.014	0.030	500	600	625	0
C30	317	322	73	.54	11	1.8	0.014	0.105	0.221	500	600	625	0
C31-1	318	321	18	.35	11	0.4	0.003	0.026	0.055	500	600	625	0
C31-2	318	321	18	.35	11	0.4	0.003	0.026	0.055	500	600	625	0
C32-1	319	320	27.5	.38	11	0.7	0.005	0.040	0.083	500	600	625	0
C32-2	319	320	27.5	.38	11	0.7	0.005	0.040	0.083	500	600	625	0
C33-1	320	323	15	.34	11	0.4	0.003	0.022	0.046	500	600	625	0
C33-2	320	323	15	.34	11	0.4	0.003	0.022	0.046	500	600	625	0
C34	321	322	47	.45	11	1.2	0.009	0.068	0.142	500	600	625	0
CA-1	325	121	67	.52	11	1.6	0.012	0.097	0.203	500	600	625	0
CB-1	318	223	72	.53	11	1.8	0.013	0.104	0.218	500	600	625	0
C35	323	325	0	.02	768	0.0	0.000	0.009	0	722	893	893	1.00

Fig. 3. Line Reliability Data cont. [23]

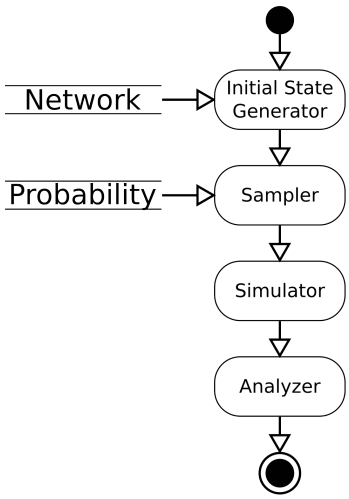

Fig. 4. Example of included graphics

$$P_o = \frac{MTTF}{(MTTF + MTTR)} \quad (1)$$

where;

- $MTTF$ is the mean time to fail in hours
- $MTTR$ is the mean time to repair in hours

The components on outage can be obtained from the MTTF and MTTR through Markov Models. A simple probability of outage can be calculated as in equation 1 using the data from Fig 1.

Both the MTTF and MTTR can be sampled (using equation 2 to produce a TTF_0 and TTR_0. A random number selected between these values not only shows where the component is in service but when it will change state.

$$T_0 = -xlog(1 - U[0, 1]) \quad (2)$$

where;

- x is the mean time
- $U[0, 1]$ is a uniform random number in the range 0 to 1

2) Sampler: The sampler takes one initial state, with some probability data to produce a final sample. Each time it is run it can produce a different sample based on the likelihood of events. The three additional outputs that are added to the initial state are:

- *Component Failures*
- *Variation in Generation*
- *Variation in Demand*

Failures are again consider here to distinguish between a component that was previously out and has little effect on the system, with a component that fails during simulation.

The probability information available from the IEEE-RTS can be used on any initial system to come up with a probability of any component being in a certain state. For lines the probability is equation 3.

$$P_f = 1 - e^{-\lambda t} \quad (3)$$

where;

- λ is the failure rate from Fig 2
- t is the time period. 0.5h in this case.

The variation in renewable generator power is not consider here but should come from an analysis of the variation in wind response over the time-frame simulated; in the UK this is half-hour blocks.

Many of the simulations produce the same result. To reduce the computational burden of simulation these can be consolidated into a single simulation.

3) Simulator: A dynamic simulator such as PSAT can be used to take each sample and say whether the resulting simulation leaves the system in a suitable state or not. A simple definition of a suitable state is that the system remains stable and not outside of limits. A more advanced definition could cover load not served and power quality.

4) Analyzer: This program consolidates the results of the simulator and other programs into readable results. These results and their formation are described next.

Each initial state can have associated with it a probability of failure by looking at the number of samples that failed. An ideal security assessment method would signal a failure if the probability of failure was above some threshold and a success if it was below. By comparing other system security schemes to this ideal we can say how many times it is in error. To extend this idea we can look not only at the number of initial states were reported incorrectly but also how badly wrong they were. The measure of how badly it was wrong is simply the difference between the threshold and the probability of failure in each initial state where it was wrong.

III. Results

The work done involved creating initial states, sampling those states and analyzing the data produced. This is detailed below.

TABLE I
SUBSET OF SAMPLED DATA

Occurrence	No. Events	Trans	Fail	Simulation
784349	0			
2220	1	G01		
2203	1	G38		
2190	1	G71		
2162	1	G04		
2149	1	G67		
...	...	...	...	...
23	1		C30	
23	1		B34	
23	1		B32-2	
22	1	A33-1		
22	1		B25-2	
...	...	...	...	...

The process of creating the initial state involved seeing which components (generators and lines) were out of service. For generators this can be done directly from equation 2, lines require changing the failure rate into a mean time beforehand.

The sampler randomly picks one initial state and runs many samples from it. The samples include whether a generator or line fails during the half-hour simulation. Lines can fail either as a transient or permanent failure. For each generator in the system a Markov Model can determine both the initial state and time remaining in that state using equation 2. If the time remaining is less than the simulation time then the generator will fault (or be repaired, but repaired generators are not turned back on during blocks). Equation 3 can create the probability of each line failing during the next half-hour, if a uniformly distributed random number between 1 and 0 is less than this then the line is set to fail.

The sampler was run over many hours to produce a set of around 900,000 samples. These were consolidated to remove duplicated entires. A small subset of this file is shown in Table I. In here it can be seen that around 780,000 samples had no failure at all and that there were about 2000 samples where component G01 failed.

The next stage was to group the results into the number of failures, i.e. create groups for each N-x. This is shown in Table II. 87% of samples has no failures at all; 12% had one component failing. These numbers may seem high; this is due to the IEEE-RTS treating each generator by its separate units; one busbar may have many generators attached. The last column in the table shows the probability of the class of failures given that one has occurred. Hence, there is a 93% chance that a failure that occured will be N-1, this yields some surprising results: for this system 6.5% of all failures are N-2 and 0.3% actually had more than two components failing simultaneously. It can be seen from the graph in Fig 5 that the decay is exponential.

TABLE II
FAILURES OF TYPES N-X

Type	Occurrence	Probability per Simulation	Probability per Failure
N-0	784349	0.86764	-
N-1	111450	0.12329	0.93146
N-2	7808	0.00864	0.06526
N-3	382	0.00042	0.00319
N-4	10	0.00001	0.00008
N-5	1	0.00000	0.00001
N-6	0	0.00000	0.00000

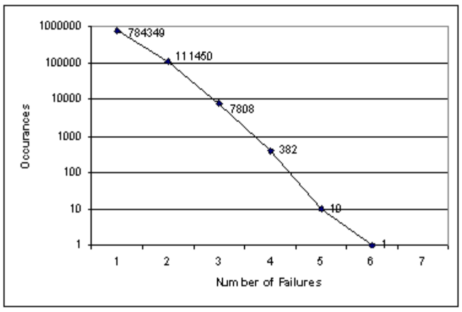

Fig. 5. Likelihood of Failure

IV. CONCLUSION

The results show that 87% of samples had no failures at all. Which, if operating conditions remain the same, gives an expected time to fail of once every 8 hours. It should be noted that this time to fail figure is quite high. This is due to the generators being treated as individual units rather than being aggregated by busbar. 93% of failures were on one components which means almost 7% of the time when a failure occurred it was on more than one component. This highlights just how important it is to go beyond N-1 security.

The probability of getting an N-2 was roughly an order of magnitude less than N-1. This seemed to hold true for the other N-x cases. There was a small number of simulations where multiple generating units failed; this is likely to affect the system very badly. It has been shown that the cost of losing the entire system is many times greater than multiple losses of individual parts.

It highlights the need for a new security assessment scheme that goes beyond a small deterministic set of test cases, particularly in large systems or systems with a high percentage of renewable generation.

ACKNOWLEDGMENT

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Paper 3

An Optimized Defence Plan for a Power System

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An Optimized Defence Plan for a Power System

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Abstract- **This paper presents a novel optimization technique for determining the setting of various emergency power system controls. This will allow for the production of a comprehensive defence plan, against events such as cascading blackouts. The goal of this technique is to retrieve a new equilibrium operation point following a severe contingency. In the proposed optimization technique described in this paper the generator tripping, load shedding and islanding are considered as the main emergency control actions. Genetic Algorithm approaches are very successful at solving nonlinear combinatorial optimization problems; these have been applied in this work to produce an optimized defence plan. A Genetic Algorithm approach is used to find the optimal combination of generators and loads to be tripped as the best solution for the network to regain a new state of equilibrium that is operationally stable, whilst maintaining supply to as many consumers as possible. System islanding may also be applied if a satisfactory state of equilibrium can not otherwise be obtained. The optimization technique uses transient stability evaluation algorithms, based on time-domain simulation, to assess the fitness of the potential solutions. The test case, presented in this paper, for the optimization technique was the Libyan power system network. In order to show the validity of the optimized defence plan, a comparison between the existing Libyan power system defence plan and the optimized defence plan is presented for the case of a major blackout in the western part of the Libyan power system that took place on 8th November 2003. The results presented in this paper show that a robust defence plan with a satisfactory amount of load shedding and system islands can be obtained by the new technique. The paper also demonstrates that the new defence plan outperforms the existing Libyan power system defence plan.**

I. INTRODUCTION

The main goal of power system security measures taken during planning and operation is to minimize the number of interrupted customers following likely incidents. This goal can be reached by implementing planning and operation rules to ensure that power systems remain viable following any credible contingency. However, abiding by these security rules does not guarantee that the network will be fully protected against all types of severe faults. This is due to the fact that major disturbances are the consequence of complex situations associated with control or protection failures. This kind of situation is rare but does occur. Instances include France in 1978 and 1987 and the Western United States in July 1996 [1]. Practically, special defensive measures called a “defence plan” are used. By limiting the geographical extent, duration and effects of the disturbances, defence plans can play an important role in minimizing the number of interrupted customers [2]. Owing to the complexity of modern power systems, the design of defence plans can be very difficult. Human experience and observation are used as the main keys in designing the necessary measures. Although using the experience of power systems engineers can be of assistance in the design of a good defence plan, the optimality of the defence plan, in terms of loss of loads, can not be guaranteed [3]. This heightens the necessity of using optimization methods to obtain more optimal defence plans. Mathematical optimization methods have been used over the years for power system control problems. However, the solution for large-scale power systems is not easy to obtain by way of ordinary mathematical optimization methods. This is due to the fact that there are many uncertainties in power system problems due to their complexity, size and geographical distribution. It is also much preferred that the solution for the power system be close to the global optimum solution. However, this can not easily be reached by mathematical methods due to the multi-objective, discontinuous nature of the problem space [4]. All of these factors therefore make it necessary to use a robust global search technique such as a Genetic Algorithm [5]. In this paper, a Genetic Algorithm is applied to find the minimum amount of load shedding, following severe faults, at various frequency thresholds that are able to secure the network, or even enhance the dynamic performance. Also, another Genetic Algorithm is applied to obtain an optimal islanding scheme to geographically restrict the extent of the fault. Practically, defence plans are designed to act against incidents which are not covered at the system planning stage. There are many methods that can be used to prevent system collapse immediately following an incident. These include generator tripping, fast valving, load shedding excitation controls and system islanding. Of these, load shedding, generator tripping and system islanding are considered to be the most effective control actions [6]. However, generator tripping is often associated with conservative networks. These defence schemes are based on the fact that, in extreme situations, it is better to shed some loads, or parts of the network, rather than to lose the whole network.

II. HOW TO DESIGN A DEFENCE PLAN

Numerous specific dynamic simulations are taken into consideration in the process of defence plan design [2, 3]. Unlike conventional operational security studies, the contingencies that are investigated for defence plan design are much more complicated than N-1 contingencies. The goal of these dynamic simulations is to assess system security and to determine the behaviour and the limits of the adopted defence measures, and to examine the impact of a new strategy [7].

A. *Necessity to represent an accurate model for the network*

As in any other study, the relevance of the study and the usefulness of the results depend on the accuracy of the system modelling. With regard to the dynamic simulation, a good representation of the dynamic components such as generators, AVR, governors, and the fast-valving system, SVC and FACTS, should be ensured. It is necessary to model the behaviour of the protection system, including unit protection such as generation unit protection, lines protection, and protection schemes that include the defence plan itself [8].

B. Incident Scenarios

Building incident Scenarios that represent different types of transient phenomena which lead to full system collapse, is one of the important steps in defence plan designing. Under secure operation conditions, power systems can withstand most likely incidents. Therefore, chosen incidents scenarios should be sufficiently complex and severe to break the system. Most of the time, the network is built to be of sufficient strength to withstand major disturbances. For this reason, the network must be weakened in order to simulate the situation that is very different from the normal operation conditions. Taking into account different weakening operation conditions such as unhealthy voltage profile, an unbalanced generation plan, an exceptional load demand, special import/export conditions and losing an important high voltage line, can be of assistance in representing severe transient phenomena that might lead to full system breakdown. Hence, this leads to a feasible defence plan. Incident scenario can be also built by using a probabilistic technique [9].

C. Simulation Tools

System collapses involve complex transients, which are a combination of slow transient and fast transient phenomena. Therefore, it is necessary to have simulation tools to study the ability of the power system to remain in synchronization for just a few seconds following the occurrence of the incident and to represent voltage, frequency and power flow variations[10].

III. LIBYA'S POWER SYSTEM

The power system in Libya consists of four geographically well-dispersed, totally interconnected major island systems. The transmission system is supplied via 55 generating plants. These are mainly simple-cycle gas-turbine plants and steam units with some diesel generators located in rural areas of the Libyan Desert. The prime fuels are natural gas, residual fuel oil and distillate. The ultra high voltage level is 400 kV with a total circuit length 442 km, a high voltage transmission level of 220 kV, and a total circuit length 13,472 km. The sub-transmission voltage level is 66 kV, with a total circuit length of 13,582 km. The distribution network's voltage level is 30 kV; with a total circuit length of 6,237 km. geographically, the Libyan Network is characterized by heavy loads with most of the generation located in the north. Light loads are located far away from the generation, in the south. For purpose of study the Libyan Power System is geographically divided into seven electrical areas [11].

IV. CURRENT DEFENCE PLAN

A. Overview

Since the current situation of the Libyan power system is characterized by weak connections in extended areas, the main goal of Libyan power system engineers was to produce a defence plan which is able to avoid propagation of severe phenomena, like loss of synchronism and voltage collapse.

B. Current Defence plan design

The Libyan defence plan design is based on the following steps [12]:

STEP 1 *Operation conditions definitions.*

In order to be able to represent severe transient phenomena that could lead to full system collapse, the 2003 Libyan network with interconnection with Egypt and the peak load situation has been considered along with some severe conditions. The conditions are attached with this paper in appendix 1.

STEP 2 *selections of assessment contingencies.*

As mentioned in Section 2.2, building comprehensive incident scenarios assists in the design of an efficient defence plan. In the Libyan defence plan, the assessing contingencies are attached in appendix 1.

STEP 3 *Contingency simulations*

The current Libyan defence plan including load shedding schemes, lines trip under frequency criterion and islanding scheme has been performed on a SICRE simulator environment [13].

STEP 4 *Local protection design and setting*

In order to achieve an accurate system, the following protection relays were implemented: out of step relays, under-voltage protection, power flow protections and power swing blocking.

STEP 5 *Load shedding scheme design*

Based on the Libyan power system topology, the Libyan network was considered as six areas. Each area has its own load shedding scheme as can be seen in Table 1. For coordination reasons, General Electricity Company of Libya recommended 49.4, 49.2, 49.0, 48.8, 48.6 Hz as frequency thresholds for load shedding. However, the choice of the first and last threshold is based on the following points. The first threshold should be fixed so as to avoid load shedding for electromechanical oscillations, even of large amplitude, in case of interconnected systems still integrated. With the amount of spinning reserve being fixed, it is a good rule to choose the first threshold that is low enough to allow the regulating energy to recover frequency drops with no load shedding. Therefore, in order to get the reasonable threshold values, the following values should be determined: maximum frequency deviation recovered by spinning reserve, maximum frequency deviation due to electromechanical oscillations and minimum frequency value. The minimum frequency threshold has to be fixed with reference to the under-frequency protection of units. In addition to the load shedding scheme, further load is shed by line trips for under-frequency protections intervention. Table 1 represents the amount of load shed and figure 1 shows the areas that were shed by line trips protection.

STEP 6 *Under-frequency islanding design*

The adopted technique of splitting the system into islands for a frequency below the last load shedding stage has both pros as well as cons. One advantage is the increase in probability of survival of some islanded power plants, with the possibility of accelerating the restoration procedure. One drawback is the diminution of the probabilities of survival of the small areas, along with instability of the units in small areas and a greater difficulty in balancing load and generation. Based on the experience of electrical Engineers from GECOL and the criteria of the designed islanding scheme, the Libyan Power system was islanded into six islands as shown in figure 1.

Table I The current load shedding scheme

AREA	LOAD SHEDDING FOR EACH THRESHOLD					
	49.4 Hz	49.2 Hz	49.0 Hz	48.8 Hz	48.6 Hz	Total
Area 1	3.30%	3.3%	0.00%	0.4%	0.0%	6.9%
Area 2	2.4%	1.8%	4.7%	3.9%	1.3%	14.1%
Area 3	1.60%	1.20%	1.2%	2.30%	1.9%	8.2%
Area 4	0.4%	0.0%	2.8%	1.7%	6.60%	11.6%
Area 5	2.9%	1.5%	2.4%	0.5%	2.1%	9.4%
Area 6	0.00%	0.9%	0.00%	1.6%	1.30%	3.8%
Area 7	0.00%	0.00%	0.00%	0.20%	0%	0.20%
Total	10.6%	5.6%	11.1%	10.7%	13.2%	54.3%

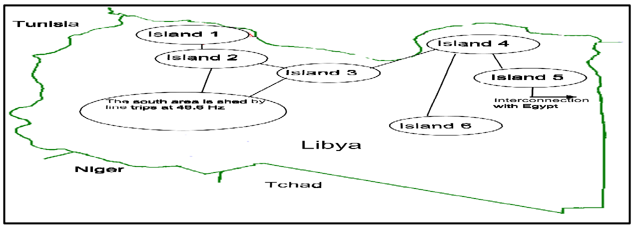

Figure 1 The Current islanding Scheme

V. OPTIMIZED DEFENCE PLAN

A. *Overview*

Generally, in this study, the same defence plan designing procedures are followed. Unlike the current defence plan, optimization techniques are applied in some critical stages. The first optimization technique is used to obtain a load shedding scheme. At this stage, the optimization technique is used to find the minimum amount of loads that should be tripped in every frequency level. At the second stage, the optimization is applied while obtaining the islanding scheme. Therefore, the optimization technique would be of assistance in finding the optimal islanding scheme.

B. *Optimization tools (Genetic Algorithm)*

A Genetic Algorithm (GA) is a global search technique used in optimization problems. It imitates the mechanisms of natural selection and genetics. [14]

C. *Optimized defence plan design*

The optimized defence plan design follows the same logic as the current defence plan. Therefore the optimized defence plane is based on the following:

STEP 1 *Operation conditions definitions.*

Unlike the current defence plan, the optimized defence plan is based on one operation situation. This is due to the fact that it is believed that if the defence plan design is based upon the worst operation conditions, it can act properly in better conditions. In this case, the weakest operation conditions for the Libyan power system is the 2003 Libyan network with interconnection with Egypt and the peak load situation with 120 MW exchange from Egypt and 64 MW from the West to the East.

STEP 2 *Assessing contingencies selections.*

The assessing contingencies reported in appendix 1 are recommended by the General Electricity Company of Libya. This is due to the fact that these contingencies are carefully chosen to represents different types of severe transient phenomena on the Libyan System.

STEP 3 *Contingency simulations.*

For the simulation and stability evaluation, a stability-assessment–optimized simulator, (PSSENG) [15, 16, 17] is used to decide whether the system is stable or not, due to its ability to give clear assessments of the system stability. The stability evaluation algorithm on PSSENG is based on a time domain simulation output.

STEP 4 *Local protection design and setting.*

PSSENG is not implemented with any type of protection system. Undoubtedly, the protection systems play a vital role in defence plan design. However, using GA helps to simplify the application of the protection system. By using GA, the solutions violating the protection elements are avoided. In other words, the power system protection is added to the assessment of the GA. So, if a certain solution causes some protection relays to be actuated, this solution will be lowly ranked.

STEP 5 *Under-frequency load shedding design.*

Unlike the current defence plan, an optimization technique is used to find the minimum amount of load shedding that is able to stabilize the network in every frequency stage. GA is used as an optimization tool.

STEP 6 *Islanding scheme design.*

As mentioned before the GA is applied to obtain an optimal islanding scheme. The idea is to produce an optimal islanding scheme that can preserve as many stable areas as possible

D. *Genetic algorithm Implementation for load shedding*

- **Encoding**

Before applying GA to an optimization problem, an encoding scheme must be decided upon. The encoding scheme should map all possible solutions to the problem into symbol strings (chromosomes).Since the aim of the optimization technique in this stage is to minimize the amount of load shedding in different frequency stages (frequency threshold) , the amount of power in every load is considered in the structure of every chromosome. Also, every chromosome is divided into five parts (5 frequency thresholds). Every part corresponds to a certain frequency stage, and is hence applied in that frequency stage. The following is an example of the chromosome structure:

F1			F2			F3			F4			F5		
4	7	6	0	0	3	88	0	12	0	0	13	0	0	14

Figure 2 chromosome structure

- **Selection**

The Roulette Wheel technique is used as the probabilistic technique to select the chromosomes [5].

- **Crossover**

  In this Algorithm the Midpoint for exchanging information was applied [5].
- **Fitness Function**

The fitness function provides an evaluation of the chromosomes' performance in the problem domain.

In this particular problem, the objective of the fitness function is to grade each chromosome with respect to the following aspects:

- Stability class: The stability evaluation algorithm will rank the chromosome according to its stability class.
- Amount of generated and load power: The chromosomes are evaluated in terms of the amount of tripped power they possess. The higher the amount of tripped power, the lower the rank of the chromosome.
- System decay rate: This index is used only for the two stable classes in order to specify the degree of stability. The lower the system decay rate, the higher the rank of the chromosome.
- Severity Index: This index is used only for the two unstable classes to specify the degree of instability. The higher the severity index, the lower the rank of the chromosome.

The corresponding fitness function can be written as

$$FF = \begin{cases} SC + \dfrac{10}{1 + \sum_{i=1}^{N_L} MVI_{Li}} + \dfrac{1}{SI} + PS & \text{Stable case} \\ SC + \dfrac{10}{1 + \sum_{i=1}^{N_L} MVI_{Li}} + \dfrac{1}{TDR} + PS & \text{Unstable case} \end{cases} \quad (1)$$

Where: SC represents the stability class and is equal to

30 for well damped stable, 10 for poorly damped stable, 5 for oscillatory unstable, or 0 for transiently unstable. NL is the number of predetermined shedding loads, MVI is the summation of the amount of load reductions, TDR is the time decay ratio, SI is the severity index and PS is the protection system evaluation.

E. Results of the GA for Load shedding

The GA operators were selected as follows: number of generations is 500, size of chromosomes is 60 and mutation Rate is 5%. The GA obtains the best solution after generation 260. Due to the complexity of the Libyan network, the GA has taken long time to evolve toward this solution. The ultimate solution is reported in Table 2. It is interesting to note that the load shedding scheme obtained by GA is similar to the current one in some senses. However, some extra load shedding is required in the new scheme in areas 1, 2 and 4. This makes the total load shedding in the network 63.32%, which is higher than that of the current scheme. It is worthy of note that the optimized solution shares with the current scheme the necessity of tripping the majority of area 4 by line trips load shedding at 48.6Hz . Also, it can be noted from Table 2 that an additional amount of load shedding is introduced in the last stage of load shedding.

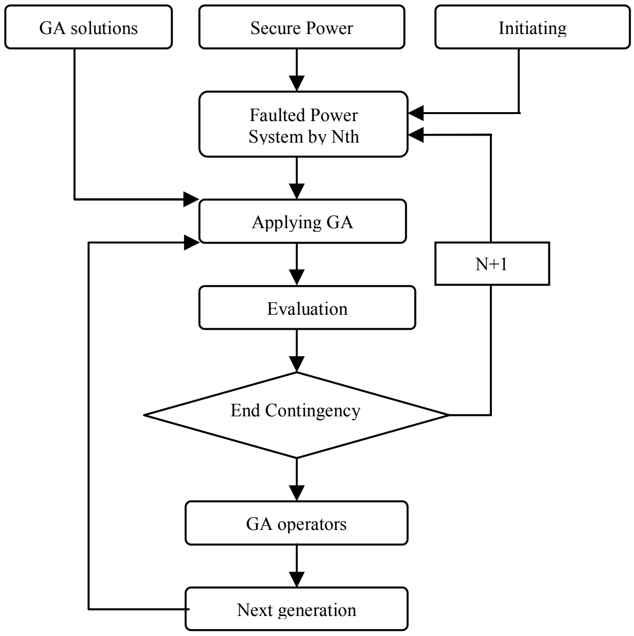

Figure 3 Load shedding algorithm flowchart

This additional amount of load shedding will play important role in saving the system in some critical situations, since it is vital in preparing the network for islanding.

Table II The optimized load shedding scheme

AREA	LOAD SHEDDING FOR EACH THRESHOLD					
	49.4 Hz	49.2 Hz	49.0 Hz	48.8 Hz	48.6 Hz	Total
Area 1	4.20%	4.10%	0.00%	2.00%	1.0%	11.30%
Area 2	2.00%	2.60%	4.10%	5.00%	3.10%	16.80%
Area 3	1.30%	1.00%	0.90%	2.50%	3.10%	8.80%
Area 4	0.32%	0.8	2.40%	2.10%	6.60%	11.6%
Area 5	2.00%	1.00%	2.10%	0.00%	3.10%	8.20%
Area 6	0.00%	1.00%	0.00%	1.00%	2.30%	4.30%
Area 7	0.00%	0.00%	0.00%	0.20%	0%	0.20%
Total	9.82%	10.60%	9.50%	12.80%	20.20%	63.32%

F. GA Implementation for islanding

The implementation of the islanding algorithm is fully explained in the accompanying paper [18] and [19].

G. Results of the GA for islanding scheme

The GA operators were selected as follows: number of Generations is 500, size of chromosomes is 60 and mutation Rate is 5%. The GA obtains the best solution after generation 394. Due to the complexity of the Libyan network, the GA has taken long time to evolve toward this solution. Referring to figure 2, in spite of the fact that the GA had completely free hand to choose the cutting point to form the islands, the GA obtained the same island formation of the current defence plan. The only change is in combining island 2 and island 3.

VI. Optimized Defence Plan Vs Current Defense Plan

A. Overview

In order to show the validity of the optimized defence plan, it is compared with the current defence plan for the case of the major blackout in the western part of the Libyan Power System took place on 8th November 2003.

B. November 2003 Blackout

Four years ago, one of the most severe blackouts was experienced in Libya. The blackout, which affected 74.0% of the served loads, was triggered by a short circuit on the 220/30 kV transformer on a power production plant on the West side of the Libyan Power System, Tripoli West Plant (on island 1). This occurred while the Libyan power system was connected to the Egyptian power system with Zero power exchange and the power transfer from the West to the East was 30 MW. Before the occurrence of the fault, the power system was 69.6% loaded. The fault was cleared on the second zone.

Dynamic evolution vs. the current defence plan

Figure 4 presents the evolution of the frequencies in the Libyan power system with the current defence plan. The dynamic evolution following the occurrence of the fault can be divided based on time into three periods. The first period, which is from 0-10s, starts with the fault occurrence which caused an immediate loss of four units in the west of Tripoli, which caused a loss of generation equal to 120 MW. At 0.8 s following the fault, three units were lost in the south of Tripoli, which caused a loss of generation equal to 237 MW. Two-generation units were lost in the Zawia Plant at 5.5s. One second later another unit in the same plant lost. This period can be distinguished by a loss of generation amount equal to 848 MW. The second Period 2 (7-12s) is characterized by a slow dynamic instability between the East and the West side of the Libya. The third Period (12s- end) started with a fast drop in voltage in the interconnected line between East the West. This is due to a loss of synchronism between the East and the West. Therefore, the interconnection lines between the East and the West were tripped due to under voltage protection at 16.33s at the same time, the Libyan Network was disconnected from the Egyptian Network. It is noticeable from Figure 5 that the East part of Libya survived while the West part of Libya fell in a cascading manner by losing four units in Homs plant until it reached the islanding stage at 48 Hz. Here, the islanding scheme played a decisive role at 19.34s where the network was splitted into three unstable islands. This led to a complete shutdown of the west.

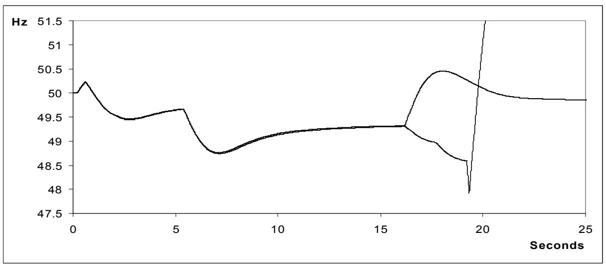

Figure 4 The dynamic evolution of the current defence plan

Dynamic evolution vs. the optimized defence plan

Figure 5 presents the evolution of the frequencies in the Libyan power system with the optimized defence plan. Similarly, the dynamic evolution in this case went in the same sequence as in the previous one. However, the extra load shedding introduced in the beginning of the optimized load shedding scheme was able to survive two generation units in the Zawaia Plant which helped to reduce the fast drop in the voltage in the interconnection lines between the East and the West of the country. Hence, the disconnection was postponed to 19.1 s. In general, the period of 10-18s is also characterized by long and slow instability due to loss of synchronism between the East and the West, leading to disconnection. Following the disconnection between the East and the West part of the country, the additional amount of load shedding introduced in the last frequency dependent on the load shedding step has properly prepared the west part of the network for islanding phase. At 23.5 s the network reaches the islanding stage where island 2 (island 2 and 3 in the current defence plan) was able to survive while island number 1 (island of Tripoli) lost its stability just following the islanding action. Comparing the optimized defence plan and the current defence plan in terms of survival load, the current defence plan was able to survive the eastern part of Libyan power system which is equal to 26.0 % of the total load and the optimized defence plan was able to preserve the east part of the Libyan power system and considerable part of the western part of the network. The whole preserved amount of loads is equal to 41.4% of the total loads. Besides this substantial increase in the amount of served load, this difference plays a vital role in reducing the restoration time.

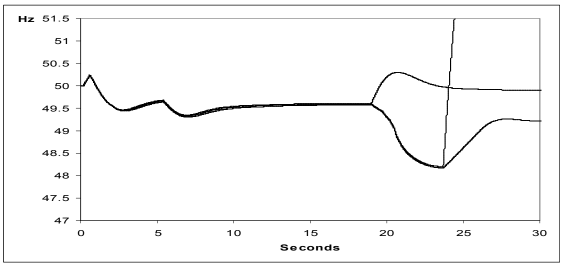

Figure 5 The dynamic evolution of the optimized defence plan

VII. CONCLUSION

The new defence plan algorithm that has been described in this paper can play an important role in obtaining the optimal islanding boundaries and the minimum amount of load shedding required stabilizing the power system after severe faults. The paper has shown that the algorithm is robust and has produced a superior defence plan when compared to the present Libyan defence plan. In particular, it recommends the amalgamation of two islands and in doing so it is able to preserve the supply to more loads. This was tested using the data from the Libyan blackout of 2003. The use of the optimization method has shown the necessity of having an additional amount of load shedding in the last frequency dependent load shedding step, not only to stabilize the network but also to prepare the system for the islanding phase**.**

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Paper 4

Controlled Islanding Scheme for Power Systems

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Controlled Islanding Scheme for Power Systems

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Abstract- **System islanding is often considered as the final stage of power system defense plans. The goal is to preserve stable areas of the faulted power systems. The islanding scheme plays an important role in the power system restoration phase as it can make the power system restoration less complex and reduce the overall restoration time. The basis for islanding is not standard but rather depends upon the nature of the utility. Even though the formation of islands is dominated by geographical proximity of the synchronous generators to maintain generation-load balance, there are some factors which can assist in designing a better islanding scheme. These factors are the type and location of the fault and the dynamic performance of every island on the system against the fault. This paper presents an optimization technique to obtain the optimal formation of islands taking into consideration the geographical distribution of the synchronous generators and the dynamic performance of every island in the system against the extreme and credible faults that lead to full system breakdown. In order to show the validity of this algorithm, the Algorithm is applied to IEEE 118 Bus System and a comparison between the proposed islanding scheme and an islanding scheme based on the geographical distribution of the synchronous generators is presented. The results presented in this paper show that taking into the account the type and location of the extreme and credible faults helps to preserve more stable area than that of the traditional islanding scheme.**

I. INTRODUCTION

A major blackout happens when a large area or a complete area of a power system collapses. The main cause of a major blackout is a succession of cascading failures that trip a transmission line or some generation units. A partial blackout may start with a severe fault which can cause a large variation in power flow and busbar voltage, which in turn can cause the outage of generation units or transmission lines. This causes imbalance in the demand and generation of power. This sort of disturbance can be the beginning of a cascading blackout when it spreads uncontrollably in the power system. For economic reasons, most power systems operate at the minimum level required for stability. This makes the likelihood of converting a local blackout to a major blackout very high. This gives rise to the necessity of having an appropriate scheme to prevent a cascading blackout from becoming a major blackout[1].A variety of emergency controls are used to prevent cascading blackouts. These emergency controls are generator tripping, fast valving, load shedding, excitation controls and system islanding [2]. However, system islanding is usually considered as the ultimate control action to preserve as many stable areas as possible. It is well known that many blackouts, including the series of 2003 blackouts, could have been avoided if appropriate defensive islanding operation were taken following the disturbances. Defensive islanding implies intentional separation of the network in controllable islands. It is not like the passive islanding where the system can be unintentionally split in uncontrollable islands.

In literature, reasonable amount of work has been undertaken in the area of islanding. This work can be divided in two categories. The first category is about grouping the generators according to slow coherency and then trying to find the minimum cutting set from interface network between the generator groups using some searching techniques [3-8]. Due to the fact that they were using slow coherency as the main algorithm , their solutions are not only maintaining load generation balances but also providing good dynamic transient performance during islanding operation. The second group presented completely deferent method for system splitting [9-10]. Unlike the first group, their studies are based on steady state stability. The ordered binary decision diagrams are used after simplifying the original power network by graph theory. This helps in narrowing the solution space. As presented in [11], the balanced islands problem is an NP-problem and it is very difficult to find the optimal solution for large power system using searching algorithm. This is due to the fact that these algorithms are not efficient in searching NP-hard searching space. So far, most of the islanding algorithms are optimized in the way that the solution space is reduced by simplifying the power network. This simplification can be achieved either using simplified version of the power network or a part of it. These kinds of simplification could make it possible to lose one of the better solutions that may exist for the original power system. It is desirable to use the original power system data configuration directly. However, this would prolong the computational time. In this paper, the algorithm used is based on dynamic performance and slow coherency of the islands. The islanding problem is treated as an optimization problem where every solution is evaluated according to its dynamic behavior. Also taking into account the types and the locations of more probable extreme faults, which cause inter-area oscillation problems, and the stability of every possible island have enhanced the scheme design. As mentioned before, in the previous work [3-8], before running the algorithm the generators are grouped according to slow coherency. However, in the proposed algorithm, the solution with slow coherency would be avoided so the ultimate solution should not have slow coherency. In general, this paper raises an argument that designing an islanding scheme against most probable contingencies can be better than designing an islanding scheme with contingencies uncertainty.

It is also very much preferred that the solution for power system be a global optimum solution. However; this can not be reached by mathematical methods. All of these factors therefore make it necessary to use a global search technique such as a Genetic Algorithm [12].

II. SIMULATION TOOLS

A. Genetic Algorithm (GA)

Genetic algorithm is a global search technique used in optimization problems by imitating the mechanisms of natural selection and genetics. Full description of Genetic Algorithm can be found in [12].

B. Stability evaluation

For the simulation and stability evaluation, PSSENG (a power system simulator) [13] was used to decide whether the system is stable or not since it is able to give clear assessments of the stability or instability of a system. The stability evaluation algorithm on PSSENG, which is based on time domain simulation output, can classify the simulation cases into the following categories:

- Transiently unstable class
- Oscillatory unstable class (including inter-area oscillations cases)
- Poorly damped stable class
- Well damped stable class

For the two unstable classes, the stability index is expressed by the severity index. Unstable cases with a detection of pole-slipping are classified in the transiently unstable class. The time taken for the system to pole-slip is used as the severity index in this class. Other unstable cases, including inter-area oscillations cases, without a detection of pole-slipping, are classified as being in the oscillatory unstable class. In this class, the calculation of the severity index is more complicated than in the previous one. The maximum magnitude of the rotor swing among all other generators is used as the main indicator of the severity index. Moreover, the frequency deviation and generator's active power are also used as auxiliary measurements in addition to the maximum rotor swing of the machine in order to give an accurate severity index. For the stable classes, the examination of the machine's rotor swings can give a decent indication of the stability of the system. The swing amplitudes can help to identify the extraction of the envelopes of the rotor swing curve for all machines. The swing of the envelopes can be approximately defined as an exponential function

$$S(t) = A\,e^{bt} \qquad (1)$$

The value of b is the system time decay which is used as an index for the degree of stability. If b is less than 12s the case is classified as being in the well damped stable class. If it is more than 12s, the case is classified as being in the poorly damped stable class [14].

III. PROBLEM FORMULATION

A severe fault may lead to blackouts in some local areas. Under certain circumstances, unexpected faults can lead to a major blackout. However, having a prepared scheme to resolve this problem can help to prevent such a transition. In order to produce this sort of scheme or solution, the production of the scheme should be treated as a constrained optimization problem. This will make the produced scheme meet the following requirements:

- Minimum possible power will be tripped in every island to maintain generation load balance
- As many stable islands as possible will be preserved**.**
- Line flows will not exceed loading limits
- System bus voltage will remain within limits

IV. METHODOLOGY

A. Algorithm overview

The idea is to produce an optimal islanding scheme that can preserve as many stable areas as possible. This scheme is optimized and assessed against some critical contingencies which are carefully chosen to cause system decent. Figure 2 shows the Algorithm flowchart. Before running the original power system, a list of more likely contingencies is artificially chosen to cause slow system coherency. The solutions produced by GA are tested and evaluated against each contingency in that list. After testing all solutions against all the contingencies, the best solutions are chosen, to contribute in the production of next generation of solutions, according to probabilistic technique. Following that the GA operators are applied to produce a better generation of the solutions.

B. GA Implementation

Encoding

Before applying GA to an optimization problem, an encoding scheme must be decided upon. The encoding scheme should map all possible solutions of the problem into symbol strings (chromosomes).Since the aim of our optimization problem is to obtain the optimal island formation with minimum amount of load shedding, every possible tie line that may aid to form island and loads are considered in the structure of the possible solutions (chromosomes). Therefore, every possible line and loads is numbered from 0 to K, where K = Number of Lines + number of Loads. Each chromosome is composed of S unique integers (S< K) with each integer corresponding to a line or load. For instance, chromosome with a value of 5214309 means that the elements number 5, 2, 1, 4, 3 and 9 are the ones that might trip.

Selection: The Rolette Wheel technique is used as the probabilistic technique to select the chromosomes [12].

Crossover: In this Algorithm the Midpoint technique for exchanging information was applied [12].

Fitness Function: The fitness function provides an evaluation of the chromosomes' performance in the problem domain. In this particular problem, the objective of the fitness function is to grade every possible island with respect to the following aspects:

- Stability class of the island: The stability evaluation algorithm will evaluate the island according to its stability class.
- Amount of load shedding that survives the island: The islands are evaluated in terms of the amount of tripped load they might need to survive. The higher the amount of tripped power, the lower the rank of the chromosome.
- System decay rate: This index is used only for the two stable classes in order to specify the degree of stability. The lower the system decay rate, the higher the rank of the chromosome.
- Severity Index: This index is used only for the two unstable classes to specify the degree of instability. The higher the severity index the lower the rank of the chromosome.

The corresponding fitness function for every island can be written as

$$F = \begin{cases} SC + \dfrac{10}{1 + \sum_{i=1}^{N_L} MVI_{Li}} + \dfrac{1}{TDR} & \text{Stable} \\ SC + \dfrac{10}{1 + \sum_{i=1}^{N_L} MVI_{Li}} + \dfrac{1}{SI} & \text{Unstable} \end{cases} \quad (2)$$

Where: SC represents the stability class and is equal to 20 for well damped stable, 10 for poorly damped stable, 5 for oscillatory unstable, or 0 for transiently unstable. NL is the number of predetermined shedding loads, MVI is the summation of the amount of load reductions, TDR is the time decay ratio and SI is the severity index.

The overall fitness function for each chromosome is

$$FF = F_1 + F_2 + \ldots\ldots\ldots\ldots + F_N \quad (3)$$

Where N is the number of islands in one chromosome.

V. 118 IEEE BUS SYSTEM

A. *Overview*

In order to show the validity of the algorithm, the algorithm is applied to IEEE 118 bus system [15]. The network is fully loaded and every generator is equipped with AVR and governor. The dynamic data can be requested from the main author.

B. Assessing contingencies

Due to the large size of 118 networks, there are many type of contingencies which are able to cause generators slow coherency. Out of these, three contingencies are carefully chosen to help find the optimal islands formation. These four contingencies are assumed to be most probable and severe contingencies.

Contingency 1: At 1.00 second permanent three phase fault on the transformer between bus SproneE and SproneW with failure of bus bar protection. The fault was cleared on the second zone.

Contingency 2: At 1.0 S permanent three phase fault on the transformer between MuskngumN and MuskngumS with failure of bus bar protection. The fault was cleared on the second zone.

Contingency 3: At 1.0 S permanent three phase fault on ClinchRV bus with protection failure. The fault was cleared on the second zone.

Contingency 4: At 1.0 S permanent three phase fault on the transformer between TannrsCKN and TannrsCKS with failure of bus bar protection. The fault was cleared on the second zone.

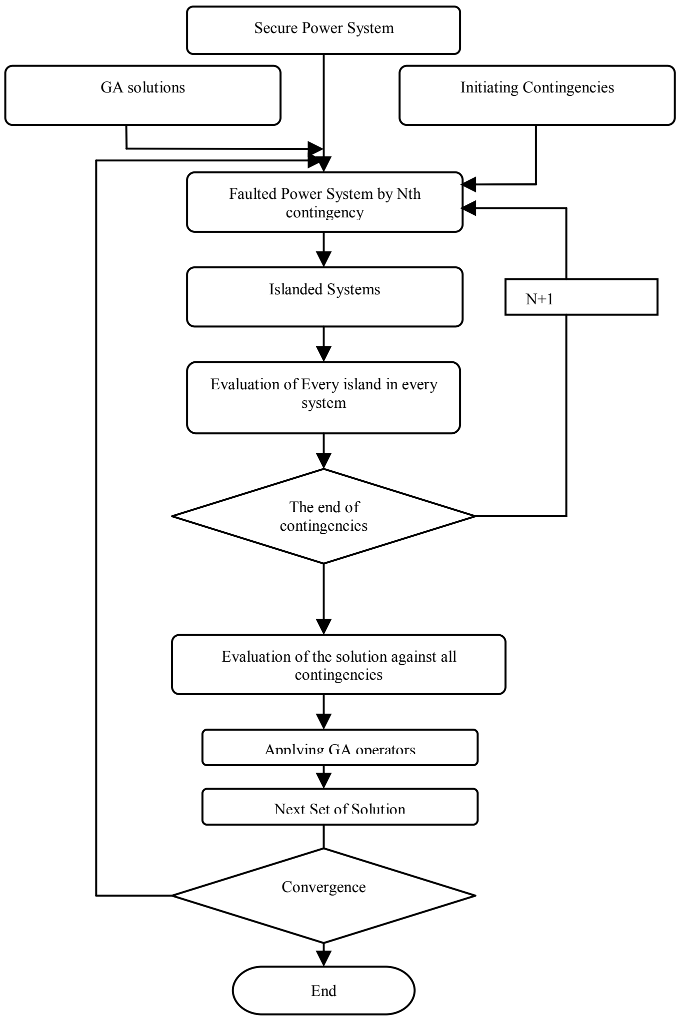

Figure 1 Algorithm Flowchart

VI. RESULT AND ANALYSIS

A. *Traditional scheme*

Based on the geographical distribution of the synchronous generators, the obvious boundaries of the islands and load

/generation balance requirement, the system can be islanded into six viable islands which can be seen in figure 3. Table 1 shows the amount of load shedding, required to maintain load / generation balance, in every island. At the stage of choosing the island boundaries, the issue of uncertainty appears. This is due to the fact that many combinations of the six mentioned islands can fulfill the requirement of the load /generation balance [16]. Practically, the islanding scheme designers analyze every island combination against some critical contingencies. However, this makes the best combination very difficult to reach in large power systems.

B. Optimized Islanding Scheme

GA criteria

Following the experience of many previous experiments, the GA operators were selected as follows: Number of generations = 150, Size of chromosomes = 35, Number of chromosomes =150 and Mutation rate =5%. It can be noticed from GA convergence on figure 2 that the best solution was found just before generation number 80 and after that all solution converged to the best one.

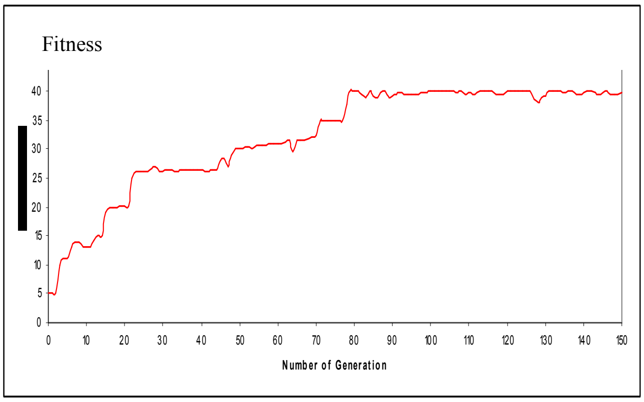

Figure 2 Genetic Algorithm Convergence

Table 1 The performance of the islands using Traditional method

	CO	Island	SC	TDR	LC
Traditional Islanding Scheme	1	1	Stable	8.5	%42.7
		2	Unstable	-	
		3	Stable	6.6	
		4	Stable	4.6	
		5	Stable	3.9	
		6	Stable	7.2	
	2	1	Stable	7.15	%34.8
		2	Stable	4.9	
		3	Stable	8.5	
		4	Unstable	-	
		5	Stable	4.7	
		6	Stable	8.4	
	3	1	Stable	8.91	%42.7
		2	Unstable	-	
		3	Stable	6.4	
		4	Stable	4.1	
		5	Stable	3.6	
		6	Stable	7.34	
	4	1	Stable	6.2	%22.4
		2	Stable	4.65	
		3	Stable	6.2	
		4	Stable	4.9	
		5	Unstable	-	
		6	Unstable	-	

GA outcome

Based on the islanding Algorithm result the optimized islanding formation can be shown in Figure 4. The algorithm was able to find five islands without any need of load shedding to maintain the generation/load balance equilibrium. Also the islands formation found by the algorithm can preserve more stable areas than that of the traditional one. It is interesting to notice that the solution obtained by the GA algorithm combined island 3 to island 4 and island 6 to 5. This is due to the fact that island 6 and island 3 can not survive following contingency 4 and contingency 2 respectively, as it can be seen on Table 2. Also, another reason for island number 3 to disappear is the large amount of load shedding required to maintain load/generation balance. Island number 2 has been divided into two islands. This happened in order to minimize the amount of the load collapse following contingency number one and number three. The boundaries of island number two have been adjusted to drop some loads to strengthen the island from the stability point of view. Based on the traditional scheme and the optimized scheme, Table 2 and Table 3 present the stability class (SC) and the time decay rate of every stable case (TDR) of every island against the assessing contingencies (CO). Also percentage of total load collapse (LC) after each contingency is presented on the tables. It can be noticed that, following the application of assessing the contingencies, the optimized scheme can maintain more serviced loads than that of traditional one. For instance, the optimized islanding scheme decreased the percentage of total load collapsed from 42.7 of the total load to 11.8 of the total load. This reduction in the collapsed area can be noticed as well following contingency number 3. It is worth noting that the optimized islanding scheme performs as good as the traditional scheme following the application of contingency 2 and 4. However it was perfectly able to preserve more areas following the application of contingency number 1 and 3. Also by observing the Time decay Rates and the amount of collapsed loads in both schemes in Table 2 and Table 3, it can be noticed that the algorithm made a decent compromise between stability and the amount of collapsed loads. In other words, the algorithm forms big island in order to avoid small islands that can not survive after some contingencies or require big amount of load shedding to survive, such as island number 6 and 3 in the traditional scheme. On the other hand, it goes towards the choice of small islands in order to preserve more stable area.

Table 2 The performance of the islands using Optimized method

	CO	Island	SC	TDR	LC
Optimized Islanding Scheme	1	1	Stable	8.5	%11.8
		2	Stable	6.3	
		3	Unstable	-	
		4	Stable	3.9	
		5	Stable	4.9	
	2	1	Stable	7.15	%34.8
		2	Stable	6.1	
		3	Stable	5.4	
		4	Unstable	-	
		5	Stable	3.1	
	3	1	Stable	8.91	%22.8
		2	Unstable	-	
		3	Stable	9.89	
		4	Stable	4.0	
		5	Stable	3.4	
	4	1	Stable	6.2	%22.4
		2	Stable	4.9	
		3	Stable	5.2	
		4	Stable	4.0	
		5	Unstable	-	

VII. CONCLUSION

By minimizing the amount of disrupted loads, the algorithm can play an important role to obtain the optimal islanding boundaries. Also, the Algorithm shows its robustness by obtaining islanding formation, which preserves more stable areas, with optimal amount of load shedding required to maintain load/generation balance. The comparison between the traditional and the optimized scheme shows that the optimized scheme performs as good as the traditional one in some contingencies and performs better in other contingencies. By using a list of assessing contingencies, the optimal islanding scheme becomes skewed towards these contingences. This makes the islanding scheme perform much better than the one designed for an open list of contingencies. Of course, the list of contingencies can be easily extended and is not in any way restricted to any particular limits. The algorithm makes good compromise between stability and the amount of collapsed loads. Finally, this algorithm will be more helpful in the case of complicated power systems where the natural boundaries of the islands are not obvious. This method will be applied to find an optimal islanding scheme for the Libyan Power System.

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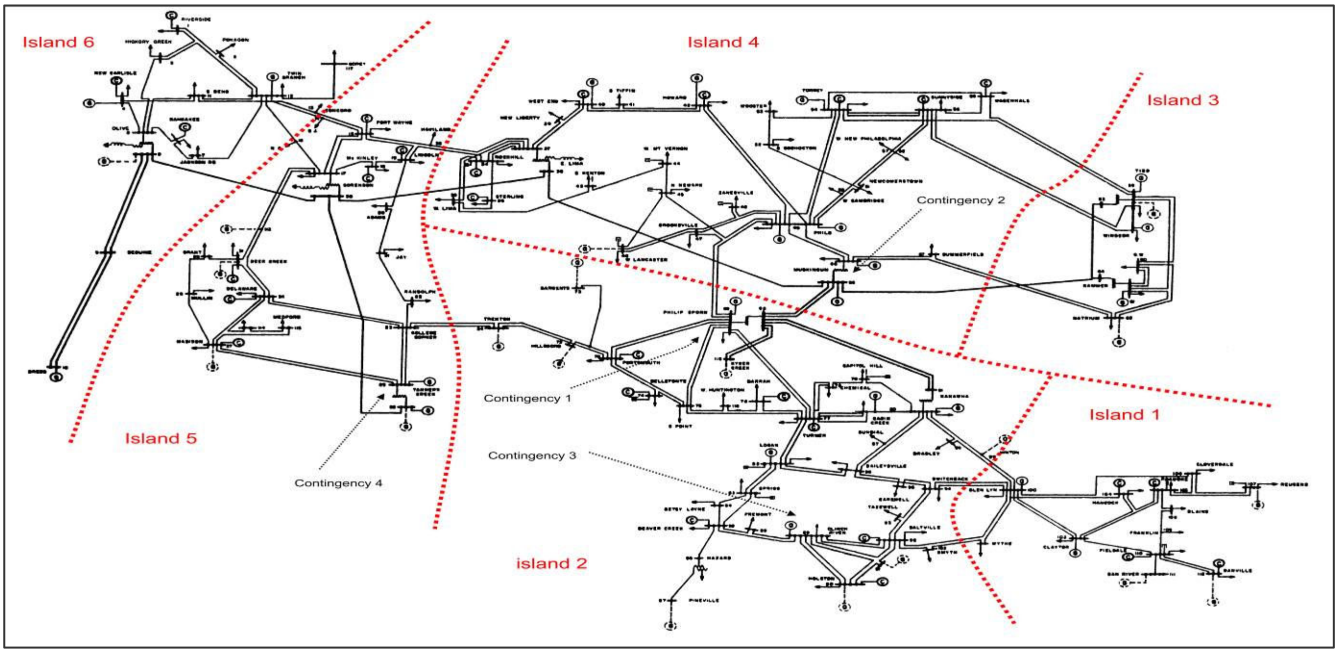

Figure 3 the performance of the islands using Traditional method

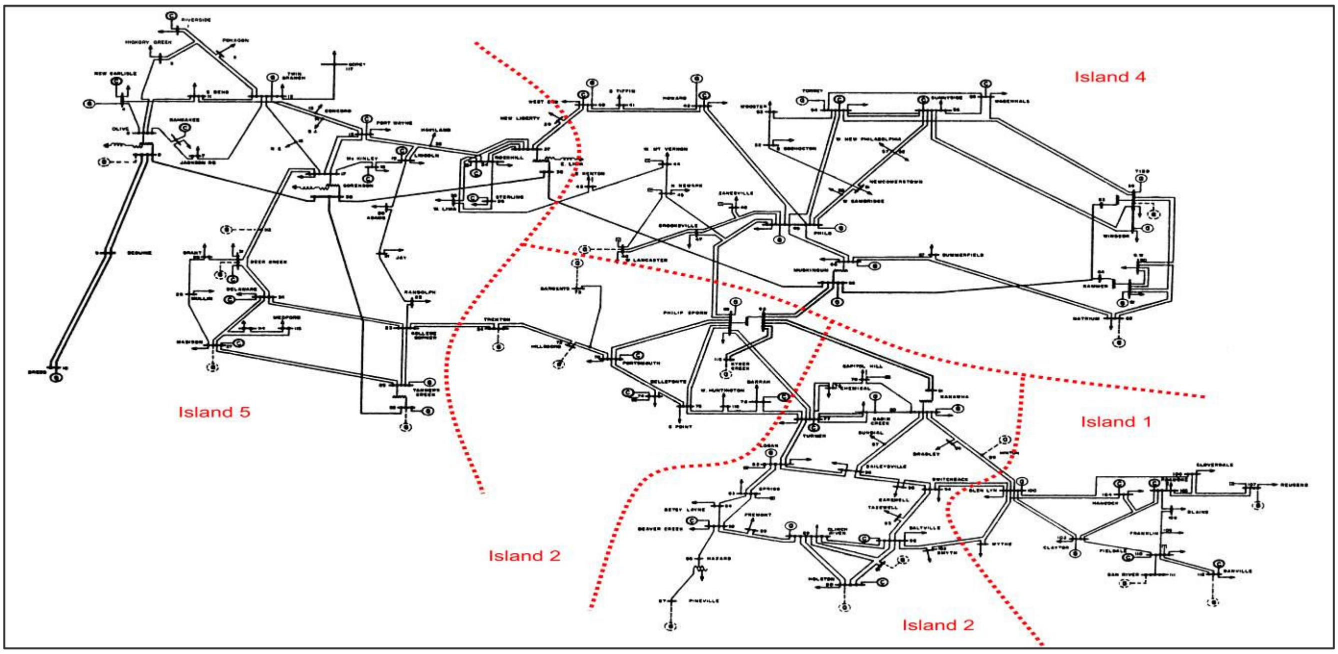

Figure 4 the performance of the islands using Optimized method

Paper 5

Analysis of the National 8th November 2003 Libyan Blackout

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Analysis of the National 8th November 2003 Libyan Blackout

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Abstract--**During last few years many blackouts have been experienced throughout the world. It seems that modern power systems are more exposed to major blackouts. Studying and analyzing real-world blackouts can play a very important role in the avoidance of such events. In this paper, the experience of 8th November Libyan blackout is presented. The blackout is studied and analyzed from a dynamic point of view. A comparison between the Libyan blackout and some international blackout is also introduced. Some suggestions and solutions are given to improve the security of the system during future major disturbances.**

I. INTRODUCTION

During the last few years, many different major blackouts have been experienced around the world. Apparently, the modern power systems are more exposed to major disturbances. The capability of power systems to respond promptly and properly to major disturbances has been decreasing. This might be due to the fact that the modern power systems are suffering from lack of investment or due to the degree of complicity and power system deregulation with its related non-mature rules.

Blackouts are consequences of various complicated phenomena and abnormal events. These complicated phenomena have to be studied carefully in order to gain sufficient knowledge of the blackout evolution. Lack of careful and detailed studies of power system transient events and protection practices during the disturbances can lead to reoccurrences of system collapse.

The main objective of a detailed study of blackouts is to clarify the reason causing the collapse by verifying the behavior and performance of the system components and identifying the phenomena affecting the system during the transient evolution. Another objective is to find some improvements in system performance on the basis of the dynamic response. In order to be able to do this, a well dynamic reconstruction should be performed [1].

In this paper, the 2003 Libyan blackout is fully reconstructed and analyzed. Performance of various power system protective schemes is analyzed. Power system stability, out-of-step protection, real power deficit, frequency relaying, and load shedding are among the aspects which are studied. Some suggestions and solutions are also recommended to decrease the chance of collapse reoccurrences. Improving the current protection scheme and revision of system relay settings are among the solutions considered to improve the system performance during abnormal events.

II. LIBYAN BLACKOUT

A. *Libyan Power System*

The power system in Libya consists of four geographically well-dispersed, totally interconnected major island systems. The transmission system is supplied via 55 generating plants. These are mainly simple-cycle gas-turbine plants and steam units with some diesel generators located in rural areas of the Libyan Desert. The prime fuels are natural gas, residual fuel oil and distillate. The ultra high voltage level is 400 kV with a total circuit length of 442 km, a high voltage transmission level of 220 kV, and a total circuit length of 13,472 km. The sub-transmission voltage level is 66 kV, with a total circuit length of 13,582 km. The distribution network's voltage level is 30 kV with a total circuit length of 6,237 km. Geographically; the Libyan Network is characterized by heavy loads with most of the generation located in the north. Light loads are located far away from the generation in the south [2].

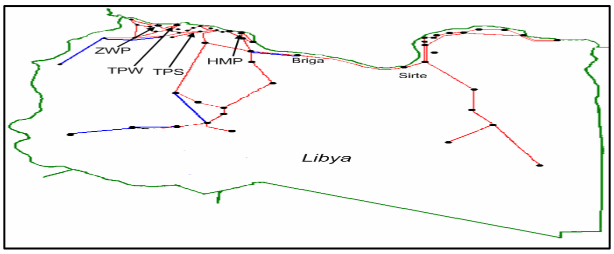

Figure 1 Libyan Power System

B. *Incident*

Four years ago, one of the most severe blackouts was experienced in Libya. The blackout, which affected 74.0% of the served loads, was triggered by a short circuit on the 220/30 KV transformer at the power production plant on the west side of the Libyan Power System (Tripoli West Plant). The Libyan power system was connected to the Egyptian power system with zero power exchange, and the power transfer from the West to the East was 30 MW. Before the occurrence of the fault, the power system was 69.6% loaded. The fault was cleared on the second zone.[3]

III. LIBYAN BLACKOUT VS INTRNATIONAL BLACKOUTS

In this section the Libyan blackout will be compared to some international blackouts, in terms of blackout severity, pre-fault conditions and Causes of the blackout. This comparison is based on ten well known blackouts including the Libyan blackout

A. Severity

To give general idea, Table (1) presents some facts and figures ten well known blackout.[4,5,6,7,8,9,10]

Table 1 Blackout information

Blackout	Customers without service	Lost load	Time duration	Affected populations
Brazil Mar. 11,1999	75.000.000	24.731	Up to 4 hours	%44.65
Iran Mar.31,2003	22.000.000	7.063	8 hours	%32.22
London Aug. 28 2003	410.000	724	0.62 hours	%5.43
Denmark & Sweden	4.000.000	6.550	5 hours	%27.86
Italy Sept. 28,2003	57.000.000	24.000	5 to 9 hours	%100.00
North America August 14,2003	50.000.000	61.800	16 to 192 hours	%15.51
Libya Nov 8 ,2003	4.000.000	1.876	0.5 to 6 hours	%70.0

In order to classify the severity of the Libyan Blackout among other blackouts, a new blackout Severity Index (SVI) was produced to give a sensible indication of system blackout severity.

A good severity index should include the effect of blackout on domestic and industrial demand. The first term (AP) on the severity index equation represents the percentage of the affected population within the domestic demand. The second term (UL/GC) is a ratio of unserved energy during the blackout period to the generation capacity of the whole network. So, the size of the unserved load and the duration of the blackout are included. Assuming the effect of blackout on the industry and the domesticity is equal; the severity index can be presented as following:

$$SVI = \sqrt{(AP)^2 + (UL/GC)^2}$$

Where AP is the percentage of affected population and the UL is amount of the unserved load in MWh and GC is the Base of the power. Based on the SVI, figure (2) presents the ten blackouts in severity order.

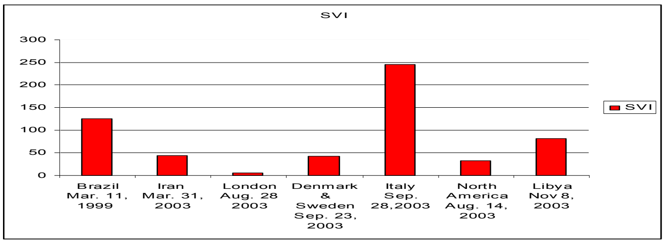

Figure 2 The Severity of Blackouts

B. Pre fault conditions & Causes of Blackouts

Table (2) summarizes the operation condition prior to the incident.

Table 2 blackouts Pre Fault conditions

Blackout	Pre fault conditions
Brazil Mar. 11,1999	Normal loading operation
Iran Mar.31,2003	High load level and some lines and power plant were out of services
London Aug. 28 2003	Two lines were out of services
Denmark & Sweden	Five transmission lines and four generation units were out of service
Italy Sept. 28,2003	High power transfer toward the country
North America August 14,2003	High temperature , High load level and some generation units and five capacitor bank were out of service
Libya Nov 8 ,2003	Normal loading operation

Table 3 Blackouts causes

Blackout	Initial cause	Supporting cause
Brazil Mar. 11,1999	Phase to ground fault as a result of lightning	Unexpected heavy loaded line tripped causing a stability problem
Iran Mar.31,2003	Unknown	Unknown
London Aug. 28 2003	Transformer Fault combined with Human Error of setting power	------
Denmark & Sweden	Internal valve fault in nuclear power plant	Double busbar fault lead to loss of two nuclear power plants
Italy Sept. 28,2003	Tree fault indirectly cause interconnection lines to trip	Heavy import of power
North America August	Significant reactive power deficiency combined with Tree	Software Problem at control centre causes the corrective action not to
Libya Nov 8 ,2003	Transformer fault	inadequate defense plan

Considering the fact presented on table 2 and 3, the incorrect protection elements was not only the initial cause in some blackouts but also a factor that accelerated the system outages in some others. Inadequate vegetation trimming which causes the contact of lines with trees was also one of the main causes that initiate the system outages. Although, the deficiencies in voltage stability and the supplying of reaction power were amongst the causes of one blackout, it played the main role in spreading the system outages in some others. The inadequate defense plan and lack of maintenance was reported in some cases. It is worthy of note that the absence of the sense of urgency before the situation degraded and inadequate training, information technology problem were reported in some cases.

IV. PRE FAULT CONDTIONS OF THE BLACKOUT

It is vital in this stage to produce an accurate steady state operating condition prior to the incident. This will help to produce an accurate dynamic model. The grid structure consists of two main areas, which are the western part of Libya (West) and the Eastern part of Libya (East). These two areas are connected through a long double line connection called the Sirte-Briga connection. The East is connected to the Egyptian network through a long, double circuit connection called the Tobruk-Salume connection. The operation condition prior to the incident can be summarized in the following numbers:

Available Power = 2536 MW

Load at the time of incident =2345Mw

Spinning reserve= 190 Mw

Sirte-Briga connection transient = 30 Mw through the East

Tobruk-Salume connection transient = 0 Mw

The situation prior to the incident presents two weak connections with risk of instability in case of severe contingencies.[3]

V. RECONSTRUCTED DYNAMIC PERFORMANCE

A. Overview

At 18.30 a severe disturbance occurred on 220Kv consisting of a three phase to ground fault on the 220/30 kV transformer at TPW power plant. The differential protection operated and gave a trip command but the circuit breaker on 220kV side did not respond due to control trip circuit failure. Therefore, distance protections at the second end of all the line connected to the busbar of TPW (busbar with the faulted transformer) operated in second zone and isolated the fault in about 380 ms leading to outage of main generation groups and 220Kv lines in Tripoli region.

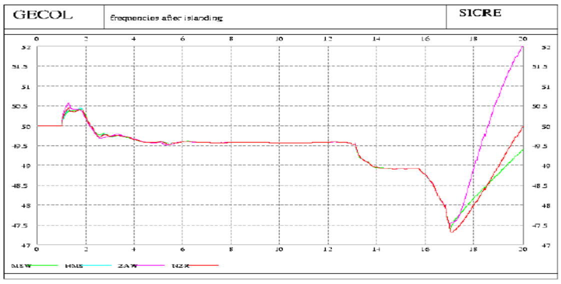

Figure 3 System frequencies during the blackout

B. Dynamic evolution

Generally, the dynamic performance of the network is presented in Figure 3. Figure 3 shows the frequencies of various bus bars following the occurrence of the fault. The dynamic evolution following the occurrence of the fault can be divided based on time into three periods.

1. First period (0-10s)

The first period, which is presented in Figure 4, starts with the fault occurrence which caused an immediate loss of four units in the west of Tripoli. This caused a loss of generation equal to 120 MW. At 0.8 s following the fault, three units were lost in the south of Tripoli, which caused a loss of generation equal to 237 MW. Two generation units were lost in the Zawia Plant at 5.5s. One second later, another unit in the same plant was lost. This period can be distinguished by a loss of generation amount equal to 848 MW. It is worthy of note at this stage that this type of fault is considered as extreme contingency, and it has very low probability of occurrence. It is noticeable that the frequency varies up to 49.6 Hz in this period for all the areas; such value is above the first stage of load shedding. It is also worthy of note that all units tripped in this period were due to auxiliary failures.

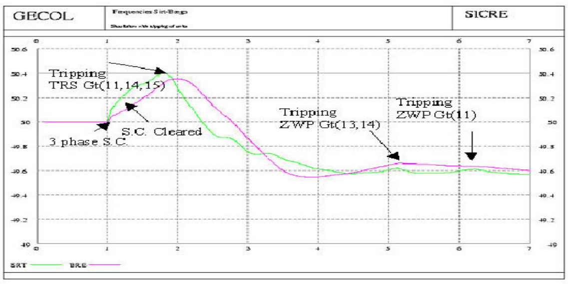

Figure 4 Sequence of events during the first stage

2. Second Period (7-12 s)

The second, which is presented in Figure 5, is characterized by a slow dynamic instability between the East and the West side of Libya. This kind of instability is due to a slow oscillation between the eastern and western generators with a slow increase of transfer power along a large distance.

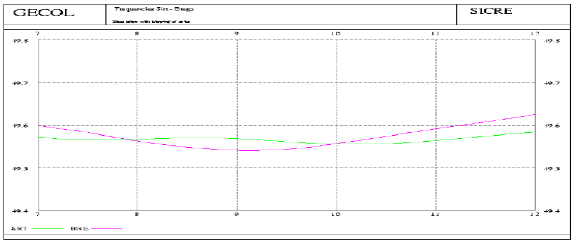

Figure 5 Sequence of events during the second stage

3. Third Period (12s- end)

It started with a fast drop in voltage in the interconnected line between the East and the West. This is due to a loss of synchronism between the East and the West. Therefore, the interconnection lines between the East and the West were tripped due to under voltage protection at 16.33s. At the same time, the Libyan Network was disconnected from the Egyptian Network. It is noticeable from Figure 6 that the eastern part of Libya survived; while the western part of Libya fell in a cascading manner by losing four units in the Homs plant. Two seconds following the separation of the East and the West of the network, the system dynamic, in terms of voltage and current related to Khoms machine , led to the under voltage and Over current generators protection near to the intervention settings. During this stage, two units in the Khoms plant were lost for reasons not completely clear. On the basis of event log, the most probable motivation is a “flame failure” for one and an unjustified intervention of the loss of excitation protection for the other. After these events, it is justified both for values and duration of the operation of the loss of excitation protections for the remaining two units.

Following the cascade tripping of Khoms generation units, the frequency drop was very fast with load shedding and system islanding. Such a stage is difficult to analyze because very small differences in the sequence of tripping and also defense plan activation can cause remaining generation units tripping for under frequency relay intervention. It reached the islanding stage at 48 Hz. Here, the islanding scheme played a decisive role at 19.34s where the network was split into three unstable islands. This led to a complete shutdown of the west.

As a general remark, in the case of rapid frequency decline, the proximity of the settings of under frequency relay for the units and islanding relay were not sufficiently able to assure good selectivity.

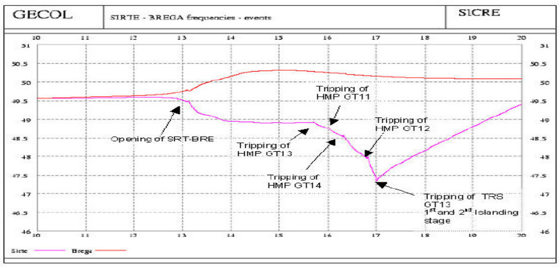

Figure 6 Sequence of events during the third stage

VI. CONCLUSION

The Libyan power system has been considerably developed during last years. Considerable number of high voltage transmission lines and substation are built. New power plants are added in order to match the increase in electrical power consumptions rate. However, due to the economical development, the increase electrical power consumption rate (ECR) is significantly high. This has emerged some difficulties in maintaining a balance between matching ECR and system security.

In this particular case , it is worthy of notice that the occurred transient stability problem was not due to electromechanical oscillation damping or fast transient stability due to short circuit of system fast variation in acceleration immediately after the consequence of units tripping. It was found that the instability is due to an angle opening between the West and the East where the maximum angle difference (about 90) was reached. The slow variation up to instability is largely dependent on the continuous operation of the frequency primary control trying to support the system until saturation of regulating energy in the most affected areas is reached. It is worth noting that the stability conditions for the Libyan system, characterized by a very long longitudinal structure, are influenced by many factors. These factors are frequency, primary control characteristics, the load typology, and power system stabilizer.

It is clear that the protection system of the generation units have plated a vital role to collapse the system. It seems that protection of the generation units have acted as apparatus protection rather than system protection. Proper protection system should be designed in a way to maintain the safe and operation of the power system as whole. They are not strictly related to protecting a specific apparatus being in danger due to its internal fault. In this sense the protection of generation units should be adjustment in away to keep the generation units connected to the grid as long as possible. It is worthy of note that the defense plan is useless if the generation unites can not operate in islanding situations

VII. RECOMMENDATIONS

Based on the above dynamic reconstruction and analysis the recommendations can be summarized in the following points:

1. The system should be monitored in terms of electromecanical phenomena.
2. The system should be reviewed in terms logic and setting for electrical supply of the auxiliaries of the gas turbine.
3. Co-ordination between grid and generation unit protections should be assured.
4. PSS gains and analysis of factors influencing the system stability should be reviewed.

5. The defense plan should be co-ordinated with the protective scheme and should be reviewed.
6. Tests on the thermal unit performance, to check their ability to face grid emergency conditions, should be conducted periodically.

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BIOGRAPHIES

Mahmud H. El-werfelli graduated from Al-fateh University (Tripoli- Libya) in Electrical Power Engineering in 2000 and obtained a Master's degree with distinction in 2005 from University of Newcastle upon Tyne in the same field. He worked for three years (2000-2003) as a planning engineer at General Electricity Company of Libya (GECOL). Currently, he is pursuing a PhD at University of Bath. The areas of interest are power system stability assessment and power system optimization problems using artificial intelligence.

Dr Rod Dunn received his B.Sc. and Ph.D. in electrical Engineering from the University of Bath in 1981 and 1984 respectively. He became a lecturer in computing and control at the University of Bath, where he is now a senior lecturer in the Power and Energy System Group.
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Miles Redfern received his BSc degree in Electrical Engineering from the University of Nottingham and his PhD degree from the University of Cambridge. His research topic was Signal Processing Techniques in Distance Protection Applications. He is Senior Lecturer with the Power and Energy Systems Group in the Department of Electronic and Electrical Engineering. His research interests include the Protection and Control of Electrical Power Systems, including embedded generation into networks and the location of Buried Utilities using Ground Penetrating Radar. He has written approximately 200 learned publications, most of which have been presented to international audiences.

James Brooks graduated from the University of Bath in 2006 with a B.Eng. in Electrical & Electronic Engineering. He is now pursuing a Ph.D. at the University of Bath. The areas of interest are in dynamic stability of system with a large penetration of renewable power, AI and simulation.

Paper 6

Design of a Transient Stability Scheme to Prevent Cascading Blackouts

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Design of a transient stability scheme to prevent cascading blackouts

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ABSTRACT

This paper presents a novel optimization technique of the settings for various emergency controls in an electrical power system. The goal of this technique is to prevent a cascading blackout and retrieve a new equilibrium operation point following a severe contingency. The main stabilizing actions are tripping generators together with load shedding. This problem is a complex mixed integer programming problem and it is very difficult to solve by ordinary optimization methods such as mathematical approaches. Genetic Algorithms are search algorithms based on the mechanics of natural selection and natural genetics, and are subject to survival of the fittest among string structures. Since the Genetic Algorithm approach is very successful at solving combinatorial optimization problems, it has been applied to solving the problem of cascading blackouts. A Genetic algorithm approach is used to find the optimal combination of generators and loads to be tripped in order to regain a new state of equilibrium in operation, and hence, to prevent the system from failing in this cascading manner. These solutions are evaluated by using the hybrid transient energy function, and the GA optimization technique is able to select the best solution. The two cases tested in order to assess the feasibility of this technique were the 14-bus IEEE network and the 20-machine, dynamically-reduced England Network. The results presented in this paper show that global or near-global optimum solutions can be ascertained within reasonable amounts of time by this new method.

Keywords: Cascading blackout, Genetic Algorithm, Power system stability.

1. INTRODUCTION

A major blackout is when a large area or a complete area of a power system collapses. The main cause of a major blackout is a succession of cascading failures that trip a transmission line or some generation units. A partial blackout may start with a severe fault which can cause a large variation in power flow and busbar voltage which, in turn, can cause the outage of generation units or transmission lines. This certainly causes imbalance in the demand for and generation of power. This sort of disturbance can be the beginning of a cascading blackout when it spreads uncontrollably in the power system. For economic reasons, most power systems operate at the minimum level required for stability. This makes the likelihood of converting a local blackout to a major blackout very high. This gives rise to the necessity of having an appropriate scheme to prevent a cascading blackout from becoming a major blackout. [1]
A variety of emergency controls are used to prevent cascading blackouts. These emergency controls are generator tripping, fast-valving, load shedding and excitation controls. According to Machowski [2], however, generators and load tripping are the most effective control. Due to this fact, generators and load tripping were considered as the main emergency controls in this technique.

Mathematical optimization methods have been used over the years for power system control problems. However, the solution for large-scale power systems is not easy to obtain by way of ordinary mathematical optimization methods. This is due to the fact that there are many uncertainties in power system problems such as complexity, size and geographical distribution. It is also very much preferred that the solution for power system be a global optimum solution. However; this can not be reached by mathematical methods. All of these factors therefore make it necessary to use a global search technique such as a genetic algorithm. [3]

2. GENETIC ALGORITHM

Genetic algorithm is sort of global search technique used in optimization problems by imitating the mechanisms of natural selection and genetics. An increasingly better approximation of the desired solution can be produced by applying the principal of survival of the fittest. In each generation, a new set of approximations of the solution are chosen according to fitness evaluation. The more 'fit' the approximation is, the higher likelihood it has to be selected to reproduce the next generation by using operators borrowed from natural genetics. Thus, the population of solutions is improved from one generation to the next with respect to their fitness evaluation. So, the least fit individuals are replaced with new offspring, which come from a previous generation, and which are better suited to the evolution of the environment.

Fig (1) shows the Genetic Algorithm Flowchart. In the first step, a set of possible random solutions is created. Every solution in the population (which can also be called an individual or a chromosome) is represented by a string of numbers that in turn represent the number of variables in the problem. Every variable is encoded in a suitable coding format (binary, integer, etc.).

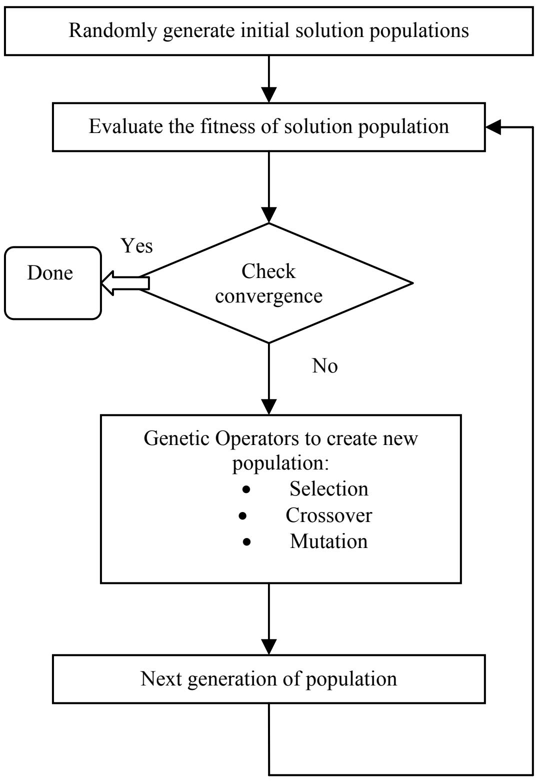

Fig (1) GA Flowchart

In the second step, every chromosome is applied to the fitness function (also called the objective function) to produce an output of fitness values. In accordance with their fitness values a probabilistic technique, such as the Roulette Wheel [4], is used to select the chromosomes that will contribute to the production of the next generation. The reason for this selection process is to keep the best and most fit chromosomes and increase the number of their offspring in the next generation, eliminating the least fit chromosome.

Having selected the parents, the crossover process then takes place by the exchange of genetic information between the selected chromosomes in order to form two new chromosomes (also referred to as children or offspring). This helps to avoid sticking in local optima.

In order to ensure that GA will search different zones of the search space, a mutation is applied by randomly selecting and changing the structure of a limited number of chromosomes. This process is repeated until all solutions converge into one optimum solution. [3]

3. STABILITY EVALUATION

For the simulation and stability evaluation, PSSENG (a *power system simulator*) [6] [7] was used to decide whether the system is stable or not since it is able to give clear assessments of the stability or instability of a system. The stability evaluation algorithm on PSSENG, which is based on time domain simulation output, can classify the simulation cases into the following categories:

1. Transiently unstable class
2. Oscillatory unstable class
3. Poorly damped stable class
4. Well damped stable class

For the two unstable classes the stability index is expressed by the severity index. Unstable cases with a detection of pole-slipping are classified in the transiently unstable class. The time taken for the system to pole-slip is used as the severity index in this class. Other unstable cases, without a detection of pole-slipping, are classified as being in the oscillatory unstable class. In this class, the calculation of the severity index is more complicated than in the previous one. The maximum magnitude of the rotor swing among all other generators is used as the main indicator of the severity index. Moreover, the frequency deviation and generator's active power are also used as auxiliary measurements in addition to the maximum rotor swing of the machine in order to give an accurate severity index. For the stable classes, the examination of the machine's rotor swings can give a decent indication of how stable the system is. The swing amplitudes can help to identify the extraction of the envelopes of the rotor swing curve for all machines. The swing of the envelopes can be approximately defined as an exponential function

$$S(t) = A\, e^{bt} \qquad (1)$$

The value of b is the system time decay which is used as an index for the degree of stability. If b is less than 12s the case is classified as being in the well damped stable class, or, if more than 12s, as being in the poorly damped stable class. [5]

4. PROBLEM FORMULATION

A severe fault may lead to blackouts in some local areas. Under certain circumstances, some small blackouts can lead to a major blackout. However, having a prepared scheme to resolve this problem can help to prevent such a transition. In order to produce this sort of scheme or solution, the production of the scheme should be treated as a constrained optimization problem. This will make the produced scheme meet the following requirements:

- As less power as possible will be tripped
- The system stability will be maintained

5. GENETIC ALGORITHM IMPLEMENTATION

5.1. Encoding

Before applying GA to an optimization problem, an encoding scheme must be decided upon. The encoding scheme should map all possible solutions of the problem into symbol strings (chromosomes).

Since the aim of our optimization problem is to minimize the amount of tripped power and tripped generations that can stabilize a power system network, the power of the generator will be considered in the structure of the chromosomes. Therefore every generator and load will be numbered from o to K, where K = number of generators + number of loads, and each chromosome is composed of S unique integers (S< K) with each integer corresponding to a certain generator or load. For instance, chromosome with a value of 5214309 means that the elements number 5, 2, 1, 4, 3 and 9 are the ones that might trip.

5.2. Selection

The Roulette Wheel technique is used as the probabilistic technique to select the chromosomes.

5.3. Crossover

In this Algorithm the Midpoint for exchanging information was applied.

5.4. Fitness Function

The fitness function provides an evaluation of the chromosomes' performance in the problem domain.

In this particular problem, the objective of the fitness function is to grade each chromosome with respect to the following aspects:

- <u>Stability class</u>: The stability evaluation algorithm will rank the chromosome according to its stability class, as mentioned in section III
- <u>Amount of generated and load power</u>: The chromosomes are evaluated in terms of the amount of tripped power they possess. The higher the amount of tripped power, the lower the rank of the chromosome.
- <u>System decay rate:</u> This index is used only for the two stable classes in order to specify the degree of stability. The lower the system decay rate, the higher the rank of the chromosome.
- <u>Severity Index:</u> This index is used only for the two unstable classes to specify the degree of instability. The higher the severity index the lower the rank of the chromosome.

The corresponding fitness function can be written as

$$FF = \begin{cases} SC + \dfrac{10}{1 + \sum_{i=1}^{N_L} MVI_{Li}} + \dfrac{1}{TDR} & \text{Stable case} \\ SC + \dfrac{10}{1 + \sum_{i=1}^{N_L} MVI_{Li}} + \dfrac{1}{SI} & \text{Unstable case} \end{cases} \tag{2}$$

Where: SC represents the stability class and is equal to 30 for well damped stable, 10 for poorly damped stable, 5 for oscillatory unstable, or 0 for transiently unstable. NL is the number of predetermined shedding loads, ΣMVI is the summation of the amount of load reductions, TDR is the time decay ratio and SI is the severity index.

6. NUMERICAL EXAMPLES

Two cases are presented in this paper. The first is that of the IEEE 14-bus network and the second case is that of the 20-machine dynamically-reduced England network. For both cases the applied faults were artificially chosen in order to drive the system into the region of instability.

6.1. IEEE 14-Bus Network

Following the experience of many previous experiments, the GA operators were selected as follows:

Number of generations = 50
Size of chromosomes = 8
Number of chromosomes =50
Mutation rate =5%

The 14-bus system is shown in Fig (2) below. The network consists of 11 loads, 2 generators and 3 synchronous condensers.

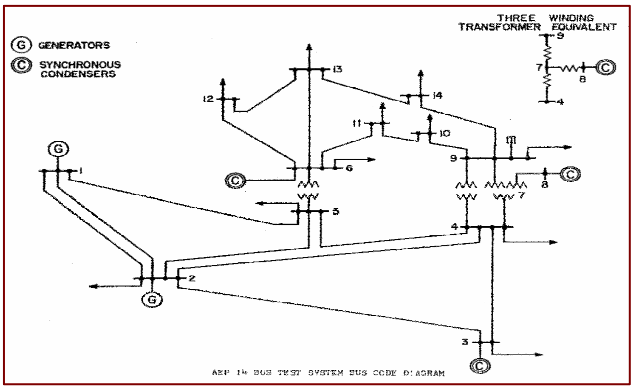

Fig (2) IEEE 14-bus Network

Two three-phase faults were applied on bus 2 and bus 5 at 0.2s while the system was fully loaded. Consequently, the line 2-5 switched out. The faults on bus 2 and bus 5 were cleared at 0.09s and 0.12s, respectively, after the contingency. This severe contingency succeeded at destabilizing the system as shown in Fig (3).

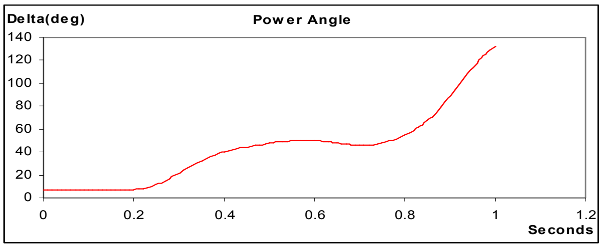

Fig (3) Rotor angle of G1 without any

Due to the simplicity of the IEEE 14-bus network, the stability control scheme can be achieved on the 5th generation as shown in Fig (4), which shows the convergence characteristics of the Genetic Algorithm.

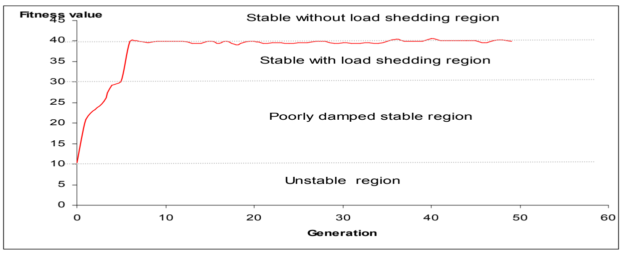

Fig (4a) GA average of solutions

As a result, the network can be stabilized, as shown in Fig (5), simply by tripping two synchronous condensers which are connected to bus 6 and 8 at 0.24s after the contingency.

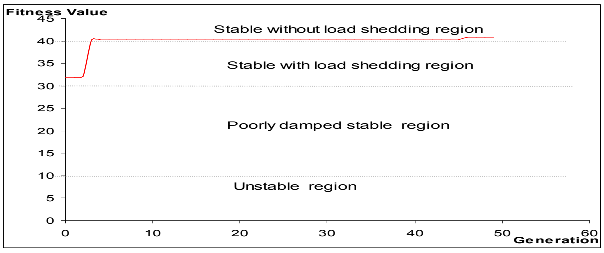

Fig (4b) GA highest Solutions

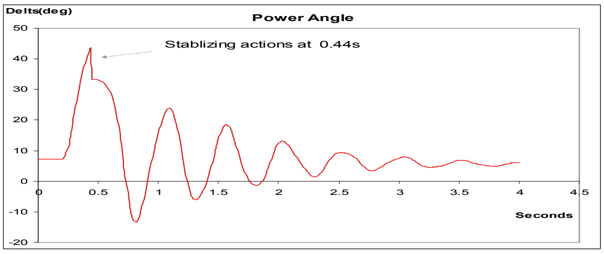

Fig (5) Rotor angle of G1 with control

Obviously, the algorithm proves its robustness by ascertaining a solution without any disruption to consumers, i.e., zero load shedding. The simulation results, shown in Fig (3) and Fig (5), illustrate the rotor angle of the main generator (the generator connected to bus 1).

6.2. 20-machine dynamically-reduced England Network

The GA operators were selected as follows:
Number of generations =75
Size of chromosomes = 10
Number of chromosomes =150
Mutation rate =5%
In the second numerical example, the algorithm was applied to the practical 20-machine, 100 bus dynamically-reduced England Network. The test system data are listed in [8] and are available from the authors. The model covers the main 400KV system and extends to cover some of the Scottish system.
This network is sufficiently complex, therefore making it amore than suitable model with which to prove the validity of the algorithm on a realistic power system network.
Two three-phase faults were applied on bus DIN04 and bus PENT4 at 0.2s while the system was fully loaded. Consequently, the line DIN04 - PENT4 switched out. The fault on bus DIN04 and bus PENT4 were cleared at 0.09s and 0.12s, respectively, after the contingency. This severe contingency did indeed manage to destabilize the system, as shown in Fig (6).

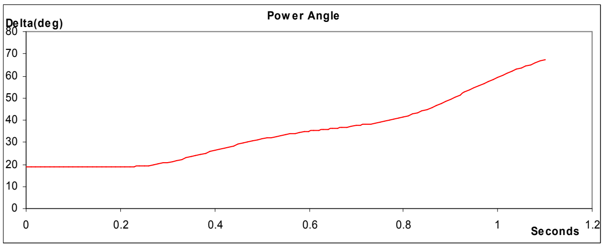

Fig (6) Rotor angle of Wylfa Generator without any control actions

It is noticeable from the convergence characteristics in Fig (7) that before the 9th generation, all solutions evolved toward the ultimate solution by means of load shedding. Due to the high capability of Genetic Algorithm to discover the solution space, however, the solutions evolved toward a better solution after the 9th generation, without any load shedding action, i.e., global minima.

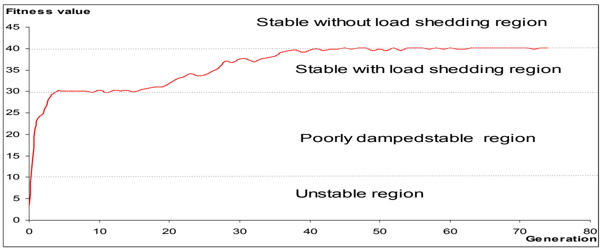

Fig (7a) GA average of solutions

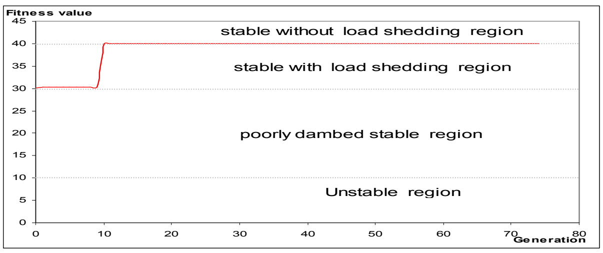

Fig (7b) GA highest Solutions

The global solution was to trip the following generators: DINORWIG, TRAWS and FIDDLWRS at 0.29s after the contingency. Fig (8) shows the rotor angle of the Wylfa generator, which is one of the most affected generators and can; consequently, give a good indication about the whole network.

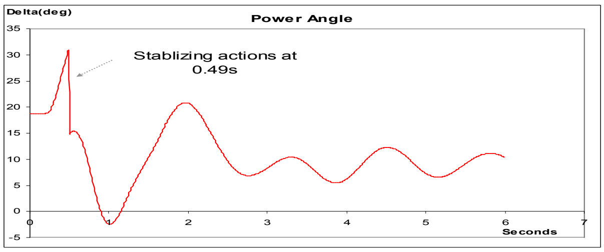

Fig (8) Rotor angle of Wylfa Generator with control actions

7. CONCLUSIONS

The objective of the optimization technique is to derive combinations of various controls to stabilize unstable transient events that could cause cascading blackouts. Using the new technique described here, Global or near global optimum solutions were obtained for both the case of the 14-bus network and the 20-machine dynamically-reduced England Network. Power systems can maintain their stability by a scheme of load and generator tripping.

In order to guarantee the robustness of the algorithm, the size of the population should be sufficiently large in order to allow discovery of the whole solution space.

This scheme can be enhanced to include more stabilizing actions, such as system islanding and fast valving, in order to convert this stabilizing scheme into a comprehensive defence plane.

Further work will focus on enhancing the scheme in terms of its speed so that the scheme can be used in an on-line environment.

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James Brooks graduated from the University of Bath in 2006 with a B.Eng. in Electrical & Electronic Engineering. He is now pursuing a Ph.D. at the University of Bath. The areas of interest are in dynamic stability of system with a large penetration of renewable power, AI and simulation.

Appendix C

Fix Power Mismatch Code

```python
def fix_mismatch(mismatch, power, min_limit, max_limit):
    """
    func fix_mismatch :: Real, [Real], [Real], [Real] -> [Real]

    change the total generated power by `mismatch`. Do this based upon current
    power of each generator taking into account its limits.
    Returns a list of new generator powers
    """

    assert(len(power) == len(min_limit) == len(max_limit))

    if mismatch == 0: return power

    # make sure we have capacity for mismatch
    assert sum(min_limit) < sum(power) + mismatch < sum(max_limit)

    done = [False for _ in range(len(power))]
    result = [0.0 for _ in range(len(power))]

    def find_limit_max(m):
        """find the index of the first generator that will
        be limited. or None """
        for n in range(len(done)):
            if (not done[n]) and (power[n] * m > max_limit[n]):
                return n
        return None

    def find_limit_min(m):
        """find the index of the first generator that will
        be limited. or None """
        for n in range(len(done)):
            if (not done[n]) and (power[n] * m < min_limit[n]):
                return n
        return None

    # deal with each generator that will be limited
    while True:
        assert(not all(done))

        total_gen = sum(power[i] for i in range(len(done)) if not done[i])
        assert(total_gen != 0)

        multiplier = 1.0 + (mismatch / total_gen)

        if mismatch < 0:
            idx_gen = find_limit_min(multiplier)
            if idx_gen is None: break

            # generator hit min limit: idx_gen
            result[idx_gen] = min_limit[idx_gen]
            mismatch -= result[idx_gen] - power[idx_gen]
            done[idx_gen] = True
        else:
            idx_gen = find_limit_max(multiplier)
            if idx_gen is None: break

            # generator hit max limit: idx_gen
            result[idx_gen] = max_limit[idx_gen]
            mismatch -= result[idx_gen] - power[idx_gen]
            done[idx_gen] = True

    # deal with all the other generators knowing that none of them will limit
    for idx in range(len(power)):
        if not done[idx]:
            result[idx] = power[idx] * multiplier
            mismatch -= result[idx] - power[idx]
            done[idx] = True

    # check nothing is out of limits
    for idx in range(len(power)):
        assert(min_limit[idx] <= power[idx] <= max_limit[idx])
    assert mismatch < 0.001
    assert all(done)
    return result
```

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