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Development of Probalistic Techniques for Network Assessment with Significant Wind Generation

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ABSTRACT

Due to increasing awareness of global warming and high energy costs, more electrical power is being generated by using renewable sources. However some of these sources are not as predictable as conventional generation and they also lack the ability to be dispatched in the same way.

The increase in the amount of wind power connected to transmission networks has been significant in some countries. But due to the stochastic nature of wind power, it is difficult to predict exactly how much power can be generated at any given time. This variable nature of wind power can cause line overloading and high voltage problems. To overcome these problems transmission networks can be upgraded but the cost of upgrade can make it uneconomical to accommodate wind power. Although wind turbines have very high availability rates, their ability to generate wind power depends on the wind speed. Most wind farms have capacity factors in the range of 30%-40%. The probability of wind farms operating at their rated output is quite low. As most techniques used to analyse new connections to transmission grids are based on conventional generation, these techniques can not be used for wind generation as they do not consider the variable nature of wind power. Probabilistic techniques have been used particularly in deregulated power systems where more than one company is involved in transmission system operation.

Ireland has very high potential for wind generation due to its geographical location. But its transmission network is weak in some of the areas suitable for wind generation and the network has a low level of interconnection with other networks. Having a high level of wind generation can create significant reliability problems. To

accommodate more wind generation, different analysis techniques have to be used to consider the variable nature of wind speed. The purpose of this research is to study and develop these probabilistic techniques and to investigate how these techniques can be used in Ireland to identify possible line overloading problems due to wind generation.

Different cases with wind generation where probabilistic methods can be used or have been used are studied. A small part of the Irish transmission network with a significant level of wind generation connected is chosen for probabilistic analysis. Deterministic approaches are generally used to investigate the performance of the network. In this study, it is shown how probabilistic techniques can be used to give a clear picture of wind generation effects on transmission line overloading. The Line Flow Sensitivity Factor (LFSF) method is used to speed up the probabilistic analysis. By using probabilistic techniques for different periods of the year, analysis based on line overloading and reverse power flow are carried out. The amount of Expected Energy Not Produced (EENP) is calculated for different periods of the year. Based on the EENP, it can be decided whether it is economical to upgrade the transmission network or to curtail wind power during high wind production periods.

DECLARATION

I certify that this thesis which I now submit for examination for the award of Master of Philosophy is entirely my own work and has not been taken from the work of others save and to the extent that such work has been cited and acknowledged within the text of my work.

This thesis was prepared according to the regulations for postgraduate study by research of the Dublin Institute of Technology and has not been submitted in whole or in part for an award in any other Institute or University.

The work reported on in this thesis conforms to the principles and requirements of the Institute's guidelines for ethics in research

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Asim Mumtaz

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1 INTRODUCTION

1.1 PROJECT BACKGROUND

Electricity can be generated from different sources, which can be divided in two groups: renewable and non-renewable. The most common generation sources are gas, coal/peat, crude oil, nuclear, hydro, wind, solar, biomass, energy from waste (EFW), wave or tidal. Most electricity is produced from non-renewable sources due to their easy availability. However, due to increasing awareness of global warming caused by the greenhouse effect and consequent obligations under the Kyoto Protocol, requirements have been established for different countries to reduce their CO_2 emission levels and to meet more of their electricity demand through renewable sources. Wind energy is one of the most significant renewable energy sources.

The variable nature of wind power creates difficulties when predicting the electrical output from wind generation and subsequent line flows in transmission lines. Regulatory changes in the power industry have led to more power generating companies gaining access to the transmission network. Safety and security of power supply is also a concern for transmission network operators. From an engineering perspective, it is necessary to apply appropriate techniques to investigate the effect of the variable output from wind farms on the network. This generally involves the application of load flow methods to solve the network and to determine the power flows in the elements of the network and the voltage at the network busses (nodes).

From a reliability point of view, any electrical system will consist of three main components [1]. These three main components are also referred to as hierarchical levels. Hierarchical Level One (HLI) relates to reliability analysis of power generation. Similarly HL II and HL III deal with transmission/distribution and consumption reliability analysis respectively. This identification of hierarchical levels is widely applied and is a useful basis for classifying the range and focus of reliability and adequacy analysis tasks.

HL I. Generation

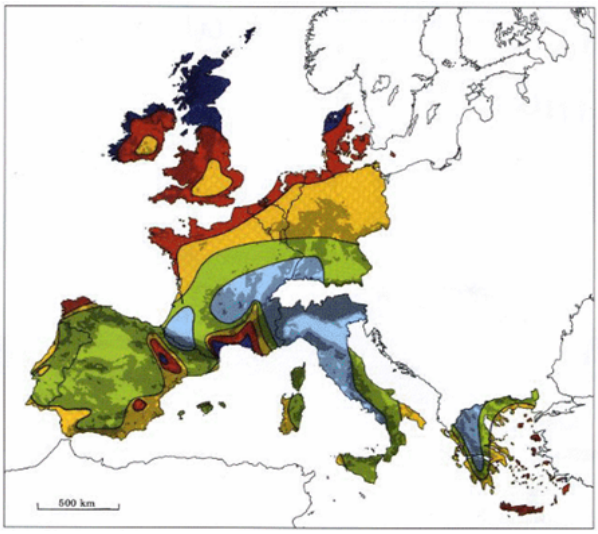
HL II. Transmission / Distribution

HL III . Consumption / Utilisation

This project considers the Hierarchical levels HL I and HL II.

1.2 THESIS OUTLINE

Ireland has one of the best wind energy resources in Europe as shown in Figure 1. However certain parts of the Irish power transmission network are not strong enough to support all available wind power without affecting reliability of power supply. As Ireland is an island and the Irish transmission network is connected only to Scotland, it does not have significant support from other transmission networks.



Colour	Open Plain	At Sea	Open Sea	Hills and Ridges
	>7.5	>8.5	>9.0	>11.5
	6.5 – 7.5	7.0 – 8.5	8.0 – 9.0	10.0 – 11.5
	5.5 – 6.5	6.0 – 7.0	7.0 – 8.0	8.5 – 11.5
	4.5 – 5.5	5.0 – 6.0	5.5 – 7.0	7.0 – 8.5
	<4.5	<5.0	<5.5	<7.0

Figure 1: EU Wind Speed Map

The overall objective of this research is to use probabilistic techniques for transmission network reliability analysis. A section of the network in the Cork/Kerry/Limerick region was selected as this is a part of the network where significant levels of wind generation has been installed or is planned. Figure 2 [18] shows the region concerned, together with the network busses involved. Transmission Buses used for analyses are shown in Appendix Table 10

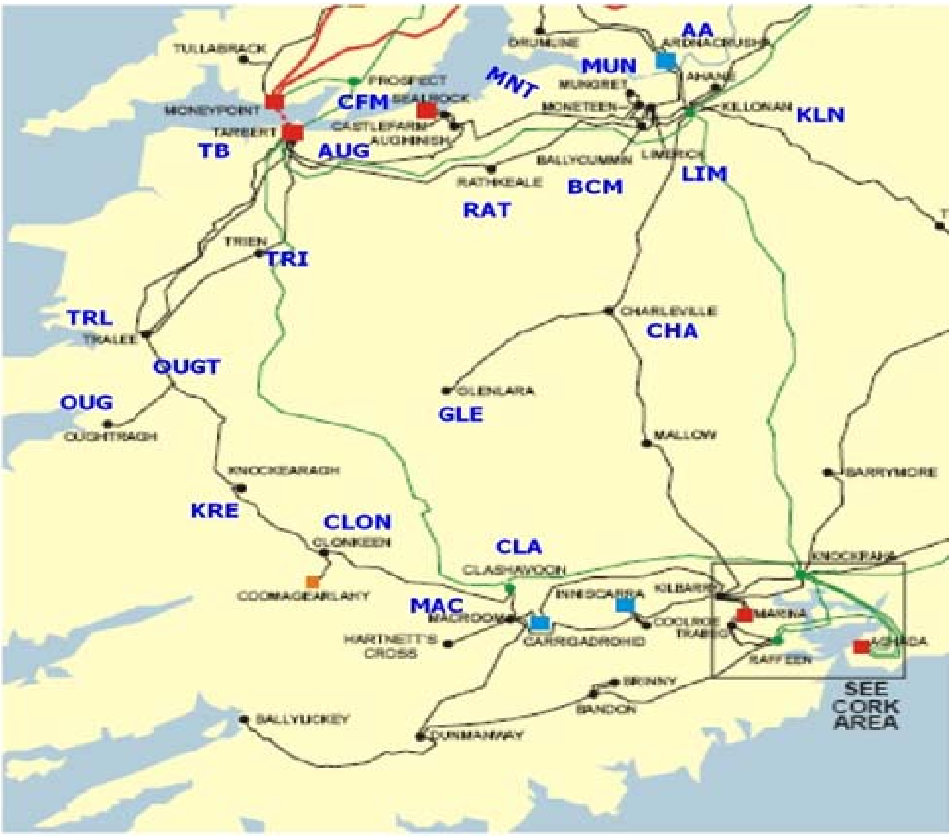


Figure 2: South Western Network

Due to the variable nature of wind power, it is difficult to predict the total generation capacity of any network with significant wind power. Wind power could be high in summer nights when demand is lowest and so creating reliability and generation adequacy problems (i.e. Sufficient generation capacity to meet demand). Similarly wind speed might not be high enough in winter when demand is high leading to reliability problems.

Regulatory changes in the power industry have led to more power generating companies gaining access to the transmission network, but the grid codes can limit the amount of wind power allowed to connect at particular points in the network. Grid codes can be restrictive for wind power since many of the grid codes are based on worst case analysis without any reflection on the probability of occurrence of the worst case. This can lead to very conservative design of the grid connection, which implies high cost. These costs will usually be borne by the wind turbine owner resulting in high energy costs. Planning and economic dispatch tools also have to be further developed to take the characteristics of wind power into consideration in order to optimise the system operation. The objective of this study is to develop such probabilistic techniques and apply them to the section of the network shown in Figure 2. The criteria and techniques first used in practical applications were all deterministically based and many of these criteria and techniques are still in use today. The essential weakness of deterministic criteria is that they do not respond to nor do they reflect the probabilistic or stochastic nature of system behaviour, of customer demands or of component failure.

As mentioned above, a part of the Irish transmission network was chosen for probabilistic analysis. The analysis focuses on the Clonkeen Group which is located in Co Kerry and consists of three wind farms:

- Commagearlahy (42 MW)
- Glanlee (30 MW)
- Coomacheo (42 MW)

The connection of the new wind farm at Coomacheo, its effect on the line flow in the Kerry region and the effects of the possible connection of future wind farms on the line flow in the Kerry and Limerick region was investigated. The possibility of the wind power curtailment at Coomacheo due to thermal overloading of particular transmission lines in the network was studied. In particular local lines would be overloaded should any critical lines in this region be out of service.

To investigate this, probabilistic analysis was used. This meant that the load flow programme has to be solved many times, which was expensive computationally. To speed up the load flow analysis, a line flow sensitivity factor method was used. The first method was based on change in bus phase angle due to change in the injected power at any other bus [2]. The line flow sensitivity factor (LFSF) could be obtained by taking the deviation of bus angles with respect to a change in power injection at any particular bus. The method used in this research was much simpler. By using the DC load flow program, the changes in transmission line flow could be calculated for any change in bus generation. Line flow before the changes in generation, line flow after the changes in generation and the total change in generation could be used to calculate the LFSF.

For the probabilistic analysis, the availability of wind farms or outage of wind turbine and critical transmission lines were also considered.

Recorded wind speed data was used as the basis for the analysis. To obtain multiple years of wind speed series from a single year of data, a first-order Markov chain method was used. Wind speed series generated by using the Markov method retained the same characteristics of the original wind data e.g. mean speed and standard deviation.

2 LITERATURE SURVEY

2.1 INTRODUCTION

This chapter presents the literature survey relating to the use of probabilistic and deterministic techniques for power transmission network analyses and the effects of increasing wind generation on transmission network performance. The first section highlights those papers that use probabilistic techniques for network assessment and compares that technique with deterministic methods. The second section deals with the use of probabilistic techniques in wind power generation modelling, specifically looking at the effects of wind generation on the transmission network with respect to line overloading and voltage performance. The third section presents an overview of the resources regarding wind generation in Ireland. The fourth section deals with different methods used to evaluate the sensitivity of transmission lines to changes in generation on any particular transmission bus. The final section deals with simulation of wind speed data for an extended period. Although the second section deals with the use of probabilistic techniques for wind generation, none of the above sections claim to be a complete review of the work in their specific areas.

2.2 PROBABILISTIC/DETERMINISTIC TECHNIQUES

Deterministic criteria and techniques have been developed and applied in power system planning and operation over many decades. Deterministic based approaches generally have very attractive characteristics such as simple implementation, straightforward understanding, and easy assessment and judgment by planners in relation to severe conditions like network outages and system peak load. Their essential weakness is that they cannot account for the stochastic nature of system behaviour, of customer demands, or of component failures [3]. However, the principles of some deterministic standards (e.g. 'N-1" criterion) must be recognized as attractive.

The application of probabilistic analysis to the power system load flow study was first proposed by Borkowa in 1974 [4]. Methodologies based on probability concepts can he extremely useful in assessing the performance of power systems [5]**.** They have been successfully applied to many areas including generation capacity planning, operating reserve assessment, distribution systems, etc. The proper measure of risk can only be achieved by recognizing the probabilistic nature of the relevant power system parameters. Different papers have suggested various methods to replace the existing deterministic techniques and some authors have also suggested the use of both probabilistic and deterministic techniques together to assess the reliability of power system. For example R. Billinton and Ran Mo [6] has used deterministic techniques to assess the effects of N-1 contingency on different buses with respect to EENS (Expected Energy Not Supplied). Probabilistic techniques have also been used to rank the contingency to show that some contingencies could have more serious implication for the system but for any given bus it may not have a significant effect. Similarly, the worst contingency for one bus may also not be the worst contingency for other buses. Deterministic and probabilistic techniques have also been used together with "system well being" evaluation method by L.S. Low and L. Goel [7]. This paper presents an approach to evaluate the composite system well-being indices under a security constrained well-being framework. The method is based on an algorithm that determines initially the healthy state probability based on a contingency listing that could be as detailed as computation limitations could tolerate. The concept of well-being indices is also applied to examine the effect of different scheduling of generation unit maintenance on the annualized system well-being indices.

Different reliability indices have been developed and used in power systems on the load side e.g. LOLE (Loss of Load Expectation) LOLC (Loss of Load Cost) and EENS (Expected Energy Not Supplied). In [8], Yuri Makarov has suggested the use of a reliability index on the generation side, EENP (Expected Energy Not Produced) and use of it with probabilistic techniques. By using EENP, "good" or "bad" locations for placing new generators can be identified. With the recent changes in electricity markets, the use of probabilistic techniques has increased. Probabilistic methods have also been used by M. Lammintausta to determine the ATC (Available Transmission Capacity) [9]. In an open market environment, ATC should not produce bottlenecks and limit free competition. Transmission capacity must be used as efficiently as possible, because it is possible that even if the deterministic transmission capacity during the limiting fault is not high enough for the peak load, it could be sufficient if the fault occurs during a lower load level. Probabilistic techniques are used by M. Lammintausta in [9] to find unused transmission capacity remaining in the transmission network.

Probabilistic techniques have also been used in small isolated power systems for reliability evaluation with the increase in renewable sources. In [10], R. Billinton and Karki used the system well-being model and probabilistic techniques are used to assess the effects of renewable sources e.g. wind energy and photovoltaic (PV). By using these techniques, it was demonstrated that although renewable energy sources may have significant lower system operating costs, addition of these sources alone can not always provide the desired level of system reliability. The addition of PV or wind energy must be accompanied by conventional units at the appropriate times to maintain the system reliability.

Probabilistic techniques can be time consuming and very slow. Pei Zhang in [11] and [12] present a method based on the concept of Cumulants and Gram-Charlier Expansion Theory to obtain probabilistic distribution functions of transmission line flows. The paper also compares with Monte Carlo simulation and shows that the model proposed in the paper is a significant improvement in reducing storage and that it is also able to accurately approximate the cumulative distribution function of transmission line flows.

2.3 PROBABILISTIC TECHNIQUES FOR WIND GENERATION

The use of renewable energy sources is increasing in modern electricity networks due to the increase in awareness of greenhouse effects of conventional generation and the limitations imposed on the reduction of CO_2 levels due to the Kyoto Protocol. Most renewable sources are stochastic in nature e.g. solar power and wind energy. Wind power is undoubtedly the most popular source of green electricity around the world. At the end of 2000, the wind energy capacity was 7.5 GW, of which 70% is installed in Europe. The European Wind Energy Association has a target of 60 GW of installed capacity by 2010 [13].

Most wind farms typically have capacity factors of 30% - 40%. Wind farms very rarely operate at high output levels but deterministic techniques often only consider the rated output in the planning and operation of transmission networks. With the use of probabilistic techniques, which also consider the stochastic nature of wind power, better network reliability analysis can be carried out. An example of this is described in [14] where a wind farm in Donegal (Ireland) was in the process of development and voltage rise problems were anticipated due to the weak transmission network in the area. Consequently, a voltage control system was installed on the wind farm. The initial analysis and grid connection design method applied by the grid company was based on a worst case scenario and during the two years of monitoring, the worst case did not occur and in fact it was not even close to the worst case scenario. Probabilistic techniques have been used by P. Jorgensen to assess the high voltage problem by considering the availability of wind turbines and using wind curtailment rather then expensive network upgrade by comparing the cost of wind curtailment and network upgrade [15]. A similar approach has also been used by J. Sveca in [16] to overcome transmission line congestion problems and to reduce the cost of network upgrades for new wind farm connection in Sweden.

Probabilistic techniques, based on Monte Carlo simulation have also been used by Armando M. Leite to evaluate reserve requirements of generating systems with considerable renewable energy sources by applying the LOLE method [13]. Due to the stochastic nature of the output from renewable energy sources, the analysis of a power system with significant renewable generation can be considerably more complicated, given the number of random variables introduced. Therefore, the determination of the required amount of system capacity to guarantee an adequate supply becomes an extremely important aspect of generating capacity expansion analysis. P. Bresesti, in [17] presents a probabilistic model for wind production representation and makes it possible to evaluate and calculate the reliability indices such as EENS, LOL and LOLE, especially for those cases in which many wind farms are installed.

2.4 WIND GENERATION IN IRELAND

Over the past 10 years, wind power generation in the Republic of Ireland has increased from 20MW to 793MW. In addition, contracts have been signed for 443.8MW of wind generation has signed contracts for connection to the network. Applications for a further

1295.2MW of wind generation have been processed as part of the Gate 2 [20] mechanism. Gate 1 and 2 refers to the transmission planning process in which wind farms are grouped based on their geographical location by TSO to speedup the application process. New applications to a capacity level of 3706MW of wind generation have been made for connection to the transmission and distribution network. At the beginning of 2007, 6737MW of total generation capacity was installed in the Republic of Ireland [Figures taken from eirgrid website in May 2007]. The peak demand for year 2006 was just over 5000MW [18].

From the above figures, it is obvious that Wind Energy Penetration (WEP) in Ireland will increase significantly in the coming years. Different security and economic issues affecting the transmission network, due to the large penetration of wind energy have been discussed in [19]. This paper considers the effects of increasing WEP with different levels of wind energy connected to the network i.e. 500MW, 1000MW, 1500MW, 2500MW and 3500MW with two different levels of peak load i.e. 5000MW and 6500MW. Another report published by ESB National Grid deals with the operational rules for wind curtailment [20]. This report looks into different rules that can be used for wind curtailment based on size of wind farms, connection dates of wind farms and Shedding Rota/Auction.

2.5 LINE FLOW SENSITIVITY FACTOR

As a means to investigate the impact of the connection of new generation on the line flows on a network, the Line Flow Sensitivity Factor (LFSF) is often used. The factor is defined for the flow on a particular line given an increase in generation at a particular bus and is the percentage of that increased generation which will flow on that line. Line Flow Sensitivity Factor (LFSF) has a number of uses in the power transmission network. In a new open market system, with separate pricing of generation and transmission, it is used to find the use of any transmission line by any power generation sources for transmission charges, system losses and congestion elimination [21] [22]. It has also been used to find the sensitivity of the transmission line to changes in generation at any particular bus. For probabilistic techniques, load flow calculation has to be carried out many times for better understanding of line overloading and reliability analyses. LFSF can help to speed up load flow analysis in such studies.

In [21], J. Yang proposed a power flow comparison method to find the use of each transmission line by any specific generator to accurately calculate the network usage charges. This method is based on removing the generation from the generator of interest and from the corresponding load in equal quantities and making this generator bus the swing bus. Then the difference in line flow on all transmission lines for the base case is determined. LFSF has also been used by E. Masaki in [22] for power flow tracing to eliminate line flow congestion. The LFSF method proposed by E. Masaki in [22] is based on the Jacobean matrix of power flow calculations. The line flow sensitivity matrix of the bus voltage is obtained by taking the derivatives of real and reactive line flow between two nodes.

In [23], D. Kirsehen suggested a method to overcome a similar problem as mentioned before e.g. usage of the network by each generator and system losses. This technique first identifies the buses which are reached by power produced by each generator. Then it determines the sets of buses supplied by the same generators, and then using the proportionality assumption, it calculates the contribution of each generator to the loads and flows. The method used for current studies is based on changes in the bus phase angle with respect to changes in bus power injections [2]. In this method, it in assumed that the power on the swing bus is equal to the sum of the injections of all the other buses and net perturbation of the swing bus is equal to the sum of the perturbations on all the other buses. By using this method the LFSF can be obtained for each transmission line to the changes in generated power at any particular bus.

2.6 SIMULATION OF WIND SPEED DATA

For probabilistic analysis of a power transmission network with a considerable amount of wind power connected, long term wind speed data is required. In most cases, wind data is not available for more than a couple of years. Different methods have been used previously to extend the data available. In [24] and [25], Ahmet D. Sahin and Zekai Sen used the Markov chain approach to wind speed modelling, based on the first and second order Markov chain approach. A model based on Autoregressive Moving Average (ARMA) has also been used in different papers [10], [26]. For both of these models, historical wind speed data is required for specific site, based on which, future hourly data are predicted using a time series model.

The ARMA model is based on two types of elements: auto-regressive and moving average. The auto-regressive element of the model considers the degree to which each hour of the data is dependent on previous values while the moving average element is a type of random walk where in each hour a number is chosen randomly and combined with previously chosen values.

In the Markov chain method, the wind speed data is divided into small states, covering the range of wind data. The probabilities of transition from one state to another are obtained and the matrix of transition probabilities is formed. The matrix based on the cumulative sum of each row is obtained. To generate the wind speed data, first the state of each wind speed value has to be obtained which can be generated by using a random number. Once the state of each value has been obtained, one more random number can be used to get the actual values of the wind speed.

2.7 CONCLUSION

From the literature survey, it was seen that deterministic approaches alone can not be used for complete analysis of transmission network in current deregulated markets with high wind power penetration. Deterministic analysis such as (N-1) contingency analysis can not accurately show the problems that wind generation can cause to the reliability and adequacy of power supply. Due to the stochastic nature of wind power, the deterministic approach should be combined with probabilistic analysis to accurately assess the economical cost to the transmission network due to wind generation. Although some papers have used this approach, they have only mainly been applied for voltage problems and not for transmission line overloading. Given that Ireland is facing a rapid increase in the connection of wind generation, and given the relatively weak transmission network, it is beneficial to consider alternative, probabilistic approaches in planning and assessing the transmission network. The LFSF method based on changes in generation at any particular bus and its effects on line flow can be used. To extrapolate multiple years of wind speed data from a single year of data, different methods were studied. The ARMA method has been used before and it does show some unusual characteristics for wind speed, for example sudden change in wind speed which in reality is less likely to happen. It is for this reason that the Markov method for wind data extrapolation is applied.

3 TRANSMISSION NETWORK AND WIND GENERATION

3.1 INTRODUCTION

This Chapter gives an overview of the development of the power generation industry and of the development of transmission networks. The typical techniques which have been applied to network analysis and planning are briefly discussed. The development of regulation in the industry is reviewed and the changes to de-regulated, market systems with greater competition are discussed. The problems which arose as a result of these market changes are identified. The role of both deterministic and probabilistic planning tools is discussed and a number of examples are presented. The method by which wind curtailment might be carried out in Ireland by the TSO is also discussed.

3.2 TRANSMISSIN NETWORK SECURITY AND RELAIBILITY

The first power generation and distribution networks were developed in New York in the 19^{th} century, mostly to supply power to street lighting and streetcars [27]. More and more small networks were constructed and they were mostly to supply populated areas. These networks were not interconnected and customers had the choice to buy electricity from any lines along a single pole. True competition existed in the electricity market. The electricity market was competitive but economically and technically unregulated. By the mid 1930's the electricity industry gradually changed from being unregulated to a regulated monopoly.

Electricity demand and generation increased steadily for the next few decades and it almost doubled every 10 years. Prices of electricity only increased with inflation or in some cases decreased in United States. As the prices were low, there was no need for competition in the electricity market.

3.2.1 DEREGULATED MARKET

During the 1970s, many factors affected the electricity supply industry. Inflation rates started to rise and then interest rates also increased. As many companies had invested in the electricity supply industry, high interest rates affected the industry's income. The energy crises in the mid 1970s also affected the prices of oil and gas and oil prices doubled. Oil was used for peak load electricity generation and in some cases for base load. Since fuel represents typically two third of the electricity delivering cost, the prices of electricity also increased sharply. These changes, together with the need to increase efficiency of the electricity market, prompted the deregulation of the power industry.

There are many players in the new deregulated markets. As compared to a regulated market, where a single company owns the transmission, generation and distribution facilities, in the new market environment, electricity could be generated by different companies and supplied by a third party through the transmission network owned by another company. Now customers have the choice to buy electricity from a company of their own choice. It has increased competition and reduced electricity prices. The selection of a supplier could be based on many factors: for example price, security of supply and transmission/distribution routing.

The main key players in electricity markets are consumers, aggregators, brokers, producers, and the regulator. Consumers are the end user of electricity; Aggregators represent a group of customers who purchase electricity in bulk; Brokers do not own their own generation facilities, but act as third party agents, Producers are actually the owners of generation facilities. Regulators are regulatory bodies looking after different issues affecting the electricity market.

The Irish transmission network has been owned and operated by ESB network since 1927. ESB is a state owned company established in 1927. EirGrid was established under the Irish and European laws including the European Communities (Internal Market in Electricity) Regulations, 2000 [28]. It took over the operation as Transmission System Operator (TSO) in 2006. All the physical assets of the transmission network were owned by the ESB and a Government White Paper [29] in March 2007 proposed to transfer ownership of all these assets to EirGrid to encourage competition. Irish transmission network consists of 6,500km overhead lines and more than 100 bulk substations.

After the deregulation of the Irish power industry, competition is less than anticipated. There are many factors effecting competition; The Irish electricity market is much smaller compared to mainland Europe or the British power industry. ESB operated on a breakeven basis since 1927 and there has been a low profit margin for new competitors who can buy bulk electricity from ESB and resell it to customers. A new electricity market (the all Island market) which operates in both the Republic of Ireland and in Northern Ireland commenced operation in November 2007.

3.2.2 SECURITY AND RELAIBILITY

Deregulation of the power industry encourages competition and efficient use of the transmission network, but it can also have some negative effects on reliability and security issues. Before deregulation, transmission, generation and distribution of power was managed by one company and in many cases reliability and security was given a high priority. Since deregulation, the power generation companies, grid companies and different load utilities are owned by different bodies. As these companies invest in different parts of the power system, their main concern is return on investment. For example if companies invested in power generation, their main concern would be generating more and more electricity to increase profit and reducing the power reserve capacity. Overhauling of equipment may also be reduced or postponed. Investment in the power grid may also be reduced.

In the planning of power systems with growth, additional generation capacity as well as enhanced transmission/distribution capacities needs to be delivered. An extremely important aspect is that reliability is interdependent with economics since increased investment is necessary to achieve increased reliability or even to maintain reliability at current and acceptable levels. It is therefore important to recognize that reliability and economics must be treated together in order to perform cost-benefit studies.

Reliability is a specific measure that describes the ability of a power system to perform its intended function. In the case of the power system, the primary function is to supply electrical energy to its end-customers. This is an important issue and power companies always try to ensure that the customer receives adequate and secure supplies within reasonable constraints. In a deregulated electrical power system that is disaggregated and privatized, there is a fundamental need for all parties to know the quality of the system sector for which they are responsible. Their benefits and interest are different; hence the information required by each party is different.

The power systems are divided into three different sections, as shown in Figure 3, on the basis of functionality and the way they relate to reliability [1]. The first level (HL I) relates to generation facilities, where total generation is compared to total load of power system. The second level (HL II) refers to integration of generation and transmission and it calculates the ability of power system to transport the generated energy to bulk load centers. The third level (HL III) refers to the complete system including distribution.

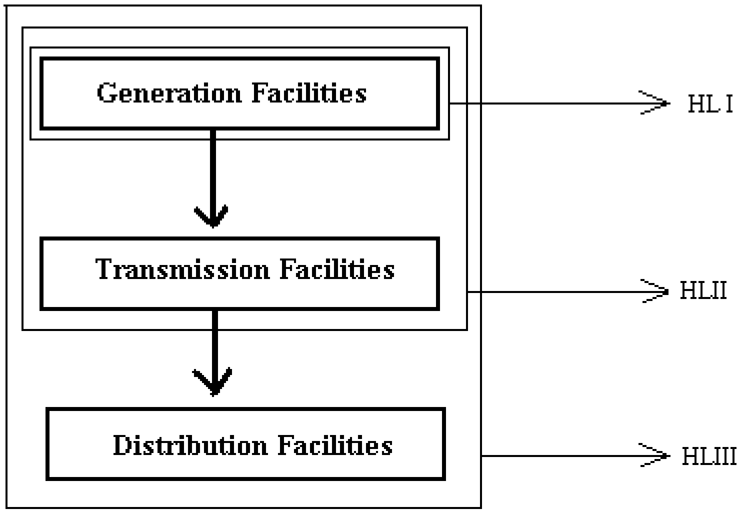


Figure 3: Hierarchical Levels Diagram of Power System

Different techniques have been used to assess the security and reliability of a power system. Deterministic techniques have been used from a long time due to their ease of understanding and implementation [1]. But there is a need to develop new techniques due to changes in system organization and the operational environment in which they now have to operate. The primary aspects in this regard are deregulation, privatization, restructuring and economic constraints. These techniques also have to change, not necessarily in terms of modelling developments, but more significantly in a way they are applied. Probabilistic techniques have been used from a long time; however the dominant practice is the use of deterministic techniques.

3.2.2.1 DETERMINISTIC TECHNIQUES

Most of the electrical power utilities use deterministic techniques to assess reliability as part of power system planning. The deterministic techniques usually applied in a composite system are designated as the (n-1) criterion, which means the system should be able to withstand the removal of any single component. This is obviously a contingency-case criterion. If the system can withstand this worst case, it would be expected to operate without violating system constraints or without the need to shed load under a specified set of contingencies. This means that there are buffer states that exist between the fully adequate state and the emergency state. Some power utilities also use (n-2) or (n-1-1) criterion by which it is intended that the system can withstand having any element on maintenance and any other out-of-service due to a failure.

The development of transmission and distribution systems was largely undertaken using deterministic planning and design criteria. Deterministic-based approaches generally have very attractive characteristics such as simple implementation, straightforward understanding and easy assessment and judgment by planners in relation to severe conditions like network outages and system peak load. Deterministic techniques are easy to use but the drawback of deterministic techniques is that they may result in the expensive design of power systems that can be under utilized except for the short period of high electricity demand. For a regulated market, deterministic criteria have served utilities companies well in the past, but one of the drawbacks of deterministic criteria is that they do not consider multiple events, and results in a power transmission network being underutilized. For a deregulated market, new techniques have to be developed to maximize the usage of the transmission network satisfying the basic reliability criterion.

3.2.2.2 PROBABILISTIC TECHNIQUES

Deterministic techniques have been used for a long time, but their lack of ability to measure the degree of success of any particular condition and likelihood of any contingency are their biggest deficiencies. Probabilistic based methodologies can be very useful to analyze the performance of the network. These techniques have been used for contingencies ranking, generation capacity planning, operating reserve assessment, and performance of the distribution system.

A system well-being model has been used in many papers [31-32]. The system well-being analysis method is based on probabilistic and deterministic techniques. This new framework reduces the gap between deterministic and probabilistic approaches by measuring the degree of success of any operating system state. In a system well-being analysis, the success states are further split into healthy and marginal states as shown in Figure 4 [31-32].

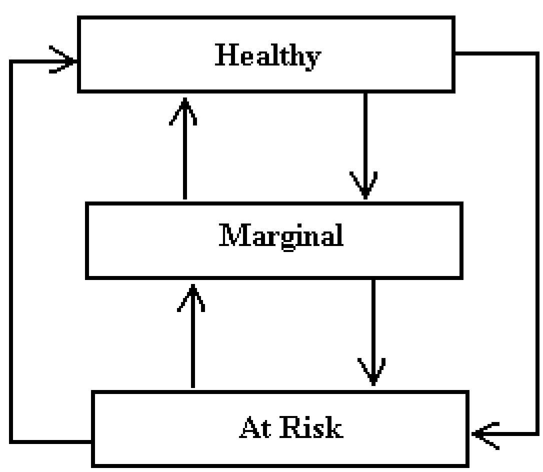


Figure 4: Composite System Operating States

Assessment techniques based on “Systems well-being” provide system designers and operators with intuitively interpretable system indices. The incorporation of deterministic criteria with probabilistic indices in monitoring the well-being of an electrical power system provides an opportunity for a more complete and comprehensive knowledge of the system. System performance is described by three different system well-being indices, namely healthy, marginal and at risk indices. These indices are really the probabilities of the system to reside in the various states, which is closely related to the deterministic criteria applied.

Different probability indices have been proposed and used, for example, EENP (Expected Energy Not Produced), EENS (Expected Energy Not Supplied), LOLE (Loss of Load Expectation), LOLP (Loss of Load Probability), Expected Load Curtailment (ELC), and Expected Duration of Load Curtailment (EDLC).

Probabilistic techniques can be used for contingency ranking. For example, many utilities use deterministic analysis methods like (n-1) and (n-1-1). By using probabilistic analysis, contingencies can be ranked on the bases of their effects on the network. It is possible in some (n-1) contingencies to have more severe effects on the transmission network than some other (n-1-1) contingencies. By using a contingency ranking method, the most severe contingency could be given priority over those cases in which more than one part of the transmission network is out of service but which might have less effect on power system operation.

3.2.2.3 MONTE CARLO METHOD

The Monte Carlo method is applied in various disciplines where there is a significant degree of uncertainty in the input data. It is typically applied to processes which are stochastic in nature and can give better results where deterministic techniques can not be used. As the inputs can vary, a large number of calculations are required to consider all possibilities. The algorithms might have to be repeated many times and that is why the Monte Carlo method is mostly used for computer-based calculation.

The Monte Carlo method has been used for wind generation analysis due to the stochastic nature of wind power. It has been used in [15] to find the total number of hours with high voltage to consider the option of disconnecting wind farms rather than costly grid reinforcements. It has also been used [16] to solve the bottleneck problems in the transmission system. The Monte Carlo approach was used to investigate the adequacy of the Irish electricity supply system as part of previous work at DIT [32].

For the current studies, the Monte Carlo method is used to take account of uncertainty in the wind data, availability of wind turbines, and critical transmission lines outage. By using deterministic techniques, analysis shows that transmission lines can become overloaded when wind farms are operated at rated output and critical transmission lines are out-of-service. But to consider the likelihood of high wind speeds occurrences, with all wind turbines operational and with one of the critical transmission lines being out-of-service, the Monte Carlo method is used. The availability of wind turbines is 96% based

Airtricity wind turbine data [40] and the figures for transmission lines availability are based on IEEE reliability test system [41].

3.3 WIND GENERATION AND CURTAILMENT

Probabilistic techniques are very important for transmission networks with high renewable energy generation, especially wind power. The stochastic nature of wind power makes probabilistic techniques favourable to use for transmission network analysis. For example in [16], probabilistic techniques have been used to overcome bottleneck problems in Sweden with high wind power. On the basis of this analysis, the numbers of hours with line overloading are determined and decisions are made about the investment required for grid reinforcement. A similar approach has also been used in [15] to calculate the number of hours with high voltage due to high wind power generation. On the basis of grid reinforcement and wind power curtailment, it is decided how much investment could be avoided. A comparison between probabilistic and deterministic techniques has also been made in [17]. It shows a (n-1) deterministic criterion applied to conventional power plant is not adequate to accurately evaluate wind farms sizing. The result confirms the combined probability of line unavailability near a wind farm with a local high wind production in very low.

3.3.1 WIND CURTAILMENT BY TSO IN IRELAND

Ireland has very high potential for wind generation and the installed capacity of wind generation is increasing every year. At the end of 2007, nearly 793 MW of wind generation is expected to be connected to the transmission network. More than 202 applications for wind farm connections totalling 3,706 MW have been received by the TSO and DSO [Figures taken from Eirgrid website in May 2007]. It is quite possible in near future that wind generation could be very high proportion of summer night valley generation.

For network security, wind power has to be curtailed in order to retain the necessary amount of conventional generation in operation to provide for all system services required to operate a safe and secure power system, including frequency and voltage control, reserve provision and ability to withstand disturbances. Wind power might also have to be curtailed due to line overloading in summer where line rating reduces due to increases in temperature. Wind generation could be more than the forecast generation based on the weather forecast. In this case, it may be necessary to curtail wind generation in order to manage the power system. In the case of loss of one or more transmission lines, wind generation might have to be curtailed. In [20], different methods have been proposed for wind curtailment. According to [20], only wind farms with more than 5MW of wind generation would be required to curtail their output if required. The following are the possible options for wind curtailments.

- Order of Size of generation capacity
- Equal Percentage Basis
- Market Generated
- Based on Connection Date
- Based on Shedding Rota

For example, using the order of size of generation capacity might involve reducing the output of the larger wind farms initially and then moving down to the smaller wind farms if additional curtailment is necessary. An alternative approach would involve the same percentage curtailment across all wind farms, irrespective of the size of the individual wind farms. The other methods might involve the allocation of curtailment based on a market outcome, or on the basis of the date of connection, or on a strict rota with all wind farms in a pre-defined sequence.

3.4 CONCLUSION

Power Transmission networks have gone through many changes since the beginning of the power industry. In the early days, power quality, reliability and access for all customers were important issues. After deregulation, competition and supply of electricity based on lower cost are also important factors. Use of renewable power resources is also increasing significantly. With these changes, the techniques used for power system analysis have to be developed. Deterministic techniques are in use for a long time. These techniques have served the power industry well. In the new deregulated market, probabilistic techniques have also showed their importance: for example how to make the maximum and efficient use of the transmission network. Decisions for network upgrade and investment in power systems in some cases are also based on probabilistic techniques. But these techniques also have some limitations. New techniques based on the combination of probabilistic and deterministic methods can help to solve transmission network problems.

4 WIND DATA MODELS

4.1 INTRODUCTION

For the analysis of power transmission networks with significant wind generation, it is important to have access to wind speed data, preferably for a number of years. Analysis of wind data helps to evaluate the wind farm site and can give a better understanding of the effects on the transmission network of wind generation. Even a small difference in the mean wind speed for a particular wind farm site can have significant impact on the overall wind generation from that wind farm. In most cases, only a few years of wind data is available. Therefore different wind data models are used in the evaluation of a wind farm site and on the analysis of the transmission network. The typical analysis methods are based on Weibull or Rayleigh probabilistic distributions, ARMA (Autoregressive Moving Average) method or the Markov Method. Each of these models uses the basic characteristics of available wind data to generate wind speed data of variable length. In this study, wind speed data from a location close to the eastern Cork/Kerry border is used in the analysis. The data obtained from local wind farm developer, consists of one full year average wind speed with a sample period of 10 minutes for the period of April 2005 to March 2006.

Different models are used in this chapter to generate wind speed profiles and the results of these models are compared against each other. Recorded wind data will be explored in terms of its statistical properties e.g. probabilistic distribution, weekly average, percentage change from mean speed etc. This data will be used as the basis for wind models and its properties will be compared against the generated wind data. As the recorded wind speed data is for every 10 minutes, it was converted to hourly wind data by taking every 6^{th} value. Initially the recorded wind data will be analyzed and the wind production data will be used to verify that the characteristics found in the wind speed are reflected in the wind production data.

4.2 WIND DATA ANALYSIS

4.2.1 MEAN WIND SPEED

The Mean wind speed and standard deviation for the recorded wind data used in this analysis is 7.7120m/s and 3.8359 m/s respectively. The maximum wind speed for this site is 23.56 m/s. Mean wind speed recorded for each month is shown in Figure 5. Wind speed significantly increases in winter as shown in Figure 5 for the months of October-January. Similarly the mean wind speed for the summer period is lower than annual average wind speed.

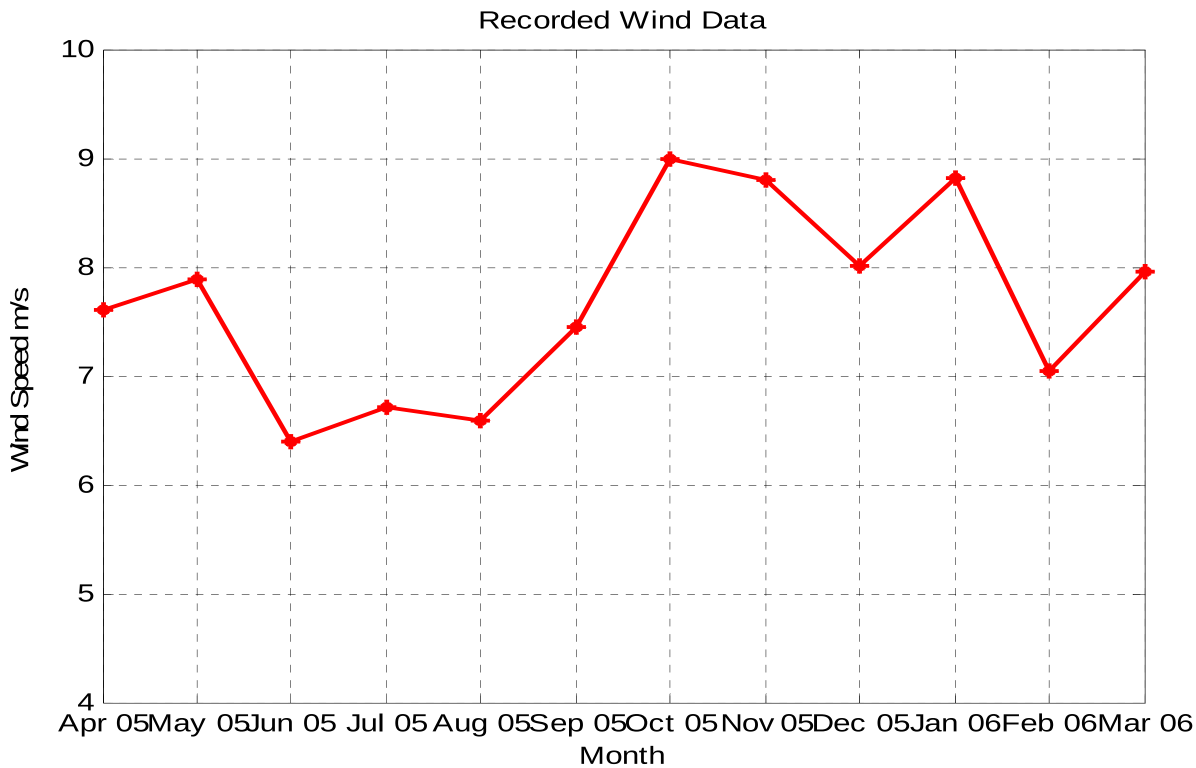


Figure 5: Monthly Average Wind Speed

Figure 6 shows the mean wind speed for each week. The winter period has higher mean speeds than the summer period.

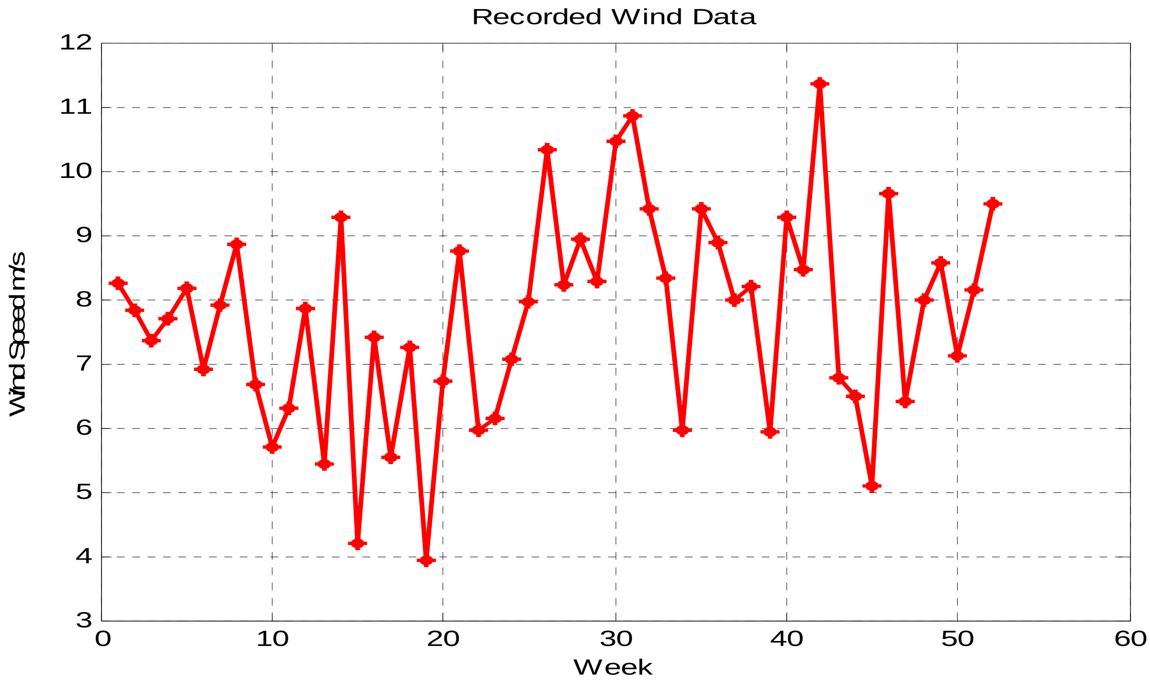


Figure 6: Weekly Average Wind Speed

4.2.2 VARIATION ANALYSIS

Figure 7 shows the percentage variation from the mean for each month. The variation from the mean for the summer period is -15% and for the winter period the deviation is 15%. In Ireland, the electricity consumption is much higher in winter than summer due to the cold weather. The rating of transmission lines also increases due to the lower daily temperature. As high wind speed conditions coincide with higher transmission line rating and higher demand, it is possible to accommodate more wind generation in the winter period than the summer period when the conditions are not as favourable.

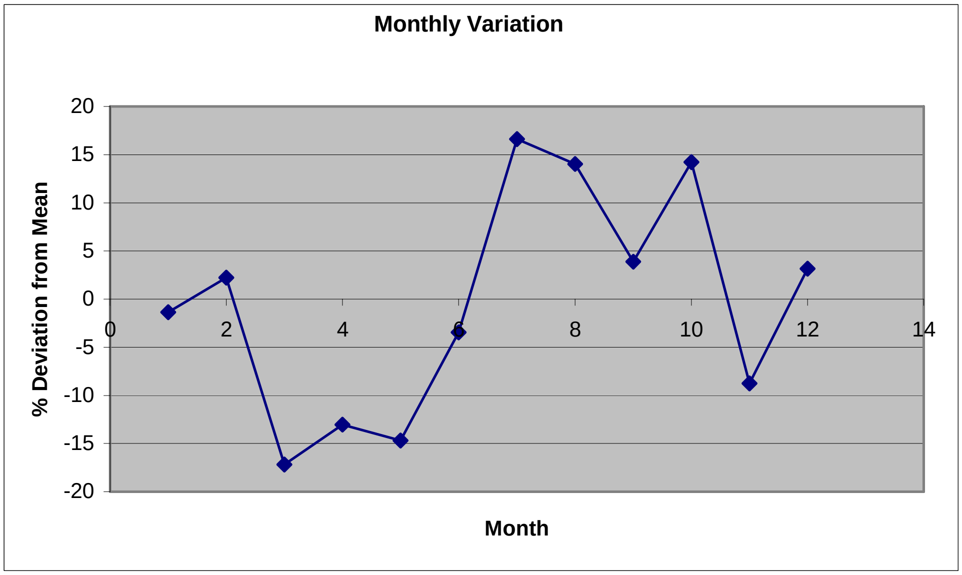


Figure 7: Percentage Variation from Mean Speed

One of the disadvantages of wind power is the sudden changes in wind speed. As it is much more likely that there can be more than one wind farm in a small part of a transmission network, a drop in wind speed over the short period of time could cause a significant change in power flow. These changes in power flow give rise to voltage fluctuation, causing problems of power quality. This problem was addressed in [33] by calculating the percentage change in wind power over different time horizons. As the recorded wind data is based on 10 minutes intervals, the percentage change in wind speed for three different time horizons (10 minutes, 1 hour, 2 hour) is plotted in Figure 8. Each of these time horizons is divided into small bins i.e. 0%-10%, 10%-20% etc. The frequency of occurrence for each bin is found. Clearly the majority of changes are small or zero when a 10 minutes time horizon is considered. As the time horizon increases to 1 and then 2 hours, there are more occurrences of large changes.

For the 10 minutes of time frame over the period of one year, the maximum percentage change is 40% and its frequency is very low. On the other hand, most of time, the changes in wind speed are less than 10%. For 1 hour and 2 hour frame, the occurrence of 10% and 20% change decrease as its less likely that the wind speed would remain the same for such a long period of time. The maximum percentage change for these two time frames is also higher than the 10 minutes time frame. (The percentage change value is determined by subtracting two consecutive values and then dividing it by the first value. This can lead to changes of greater than 100% in some cases as shown in Figure 8)

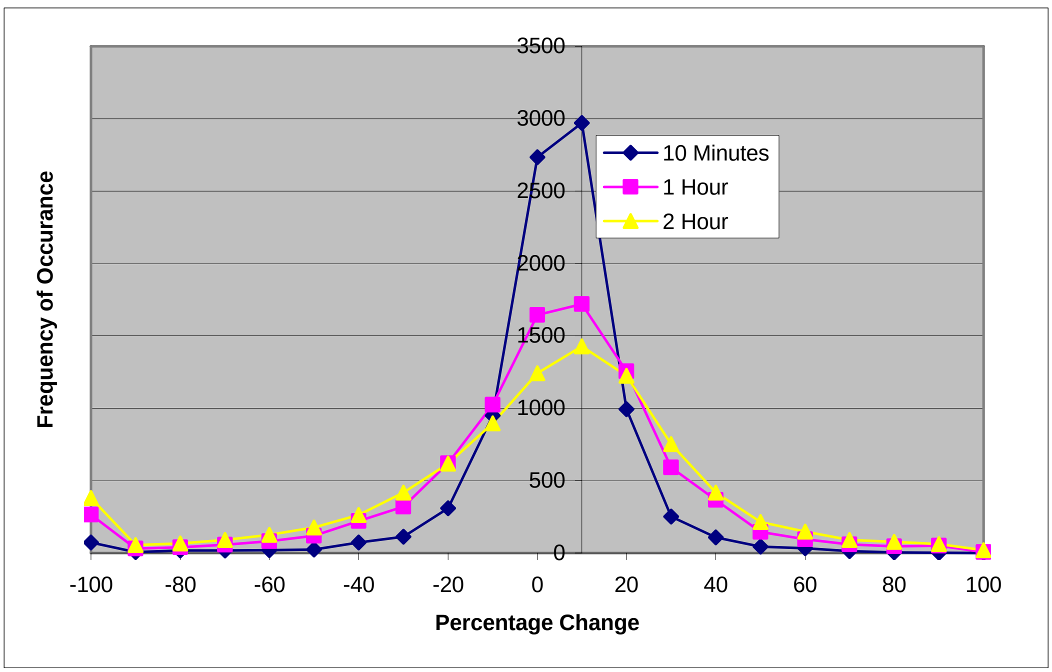


Figure 8: Plot of the Percentage Variation on Three Different Time Horizons for the Recorded Wind Data

4.3 WEIBULL AND RAYLEIGH DISTRIBUTION

Analysis of wind speed data and the ability to describe the variation in wind speed is very important for the wind industry. Wind farm developers need this information to estimate the cost and income from wind farms and wind turbine designers need the information to optimize their design of wind turbines to reduce the generation costs.

Annual wind speed data of any site would show that moderate and fresh winds are quite common while strong gale force winds are rare. Weibull and Rayleigh probability distributions are used to describe the wind variation of typical sites. The Weibull distribution has two parameters, k shape factor and c scale factor.

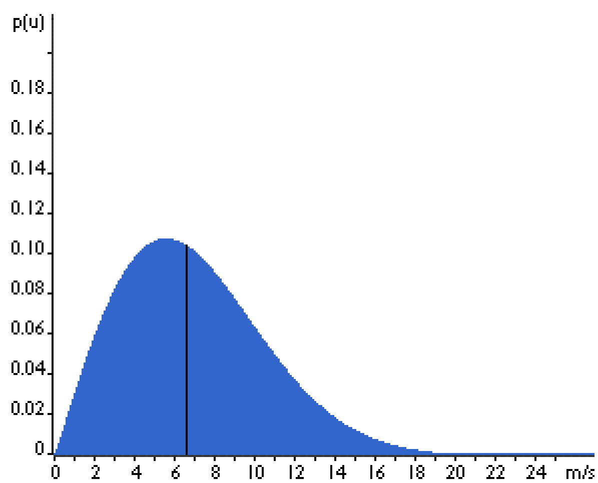


Figure 9: Probability Density Function

Figure 9 is an example of the Weibull probability distribution for a particular site which has a mean wind speed of 7 m/s, and the a shape of the curve is determined by a shape parameter of 2 (k=2). As it can be seen, the probability is high for wind speeds between

4 m/s to 8 m/s and it decreases for the high wind speed. The Weibull probability density is defined as:

$$p(U) = \left(\frac{k}{c}\right)\left(\frac{U}{c}\right)^{(k-1)} e^{-\left(\frac{U}{c}\right)^{k}} \tag{4.3.1}$$

Where k=Shape Factor

c=Scale Factor

The Cumulative Probabilistic function is:

$$F(U) = 1 - e^{-\left(\frac{U}{c}\right)^{k}}$$

The inverse function is given by:

$$U = (-\ln(1 - F(U))^{1/k} c \tag{4.3.2}$$

U is wind speed in m/s

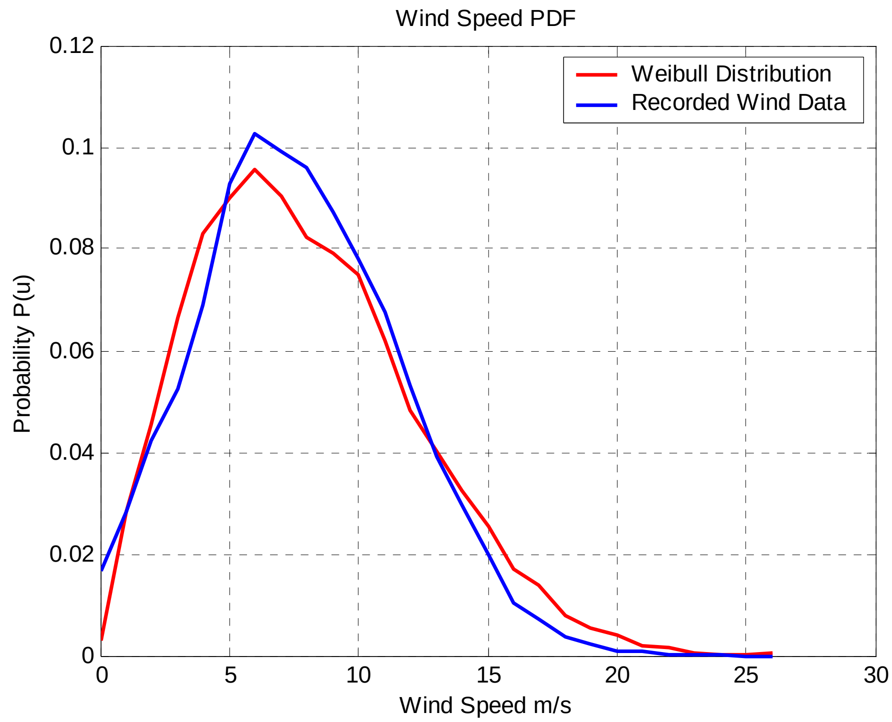


Figure 10: PDF for Recorded Wind Data and for Weibull Distribution

Figure 10 shows the comparison between the PDF (Probability Density Function) as recorded directly for the recorded wind data and the distribution of the data generated by Weibull Distribution. The k (Shape factor) and c (Scale factor) for the Weibull Distribution are 2 and 9 respectively.

If the shape parameter is exactly 2, the distribution is known as a Rayleigh distribution. Wind turbine manufacturers often give standard performance figures for their machines using the Rayleigh distribution.

$$p(U) = \frac{\pi}{2}\left(\frac{U}{\overline{U}^2}\right)e^{-\frac{\pi}{4}\left(\frac{U}{\overline{U}}\right)^2}$$

$$F(U) = 1 - e^{-\frac{\pi}{4}\left(\frac{U}{\overline{U}}\right)^2} \tag{4.3.2}$$

$$\overline{U} = c\Gamma\left(1 + \frac{1}{k}\right)$$

Γ is the Gamma function

U is Wind Speed

$\overline{U}$ =Average Wind Speed

k=Shape Factor

c=Scale Factor

$$\sigma_{\overline{U}}^2 = \overline{U^2}\left(\frac{\Gamma\left(1+2/k\right)}{\Gamma^2\left(1+1/k\right)} - 1\right)$$

Where $\overline{U}$ is mean speed

The inverse function is given by:

$$U = \sqrt{-\ln(1 - F(U)) * \frac{4}{\pi}}\,\overline{U} \tag{4.3.3}$$

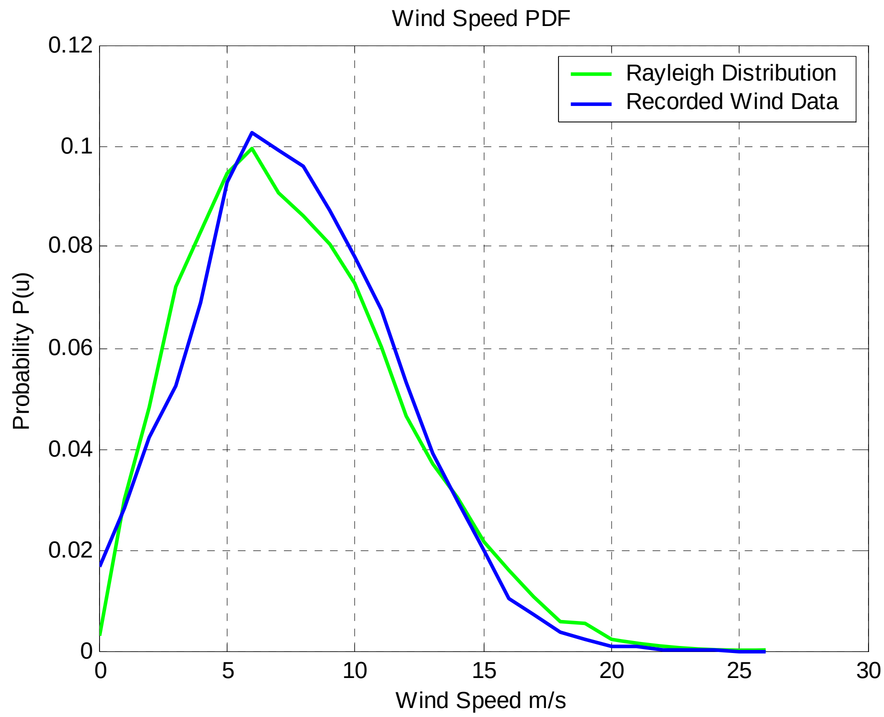


Figure 11: PDF for Recorded Wind Data and Rayleigh Distribution

Figure 11 shows the plot of Rayleigh Distribution with mean wind speed of 7.7215 m/s. Figure 12 shows the comparison between Rayleigh, Weibull distribution and PDF of the recorded wind data. It can be seen, PDF of Rayleigh and Weibull distribution is almost same as the PDF of recorded wind data.

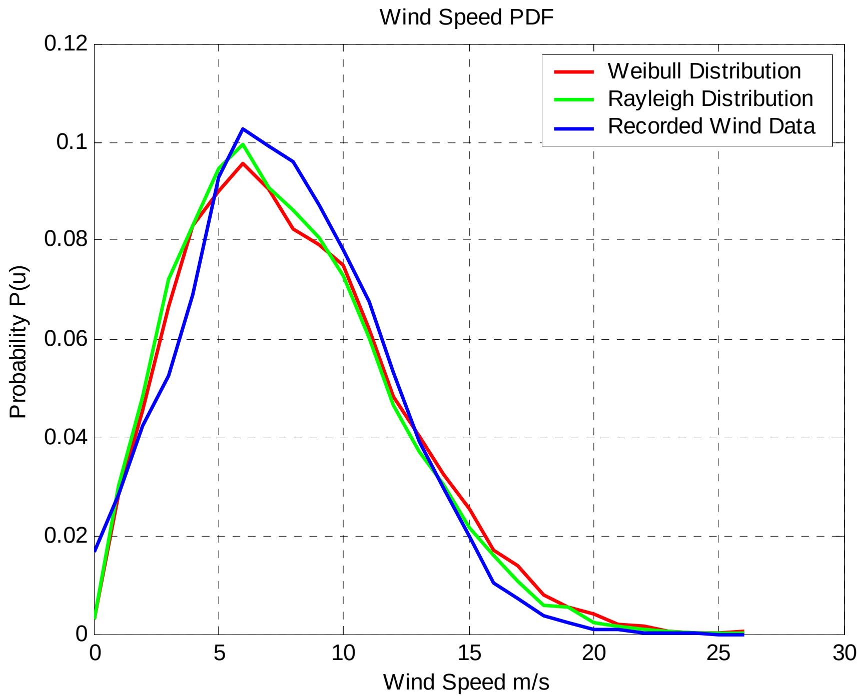


Figure 12: Rayleigh Distribution, Weibull Distribution and Recorded Wind Data

4.4 MARKOV'S CHAIN PROCESS

Markov's Chain is a discrete-time stochastic process. It is based on series of states of a system. At each time, these states may change from one to another state or may remain unchanged. The probability of transition from one to another state is determined in the Markov chain process. All these sequence of states must have the Markov property, which is all future state is conditionally independent of every prior state given the current state.

In the Markov process, the probability of being in a given state at given time can be obtained from information about the preceding conditions. The process is a system of moving from one state to another state. The order of Markov's chain process determines the number of time steps influencing the probability distribution of the present state. Many natural processes are considered as Markov processes.

The probability transition matrix is a tool for describing the Markov chain behavior. Each element of the matrix represents the probability of change from one state to another. The Markov chain modeling approach has frequently been used for the synthetic generation of rainfall data, stream flow data, and also to compare the performance of stochastic approaches for forecasting river water quality. However, very little work has been done on the synthetic generation of wind speed data using Markov chain models [24].

A first order Markov chain model is generally used for modeling and simulation of wind speed data. It is expected that a second order or higher Markov chain model can improve the results of synthetically generated wind speed data. The Markov chain of the first order is one for which each subsequent state depends only on the immediately preceding one. Markov chains of second or higher orders are the process in which the next state depends on two or more preceding ones [24]-[25].

Let X(t) be a stochastic process, possessing discrete states space S={1,2,3,…..k}. In general, for a given sequence of time points $t_1 < t_2 < ..... < t_{n-1} < t_n$ the conditional probabilities should be

$$\Pr\{X(t_n) = i_n \mid X(t_1 = i_1, ..., X(t_{n-1}) = i_{n-1}\} = \Pr\{X(t_n) = i_n \mid X(t_{n-1}) = i_{n-1}\} \qquad (4.4.1)$$

The conditional probabilities $\Pr\{X(t) = j \mid X(s) = i\} = Pij(s,t)$ are called transition probabilities of order r=t-s from state i to state j for all indices $0 \leq$ s<t, with $1 \leq i$ and $j \leq k$. They are denoted as the transition matrix P. For k states, the first order transition matrix P has a size of $k \times k$ and takes the form

$$P = \begin{bmatrix} P_{1,1} & P_{1,2} & \cdots & P_{1,k} \\ P_{2,1} & P_{2,2} & \cdots & P_{2,k} \\ . & . & . & . \\ . & . & . & . \\ . & . & . & . \\ P_{k,1} & P_{k,2} & \cdots & P_{k,k} \end{bmatrix} \quad (4.4.2)$$

The state probabilities at time t can be estimated from the relative frequencies of the k states. If n_{ij} is the number of transitions from state i to state j in the sequence of speed data, the maximum likelihood estimates of the transition probabilities is:

$$p_{ij} = n_{ij} / \sum_{j} n_{ij} \quad (4.4.3)$$

The transition probabilities of any state vary between 0 and 1. The summation of transition probabilities in a row equals one. Mathematically, it can be expressed as:

$$\sum_{j=1} p_{ij} = 1 \quad (4.4.4)$$

4.4.1 WIND SPEED DATA GENERATION

In order to calculate the Markov chain transitional probabilities, initially the wind speed variation domain is divided into many states. Such a state categorization may be rather arbitrary depending on the purpose of the analysis. In wind speed modelling, this depends on the average wind speed $\overline{V}$ and standard deviation S_υ. To increase the accuracy of the generated data, it is observed that, wind speed variation domain should be divided into more states. But for current studies, the first order Markov chain process is used and state categorizations are based on the standard deviation S_υ.

Let the number of states at each time instant be n. Hence, there will be n×n transition between two successive time instances. It is then possible to find the number of transition probabilities, p_{ij} from a state at time t to another state at time t + 1 and accordingly, the following, transition probability matrix $P_{t,t+1}$ can be prepared from observed wind speed data.

$$P = \begin{bmatrix} P_{11} & P_{12} & P_{13} & P_{14} & \cdots\cdots & P_{1n} \\ P_{21} & P_{22} & P_{23} & P_{24} & \cdots\cdots & P_{2n} \\ P_{31} & P_{32} & P_{33} & P_{34} & \cdots\cdots & P_{3n} \\ P_{41} & P_{42} & P_{43} & P_{44} & \cdots\cdots & P_{4n} \\ . & . & . & . & \cdots\cdots & . \\ . & . & . & . & \cdots\cdots & . \\ . & . & . & . & \cdots\cdots & . \\ . & . & . & . & \cdots\cdots & . \\ . & . & . & . & \cdots\cdots & . \\ P_{n1} & P_{n2} & P_{n3} & P_{n4} & \cdots\cdots & P_{nn} \end{bmatrix} \tag{4.4.5}$$

With the hourly wind speeds this matrix shows the transition probabilities, p_{ij}, of hourly wind speed in state *i* at hour t to state j at hour t+1 given n wind speed states. Any states probabilities vary between zero and one. On the other hand, the row summation in the transition matrix is equal to 1,

$$\sum_{j=1}^{n} p_{ij} = 1 \qquad (4.4.6)$$

The transition probability matrix elements constitute the relative frequency of the measured wind speed that fall into the *j* th state at time t+1 provided that it was at the *i* th state at the previous time step. Successive multiplications of $P_{t,t+1}$ matrix by itself, until a categorization of the transition probabilities, lead to the population transition probability matrix. It is this stable transition probabilility matrix that is used in the modelling of wind speed time series by the first-order Markov chain.

4.4.2 APPLICATION

The wind speed data used in this analysis is for the period of April 2005 to March 2006. The wind speed data has an interval of 10 minutes and it is converted to hourly wind data by taking every sixth value in the wind speed available. The maximum and mean wind speed $\overline{V}$ for this site is 23.73 m/s and 7.72 m/s respectively. The standard deviation S_υ is 3.8359 m/s. The recorded wind speed data for one week is plotted in Figure 13.

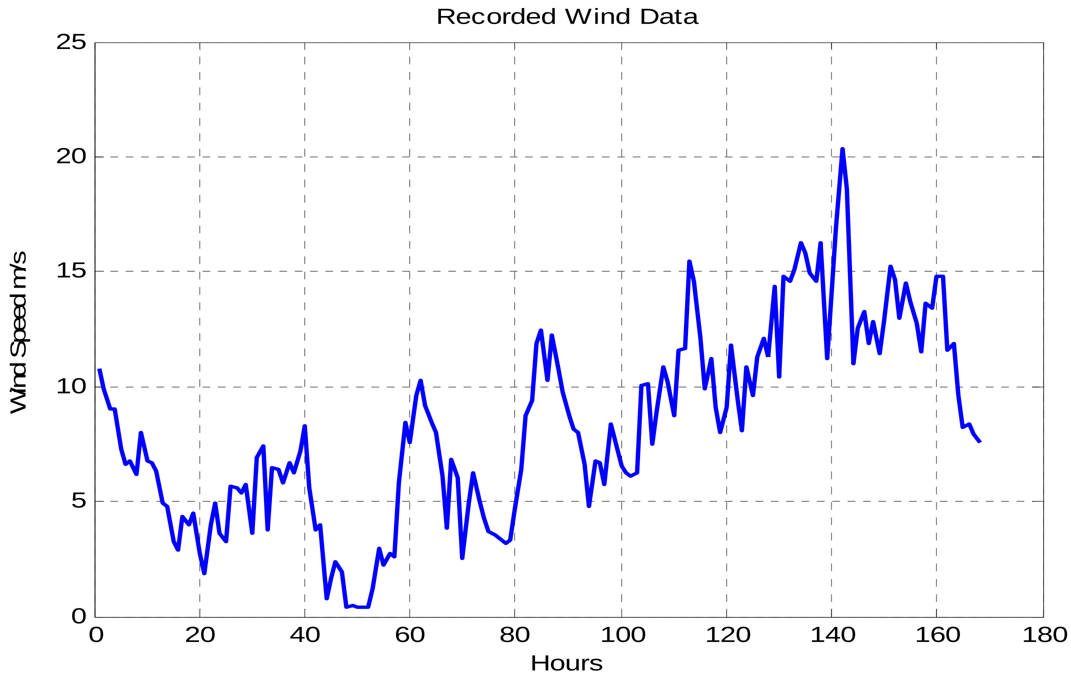


Figure 13: Plot of the Recorded Wind Speed

To generate the wind speed data by using Markov process that has same characteristic e.g. mean wind speed $\overline{V}$ and standard deviation S_{υ} as the original wind speed data, it is divided into seven different states based on standard deviation. The length of each state is equal to the S_{υ} of 3.8359. The transitional probabilities of each state are obtained and are shown in Mat A. It can be seen that if wind speed value is in first state i.e. between 0 and 3.8359 m/s, the probability of wind speed for next hour going to 2nd and 3rd state is 0.2337 and 0.0057 respectively. Similarly the probabilities of wind speed remaining in one state or going into next states are shown in Mat A.

$$\text{Mat A} = \begin{bmatrix} 0.7606 & 0.2337 & 0.0057 & 0 & 0 & 0 & 0 \\ 0.1051 & 0.7263 & 0.1635 & 0.0051 & 0 & 0 & 0 \\ 0.0026 & 0.1862 & 0.6741 & 0.1345 & 0.0026 & 0 & 0 \\ 0 & 0.0197 & 0.2912 & 0.6144 & 0.0722 & 0.0025 & 0 \\ 0 & 0 & 0.049 & 0.3874 & 0.5045 & 0.0541 & 0.0045 \\ 0 & 0 & 0 & 0.0370 & 0.5556 & 0.3704 & 0.0370 \\ 0 & 0 & 0 & 0 & 0 & 1.0000 & 0 \end{bmatrix} \quad (4.4.7)$$

The cumulative sum of each row can be obtained and is shown in Cum_Mat B.

$$\text{Cum\_mat B} = \begin{bmatrix} 0.7606 & 0.9943 & 1.0000 & 1.0000 & 1.0000 & 1.0000 & 1.0000 \\ 0.1051 & 0.8314 & 0.9949 & 1.0000 & 1.0000 & 1.0000 & 1.0000 \\ 0.0026 & 0.1888 & 0.8629 & 0.9974 & 1.0000 & 1.0000 & 1.0000 \\ 0 & 0.0197 & 0.3109 & 0.9253 & 0.9975 & 1.0000 & 1.0000 \\ 0 & 0 & 0.0495 & 0.4369 & 0.9414 & 0.9955 & 1.0000 \\ 0 & 0 & 0 & 0.0370 & 0.5926 & 0.9630 & 1.0000 \\ 0 & 0 & 0 & 0 & 0 & 1.0000 & 1.0000 \end{bmatrix} \quad (4.4.8)$$

If the recorded wind speed data is based on 10 minutes interval, then it is less likely that the wind speed would change from one state to another state. With the increase in the time period, the state transition probability increases, Mat A shows the transition probabilities for 10 minutes wind speed data and Cum_Mat B is the cumulative sum of each row.

$$\text{Mat A}=\begin{bmatrix} 0.8850 & 0.1147 & 0.0004 & 0 & 0 & 0 & 0 \\ 0.0524 & 0.8639 & 0.0835 & 0.0002 & 0 & 0 & 0 \\ 0.0001 & 0.0951 & 0.8293 & 0.0755 & 0.0001 & 0 & 0 \\ 0 & 0.0001 & 0.1730 & 0.7761 & 0.0505 & 0.0003 & 0 \\ 0 & 0 & 0.0007 & 0.2570 & 0.7058 & 0.0358 & 0.0007 \\ 0 & 0 & 0 & 0 & 0.3706 & 0.6014 & 0.0280 \\ 0 & 0 & 0 & 0 & 0.1250 & 0.5000 & 0.3750 \end{bmatrix} \quad (4.4.9)$$

$$\text{Cum\_MatB}=\begin{bmatrix} 0.8850 & 0.9996 & 1.0000 & 1.0000 & 1.0000 & 1.0000 & 1.0000 \\ 0.0524 & 0.9163 & 0.9998 & 1.0000 & 1.0000 & 1.0000 & 1.0000 \\ 0.0001 & 0.0952 & 0.9245 & 0.9999 & 1.0000 & 1.0000 & 1.0000 \\ 0 & 0.0001 & 0.1731 & 0.9492 & 0.9997 & 1.0000 & 1.0000 \\ 0 & 0 & 0.0007 & 0.2577 & 0.9635 & 0.9993 & 1.0000 \\ 0 & 0 & 0 & 0 & 0.3706 & 0.9720 & 1.0000 \\ 0 & 0 & 0 & 0 & 0.1250 & 0.6250 & 1.0000 \end{bmatrix} \quad (4.4.10)$$

Based on the initial wind speed state, a uniformly distributed random number can be generated. This random number values which are used in the model have a uniform probabilistic distribution and are between 0 and 1. It can be used to determine the state of next wind speed value. For example

Wind speed state=2^{nd}

Random number_1= 0.8916

Then the state of the wind speed value is 3^{rd}. To determine the actual value of wind speed, one more uniformly distributed random number is generated. This random number is multiplied by the length of states which is same for each state,

Random number _2=0.5023

State Wind Speed $=3.8359\times 0.5023=1.92677$

$$\text{Actual Wind Speed}=(3.8359\times 2)+1.92677$$

$$=9.598 \text{ m/s}$$

By using the Markov process, a multi year wind speed data record can be generated. For example, for 10 years of data, mean speed $\overline{V}$ and the standard deviation S_{υ} is 7.76m/s and 4.05 respectively. The difference between these values for the recorded and generated data by using Markov method is negligible. The PDF of Markov data and recorded data is shown in Figure 14.

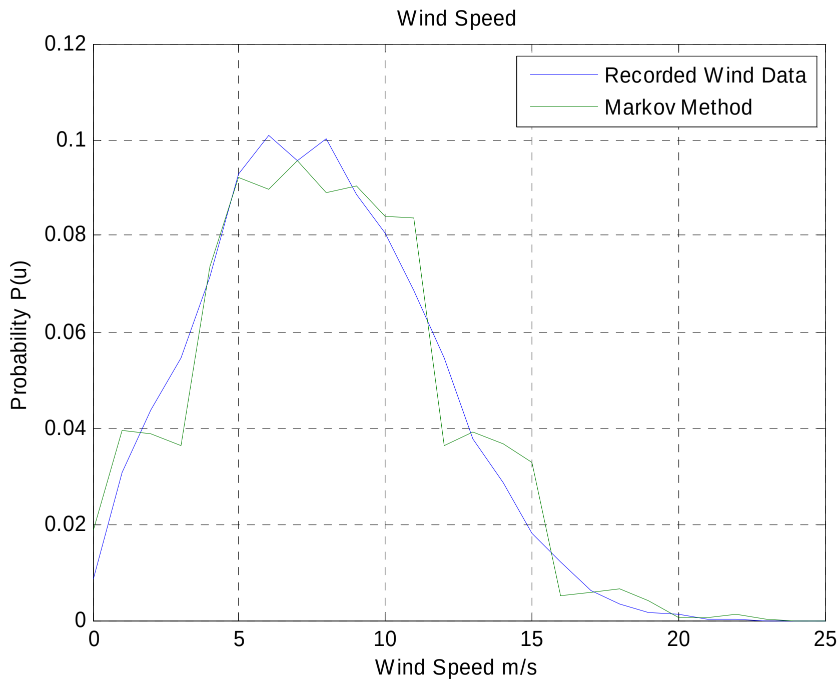


Figure 14: Probability Density Function of Markov and Recorded Data

4.5 AUTOREGRESIVE MOVING AVERAGE (ARMA)

An ARMA model consists of two elements: AutoRegressive (AR) and MA (Moving Average). The auto-regressive element of the model considers the degree to which each hour of the data is dependent on previous values while the moving average element is a type of random walk where in each hour a number is chosen randomly and combined with previously chosen values.

4.5.1 THE AUTOREGRESSIVE (AR) PROCESS:

In the autoregressive process, the current value of the time series y(t) is expressed linearly in terms of its previous values (y(t-1), y(t-2). ..) and a random noise a(t). The order of this process depends on the oldest previous value at which y(t) is regressed on. For an autoregressive process of order p (i.e., AR(p)), this model can be written as:

$$y(t) = \phi_1 y(t-1) + \phi_2 y(t-2) + ...\phi_p y(t-p) + a(t) \quad (4.5.1)$$

By introducing the backshift operator B that defines y(t-1) = By(t), and consequently

$$y(t-m) = B^m y(t) \quad (4.5.2)$$

Equation (4.4.1) can be written in the form

$$\phi(B) y(t) = a(t) \quad (4.5.3)$$

Where

$$\phi(B) = 1 - \phi_1 B - \phi_2 B^2 ....- \phi_p B^p \quad (4.5.4)$$

4.5.2 THE MOVING-AVERAGE (MA) PROCESS:

In the moving-average process, the current value of the time series y(t) is expressed linearly in terms of current and previous values of a white noise series a(t),a(t-1)….. [34]-[35].This noise series is constructed from the forecast errors or residuals when load observations become available. The order of this process depends on the oldest noise value at which y(t) is regressed on. For a moving average of order q. (i.e., MA(q)), this model can be written as:

$$y(t) = a(t) - \phi_1 a(t-1) - \phi_2 a(t-2) - .... - \phi_q a(t-q) \qquad (4.5.5)$$

A similar application of the backshift operator on the white noise series would allow equation (4.4.5) to be written as:

$$y(t) = \theta(B)a(t) \qquad (4.5.6)$$

Where,

$$\theta(B) = 1 - \theta_1 B - \theta_2 B^2 - .... - \theta_q B^q. \qquad (4.5.7)$$

4.5.3 THE AUTOREGRESSIVE MOVING-AVERAGE (ARMA) PROCESS:

In the autoregressive moving average process, the current value of the time series y(t) is expressed linearly in terms of its values at previous periods (y(t-l),y(t-2), ...) and in terms of current and previous values of a white noise (a(t),a(t-l),a(t-2). ...). The order of the ARMA process is selected by both the oldest previous value of the series and the oldest white noise value at which y(t) is regressed on. For an autoregressive moving-average process of order p, and q (i.e., ARMA (p,q)), the model is written as:

$$y(t) = \phi_1 y(t-1) + ... + \phi_p y(t-p) + a(t) - \theta_1 a(t-1) - ..... - \theta_q a(t-q) \quad (4.5.8)$$

By using the backshift operator defined earlier, equation (4.4.8) can be written in the following form:

$$\phi(B) y(t) = \theta(B) a(t) \quad (4.5.9)$$

4.6 CONCLUSION

The requirement exists for the ability to generate wind speed data with specific characteristics (mean, standard deviation, etc.) as part of reliability assessment of networks with significant wind generation. In developing such models to generate wind speed data, it is important that the essential characteristic of the source data is replicated in the generated data. With basic approaches to wind speed data generation, such as the Rayleigh or Weibull methods, the generated data can be guaranteed to have the same mean wind speed. However, it can be difficult to replicate the seasonal, daily or other variations. For example, as shown in Figure 6, the mean weekly wind speed of the source data can change significantly over the course of the year (between summer and winter). However, with a Weibull or Rayleigh distribution would include no seasonal variation.

Data generated from the ARMA method could have a high level of variation from hour to hour in wind speed but in reality, wind speed value does not change significantly for two consecutive hours. As Figure 8 shows the frequency of percentage change varies for different time frame. For a short duration (e.g. 10 Minutes), the frequency of deviation for small percentage change in wind speed is very low. As the time frame increases (e.g. 1hour or 2 hour) the frequency of deviation also increases. The maximum percentage changes in wind speed for the 10 minutes time frame is 40% and for 2 hours it is 70%. Weibull and ARMA methods can not re-produce these characteristics of wind data. As the Markov method considers the probability of wind speed change for two consecutive hours, wind data can be produced on the bases of short duration and long duration. For short durations, the probability of change in wind speed would be small and vice versa. But wind data produced using the Markov method still can not show seasonal variations if the Markov method is applied to one year period. This problem can be overcome by producing the wind speed data for each month based on the original data for the same month. Figure 15 compares the mean wind speed for wind data produced using Weibull and Markov method against the recorded data. For Weibull data, the percentage change in mean wind speed for different period of the year is the same.

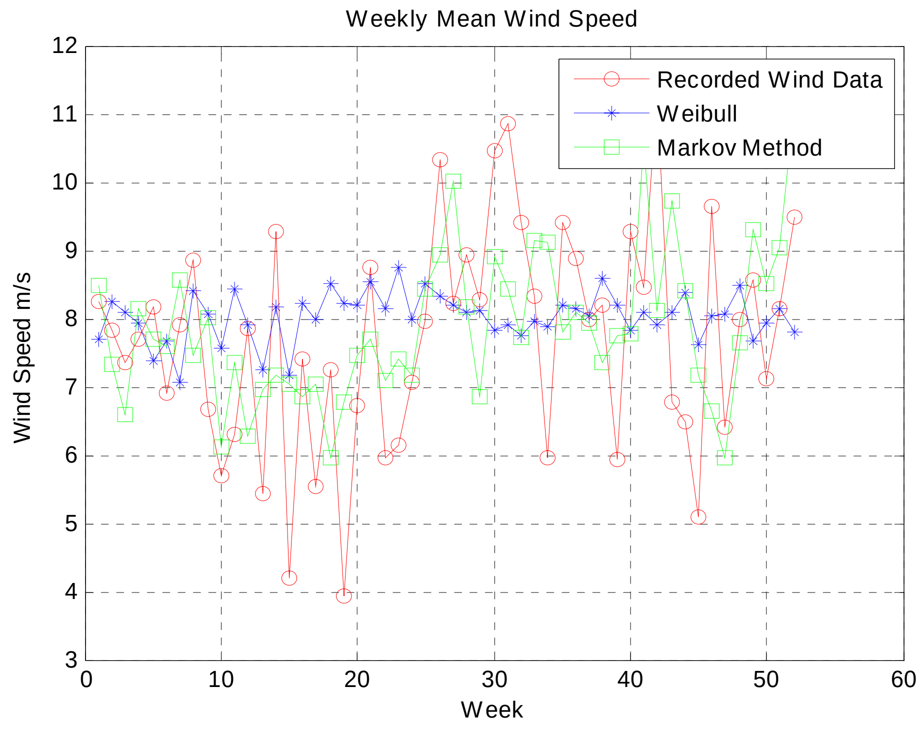


Figure 15: Weekly Mean Speed for Recorded, Weibull and Markov Wind Data

5 NETWORK REPRESENTATION

5.1 INTRODUCTION

This chapter presents the details of the area used for the subsequent probabilistic analyses. Due to the significant amount of wind generation capacity already connected and the additional wind generation expected in this area as part of the Gate 1 and 2 Group Processing Scheme [18], it makes it an ideal location to apply the probabilistic techniques. Some transmission lines are already proposed for upgrade and new substations are planned in the Kerry and Limerick area. By using probabilistic techniques, analysis can be carried out to assess the economical benefits of upgrading the network or using wind curtailment to avoid network investment. The first two sections give details about the transmission network and new wind generation expected to be connected in the Kerry region. The third section describes some of the potential overloading of the network which may result in wind power curtailment. The fourth section shows how the network is modelled using Matlab. The fifth section is used to point out different factors influencing the power flow for the Kerry/Limerick region. The last section shows the cross-correlation between two different wind sites data for seven years period to highlight the possibility of high output from all wind farms in the area at the same time.

5.2 SOUTH WEST TRANSMISSION NETWORK

The part of network considered in this study is actually a part of Irish transmission network (Kerry/Cork/Limerick). Figure 16 [28] shows the location of all transmission buses.

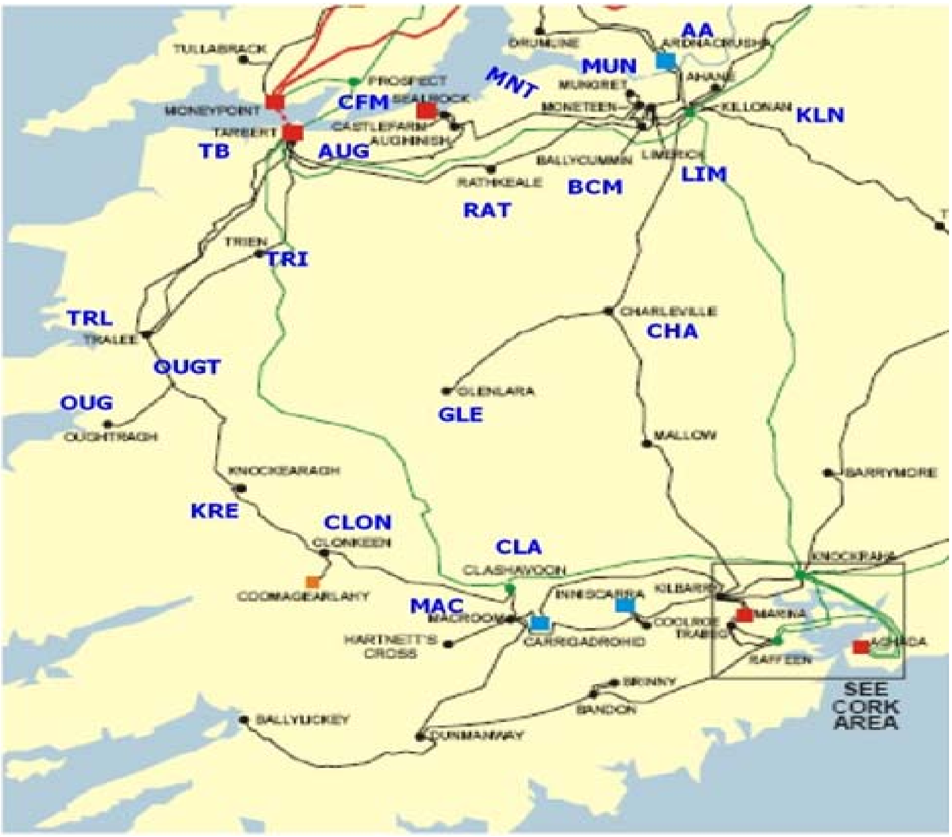


Figure 16: South Western Region

A single line diagram [28] of the entire system is shown in Figure 17 and also in appendix A Figure 70. Ireland, particularly in the south and south-west has a considerable wind energy resource which is currently being developed.

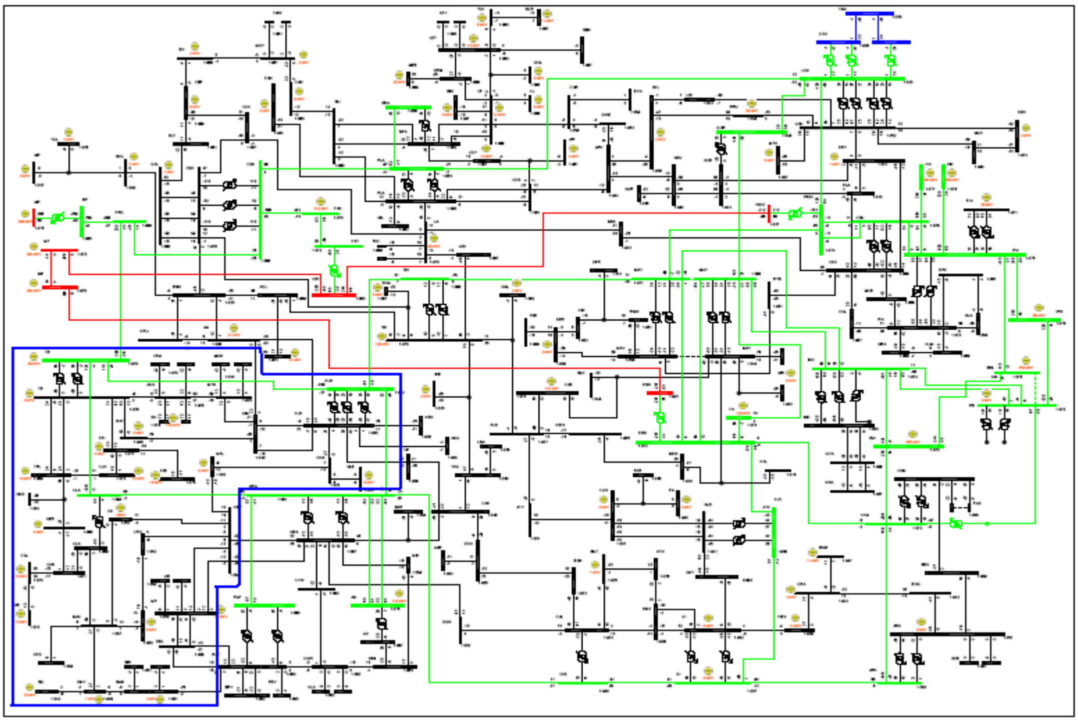


Figure 17: Irish Transmission Network

The section of the network under consideration consists of 36 buses, 23 generators, 44 transmission lines and 6 transformers. This section of the network is mainly at 110kV transmission voltage level, comprising 33 busses at this level in addition to three 220kV lines. There are 9 wind farms, 2 hydro and 5 thermal generators connected in this network. The five remaining generators represent transmission lines and they connect this small network with the rest of the Irish transmission network. Figure 18 [28] shows the part of the network under consideration in more detail.

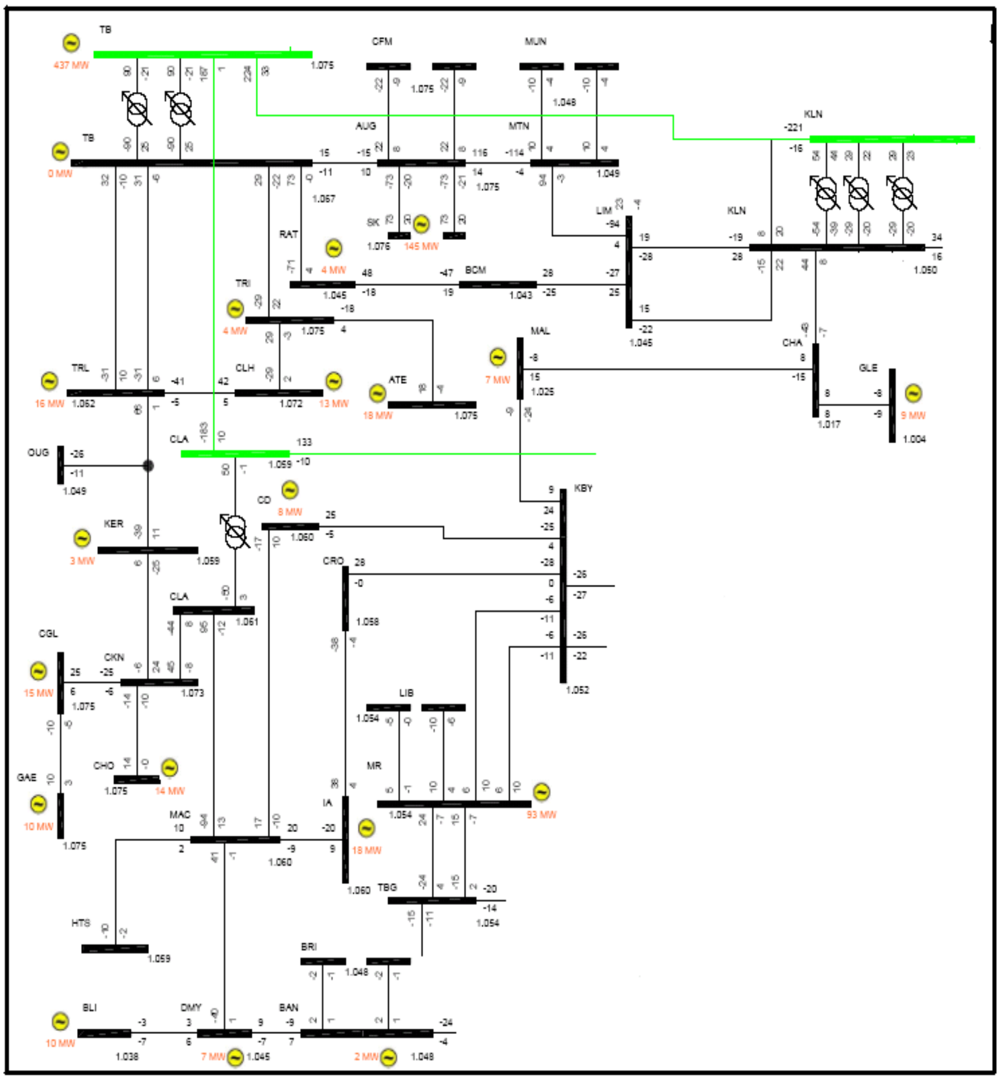


Figure 18: Cork/Kerry Transmission Network

The generators connected at busses Killonan 220kV, Tarbert 220kV, kilbarry 110kV, Marina 110kV and Bandon 110kV represent the connection of this section of the network to the full Irish transmission network. Generators are used as power is generally fed into the network at these points. The load at busses Marina 110kV, Clashavoon 220kV, Limerick 110kV, Killonan 110kV and Killonan 220V represent the fact that power is generally fed from the network at these points

The section of the network shown in Figure 18 is of sufficient detail to allow for the consideration of probabilistic methods of network assessment. At the same time, it is small enough to allow for the repeat solution of the network which is part of the Monte Carlo analysis. Figure 19 shows the wind farms that have applied for connection in red and orange colours and those that already have full connection offer in green in December 2004 [36].

As it can be seen for the south west region, the numbers of wind farms that have applied and received connection offers are significantly greater than other areas.

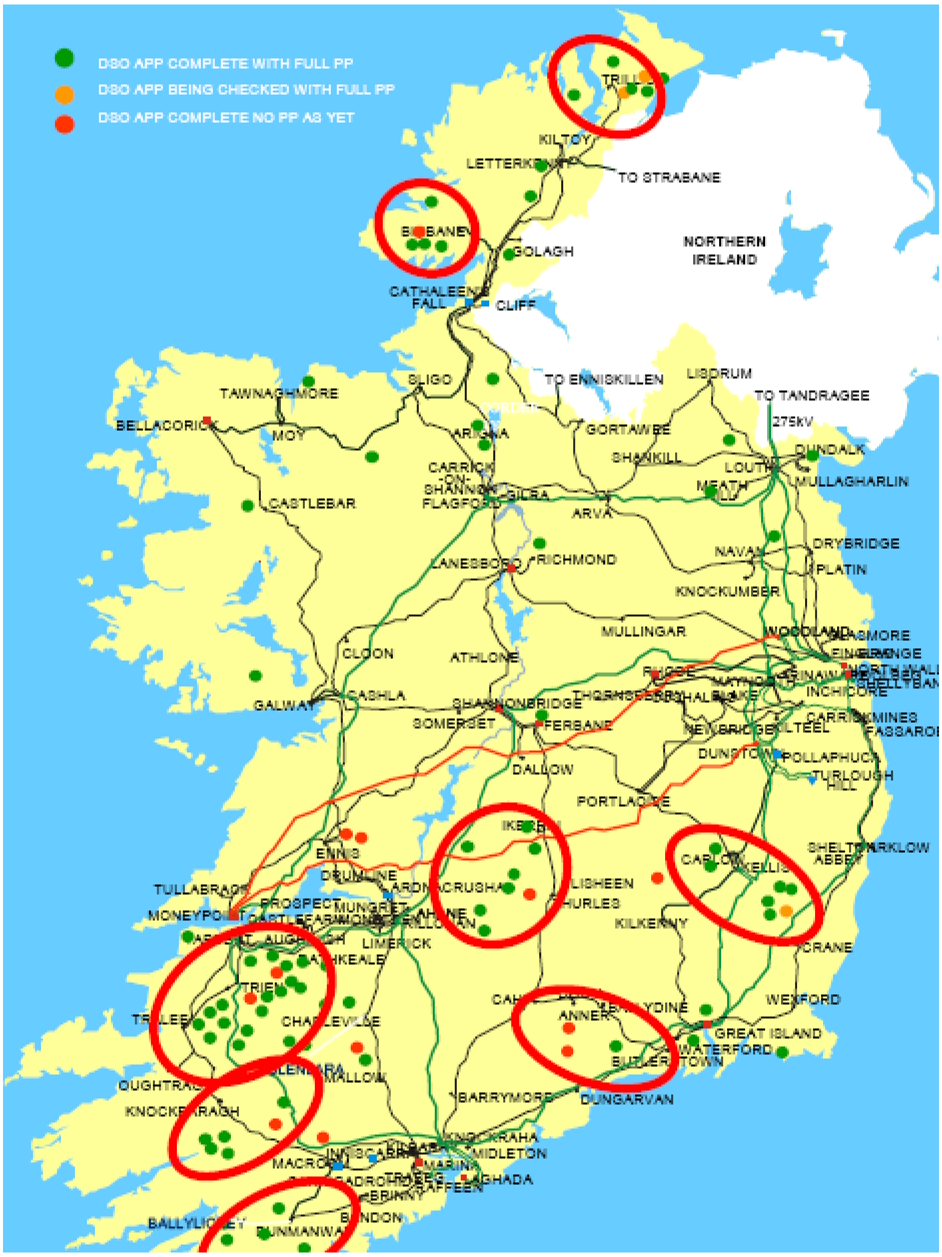


Figure 19: Wind Farm Connection Application under Process [36]

5.3 CLONKEEN GROUP

The total generation at the Clonkeen (CLON) 110kV bus is 114MW at the end of 2007. This figure includes wind farms connected (42.5 MW) and 72 MW of wind generation in Gate 1 wind farms application process. The generation at Commagearlahy (CGL) comes from three separate wind warms which are

- Commagearlahy 42MW
- Glanlee 30MW
- Coomacheo 42MW

The line rating for these transmission lines for summer period is 107MW and the rated output for Commagearlahy is 114MW. Commagearlahy 110kV bus is connected to Clonkeen (CLON) 110kV bus, which is in-turn connected to Knockearagh (KER) 110kV and Clashavoon (CLA) 110kV bus as shown in Figure 20.

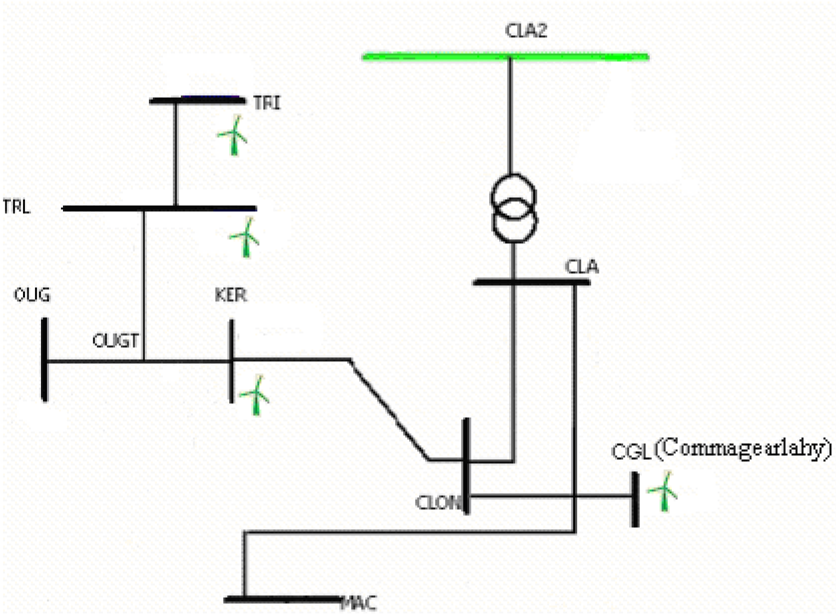


Figure 20: Commagearlahy 110kV Bus Connection

Should the Knockearagh (KER) 110kV to Clonkeen (CLON) 110kV transmission line be removed from service, this would cause Clonkeen (CLON) 110kV to Clashavoon (CLA) 110kV transmission line to become overloaded and vice versa as shown in Figure 21 (PSSE Result). The line rating for these transmission lines for summer period is 107MW. To consider the reactive power flow, the line rating is reduced by 20% because of DC load flow and the rated output for Commagearlahy is 114MW.

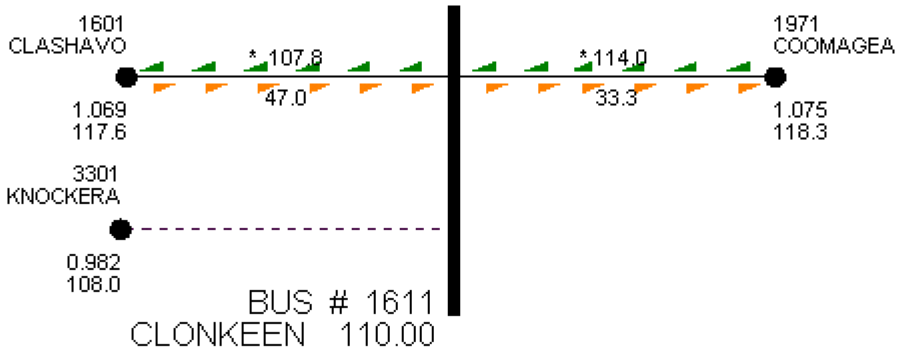


Figure 21: Contingency Case

In the Gate 1 group processing scheme, 220 MW of additional wind generation has been granted permission to connect in West Limerick and Kerry region. This includes the additional generation for the Clonkeen which has received connection offers from TSO [28]. At present, the location of connection and size of new wind farms is not known. It is also not known how many of these wind farms will accept connection offers.

5.4 ANALYSIS OF NETWORK

Analysis of the network relates to the size and duration of possible wind power curtailment for the Clonkeen group wind farms under three different scenarios, Summer, Summer night valley (SNV) and Winter. Summer analysis are carried out for peak demand for summer day period. A summer night valley refers to the minimum demand period of the year which is summer midnight. Similarly winter period refers to the maximum demand level for winter period.

Wind power curtailment for the Clonkeen group can be caused due to transmission line overloading in summer or winter, high voltage problems due to high wind generation connected in a weak transmission network, unplanned outages, planned outages during summer (low demand) period and scheduling of generating units in the Kerry, Cork and West Limerick region.

As described above, one assumption which can be made is that all connected and expected wind generation is dispatched at their rated output for both summer and winter cases. This leads to worst case scenarios. In the Forecast Statement [28], the transmission and distribution connected wind generation is dispatched at 35% of their rated limits. The reason for rated output being used is the planning guidelines that the TSO is believed to follow. Different levels of wind curtailment are required in different scenarios. For example, the summer period, winter period, (n-1) contingency case and maximum wind generation that can be connected without requiring any wind curtailment at a different bus.

The focus of the network analysis study is on the N-1 contingency analysis, maximum wind generation that can be connected at different nodes before critical lines become overloaded based on deterministic techniques.

5.4.1 TRANSMISSION SYSTEM AND SCHEDULLING UPDATE

Due to the additional generation in the Kerry and West Limerick region, the TSO has approved the uprating of different existing transmission lines [28]. The rating of the 110 kV transmission lines for the summer and winter periods is 107MW and 126WM respectively [28]. In the Kerry region, the following transmission lines are approved for uprating:

- Tarbert – Tralee 110 kV
- Oughtragh Tee – Tralee 110 kV
- Knockeragh – Oughtragh Tee 110 kV

The rating of Tarbert – Tralee 110 kV transmission line would increase to 137 MW and 164 MW for the summer and winter periods respectively. The rating of the other two transmission lines would increase to 187 MW and 223 MW. The TSO has also made suggestions for the uprating of following transmission lines,

- Clonkeen – Knockearagh 110 kV
- Clashavoon – Clonkeen 110 kV
- Clashavoon – Macroom 110 kV

For power scheduling, the transmission network is divided into five regions. Active power flow in Kerry and West Limerick region is controlled by the generation at Tarbert. To compensate for the additional wind generation, output from Tarbert and Aghada thermal power units is reduced.

5.4.2 FACTORS FOR CONSIDERATION

As is clear from the above, there are a number of factors which affect the possibility or degree of curtailment of output from the Clonkeen wind farms. These significant factors are listed below:

- Contingencies
- Level of wind generation
- Location of wind generation

- Demand load levels
- Seasonal factors

Addressing each of these factors in turn; it is clear that the potential for overload is greatly increased if a contingency (for example, a line outage) is present in the network. Under these circumstances, the power flow will increase in certain lines, possibly causing the rated power flow to be exceeded. Usually, the power flow is much less than the rated level under the base case conditions. Wind power curtailment might be required if there is an outage of the 110 kV Clonkeen to Clashavoon or the 110kV Clonkeen to Knockeareagh lines (see Figure 20). As these two transmission lines are used to transfer the generated power at the Clonkeen group wind farms, the outage of either of these lines might overload other transmission lines. The rating of these transmission lines is 107 MW for summer. By considering the reactive power flow, the maximum power that can be transferred using these transmission lines would be limited to approximately 85 MW. During high wind generation, or in the case of an outage of the 110 kV Clonkeen – Clashavoon transmission line, reverse power flow might be caused through the transformer connecting 110 kV Clashavoon to the 220 kV Clashavoon transmission bus.

The second significant factor is the level of wind generation for the purposes of network analysis. As described earlier, one approach is to assume maximum power output from all wind generation plant. This is obviously an assumption which will lead to the greatest levels of overload. Consequently, the potential for the addition of wind generation is limited under this assumption. For example, less than 20 MW of wind generation can be connected to the 110 kV Knockearagh (KER) node before 110 kV Clonkeen – Clashavoon transmission line becomes overloaded as shown in Figure 22 (PSS/E Result). The line rating is reduced by 20% to consider the reactive power flow.

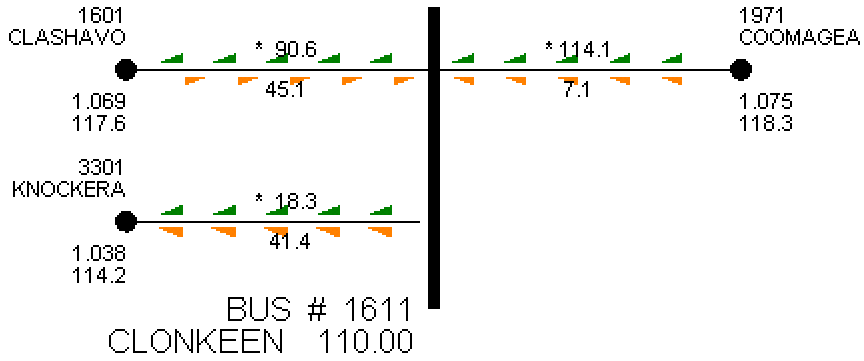


Figure 22: 20MW of Additional Generation at KER 110kV

Similarly, based on deterministic techniques, not more than 27MW of new generation can be connected at 110 kV Oughtragh Tee node before its line flow exceeds the thermal rating for the above transmission line. It shows that even a small amount of additional wind generation can cause line loading and hence power curtailment for the Clonkeen group.

The location of the wind generation is also a significant factor with regard to the potential overloading of lines. Lines which are close to the additional wind generation will carry a greater load (unless this is offset by local load) and hence the potential is greater for overload, particularly during contingencies.

In considering the potential overloads in the network, the level of the demand in the network is important. In the case of a section of the network with no additional wind generation (or embedded generation of any form), the power flow is from generation to load. Hence the line loading is proportional to the demand within the network. However, the addition of generation (wind generation in this case) will result in some or all of the demand being offset, thus possibly reducing the line loading. In the case of high levels of wind generation matched with low levels of demand, the power flow in some elements of the network will be reduced or may be reversed when generation exceeds load.

Consideration also needs to be given to seasonal factors with regard to the performance of the network. During the winter period, the transmission line rating of the 110 kV lines is higher than during the summer period due to the lower average temperatures. However demand is also higher during the winter period leading to higher line flows.

5.5 NETWORK MODELLING

As part of the analysis in this thesis, a load flow programme was developed and used to model and investigate the network. The programme was implemented in Matlab which gives flexibility in data entry and use. The load flow programme consists of 4 data files and 6 Matlab M-files. The data files are used for the input data and contain generation, load, voltage magnitude, transmission lines rating, resistance and reactance of transmission lines.

When these files are executed, the output files are generated and these consist of a bus report, line report and transformer report. The result of the Matlab programme is compared with the results from the PSS/E programme. The difference between

Matlab and PSS/E results for active power was negligible, except for the flow between Tarbert (TB) 220kV to Killonan (KLN) 220kV line, where the difference for active power flow is 6.5MW hence the total line flow is 156MW so the difference would only be 3%. In some cases, the difference of reactive power flow was up to 10MVAr. The main cause of this difference would be due to the values of bus voltage. The Matlab and PSS/E results are shown in Appendix C TABLE 11.

5.6 INITIAL NETWORK ANALYSIS

The network diagram is shown in Appendix A Figure 65. Conventional generation of 590 MW is connected to Tarbert 110 kV and 220 kV Bus. For the summer 2008 case, the dispatched power from Tarbert is 204 MW. Due to the very high generation capacity, Tarbert 220 kV Bus is chosen as the slack Bus to provide the difference in active and reactive power. The Prospect (PRO) – Tarbert (TB) 220 kV line transfers 288 MW, 110 kV Knockraha (KRA) – Kilbarry (KBY) transfers up to 100 MW, 220 kV Shannonbridge (SH) – Killonan (KLN) transfers 47 MW and 110 kV Raffeen (RAF) – Bandon (BAN) transfers 32 MW of active power to the South West region. Active power from the above transmission lines is taken as generation connected directly to these buses. Similarly other transmission lines that are used to transfer power from the South West region to other parts of network not considered for this analysis and therefore are represented as loads.

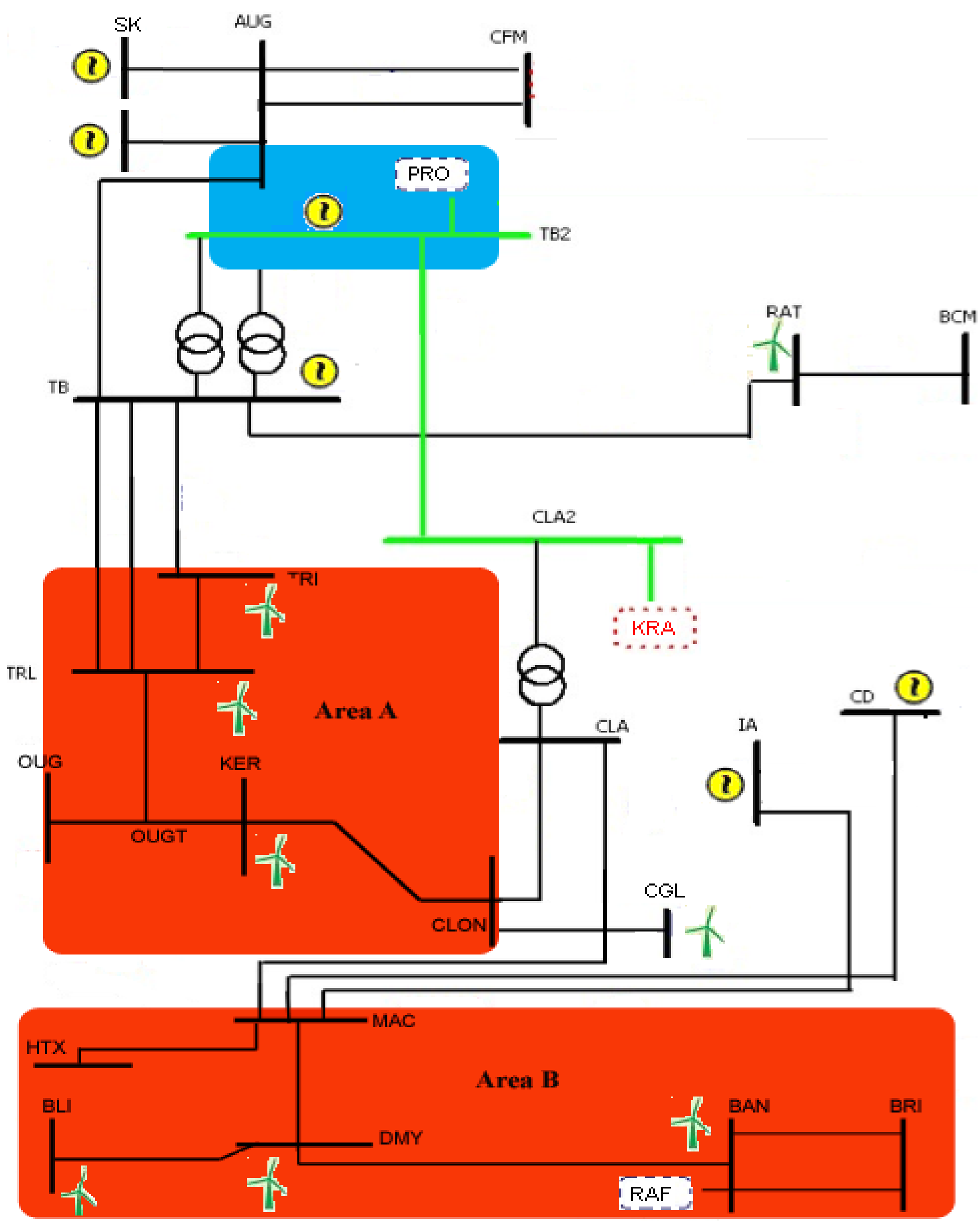


Figure 23: Embedded Wind Generation

In Figure 23, 492 MW of generation is connected in the blue coloured area (204 MW from Tarbert and 288 MW from 220 kV Prospect transmission line). The two red coloured areas show included demand connected to local transmission buses and a significant amount of wind generation is also present in these areas. During low wind generation periods, active power is transferred from the Tarbert 110 kV Bus to these two areas to supply local demand. When wind generation is high, local demand can be supplied by the local wind generation and the conventional generation from

Tarbert has to be curtailed to accommodate wind power. The loading on 110 kV transmission lines between Tarbert, Trien and Tralee is reduced and for the low wind generation period, loading on these lines increase as they are used to transfer power from Tarbert.

For the winter period, when local demand and line rating is high due to low temperatures, more wind generation can be accommodated in the transmission network because embedded wind generation can be used locally and more additional generation can be transferred to other areas due to high line rating. Similarly for the summer period, the demand and transmission line rating is low due to high temperatures, there is less capacity to absorb embedded wind generation locally, and transfer capability of transmission lines also reduces. Analysis for the summer period is more important as they give rise to more severe conditions that the TSO has to deal with.

5.7 CROSS CORRELATION

Correlation is a standard method to calculate the degree to which any one series is correlated to a time lagged (auto correlation) version of itself or two series are correlated to each other (cross correlation) [37].

Generation from different conventional plant is not correlated to any other conventional generation plant. Outage of one plant would not affect the output of the other plant. In the case of wind generation, most of the wind farms are located in a relatively small geographical area due to the high wind speed profile of the area. Changes in wind speed for one wind farm would also affect the wind speed for other wind farms. As most of the wind farms are connected to a weak transmission network, the change in speed would result in a change in generation for all wind generation in a small geographical area and could result in significant effects on line flow and thus result in voltage fluctuation and other power quality problems.

It is very important to find the correlation between two different wind farms due to the fact that change in output from one wind farm could occur at the same time as the change in generation to the other wind farms if they are highly correlated. The correlation coefficient is the index which indicates the linear dependence of the two series. If correlation coefficient is unity, the two series are highly correlated. If it is -1, they are negatively correlated which means an increase in one series would occur at the same time as a decrease in the other series. If the correlation coefficient is zero, the two series are not correlated at all or they are linearly independent. The correlation coefficient of the two series can be determined by using following equation,

$$Cross-Corr = \frac{\Sigma\left[\left(x_i-\bar{x}\right)\left(y_i-\bar{y}\right)\right]}{\sqrt{\sum\left(x_i-\bar{x}\right)^2}\sqrt{\sum\left(y_i-\bar{y}\right)^2}} \tag{5.1}$$

x_i and y_i are series values at any given time, $\bar{x}$ and $\bar{y}$ are mean values for each series.

Wind speed data for two different sites in the South West region is available for the period of 1994-2001. The data was sourced from the Irish Meteorological Services

Met Eireann. The geographical locations of the two sites (Shannon and Valentia) are shown in Figure 24. The distance between these two sites is 85miles.

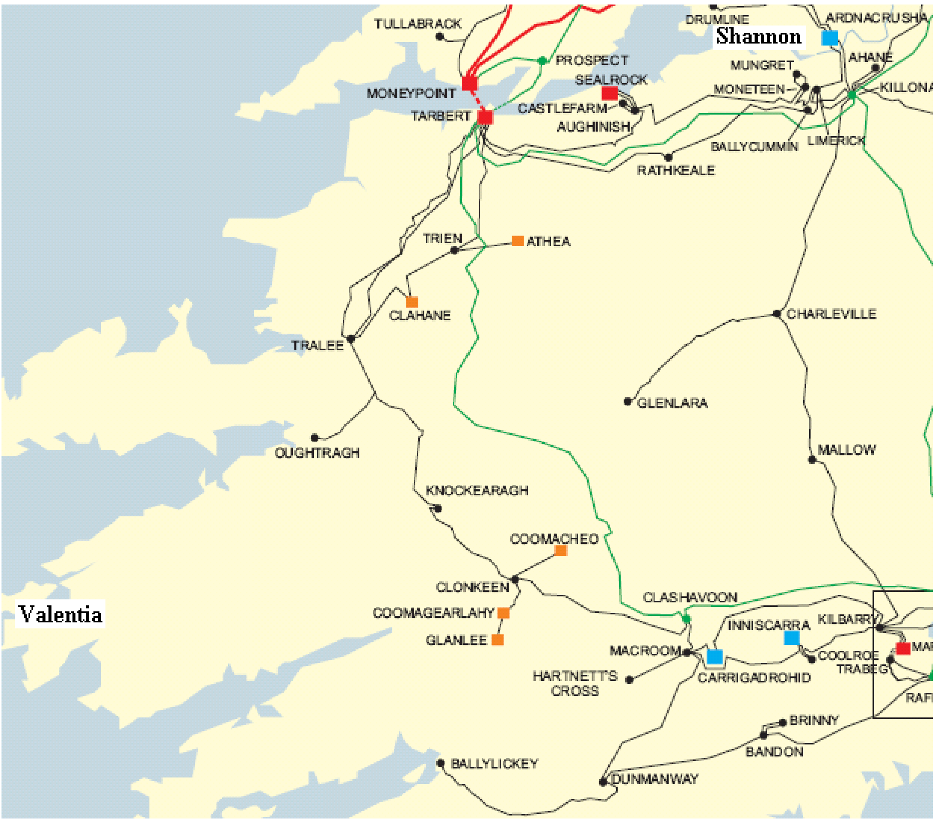


Figure 24: Location for Valentia and Shannon

The cross correlation for these two sites is determined in Excel by using the CORREL function for each year. Average correlation coefficient for the data period is 0.753 which means these two sites are highly correlated. Figure 25 shows the variation in Cross-Correlation over the period of 1994-2001.

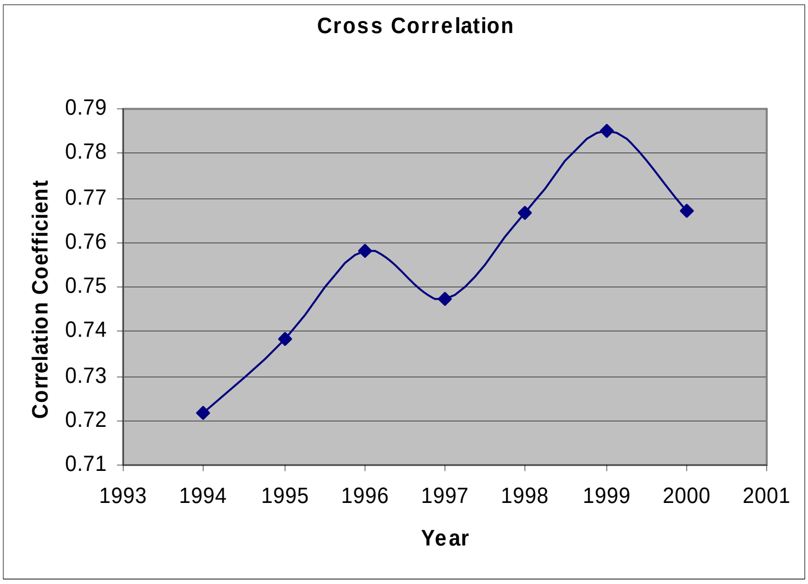


Figure 25: Annual Cross Correlation Coefficient

From Figure 25, we can assume that most of the wind farms in the Kerry region are highly correlated because the distance between Shannon are Valencia is more than the distance between the wind farms located in Kerry region (Coomacheo, Coomagearlahy, Glanlee, Bandon, Dunmanway and Ballylickey). These six wind farms are located within a radius of 40 miles.

5.9 CONCLUSION

There is significant potential for wind generation in the west of Ireland. But due to a weak transmission network and different network security issues, the network capacity to accept additional wind generation is limited.

Deterministic analysis based on rated output of generation can be applied to highlight line overloading problems, reverse power flow and the amount of additional wind generation that can be connected in the Kerry region. For the base case, the line flow is within limits and line overloading is a possibility for the contingency case. The probability of a critical line being out-of-service has to be considered. By using Node Participation Factor (NPF), it is seen that wind generation in Kerry or Limerick region does not have significant effect on the line flow in the other regions as shown in Table 1.

Lines	Base Case	N-1 Contingency
CLA1-CLON	-0.522	-0.967
TRL-OUGT	-0.483	0.0
TB1-TRI	-0.172	0.0
TRI-TRL	-0.169	0.0
TB1-TRL	-0.165	0.0
CHA-MAL	-0.138	-0.266
CD-MAC	-0.070	-0.137
CRO-IA	-0.066	-0.129
IA-MAC	-0.066	-0.129
AUG-MTN	-0.009	-0.064
BCM-LIM	-0.007	-0.054
BCM-RAT	0.007	0.054
KLN1-LIM	0.007	0.050
LIM-MTN	0.008	0.062
RAT-TB	0.008	0.055
AUG-TB	0.009	0.064
CRO-KBY	0.066	0.129
CD-KBY	0.070	0.137
KLN2-TB2	0.127	0.160
KBY-MAL	0.136	0.264
CHA-KLN	0.138	0.266
CLA-MAC	0.138	0.268
CLA2-TB2	0.385	0.699
CLON-KER	0.462	OUT-OF-SERVICE
KER-OUGT	0.462	0.0

Table 1: LFSF

Initial network analysis also highlights the fact that wind curtailment could be high depending on the different wind profiles used in the analysis. It also shows that wind curtailment is much more likely for the summer case and the amount of additional wind generation that can be connected to the network also increases for the winter period.

As most of the wind farms act as embedded wind generation within the transmission network, the line flow on different transmission line reduces with the increase in wind generation. Output levels from different wind farms located in the region are likely to rise and fall together due to the high cross-correlation of wind data from these sites. That is, high wind generation is much more likely to occur at the same time from different wind farms and would reduce the line loading for those transmission lines that are used to transfer power to these areas.

In the next chapter, probabilistic techniques would be applied for the summer period to find the likelihood of having line overloading occurring due to additional wind generation and the maximum amount of wind generation that can be connected to the network before transmission lines become overloaded. These techniques will also be used to compare the results of initial network analysis based on deterministic techniques.

6 PROBABILISTIC NETWORK ANALYSES

6.1 INTRODUCTION

This chapter applies probabilistic techniques to compare the results of the network analysis based on deterministic techniques. The first section describes the LFSF in detail and compares the line flow calculated using load flow and the LFSF method and describes how this method could be expanded to include the effects of change in generation from more than one bus. The second section describes the general line flow in the network and how different levels of wind generation can affect it. The third and fourth sections use probabilistic techniques to show the probability of having reverse power flow and line overloading on critical transmission lines. The fifth section describes how higher levels of wind generation can effect the line overloading and reverse power flow using probabilistic techniques for different periods of the year. The sixth section considers the degree of curtailment of wind generation required due to network consideration.

6.2 LINE FLOW SENSITIVITY FACTOR

The Line Flow Sensitivity Factor (LFSF) is used to determine the effects of the changes in generation on different transmission lines. It is an easy and efficient method to predict the line flows, especially in the case of wind generation where the output changes very frequently. It would also give an indication of which transmission lines are more sensitive to changes in the output from a particular generator. Hence LSFS techniques can be used for planning purposes.

6.2.1 CALCULATION OF SENSITIVITY FACTOR

6.2.1.1 LFSF BASED ON CHANGES IN PHASE ANGLE

The method used here to calculate the sensitivity factor is based on the method described in [2]. The line flow sensitivity factor was derived using the following equation:

$$\theta = [X]P \tag{6.1}$$

Where

θ is the bus phase angle

P is injected bus power

X is reactance matrix

This equation represents the statement of the DC load flow problem in matrix form. DC load flow is s particular case of the load flow problem which describes the voltage and power flow in a network. The DC load flow is assumed by making the following assumptions:

- the resistive part of the line impedance is neglected,
- the bus voltages at all points in the network are assumed to be 1 pu, and
- the phase angles of the bus voltages are small such that it can be assumed that:

$$\sin\theta \approx \theta$$

Consequently, the non-linear, conventional load flow problem resolves to DC load flow representation as given in equation 6.1 above.

As it is clear from the above, the DC power-flow model is linear between active power flow and bus phase angle. If we are interested in the changes in bus phase angles $\Delta\theta$ for a given set of changes in the bus power injections, ΔP, the following calculation can be used,

$$\Delta\theta = [X]\Delta P \qquad (6.2)$$

It is assumed that the power on the swing bus is equal to the sum of the injections of all the other buses and net perturbation of the swing bus is equal to the sum of the perturbation on all the other buses.

Suppose that we are interested in calculating the generation shift sensitivity factors for the generator on bus ***i***. To do this, the perturbation on bus ***i*** will be set equal to +1 and the perturbation on all the other buses to zero and then the equation can be solved for the changes in bus phase angles using the matrix calculation.

$$\Delta\theta = [X]\begin{bmatrix} +1 \\ -1 \end{bmatrix} \begin{matrix} --row\ i \\ --ref\ \ row \end{matrix}$$

In the above equation, the vector of bus power injection perturbations represents the situation when a 1pu power is injected in bus ***i*** and is compensated by 1pu decrease in power at the reference bus. The Δθ values are thus equal to the derivative of the bus angles with respect to a change in power injection at bus ***i***. The required sensitivity factors for the line flow on a line ℓ connecting buses n and m is given by

$$a_{li} = \frac{df_l}{dP_i} = \frac{d}{dP_i}\left[\frac{1}{x_l}(\theta_n - \theta_m)\right] \tag{6.3}$$

$$= \frac{1}{x_l}\left(\frac{d\theta_n}{dP_i} - \frac{d\theta_m}{dP_i}\right) = \frac{1}{x_l}\left((X_{ni} - X_{mi}) - (X_{ns} - X_{ms})\right) \tag{6.4}$$

Where

$X_{ni} = n^{th}$ Element from the Δθ vector

$X_{mi} = m^{th}$ Element from the Δθ vector

x_l=line reactance for line *l*

The generation sensitivity factor is the change in line flow due to the change in the generated power. The change in generation ΔP_i is exactly compensated by an opposite change in generation at the reference bus, if the other generators remain constant. The a_{li} factor then represents the sensitivity of the flow on line ℓ to a change in generation at bus i. For example, if one generator is shut down due to some fault, then all the generation lost would be made up by the reference generation. Assume that generator ***i*** was generating ΔP_i^0 MW, then

$$\Delta P_i = - \Delta P_i^0$$

The new power flow on each line in the network could be calculated using a precalculated set of "a" factors as follows

$$\hat{f}_l = \hat{f}_l^{o} + a_{li}\Delta P_i\ , \qquad \ell = 1.......L \qquad (6.5)$$

Where

$\hat{f}_l$ = flow on line ℓ after the generator on bus ***i*** fails

f_l^{o} =flow before the failure

The outage flow on each line can be compared to its limits and those exceeding their limit can be highlighted.

6.2.1.2 LFSF BASED ON CHANGES IN LINE FLOW

The method used to calculate accurate LFSF a_{li} factors is derived from the above approach and is based on line flow before the change in generation, line flow after the change in generation and total change in generation as compared to the first method which is based on changes in bus phase angle. By using the load flow programme, the changes in transmission line flow can be calculated for any change in bus generation. The line flow before the changes in generation, line flow after the changes in generation and the total change in generation can be used to calculate the LFSF.

$$a_{li} = \frac{\hat{f}_l - f_l^{o}}{\Delta P_i} \qquad \text{For } \ell = 1.......L \qquad (6.6)$$

Where

$\hat{f}_l$ = flow on line ℓ after the change in generation

f_l^{o} =flow before the change in generation

ΔP_i =Change in real power for Bus *i*

The LFSF a_{li} can be used to find the new line flow by using Equation 6.5. LFSF would be different for each transmission line for the changes in each bus real power. For accurate values of LFSF, the maximum and minimum change in generation can be used to get two different LFSF and by using the average value, an approximate result can be obtained. Table 1 shows the sensitivity factors of transmission lines in the area for the changes in generation at the 110kV Clonkeen bus. It can be seen that only the transmission lines near to the participating nodes have high sensitivity factors. The transmission network diagram is shown in Figure 23.

Transmission lines that are only connected directly to the 110kV Clonkeen bus are more sensitive to the changes in the generation at the Clonkeen Group. In the contingency case, when the 110kV CLON-KER transmission line is out-of-service, the sensitivity of the transmission lines connected to Knockearagh reduces significantly.

This method can be extended to calculate the line flow due to changes in generation at more than one bus. For example, in the transmission network, there is more than one bus which is experiencing a change in generation from a power source. The LFSF for each transmission line due to change in generation from each bus can be calculated. For two buses i and j with the change in generation, there are two LFSFs for each transmission line, the new line flow for transmission line ℓ is

$$\hat{f}_l = f_l^o + a_{li}\Delta P_i + a_{lj}\Delta P_j \quad \text{For } \ell = 1 \ldots\ldots L \qquad (6.7)$$

Where a_{lj} = LFSF for line ℓ due to change in generation at bus $\boldsymbol{j}$

a_{li} = LFSF for line ℓ due to change in generation at bus $\boldsymbol{i}$

This method can be applied if the change in generation applies to multiple buses but as this method is applied to reduce the time as compared to load flow programme, by including more and more buses, the computation time would increase. We are applying a linear method on a non-linear system but the results obtained are sufficiently accurate and can be used for probabilistic analysis.

6.2.2 RESULT COMPARISION

The line flow sensitivity factor is less time consuming compared to normal load flow method to find the transmission line flow. Analysis was carried out for each hour in one year (8760 hours). The time taken by the LFSF method was 56 seconds as compared to normal load flow method which takes a number of hours. As the number of hours increases, the time taken for each hour analysis also increases and for more than one year analysis, the load flow Matlab programme might take up to several hours which make it impractical to use for analysis.

The generated power on different buses was increased by 100MW and line flow was calculated by using the Matlab load flow programme. Line flow was also calculated by using LFSF. The results are shown for the increase in generation of 100MW on the 110kV Commagearlahy bus in Appendix C TABLE 13.

The maximum difference between the LFSF line flow and actual line flow based on the matlab analysis, for the changes in generation at the 110kV Commagearlahy was less than 25MW for all transmission lines. For 60% of transmission lines, line flow was the same for both cases and only three transmission lines have more than 10MW of difference as shown in Figure 26.

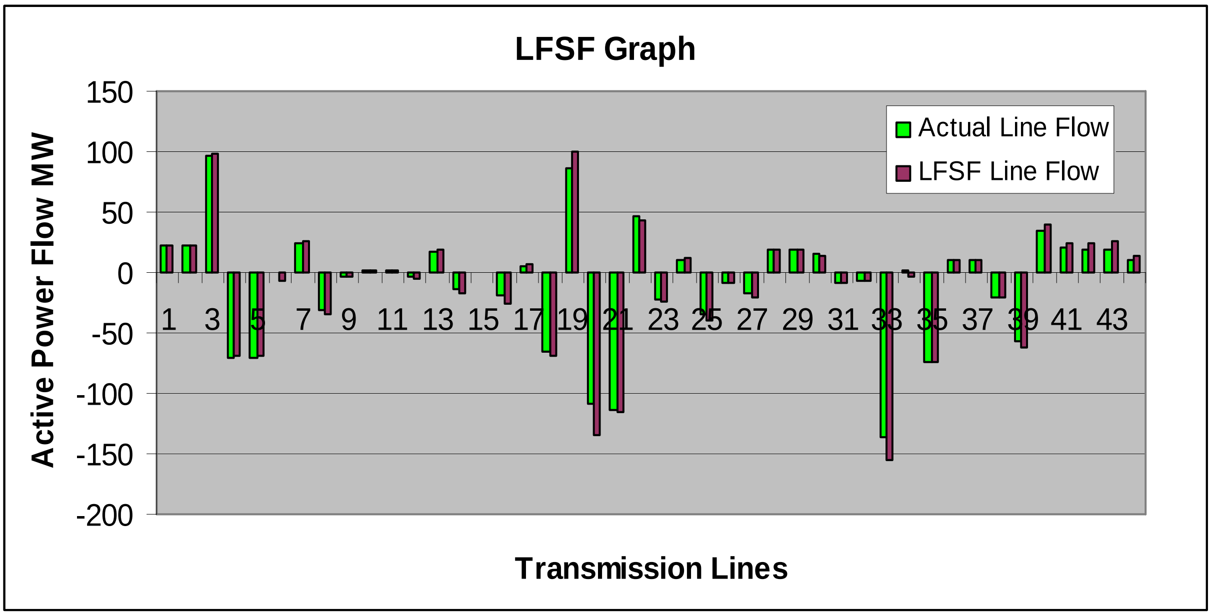


Figure 26: Actual and LFSF Line Flow Based on Phase Angle Method

As it can be seen, the method is sufficiently accurate to be used for network analysis. The accuracy of the result would only depend on the actual difference, not on percentage difference of actual line flow. In the above case, the maximum difference was 25MW which is 15% of actual line flow and similarly the 2^{nd} maximum difference was 16MW which 16% of actual line flow. In the 2^{nd} case, the percentage difference is higher but the actual difference is less. So to make a decision on whether the LFSF method can be used or not, the actual limit would be much practical then the percentage difference.

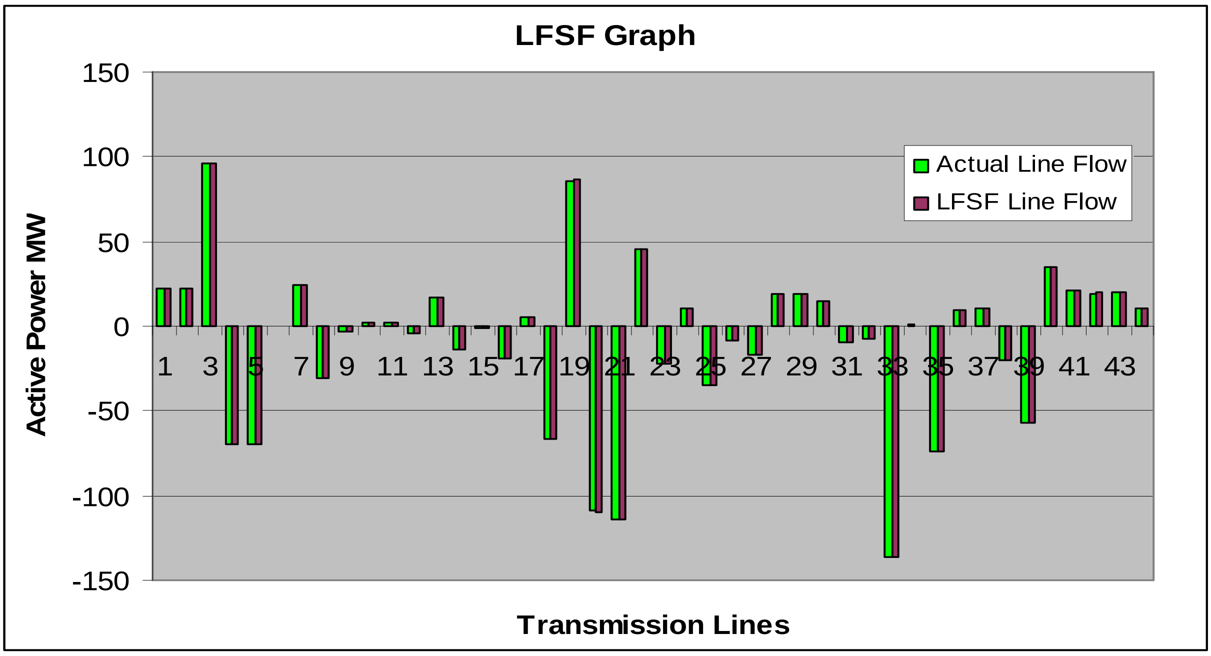


Figure 27: Actual and LFSF Line Flow Based on Line Flow Method

Figure 27 compares the lines flow for all transmission lines with the actual line flow and the line flow calculated by using LFSF based on changes in line flow. The difference between both lines flow is zero in most cases and maximum difference in 0.5MW.

The line flow results for the change in generation at two buses are shown in Appendix C TABLE 14. The difference between line flows calculated using load flow and LFSF is also shown. In most of the cases it is zero and maximum difference is only of 0.01p.u or 1MW for only transmission lines which shows that this method is accurate enough and can be used for line flow analyses.

6.3 PROBABILISTIC ANALYSIS

Probabilistic analyses are carried out by considering the availability of wind turbines, the outage rate of the transmission lines and the wind profile.

6.3.1 TRANSMISSION LINES AVAILABILITY

The analysis of the availability was based on two transmission lines, 110kV CLON-KER and 110kV CLON-CLA. The length of the CLA-KER (110kV) transmission line is 30km. Based on the IEEE Reliability Test System, the outage for this transmission line is 1 per year and 10 hours for each outage. Similarly the length of second transmission line 20km and the outage is 0.6 per year and 10 hours for each outage. For this analysis, one outage per year for each transmission line is used. Transmission line availability is only considered for N-1 analysis as there is no need to consider its availability for the Base Case analysis.

6.3.2 WIND TURBINE AVAILABILITY

The availability of each wind turbine taken as 97% based on Airtricity wind turbine data. This translates to an average outage period of 260 hours per year. For the analysis here, it is assumed that there are 4 outages per year with an average outage period of 66 hours. There is already 14.9 MW of wind generation connected at this bus. Under the Gate 2 arrangements and additional 100MW of capacity has been approved. This additional generation is represented as 43 units of 2.3MW Siemens wind turbines.

The flow chart in Figure 28 gives an overview of the operation of the Monte Carlo analysis. The Matlab programme initially reads in the data files. A random draw is made to determine the availability of each of the transmission lines for each hour. Likewise, a random draw is made to determine the availability of each wind turbines. The wind speed data is then obtained at this time period (based on the Markov process) and the output of the total number of available wind generators is obtained.

In general, we are only interested in the cases where the critical transmission line is out-of-service. In the cases where a critical line is unavailable, the line flows in the network under these conditions are calculated. Obviously, if the line flow on a particular line exceeds the line rating, the curtailment of the level of wind generation output is determined.

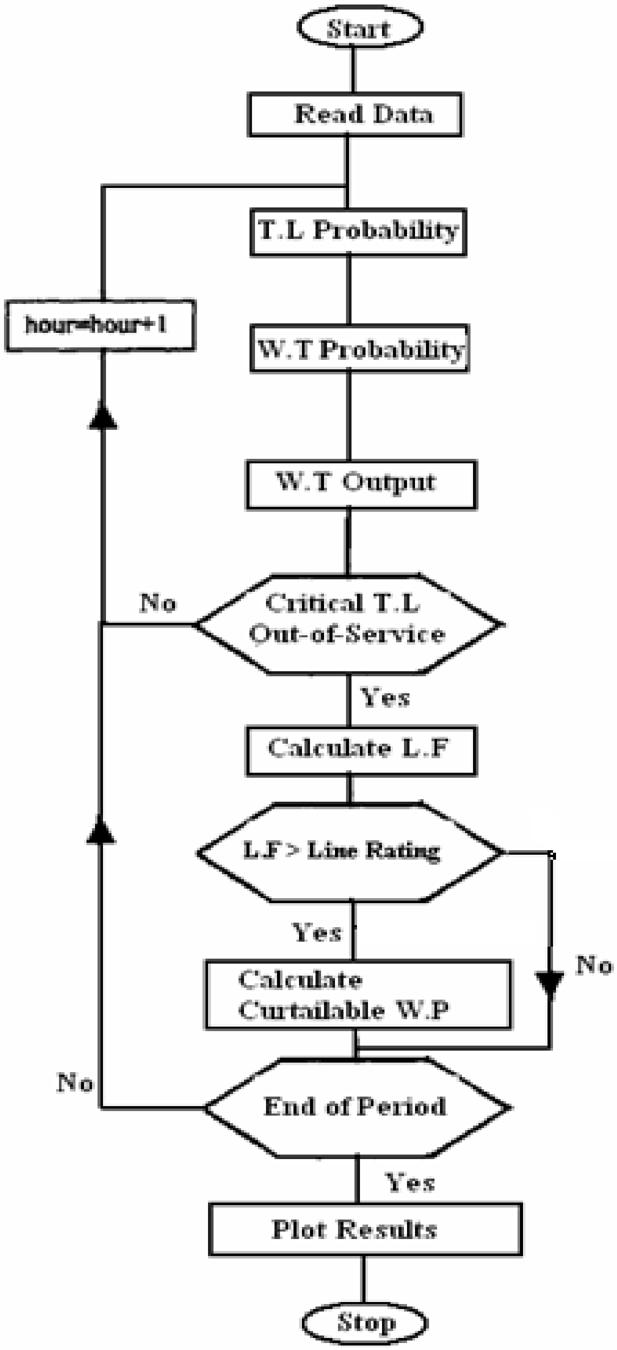


Figure 28: Flow Chart Diagram

6.3.3 WIND SPEED DATA

The wind speed data used is generated by using Markov's method based on recorded wind data for the period of April 2005 to March 2006 as described in section 4.4. For summer and winter analysis, separate wind data is generated for each period, as there is a significant difference in the mean values.

6.3.4 CONTINGENCY LOAD FLOW ANALYSIS

For N-1 contingency analyses, load flow analysis was carried out only for the outages of one transmission line, i.e. 110kV CKN-CLA transmission line. As the outage of the CKN-CLA transmission line would have the greatest effect on line flow.

6.4 BASE CASE ANALYSIS

6.4.1 LINE FLOW ANALYSIS

Base case analyses for summer peak demand, summer night valley demand, and winter peak demand period for year 2008 are used to investigate the line flow and to show how different levels of wind generation can affect the line loading.

6.4.1.1 SUMMER NIGHT VALLEY 2008

The Summer Night Valley case is important because this represents the time of the minimum load demand level. The load connected in Areas A and B is 57.5 MW and 37.2 MW respectively at this time.

If the wind generation is dispatched at one third of the rated output, the local demand can be supplied by the wind generation. The active power transferred through the

110kV Trien (TRI) and 110kV Tralee (TRL) buses would be -4 MW. The line flow through the 110 kV CLA-MAC transmission line is 36.5 MW.

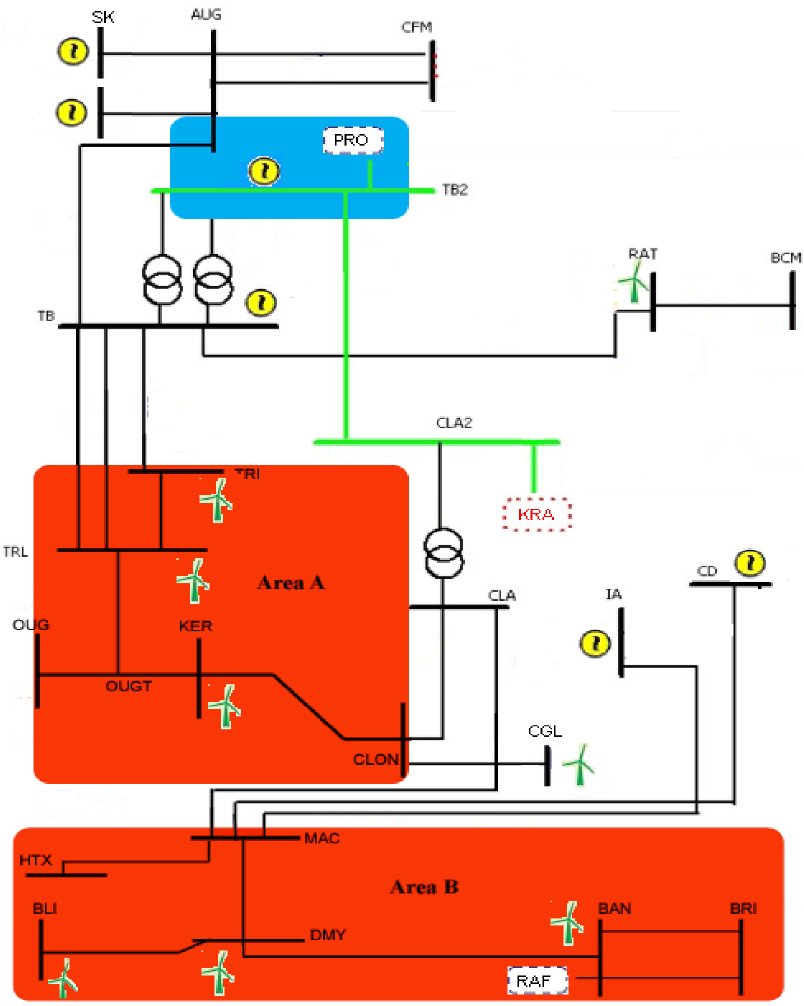


Figure 29: Embedded Wind Generation

If dispatched wind generation is increased to rated output (which for Areas A and B is 184 MW and 53 MW respectively), the wind generation output is greater than demand in both areas and the extra power is supplied to load external to the area. The maximum reverse power flow through the 220 kV CLA- 110kV CLA transformer is 49.7 MW.

Wind curtailment is much more likely to occur for summer night valley, when wind generation is higher than local demand due to the need to have conventional generation to supply the reactive power. High wind generation could result in a high voltage problem. For this particular case, it causes a significant level of reverse power through the 220 kV CLA- 110kV CLA transformer.

For this extreme case, where wind power is generated at rated output and local demand connected is reduced to its minimum level, the loading on the critical transmission line 110kV CLON – CLA is 60% of the line rating. Therefore, a high level of wind generation might cause reverse power flow, but for the base case, line flow is much below than the transmission line rating.

6.4.1.2 SUMMER DAY 2008

Total load connected in areas A and B for the summer period is 143 MW and 104.2 MW respectively for summer 2008 at peak demand which normally occurs in mid afternoon.

If wind generation is dispatched at one third of rated output, 83.4 MW of active power has to be supplied by generation at Tarbert through 110kV Trien and 110kV Tralee transmission buses for Area A. For Area B, 75 MW power is supplied through 110 kV CLA-MAC transmission line. The difference in supplied power and load in these two areas is supplied by local wind generation.

If wind generation is increased to rated output, the power supplied by Tarbert generation reduces and hence reducing line loading. The power supplied to Area A by Tarbert is reduced to -37 MW. As the rated output of the connected wind generation in Area A is 184MW, it is more than local demand and extra generated power has to transfer to other areas which results in reverse power flow through the 220 kV CLA – 110 kV CLA transformer. The power supplied to Area B through 110 kV CLA- 110 kV MAC transmission line reduces to 51.2 MW. The rated output of the wind generation connected in Area B is 53 MW.

6.4.1.3 WINTER 2008

For the winter case, the load connected in Area A and B is 151.2 MW and 98.9 MW respectively. For one third wind generation (62 MW), the active power supplied by Tarbert is 93 MW for Area A. For Area B, power supplied through 110kV CLA – 110kV MAC is 85.3 MW. The local wind generation is used to supply 18.7 MW of demand.

If wind generation is dispatched at the rated output which for Area A and B is 184 MW and 53 MW respectively, the power supplied by Tarbert generation to Area A reduces to -28.4 MW. For Area B, the active power supplied reduces to 61 MW. The network diagrams for rated and one third wind generation is shown in Appendix A Figure 66 and Figure 67.

6.4.1.3 RESULTS

The line flow for all the transmission lines for the three scenarios above is shown in Appendix B. An increase in embedded wind generation reduces the need to transfer active power from conventional sources. In this particular case, high wind generation can cause reverse power through the 220 kV-110kV Clashavoon transformer. The probability of high wind generation causing reverse power is discussed in the next section.

From the above three different scenarios, it is obvious that increases in wind generation reduced the dependency on the supply of active power by conventional generation. The high wind generation for the extreme case, when local demand is minimum, does not cause line overloading.

Reverse power flow through the transformer is possible but only if the wind generation is dispatched at rated output, for example for the summer night valley case. When wind generation is dispatched at the rated output, under these circumstance, the reverse power through the 220 kV -110 kV CLA transformer is 49.7 MW. For the other two cases, summer and winter, it is 10.6 MW and 6.5 MW respectively as shown in Table 2.

To investigate the effect of different wind generation levels in different areas (Area A and Area B) on reverse power flow through 110kV CLA-220kV CLA transformer, probabilistic analysis based on wind generation dispatched at rated and one third of rated output for Area B are discussed in the next section. Wind generation levels in Area A depends on wind speed data generated using Morkov’s method.

	Load A (MW)	Load B (MW)	Wind Generation Level	Power Supplied to A (MW)	Power Supplied to B (MW)	Reverse Power Flow (MW)
S.N.V	57.5	37.2	One Third Output	-4	36.5	7.4
			Rated Output	-120	13.7	-49.7
Summer	143	104.2	One Third Output	83.4	75	47.9
			Rated Output	-37	51.2	-10.6
Winter	151.2	98.9	One Third Output	93	85.3	51.8
			Rated Output	-28.4	61	-6.5

TABLE 2: BASE CASE RESULT

All of the above figures do not consider the outage of wind turbines and the probability of high wind speed coinciding with low demand. If we consider these probabilities, the line loading and likelihood of having reverse power through the 110kV CLA-220kV CLA transformer would reduce. The total wind generation connected in Area A is 184 MW including the additional generation in the Gate 1 planning scheme. The number of wind turbines connected in Area A can be more than 80. By considering the probability of having high wind speed and all wind turbines operational, the number of hours with line overloading and a reverse power flow problem can be determined. By choosing a wind curtailment option (rather than costly transmission network upgrade), the cost of accommodating more wind generation can be reduced significantly. In the next section, the numbers of hours with reverse power flow are calculated for different scenarios by considering the availability of wind turbines and by using the previous years wind speed data.

6.4.2 PROBABILISTIC REVERSE POWER FLOW

Reverse power flow through a transformer can be a problem if it is not designed to accommodate such operational conditions [38]. Control of the tap changer might be designed for one direction of flow. If reverse power flow occurs and it is not anticipated, errors can occur for tap changer setting resulting in damaging system voltage and running tap setting to its limits. It can result in excessive high or low voltage.

Load flow analysis shows that, in the non-contingency condition, active power would flow from 220kV CLA to 110kV CLA bus through the transformer when wind generation from the Clonkeen group is moderate. In the case of high wind generation, where all the wind farms in Area A are producing rated output, there is a probability of reverse power flow. The amount of active power flowing in the reverse direction depends on different factors, For example, the amount of active power generated in Area B and demand levels for summer, summer night valley, and winter cases for both areas.

Analysis is carried out on different levels of wind generation in Area B. The first case considers the scenario where the wind generation is one third of rated power in Area B and the second scenario considers the case where the wind generation is dispatched at the rated output. The amount of wind generation in Area A would depend on probability of wind turbine outages and wind speed at Coomacheo. A cross-correlation of 1 is assumed for all four wind farms in Area A, due to all these four wind farms being in a radius of 40 miles.

6.4.2.1 SUMMER NIGHT VALLEY 2008

For summer night valley, the probability of having reverse power flow through transformer is very high as compared to summer and winter case analysis. The level of local demand is lowest, therefore there is less capacity to absorb local wind generation and any extra amount of power has to be transferred through this particular transformer or the 110 kV CLA- 110 kV MAC transmission line. The amount of power that can be transferred to Area B through the 110 kV CLA- 110 kV MAC transmission line would also depend on the local wind generation and demand level in Area B. Line flow is arranged from lower value to higher value.

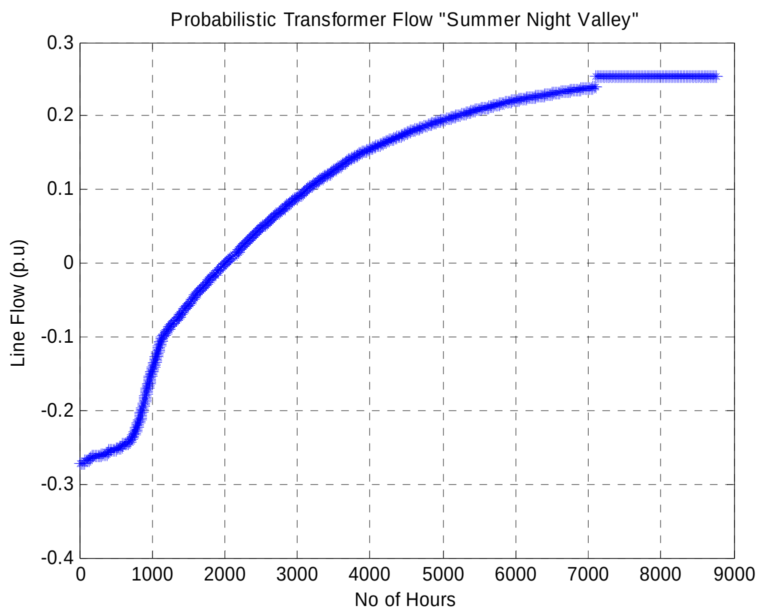


Figure 30: Active Power Flow for One Third Outputs

Figure 30 shows the active power flow through the 220 kV CLA – 110 kV CLA transformer when wind generation is dispatched at one third of rated output in Area B. For one year analysis based on wind data for summer period generated using the Markov's method, the number of hours with reverse power is 2000, and maximum reverse power is 27.5 MW. When the wind speed is equal to or greater than the rated wind speed, the output of the wind turbine is equal to rated output and wind turbine output would not increase regardless of the increase in the wind speed greater than the rated speed as shown in equation 6.9. That's why the graph shows the straight line for the last 1800 hours.

If $U \geq U_{cut\_in}$ and $U < U_{rated}$

$$P = P_{rated}\left(\frac{U}{U_{rated}}\right)^3 \tag{6.8}$$

If $U_{cut\_out} > U \geq U_{rated}$ (6.9)

$$P = P_{rated}$$

If $U < U_{cut\_in}$ or $U > U_{cut\_out}$

P=0

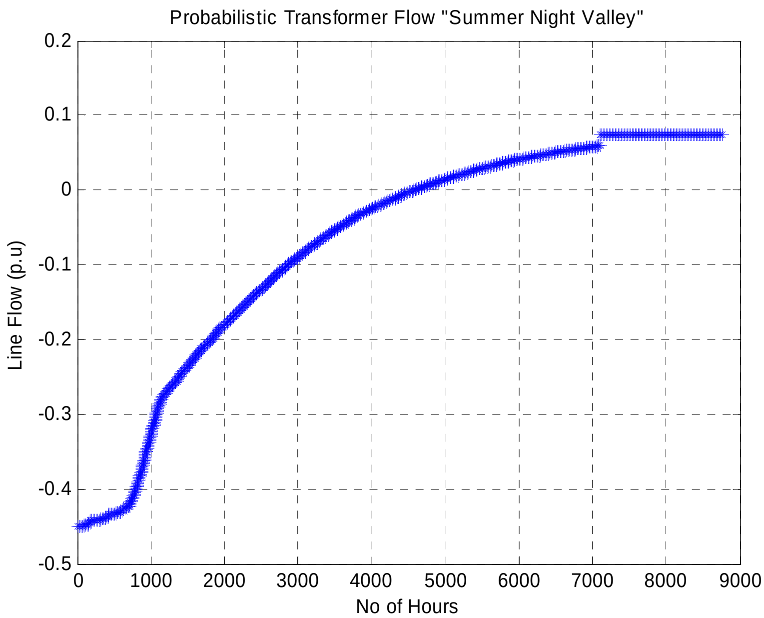


Figure 31: Active Power Flow for Rated Outputs

If the wind generation in Area B is increased to rated output, the level of reverse power flow increases significantly as the local demand in Area B can be supplied by wind generation and the active power transferred through the 110 kV CLA – 110 kV MAC line reduces, resulting in an increase in reverse power flow through the 220 kV

CLA – 110 kV CLA transformer. For one year analysis, there are 4860 hours with reverse power flow and maximum active reverse power is 45 MW as shown in Figure 31.

6.4.2.2 SUMMER 2008

Analysis based on the summer 2008 load data shows a decrease in active reverse power flow. As the local demand increases, more wind generation is absorbed locally and hence reducing the amount of power to be transferred to other areas. If wind generation in Area B is dispatched at one third of rated output, no reverse power flow is observed as shown in Figure 32 as all the additional power is transferred to Area B.

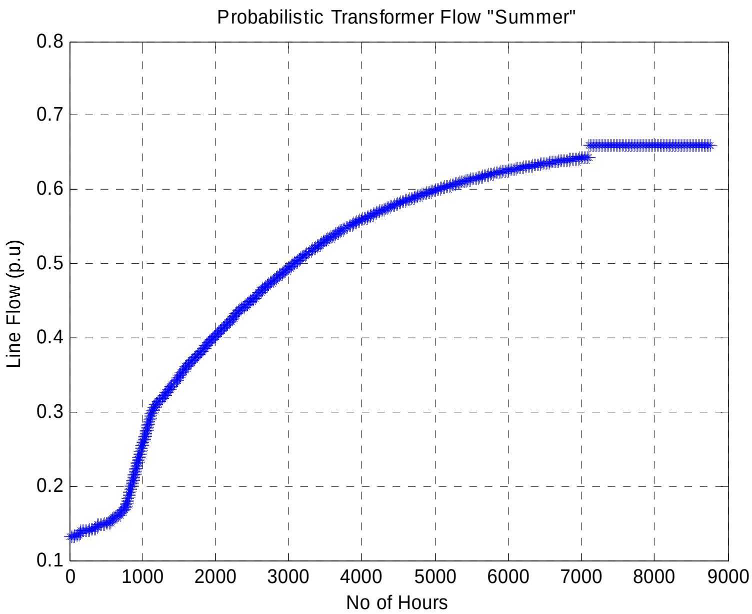


Figure 32: Active Power Flow for One Third Outputs

Increasing the wind generation level in Area B results in a decrease in active power flow through the 110kV CLA – 110kV MAC transmission line resulting in reverse power flow. The number of hours with reverse power is 856 and maximum level of reverse power flow is 5.6 MW as shown in Figure 33.

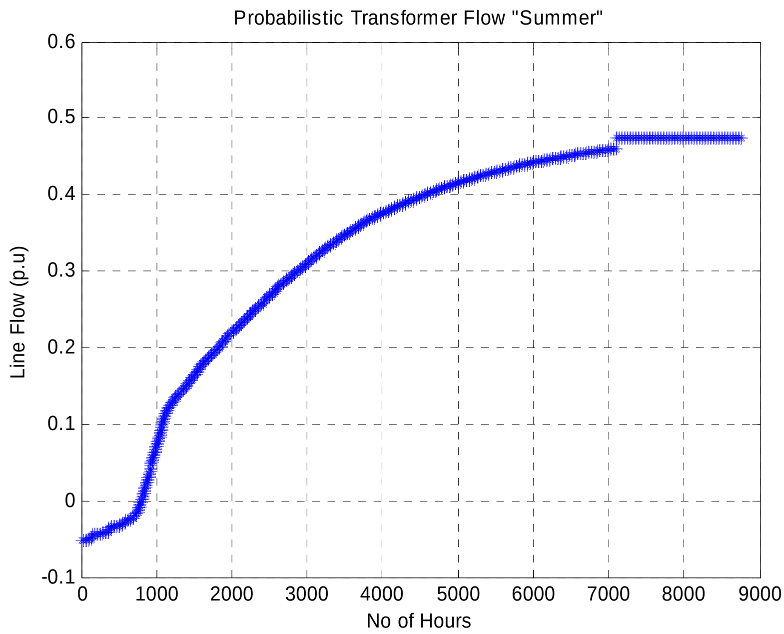


Figure 33: Active Power Flow for Rated Output

6.4.2.3 WINTER 2008

For winter case, the demand level is highest and any amount of wind generation can be absorbed locally. There is no reverse power flow as shown in Figure 34 for one third wind generation in Area B.

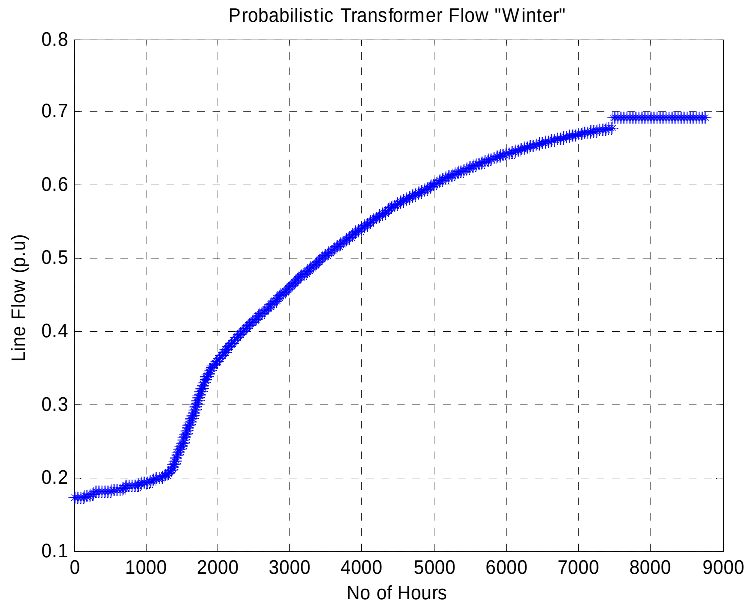


Figure 34: Active Power Flow for One Third Outputs

But if the generation level is increased to the maximum, the reverse power flow is a possibility but the amount of reverse power is negligible as shown in Figure 35.

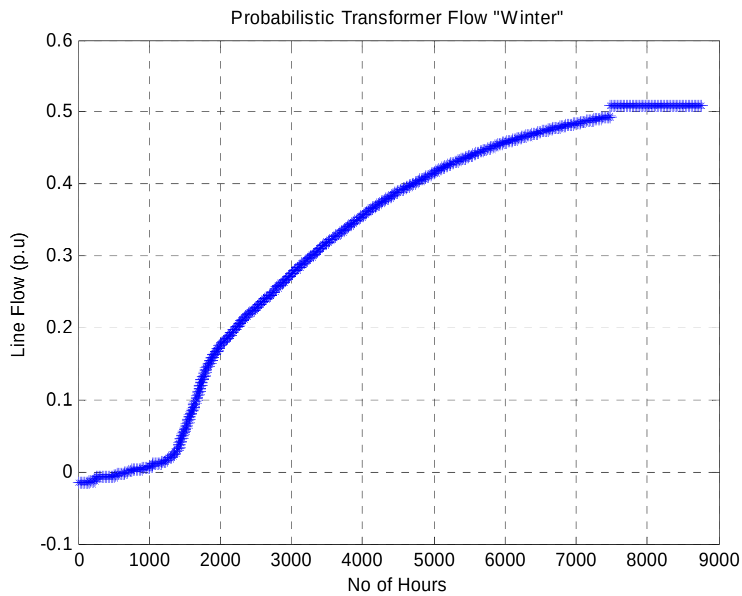


Figure 35: Active Power Flow for Rated Outputs

6.5 CONTINGENCY ANALYSES

6.5.1 LINE FLOW CONTINGENCY ANALYSES

As it is observed in the deterministic analysis, outage of any transmission line connected to Clonkeen 110kV or Knockearagh 110kV will cause line overloading in extreme conditions (when power is generated at rated output). Load flow analysis was carried out based on the Summer 2008 Forecast Statement data [28] and results showed that it is true in the case of Clonkeen 110kV but if the 110kV transmission line between KER-OUGT is out-of-service, it would help to use the active power generated by Clonkeen group, because, based on summer 2008 forecast power demand, 46MW power is transferred to the 110 kV Knockearagh bus by this transmission line to supply the local load which in the case of outage of 110 kV KER – 110kV OUGT can be supplied by the Clonkeen Group. The network diagram is shown in appendix A Figure 65.

For better understanding, probability analysis was used based on 2005 wind speed data. The results show that there is only a low probability of having power generated at rated output and outage of critical transmission lines. Figure 36 and Figure 37 show line flow probability and Cumulative probability distribution for the 110kV CLON-CLA transmission line when the 110kV CLON-KER is out-of-service.

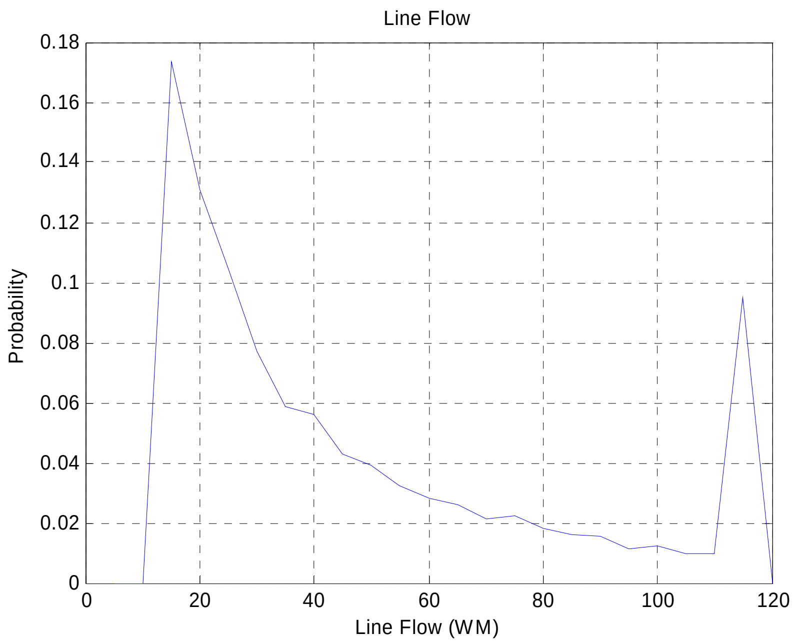


Figure 36: Probabilistic Line Flow

There is only a 10% probability of having power generated at a level greater than 100MW based on the Coomacheo wind farm. The reason for the first peak in the graph is when the wind speed becomes greater than the cut in speed (U_{cut_in}), the wind turbines start generating power. Similarly for the second peak in the graph occurs due to wind speed becoming equal to or greater than rated wind speed (U_{rated}) when rated power is generated.

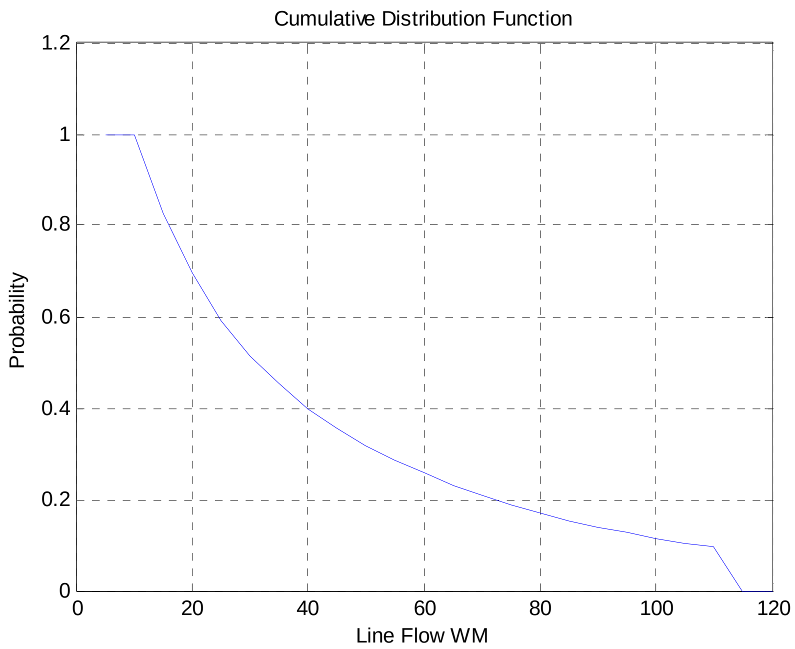


Figure 37: Cumulative Distribution Function

By considering the probability of outage of critical transmission lines, with all three wind farms operating at their rated output, and all wind turbines in operation, it would reduce the probability of having line overloading as shown in Figure 38. Wind data generated by Markov method for six years (52560 hours) is used for probabilistic analysis. Load flow analysis is carried out for six years and the line flow is only calculated if the 110kV CLON-KER is out-of-service to reduce the computation time. Line flow is arranged from lower value to higher value. Figure 38 shows the line flow for the final few hours for six years analysis period.

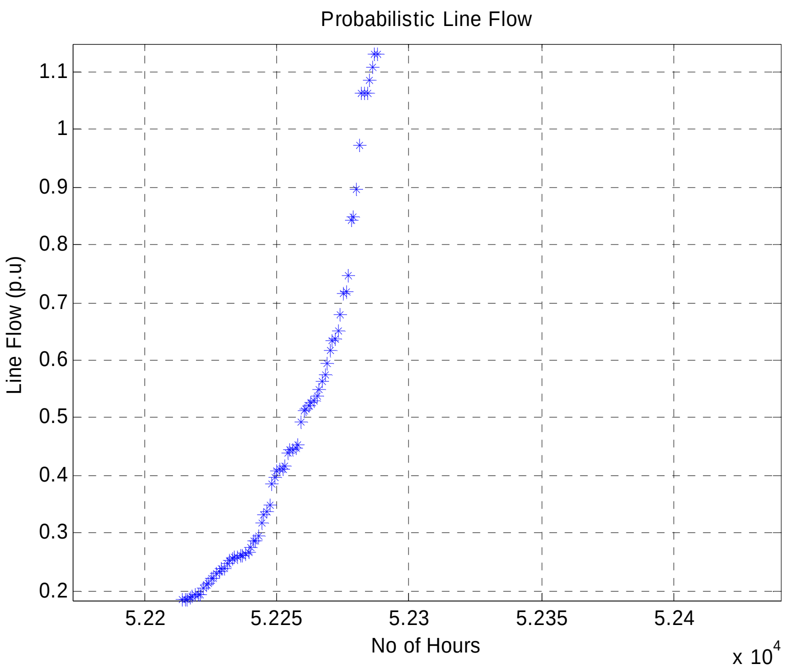


Figure 38: Line Overloading

6.5.2 REVERSE POWER FLOW CONTINGENCY ANALYSES

In the case of an outage of the 110kV CLON-KER line, there is the possibility of having reverse power flow through that particular transformer if the Clonkeen group wind farms are operating at high output. All the generated power (up to 115 MW) has to be transferred to the network by using either the 220kV CLA - 110kV CLA transformer or the 110kV CLA – 110kV MAC transmission line. Power flow through the 110kV CLA – 110kV MAC line would also depend on the generation in the red Area B. A reverse power flow diagram is shown in Appendix A Figure 68.

If the wind generation is dispatched at one third of rated output except for the Clonkeen group, load flow analyses carried out (without considering the probability of wind turbine outage and transmission line availability) shows that there is only a very small probability of 10% of having reverse power flow through the transformer in high wind power generation conditions when 110kV CLON-KER is out-of-service as shown in Figure 39.

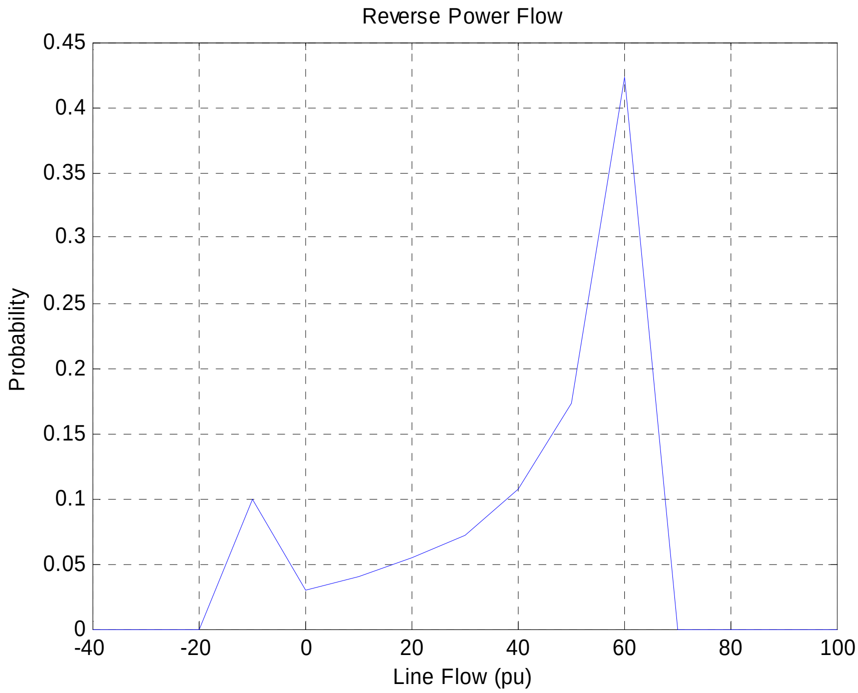


Figure 39: Reverse Power Flow

If we use Monte Carlo analyses to consider the stochastic nature of wind speed, and including the availability of wind turbines and the transmission line outage rate in the analyses, for the period of six years, the number of hours resulting in reverse power flow is 25 as shown in Figure 40.

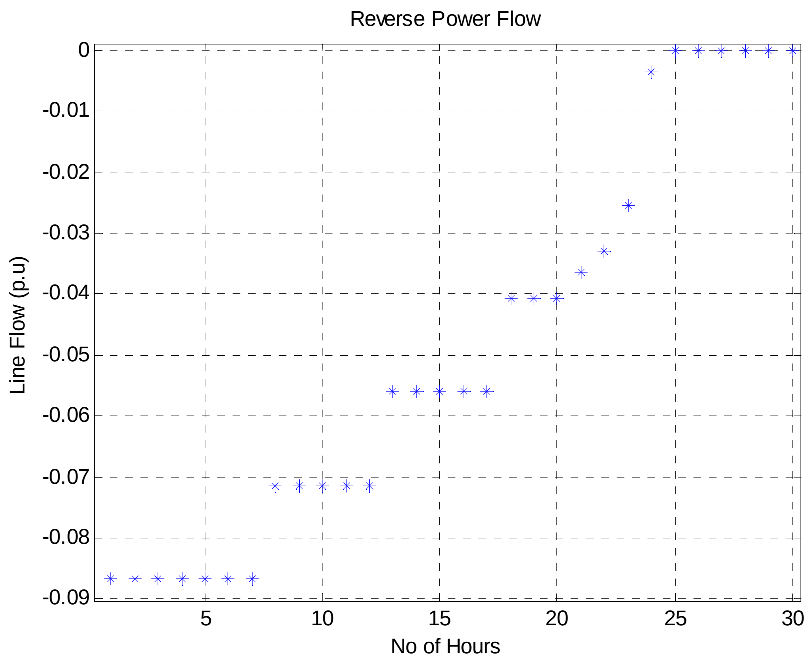


Figure 40: No of Hours with Reverse Power Flow

The outage rate for this transmission line is taken as one outage per year and ten hours for each outage based on the length of transmission line. The numbers of hour are arranged in ascending order. To reduce the computation time, the line flow is only calculated for the outage of 110kV CLON-KER. Reverse power flow through this particular transformer only occurs when line flow on 110kV CLON-CLA is more than 90MW.

6.6 ADDITIONAL GENERATION

According to the deterministic technique analysis, the amount of additional generation that can be connected to Knockearagh 110kV Bus for the summer period is 17MW before the critical 110 kV CLON – 110kV CLA transmission line becomes overloaded. Similarly, for winter, up to 80MW of additional wind generation can be connected to the same point based on rated output from all the wind farms in the Kerry region.

For probabilistic analysis, 40 MW of additional generation is connected to the 110kV Knockearagh Bus. The analysis was carried out for three different scenarios; summer, winter and summer night valley. The wind profile used for each case is based on Markov's wind data generated from the 2005 Coomacheo wind data profile. Wind data for the summer period is based on the Coomacheo wind data for the period of April 2005-September 2005. Similarly for the winter period, the wind data profile is based on Coomacheo wind data for the period of October 2005-March 2006. Analysis was carried out for one year for two different levels of wind generation connected to 110kV Ballylickey, Bandon and Dunmanway transmission buses. Output from wind farms connected to 110 kV Clonkeen, Knockearagh, Trien and Tralee buses depends on availability of wind turbines and wind data profile generated using Markov's Method. The critical line flows for the summer and winter period for both scenarios are shown in Appendix A, Figure 69 and Figure 70.

6.6.1 SUMMER NIGHT VALLEY 2008

6.6.1.1 ONE THIRD OUTPUT

For summer night valley, the load level is lowest. High wind generation can not be absorbed locally and additional wind generation has to be transferred to other parts of network. The wind profile used for the summer night valley analysis is based on summer 2005 Coomacheo wind data generated using the Markov's method. The rating for the 110 kV CLA-MAC and 110 kV CLA-CLON transmission line for the summer period is 107 MW. As these analysis are based on active line flow only, rating is reduced by 20% to 85 MW to represent the reactive power flow.

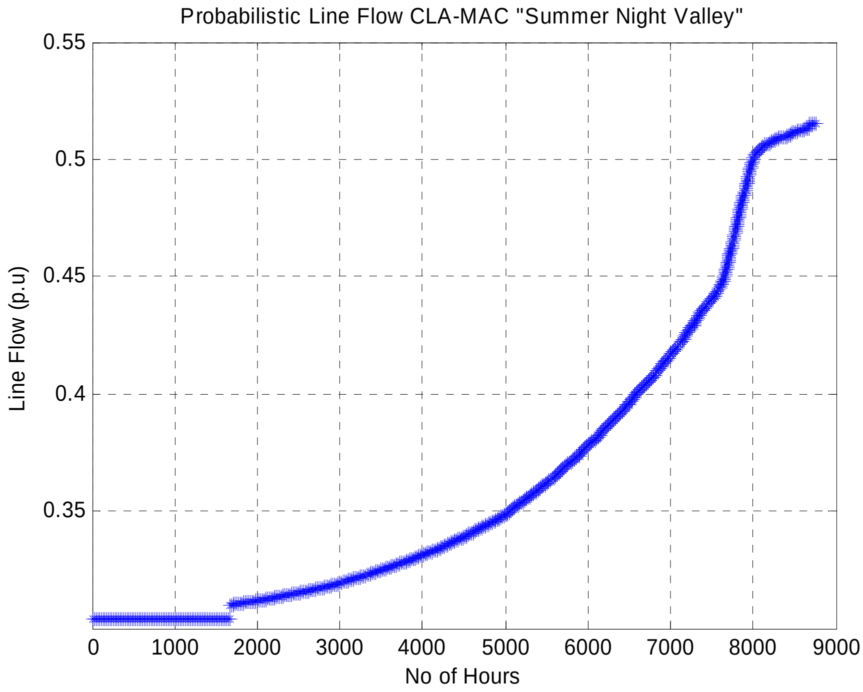


Figure 41: Active Power Flow for One Third Outputs

For the first scenario, the wind generation dispatched in Area B is one third of rated output. Figure 41 and Figure 42 shows the line flows for both transmission lines. For 110 kV CLA-MAC transmission line, the line flow is 52 MW. For 110 kV CLA-CLON transmission line, the flow exceeds the rating by 5 MW. If wind generation from Clonkeen group wind farms has to be curtailed to reduce the line flow, the annual amount of wind generation curtailed is 2.631 GWh which is less than 1% of annual wind generation based on 35% capacity factor.

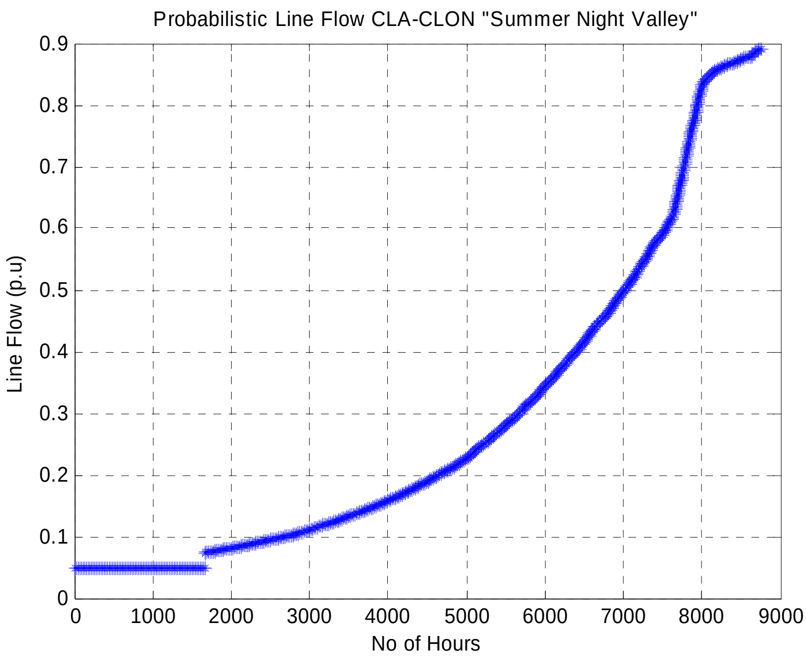


Figure 42: Active Power Flow for One Third Outputs

Due to the level of local load at its minimum, the reverse power is likely to occur for summer night valley case. The maximum reverse power is 37 MW and the number of hours with reverse power flow is 2500 hours as shown in Figure 43.

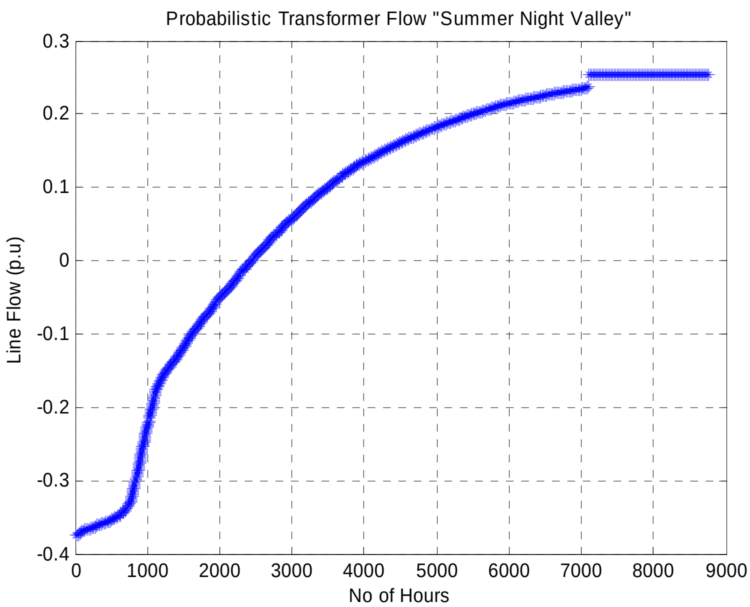


Figure 43: Reverse Power Flow for One Third Outputs

6.6.1.2 RATED OUTPUT

For the second scenario, wind generation connected to 110kV Ballylickey, Bandon and Dunmanway transmission Buses is dispatched at rated output. The line loading for 110 kV CLA-CLON transmission line reduces to 81 MW. Similarly this increase in generation also has effects on the line flow for 110 kV CLA-MAC transmission line.

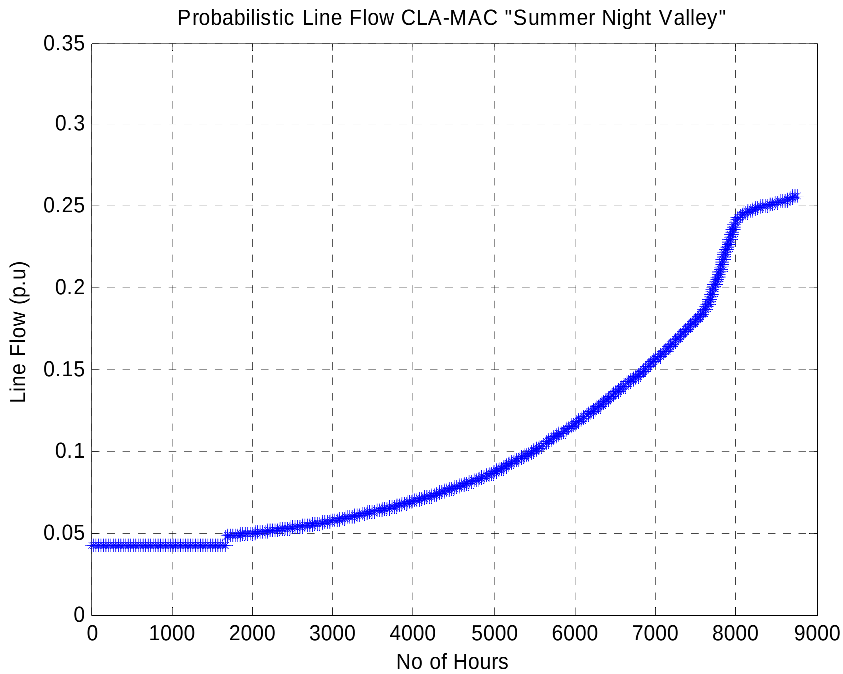


Figure 44: Active Power Flow for Rated Outputs for CLA-MAC

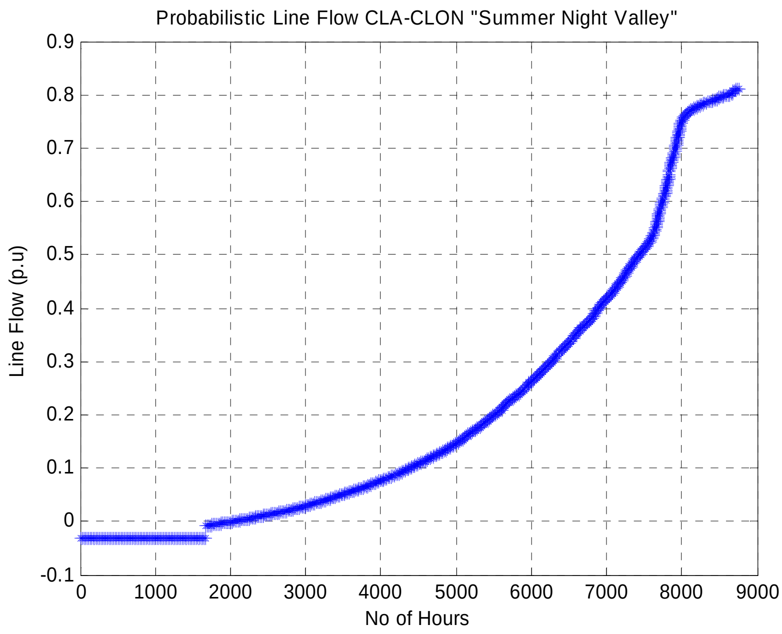


Figure 45: Active Power Flow for Rated Outputs for CLA-CLON

For rated output, the reverse power flow increases due to increase in the level of wind generation level in Area B. The maximum reverse power is 55.48 and the number of hours with reverse power flow is 5000 as shown in Figure 46.

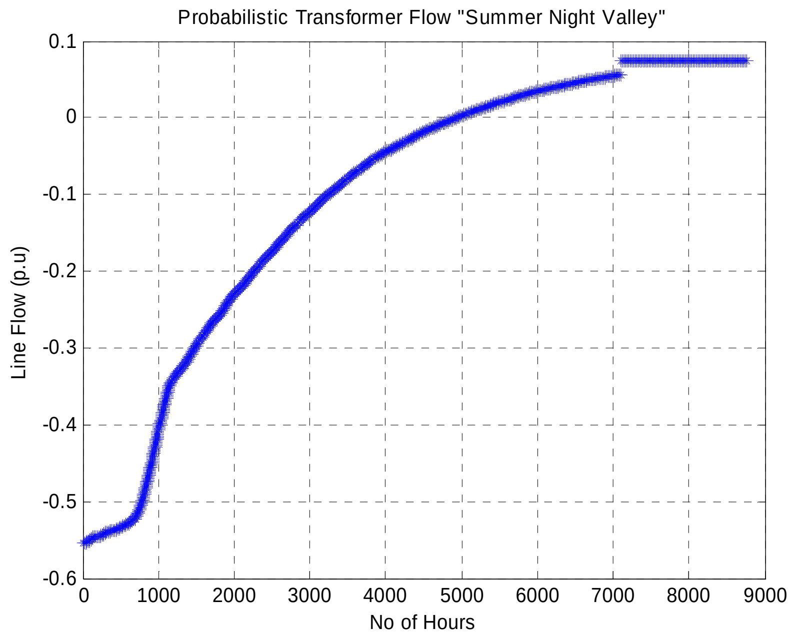


Figure 46: Reverse Power Flow for Rated Outputs

6.6.2 SUMMER 2008

6.6.2.1 ONE THIRD OUTPUT

Wind generation connected in Area B, to 110kV Ballylickey, Bandon, Dunmanway transmission buses is dispatched at one third of rated output. By using wind profile generated by using Markov's method based on summer wind profile of recorded data, line flow analyses are carried out for a one year period. Figure 47 shows the line flow for 110 kV CLA – 110 kV MAC transmission line and Figure 48 shows the line flow for critical 110 kV CLON – 110 kV CLA transmission line.

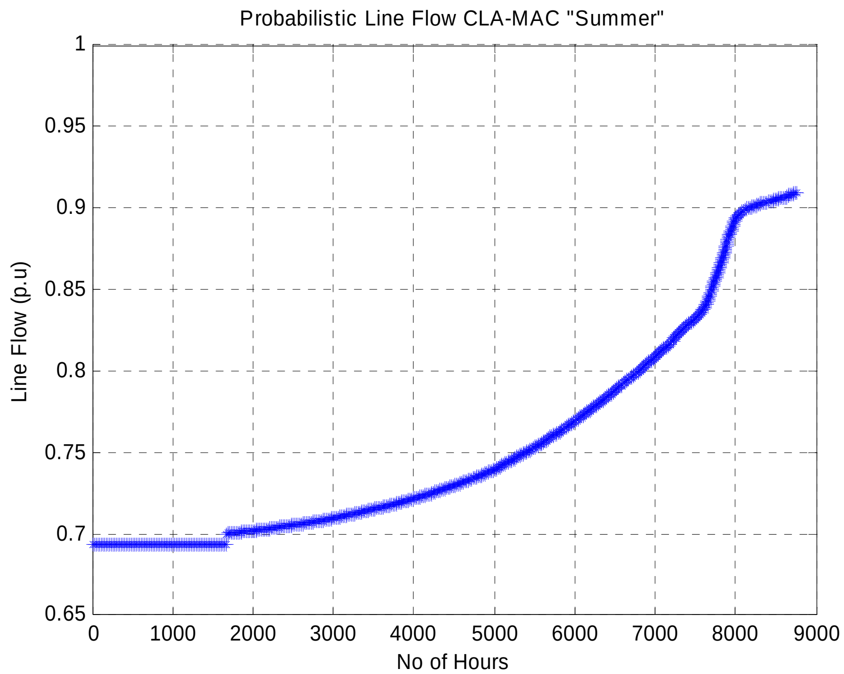


Figure 47: Active Power Flow for One Third Outputs for CLA-MAC

Figure 47 and Figure 48 shows the line overloading for both transmission lines. For the 110 kV CLA – 110 kV MAC, the number of hours with line overloading is 950 but it only exceeds the rating by 6.5MW as shown in Figure 47.

Similarly for the 110 kV CLON – 110 kV CLA transmission line, the number of hours with line overloading is 700 but it only exceeds by 4MW as shown in Figure 48. If wind generation is curtailed to reduce the line flow to 85 MW for the 110 kV CLON – 110 kV CLA transmission line, the amount of wind generation that needs to be curtailed for one year is 1.737 GWh. For the 110 kV CLA – 110 kV MAC transmission line, wind curtailment from the Clonkeen group wind farms would not have a significant effect as line flow depends more on the demand in Area B rather than generation from Area A.

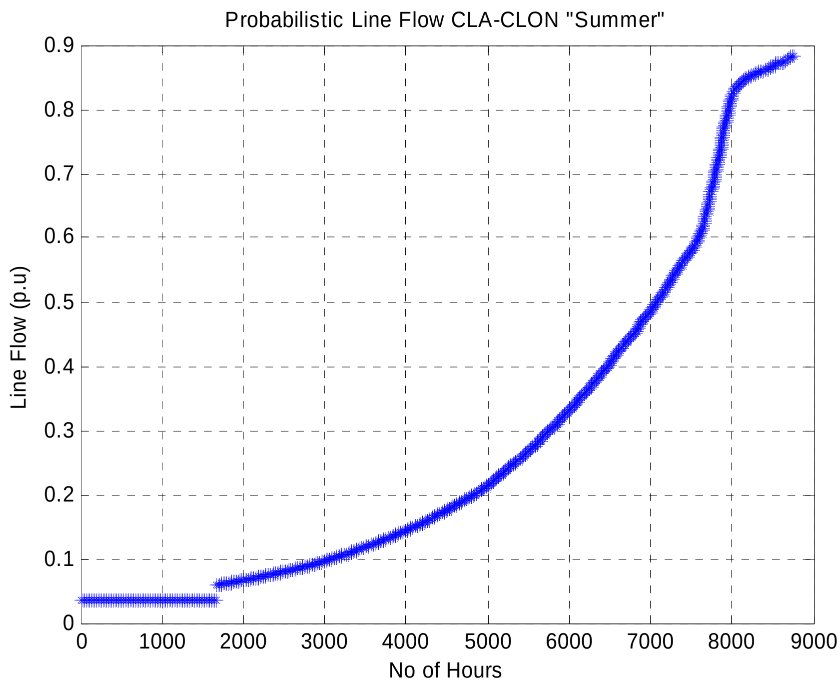


Figure 48: Active Power Flow for One Third Outputs for CLA-CLON

For summer period, the reverse power flow is less likely to occur due to the increase in the local load level as shown in Figure 49.

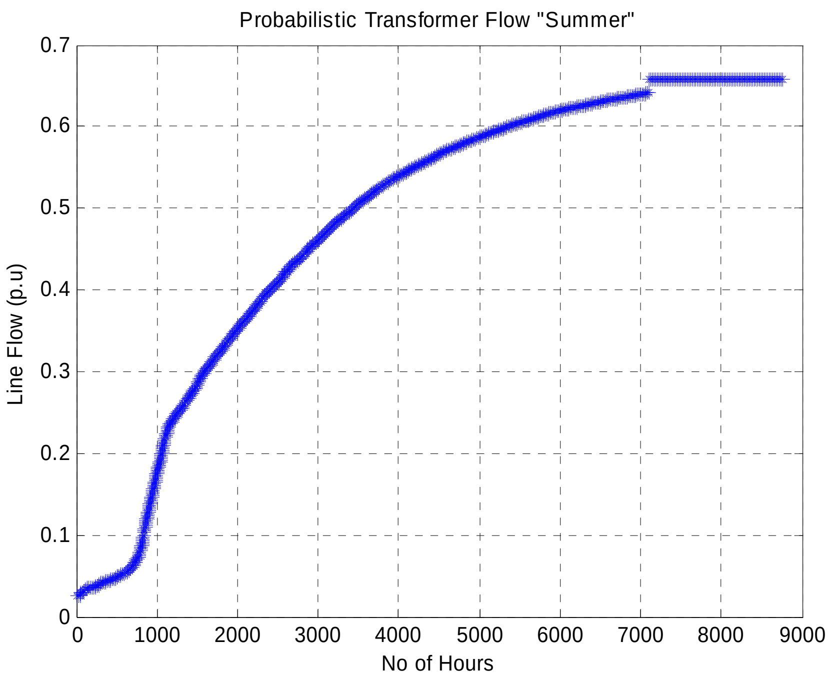


Figure 49: Reverse Power Flow for One Third Outputs

6.6.2.2 RATED OUTPUT

For the second scenario, wind generation connected to 110kV Ballylickey, Bandon and Dunmanway transmission buses is dispatched at rated output. As mentioned before, line flow for 110 kV CLA – 110 kV MAC transmission line depends more on demand from Area B. By increasing the wind generation locally, demand levels that have to be supplied by this transmission line reduces and line flow is reduced significantly to 65 MW as compared to 91 MW for the first scenario. The line flow is shown in Figure 50.

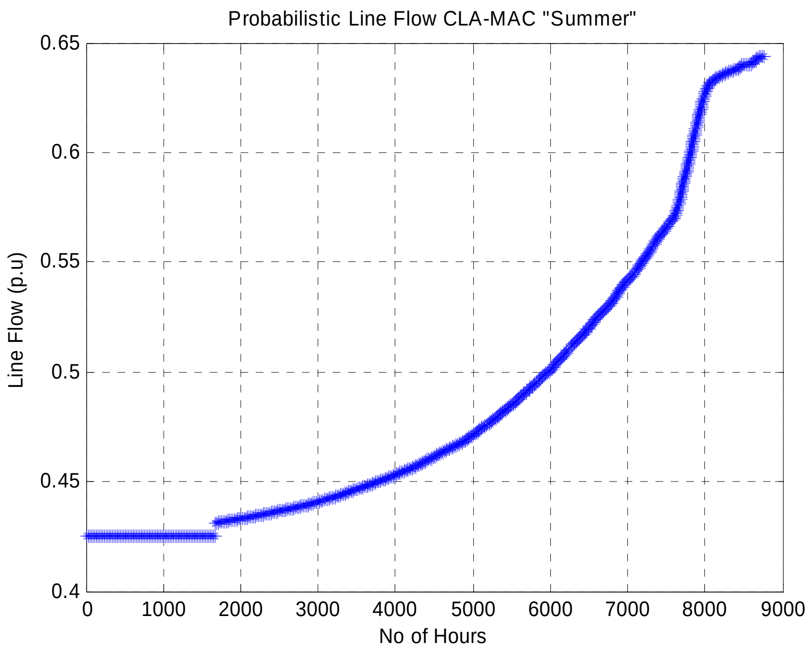


Figure 50: Active Power Flow for Rated Outputs for CLA-MAC

Similarly for the 110 kV CLA – CLON transmission line, the line flow is reduced to 80 MW as shown in Figure 51, which shows that the increase in wind generation in Area B does not have much effect compared to the line flow for 110 kV CLA – MAC transmission line. There is no need for wind curtailment for this scenario.

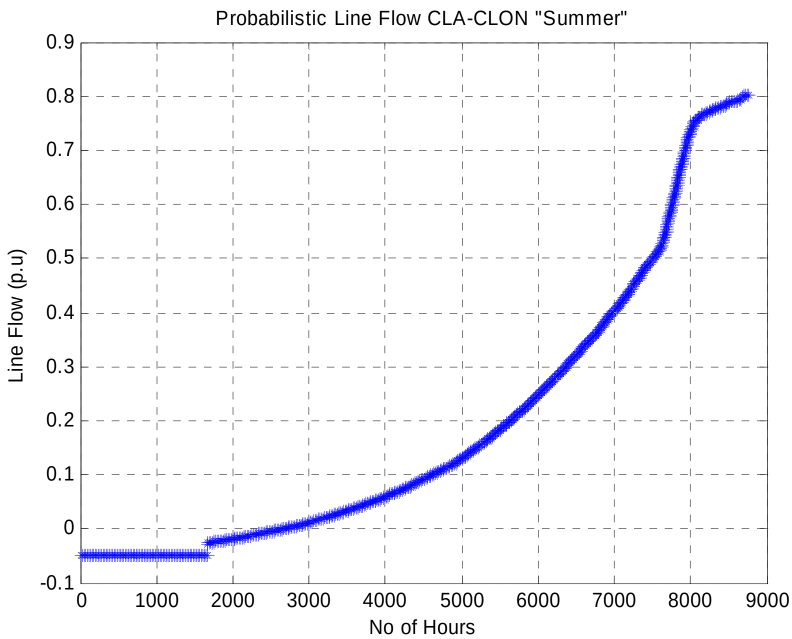


Figure 51: Active Power Flow for Rated Outputs for CLA-CLON

When the wind generation in Area B is dispatched at rated output, the reverse power flow occurs for 1000 hours with maximum power flow of 15.7MW.

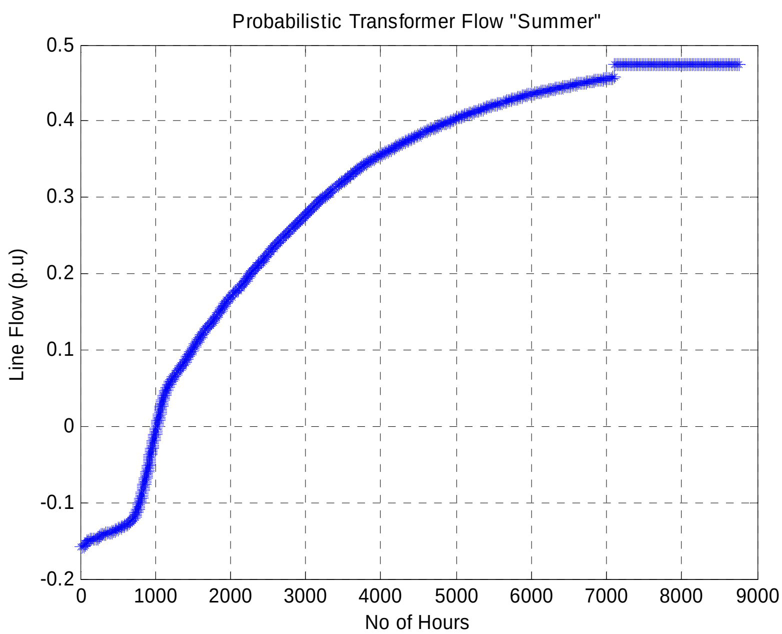


Figure 52: Reverse Power Flow for Rated Outputs

6.6.3 WINTER 2008

6.6.3.1 ONE THIRD OUTPUT

For the winter period, the rating for these two transmission lines increases to 126 MW. By reducing the line flow to take account of the reactive power flow, the rating is reduced to 102 MW.

For the first scenario, the wind generation is dispatched at one third of rated output for Area B connected to 110kV Ballylickey, Bandon and Dunmanway transmission buses. The line flows for one year, based on the wind profile generated by using Markov's method based on recorded data, are shown in Figure 53 and Figure 54.

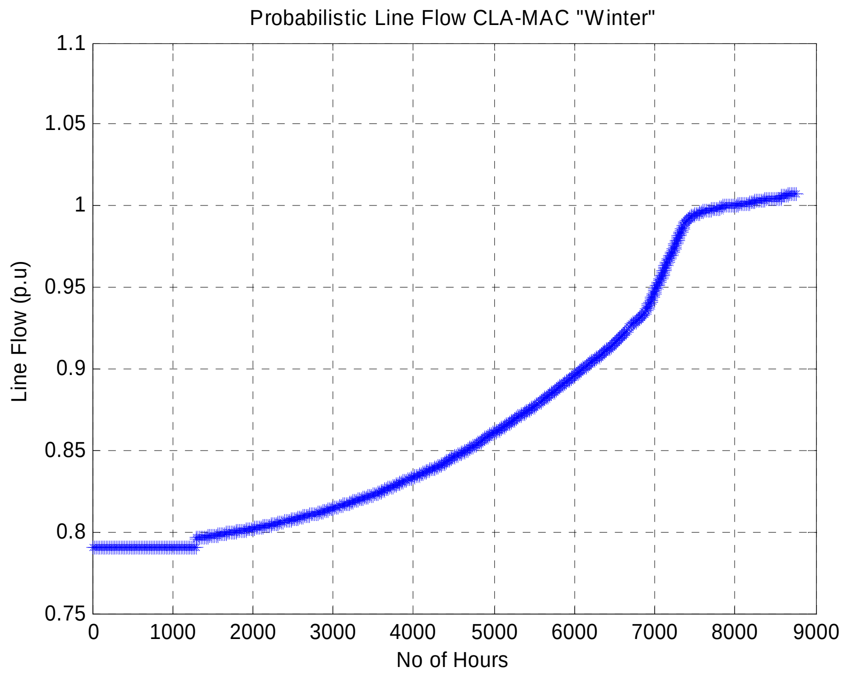


Figure 53: Active Power Flow for One Third Outputs for CLA-MAC

For the 110 kV CLA – MAC transmission line, the maximum level observed is 101MW. For the 110 kV CLA- CLON transmission line, it is 94 MW. Both levels of line flows are just below the rated value. Although there is an increase in demand for the winter period, due to the increase in the transmission line rating, the line flow does not exceed rating.

For the last 1000 hours, the increase in the level of wind generation is very small as compared to the first 7000 hours. It shows that the number of hours with high wind generation can be high but the level by which the wind generation increases is reduced as observed in Figure 54.

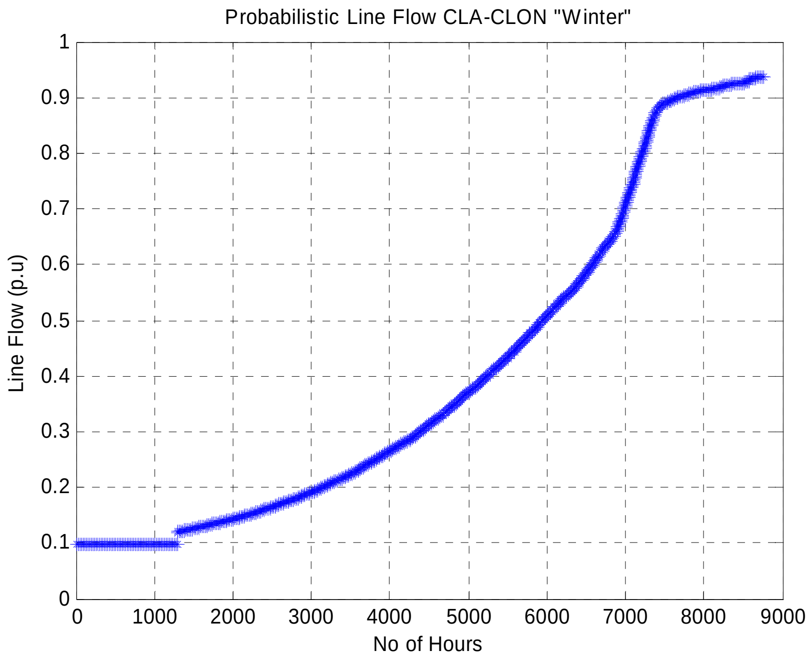


Figure 54: Active Power Flow for One Third Outputs CLA-CLON

For winter period, the reverse power is not observed due to the increase in local load level as shown in Figure 55.

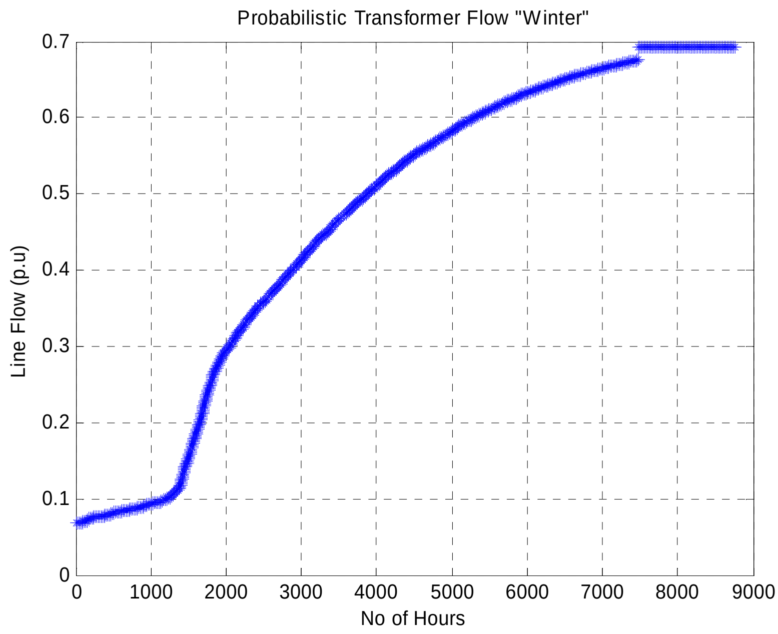


Figure 55: Reverse Power Flow for One Third Output

6.6.3.2 RATED OUTPUT

For the second scenario, wind generation connected to the 110kV Ballylickey, Bandon and Dunmanway transmission buses is dispatched at rated output. By increasing the wind generation locally, demands levels that have to be supplied by 110 kV CLA – MAC transmission line reduces and line flow is reduced significantly to 74 MW as compared to 101 MW for first scenario. The line flow is shown in Figure 56.

Similarly for the 110 kV CLA – CLON transmission line, the line flow is reduced to 86 MW as shown in Figure 57, which shows that increase in wind generation in Area B does not have much effect on line flow for the 110 kV CLA – CLON as compare to the line flow for the 110 kV CLA – MAC transmission line.

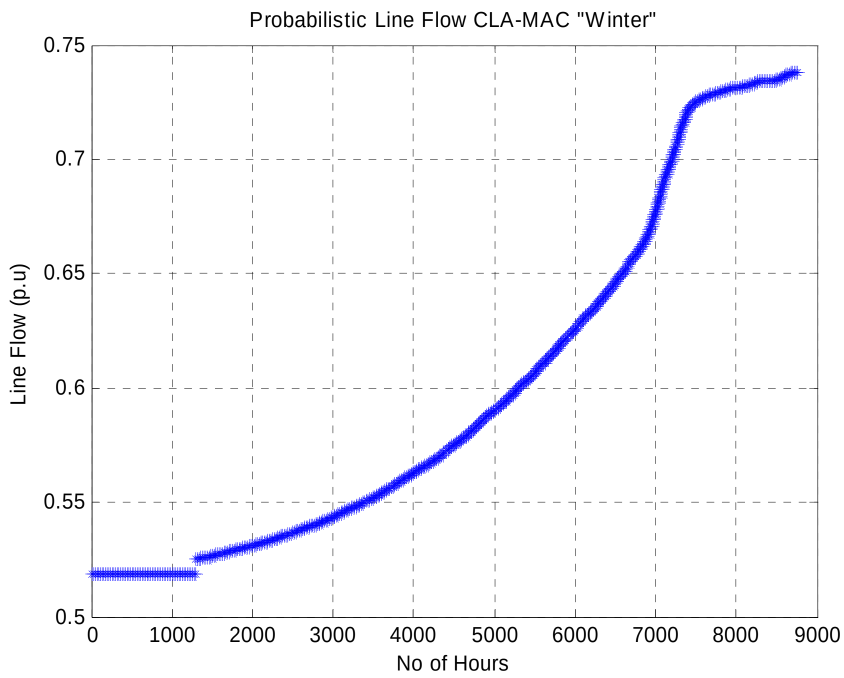


Figure 56: Active Power Flow for Rated Outputs for CLA-MAC

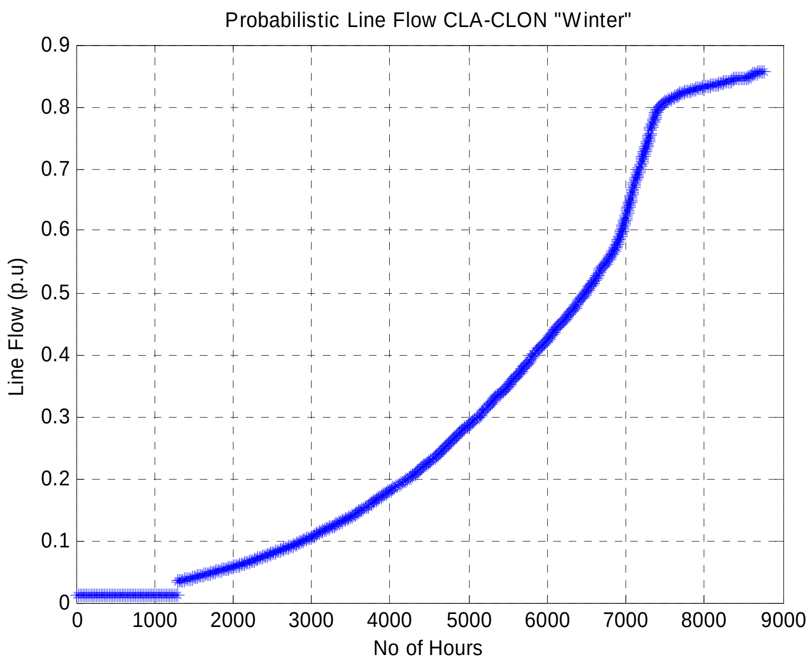


Figure 57: Active Power Flow for Rated Outputs for CLA-CLON

Due to the increase in the local generation, the reverse power is a possibility but reverse power flow level and number of hours are less as compared to other two cases.

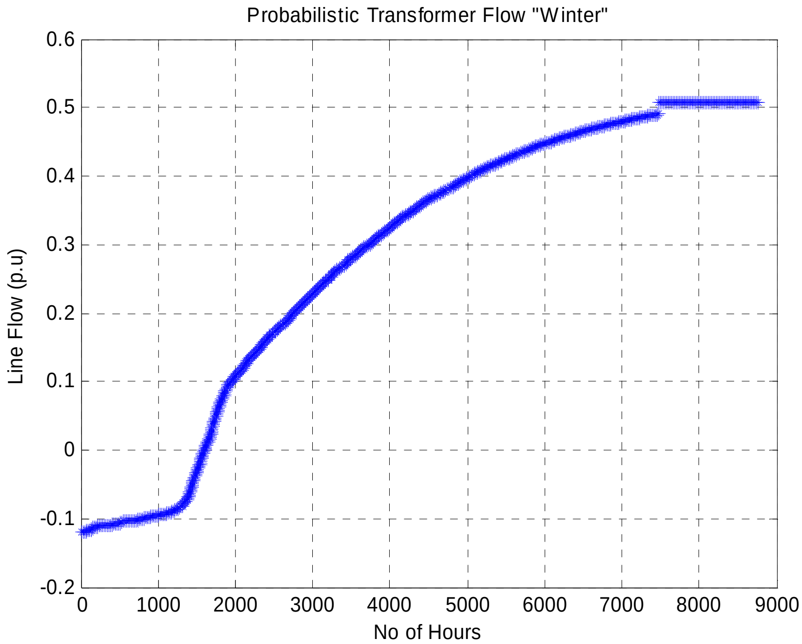


Figure 58: Reverse Power Flow for Rated Output

6.6.4 RESULTS

The result for maximum level of line flow for critical lines and reverse power flow through 220kV CLA-110kV CLA transformer with numbers of hours is shown in Table 3. If the wind generation level in Area B is one third of the rated output, the line loading increases but the probability of having reverse power flow reduces.

For the second scenario, where the wind generation in Area B is dispatched at the rated output, the line loading reduces but the probability of having reverse power flow through transformer increases significantly as shown in Figure 70 .

	Line Rating (MW)	Wind Output Level	110 kV CLON-CLA		110 kV CLA-MAC		Reverse Power Flow	
			Max. L.F (MW)	No. of Line Overloading hours	Max. L.F (MW)	No. of Line Overloading hours	Max. Flow	No. of RPF hours
S.N.V	85	33% Output	89.05	600	51.55	0	-37.5	2500
		100% Output	81.1	0	25.63	0	-55.48	5000
Summer	85	33% Output	88.29	700	90.93	950	0	0
		100% Output	80.1	0	64.3	0	-15.7	1000
Winter	102	33% Output	93.83	0	100.7	0	0	0
		100% Output	85.67	0	73.77	0	-11.98	1585

Table 3: Additional Wind Generation Case Results

Figure 59 and Figure 60 shows the line flow for the two scenarios where the wind generation in Area B is dispatched at one third of the rated output and rated output respectively for 110kV CLA-110kV MAC transmission line.

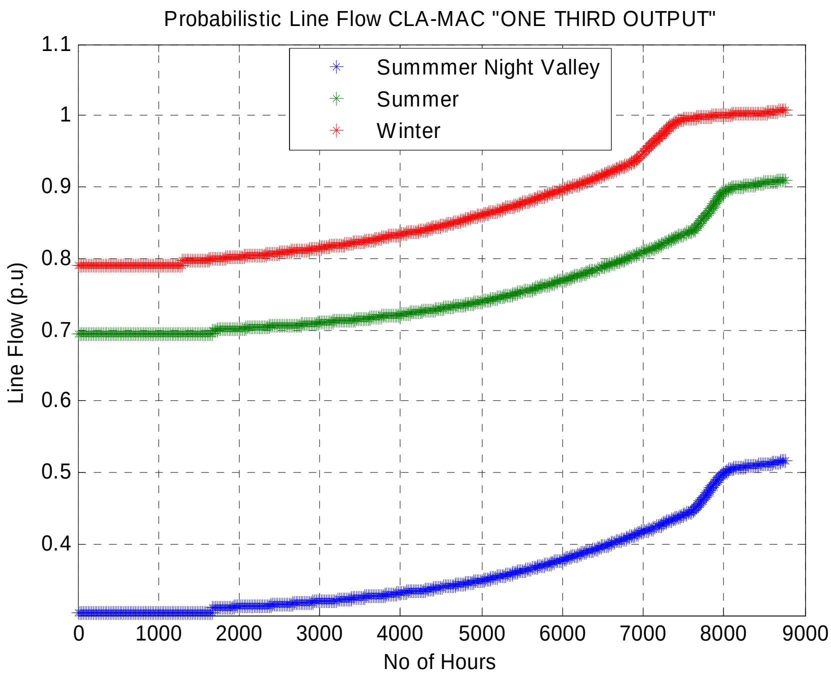


Figure 59: Line Flow for CLA-MAC for One Third Output level

If we compare Figure 59 with Figure 60, it is obvious that the line loading reduces if the wind generation is increased in Area B.

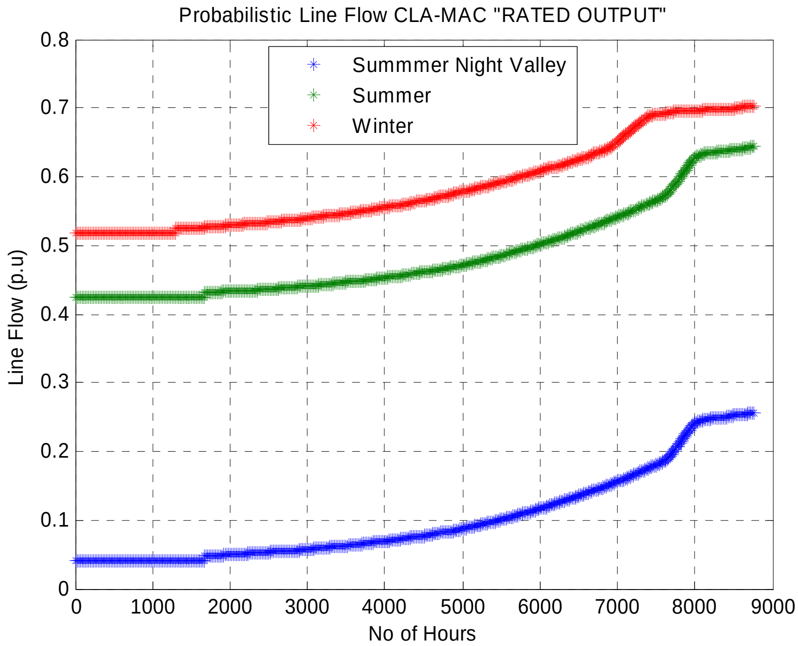


Figure 60: Line Flow for CLA-MAC for One Rated Output level

The line flow for 110kV CLA-CLON transmission line for both scenarios is shown in Figure 61 and Figure 62. Similarly, the line flow reduces if the wind generation dispatched in Area B is increased to rated output.

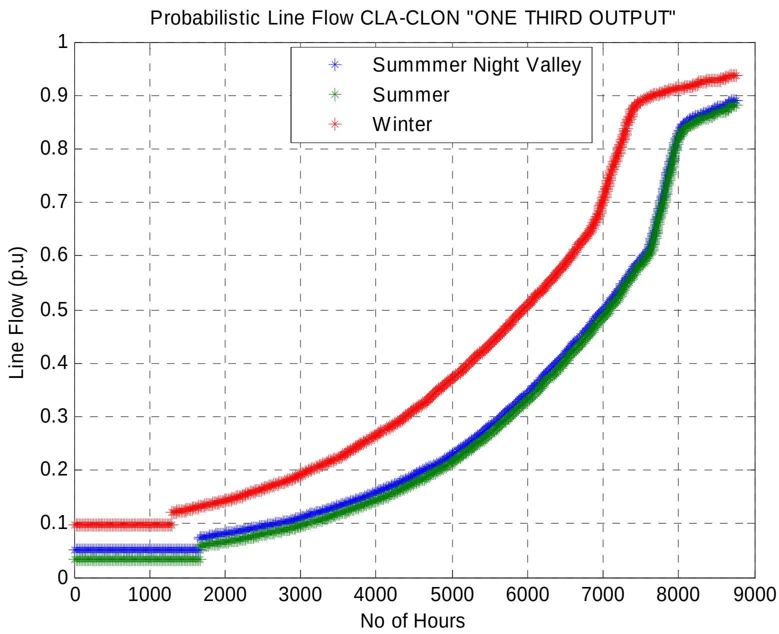


Figure 61: Line Flow for CLA-CLON for One Third Output level

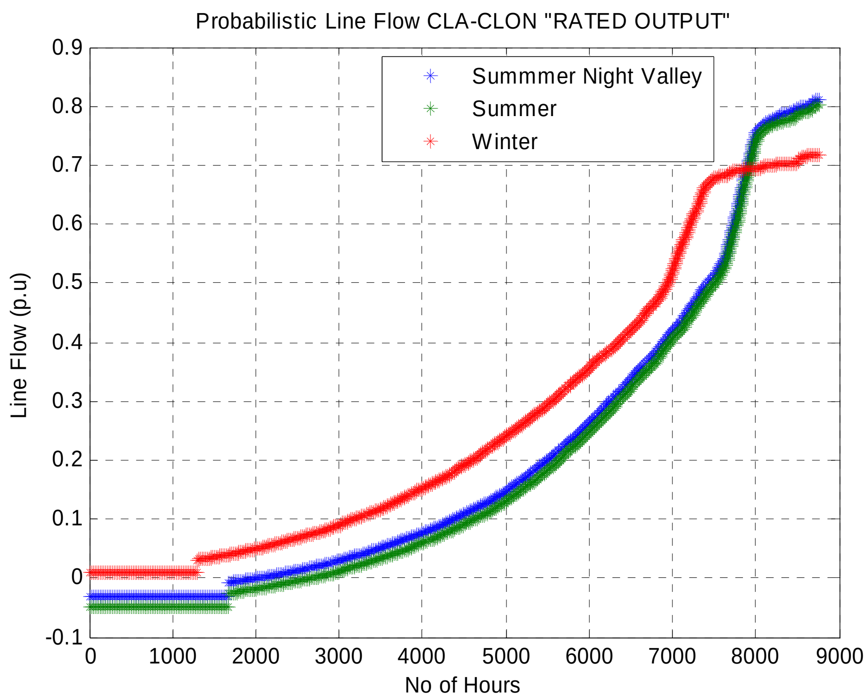


Figure 62: Line Flow for CLA-CLON for One Third Output level

For 220kV CLA-110kV CLA transformer, the reverse power flow increase if the wind generation level in Area B is increased as shown in Figure 63 and Figure 64.

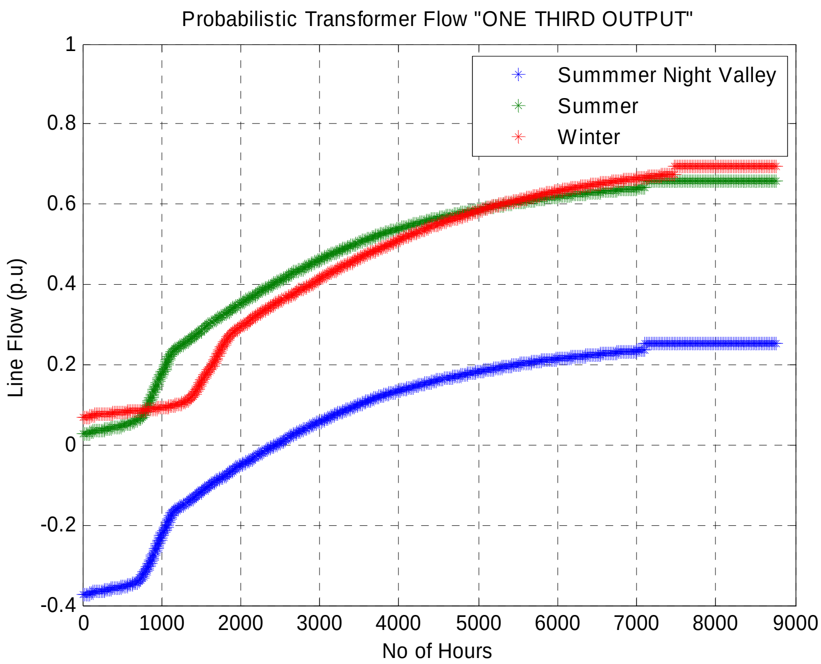


Figure 63: Reverse Power Flow for One Third Output

The reverse power flow level is very high summer night valley case but the numbers of hours with summer night valley period in one year are less as compare to other two cases. Due to high correlation expected for the wind farm located in the south west region, using second scenario for analysis when the wind generation is dispatched at the rated output is a realistic approach.

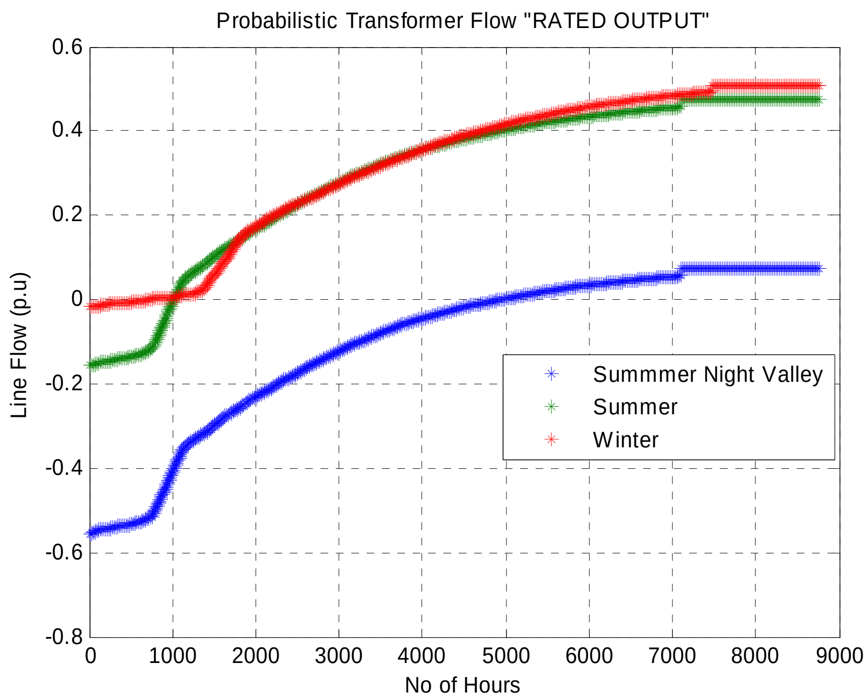


Figure 64: Reverse Power Flow for Rated Output

6.7 EXPECTED ENERGY NOT PRODUCED (EENP)

Wind curtailment from has Clonkeen group wind farms can be justified only due to the following reasons

- Line overloading of 110 kV CLA-CLON transmission line
- Line overloading of 110 kV CLA-MAC transmission line
- Reverse power flow through 110 kV CLA-220 kV CLA transformer

The amount of wind curtailment required to eliminate the possibility of reverse power flow and line overloading is calculated for each case, winter, summer and summer night valley for two different scenarios based on the level of dispatched wind power connected to 110kV Ballylickey, Bandon and Dunmanway transmission Buses.

6.7.1 BASE CASE

No wind curtailment is required due to line overloading for any transmission line in the network for the non-contingency case. There is a possibility of reverse power flow through the 110 kV CLA-220 kV CLA transformer.

For the winter case, there is no need for wind curtailment for the first scenario when the wind generation is dispatched at one third of rated output in Area A due to reverse power flow but if it is increase to maximum output, the total annual wind curtailment required is 1.7192 GWh.

Similarly for summer period, wind curtailment due to reverse power flow is only possible if the wind generation is dispatched at the rated output for Area B and the amount of wind curtailment required is 8.6193 GWh.

For the summer night valley case, wind curtailment is required for both scenarios. The total annual wind curtailment required to eliminate reverse power flow is 141 GWh. If the dispatched wind generation connected in Area B is increased to the maximum level, it is increased to 256GWh.

6.7.2 ADDITIONAL WIND GENERATION

Additional wind generation of 40MW is connected to the 110 kV Knockearagh bus and all of other wind generation connected in the Kerry region is present in Forecast Statement [28].

6.7.2.1 LINE OVERLOADING

For the winter case, there is no need for wind curtailment for both scenarios, as there in no overloading.

For the summer case, wind curtailment is a possibility depending on different scenarios. If the wind generation dispatched in Area B is one third of rated output, there is a possibility of line overloading for both critical lines. Wind curtailment of 1.738 GWh is required to reduce the line overloading on the 110 kV CLA-CLON transmission line. The line overloading on the 110 kV CLA-MAC transmission line can not be eliminated by wind curtailment from the Clonkeen group due to line flow influenced by the levels of demand in Area B rather than amount of wind power generated by the Clonkeen group. If the dispatched wind power is increased to rated output, the line overloading problem is eliminated for both transmission lines.

Wind curtailment for the summer night valley case is a possibility based on exactly the same conditions and scenarios described for the summer case. The level of wind curtailment required to reduce the line overloading on the 110 kV CLA-CLON transmission line is 2.631 GWH. There is no line overloading problems if the wind generation in Area B is increased to rated output.

6.7.2.2 REVERSE POWER FLOW

For the winter period, there is no reverse power flow through the 220 kV CLA – 110 kV CLA if the wind generation in Area B is dispatched at one third of rated output. If the wind generation is dispatched at the rated output, reverse power flow is observed for 2000 hours and the maximum level of reverse power is 11MW. Total annual wind curtailment required based on the winter period data is 44.192 GWH.

Similarly for the Summer period, there is no reverse power for the first scenario, but if the wind generation is dispatched at the rated output, reverse power is a possibility when wind generation is high from the Clonkeen group. The annual wind curtailment required based on the summer period data is 36.358 GWh.

For the Summer night valley case, reverse power is a very high possibility due to the local demand level being lowest. For the first scenario, the number of hours with reverse power flow is 2500 and maximum level of reverse power flow is 38 MW. The annual curtailment is 141 GWh. For the second scenario, when wind generation is dispatched at rated output, the annual curtailment is 315 GWH.

6.8 CONCLUSION

For the base case analysis, there is no need for wind curtailment due to line overloading. This analysis also shows that by increasing wind generation levels in an area where significant amount of load is connected, it helps to reduce the line loading due to embedded generation.

But high levels of wind generation can also cause reverse power flow through transformer especially when local load is at its minimum level. For the summer night valley case, when the generation in Area B is high as well in Area A, reverse power flow increases. For the Summer and Winter period, reverse power is only observed for the high wind speed scenarios in Area B but its levels is not significant. Due to the close proximity of wind farms in Area A and B, cross-correlation for their wind profile would be high and it's much more likely the high wind generation is going to occur at the same time leading to an increase in risk of reverse power flow.

The Annual wind curtailment for the base due to reverse power flow through transformer for the Summer night valley, summer and winter case is 256GWh, 8.6193 GWh and 1.7192 GWh respectively. The winter period is half of the annual period, summer is 33% and summer night valley is only 17%. The total wind curtailment required to eliminate reverse power flow for the case when the wind generation in Area B is dispatched at the rated output is

$$\text{Total Annual Wind Curtailment} = 256*17\%+8.6193*33\%+1.7192*50\%$$
$$= 47.22 \text{ GWh}$$

For the contingency case, the probability of the critical transmission line being out-of-service is very small. Based on IEEE Reliability Test System, for these two critical transmission lines, 110kV CLA-CLON and 110 kV CLON-KER, are assumed to have one outage per year and 10 hours for each outage per year. Probability distribution function shows that there is only 15% probability of having line flow greater than line rating when the critical transmission line is out-of-service, this further reduces the risk of line overloading and reverse power flow. If we consider all probabilities in the system, for the six year period, there are only 25 hours resulting in line overloading and reverse power.

From the above two analysis, it is obvious that for wind farm developers, the restriction on reverse power flow should be a major concern rather than contingency case as the probability of critical transmission lines being out-of-service with high wind speed is very low.

According to the Deterministic technique analysis, for the summer case, 17.8 MW of additional generation can be connected to the 110kV KER bus. For additional wind generation analyses, 40MW of additional wind generation was connected to the 110kV KER bus. Analysis show that high level of wind generation in Area B would help to reduce the line overloading or in other words the line overloading problem was eliminated when the wind generation in Area B is increased to rated output. It also shows that additional wind generation in Area B can reduce the line loading or 110 kV CLA-MAC line as the loading on this lines depends on the difference in load connected and power generated in Area B. Due to high cross-correlation for wind farms in Area A and Area B, the wind generation is expected to occur at the same time, thus reducing the risk of line overloading.

Reverse power flow in the case of additional wind generation is possible due to the same reason as mentioned for the base case. The occurrence of high wind generation at the same time in Area A and B would be a worst case scenario for reverse power flow. If the wind generation is dispatched at one third of rated output for the area B, the level of reverse power flow reduces significantly but due to high cross-correlation, it is less likely that Area A experiences high wind speed and Area B experiences moderate or low wind speed. The method used for base case to calculate the annual wind curtailment required due to reverse power flow can be used for additional wind generation

Total Annual Wind Curtailment = 315*17%+36.35*33%+44.192*50%

= 87.64 GWh

Wind curtailment is a high possibility due to reverse power flow restriction. Allowing reverse power flow would a positive effect on the wind capacity factor. The loading on 110 kV CLA-MAC transmission line does not depend significantly on the wind generation output for the Clonkeen group, and its loading for summer and winter period during high generation is very high. It would make much more sense to upgrade 110 kV-CLA-MAC transmission line and to find some solution to the reverse power flow problem. Line overloading on 110 kV CLA-CLON line is only possible in extreme cases when the wind generation in Area A is high and in Area B is low. Wind curtailment required to eliminate line overloading on that particular line would be insignificant.

7 CONCLUSION AND FUTURE WORK

7.1 CONCLUSION

This thesis used probabilistic techniques for assessment of a transmission network with significant levels of wind generation. Deterministic techniques have generally been used in the analysis of the transmission network. One reason for the approach has been that the reliability of conventional sources used for power generation and of the transmission systems that have been operated and owned by one company. Since the increase in renewable sources and the deregulation of the power system, the use of deterministic techniques for network analysis only is not the suitable option. To consider the variable nature of different renewable sources, the probabilistic techniques can be used to give a better understanding of the effects these sources have on the transmission network.

Probabilistic techniques have been used in [15] and [16] for high voltage and line overloading problems respectively. Ireland has a high potential for wind generation and the amount of wind generation connected to the transmission network is increasing rapidly. But many suitable areas for wind generation do not have a strong transmission network which could result in line overloading and high voltage problems. To overcome these problems, there are two solutions: either upgrade the transmission network or reduce the level of additional wind generation. Transmission network upgrading is very costly and could make a wind generation project economically unviable. Wind power curtailment is the second option but it could result in a significant amount of wind generation not being allowed to connect to the transmission network. By using probabilistic techniques, a better understanding of the behaviour of the transmission network with significant wind generation can be achieved.

In this thesis, the probabilistic techniques were applied to a part of the Irish transmission network with a significant amount of wind generation. Wind speed data recorded over the period of the one year was used to develop a Markov’s model to generate the wind profile for the area. Analyses based on deterministic techniques was carried out and were compared to the probabilistic techniques.

According to the deterministic analysis, the wind generation already connected can cause transmission network constraints for the contingency case. But probabilistic analysis shows that these constraints would not have significant effect on line flow and can easily be avoided by wind curtailment for the short period of time when wind generation is high.

When probabilistic techniques were applied, it was observed that the line overloading for the contingency case is a rare occurrence and the implementation of constraints on generation would not result in a significant decrease of the capacity factor. The reverse power flow during summer night valley period is a high possibility. Up to 40MW of additional wind generation is connected to the 110 kV Knockearagh bus and the results have shown that the line overloading is a rare possibility but the reverse power flow level can increase significantly. To accommodate additional wind generation, the solution to the reverse power flow problem should be a high priority. If line overloading occurs, it can be overcome without a significant level of wind curtailment. Analysis also shows that wind generation does not always result in an increase of line loading. Additional wind generation connected to the distribution network reduces the risk of line overloading. As for most of the wind generation farms the rated output is not high, and wind power can be used locally. Thus reduces the amount of power transferred to supply local load.

The Expected Energy Not Produced (EENP) due to line overloading and reverse power flow is calculated for different cases. A decision can be made on the basis of the cost of wind curtailment and transmission network upgrade to choose the suitable option.

The analysis shows the use of probabilistic techniques for wind generation analysis is a valuable method to assess the capability of the transmission network. Deterministic techniques are suitable for conventional generation where the output can be controlled and they can operate at any desired level. Whenever wind generation depends entirely on the wind speed with typical levels of capacity factor for wind farms in the region of 30%-40%. Under these circumstances, probability gives a complete picture of the choices available when significant wind power is being accommodated.

7.2 FUTURE WORK

This thesis has reported on the application of probabilistic techniques to the assessment of transmission networks with significant wind generation. A number of assumptions have been made which allowed for the development of a Monte Carlo approach to assess the network performance. Further work in this area would involve looking at some of the limitations which were imposed because of these assumptions.

One aspect of future work would be to allow for an hourly fluctuation in the network demand. In the analysis presented above, the variation in load was considered by investigating the network performance for three loading conditions: the peak winter load, the peak summer load and the summer night valley (minimum) load. A more realistic representation of the load would be to allow for the stochastic nature of demand but to follow the typical daily, weekly and season variations. This would obviously increase the complexity of the assessment techniques but would improve the accuracy.

In the analysis presented above, a section of the network covering the Cork/Kerry/Limerick region was considered. Connections to the remainder of the network involved the replacement of the actual line flows with either generators or loads, depending on the power flow direction. The greater the area considered, the better the representation of the actual situation and hence the better the accuracy. As before, however, this would increase the computational requirements of the analysis. On the other hand, it would allow for the consideration of a greater percentage of the actual wind generated which has been connected. In fact, if the full network were considered, the actual dispatch of conventional generation could be included.

This analysis has looked at issues associated with power flow. A full ac loadflow solution of the network would allow for problems of voltage variation due to fluctuating wind power generation to be considered. Again, an ac loadflow would increase the computational effort as the dc loadflow approach or the use of the load flow sensitivity factor would not be adequate.

An additional consideration would be the variable output from multiple wind farms. In the analysis, it was assumed that there was perfect correlation between the outputs in the region. In reality, although the wind farms might be located in close proximity, perfect correlation would not occur and all wind generators would be unlikely to reach peak or at zero output (or any other level) at the same time. Using various levels of correlation would allow the effect of distant wind farms to be considered.

In any future work, it is clear that two limitations would need to be addressed. For each of the enhancements described above, the computation effort would increase significantly. Therefore extra resources in computation would be required if the analysis is to be carried out in a reasonable time. The other issue is that of availability of information. Each enhancement leads to a more realistic representation of the network's behaviour. At the same time, additional information and data, including detailed knowledge of load fluctuation and generation dispatch, would be required.

REFERENCES

1. R. Allan, R. Billinton, "*Probabilistic Assessment of Power Systems*" 2000 Proceeding of the IEEE, Volume 88, Issue 2, pp 140-142
2. Allen J.Wood and Bruce F. Wollenberg, "*Power Generation Operation and Control*" Wiley Publisher, 2nd Edition 1996
3. R. Billinton, R.N. Allan "*Reliability assessment of large electric power systems*", Kluwer Academic Publishers, 1988
4. B. Borkowska, "*Probabilistic load flow*", IEEE Trans. Power App and System., Apr. 1974, vol. PAS-93, pp. 752-759
5. R. Billinton and RN. Allah *"Reliability Evaluation of Power System"* Plenum Press New York, 1996.
6. R. Billinton and Ran Mo "*Deterministic/Probabilistic contingency evaluation in composite generation and transmission system*" Power Engineering Society General Meeting held in Denver Colorado , 2004, IEEE Volume, Issue, 6-10, pp 2232-2237, vol. 2
7. L.S. Low and L. Goel, "*Incorporating Deterministic Criteria in the Probabilistic Framework for Composite Generation and Transmission Systems*" Power Engineering Society Summer Meeting held in Seattle Washington, 2000. IEEE, 2000, pp. 2069-2074, vol. 4
8. Yuri V. Makarov, "*Probabilistic assessment of the energy not produced due to transmission constraints*" Power Tech Conference Proceedings held in Bologna Italy, 2003 IEEE Bologna, Issue. 23-26, pp. 30-36, vol. 4
9. M. Lammintausta, R. Hirvonen, and M. Lehtonen "*Transmission capacity assessment by using simple probabilistic planning*" Power Tech Conference

Proceedings held in Bologna, 2003 IEEE Bologna, Issue. 23-26, pp. 345-356, vol. 2

10. R. Billinton and R. Karki "*Maintaining supply reliability of small isolated power systems using renewable energy*" Generation, Transmission and Distribution, 2001 IEE proceeding-, vol. 148, pp 530-534
11. Pei Zhang and Stephen T. Lee "*Probabilistic load flow computation using the method of combined cumulants and Gram_Charlier expansion*" IEEE transactions on power systems 2004, vol. 19, No. 1, pp. 676-682
12. Pei Zhang and Stephen T. Lee "*A new computation method for probabilistic load flow study*" International Conference on Power System Technology 2002, pp. 2038-2042, vol. 4
13. Armando M. Leite da Silva, Luiz Antonio F. Manso, "*Application of Monte Carlo Simulation to generating system well being analysis considering renewable sources*" 8th international Conference on Probabilistic Methods to Power System, Iowa State University, 2004, pp.439-444
14. H. Bindner and P. Lundsager "*Integration of wind power in the power system*" 28th Annual Conference of the Industrial Electronics Society, IEEE 2002, pp. 3309-3316, vol. 4
15. P. Jorgensen and J. O. Tande "*Probabilistic load flow calculation using Monte Carlo techniques for distribution network with wind turbines*" 8th International Conference on Harmonics and Quality of Power, Athens, 1998, pp.1146-1151, vol.2
16. J. Sveca and L. Soder "*Wind Power Integration in power system with bottleneck problems*", 2003 IEEE Bologna Power Tech Conference Proceedings held in Bologna, pp. 7, vol. 2

17. P. Bresesti and R. Calisti "*Probabilisitc model for adequacy evaluation of electric network with sizeable wind power generation*", Power System Conference and Exposition held in New York, 2004 IEEE, pp. 1324-1328, vol. 3

18. Eirgrid PLC, "*Transmission Forecast Statement 2007-2013*" 2007, Available [Online], http://www.eirgrid.ie, [Accessed: Jul. 15, 2007]

19. International Energy Agency,"*Impact of wind power generation in Ireland on the operation of conventional plant and the economic implications*", 2004 [Online] Available: http:www.ieawind.org, [Accessed: Nov. 18, 2006]

20. Commissioner for energy regulation website, "*Options for Operational Rules to Curtail Wind Generation*" Version 1.0, Published by ESB National Grid on July 16th 2004, [Online] Available: http:www.cer.ie [Accessed: Jul, 5, 2006]

21. J. Yang, and M. D. Anderson "*Tracing the flow of power in transmission network for use-of-transmission-system charges and congestion management*" Winter Meeting of Power Engineering Society held in New York, 1999 IEEE, pp. 399-405, vol.1

22. E. Masaki and T. Ogawa "*Line Flow congestion elimination using generator power flow tracing method*" 2004 International Conference on Power System Technology, Singapore, pp 850-855, vol. 1

23. D. Kirschen and R. Allan "*Contributions of Individual Generators to load and flows*" Generation, Transmission and Distribution, IEEE, 2002, pp. 186-190 Vol. 149,

24. Ahmet D. Sahin, and Zekai Sen, "*First-Order Markov Chain approach to wind speed modelling*" Journal of Wind Engineering and Industrial Aerodynamics, 2001, pp. 263-269 vol. 89

25. M.A. Bawadi, W.M.A. Wan Hussin, T.A. Majid, and S.A.M. Sanusi, "*First and second order Markov chain models for synthetic generation of wind speed time series*" Journal of Wind Engineering and Industrial Aerodynamics, 2003, pp. 693-708, vol. 30

26. R. Billinton, H. Chen, "*A sequential simulation technique for adequacy evaluation of generation systems including wind energy*" IEEE Transation on Energy Conversion, 1996, pp. 728-734, vol. 11

27. R R. Talluri "*Purchasing electricity for the cement industry in regulated markets and deregulated markets*" Cement Industry Technical Conference held in Chattanooga, 2004 IEEE, pp.41-49

28. Eirgrid PLC, "*Transmission Forecast Statement 2006-2012*" 2006, Available [Online], http://www.eirgrid.ie, [Accessed: May 15, 2006]

29. Department of Communications Marine and Natural Resources, Available [Online], http://www.dcmnr.gov.ie, [Accessed: Dec. 11, 2005]

30. R. Billinton, G. Lian, "*Composite power system health analysis using a security constrained adequacy evaluation procedure*" IEEE Transactions on Power Systems, 1994, pp. 936-941, vol. 9

31. R. Billinton, M. Fotuhi Firuzabad "*A basic framework for generating system operating health analysis*" IEEE Transactions on Power Systems,1994, pp, 1610-1617, vol. 9

32. W. Carr and M.F. Conlon, "Simulation of Wind Speed Records for Use in Generation Adequacy Assessment Calculation", *40th Universities Power Engineering Conference*, University College Cork, September 2005

33. Coelingh, J.P, "*Geographical Dispersion of Wind Power Output in Ireland*" 1999 Irish Wind Energy Association, www.iwea.com

34. S.Karimi, M. Fotuhi, "*Time Series Application on Reliability Evaluation of Power Systems Including Wind Turbine Generators*" Paris, France, 2006

35. R. Billinton, H. Chen, "*Time-Series Models For Reliability Evaluation Of Power Systems Including Wind Energy*"*Microelectron. Reliab.,* Vol. 36, No. 9, PP. 1253 -1261, 1996,

36. Commissioner for Energy Regulation website, "*Approach to processing current wind application*" 2004, [Online] Available: http:www.cer.ie [Accessed: Jul, 5, 2006]

37. University of Western Australia educational resources website,, Cross correlation, Available [Online] http://local.wasp.uwa.edu.au/~pbourke /other/correlate/: [Accessed: Sep 23, 2006]

38. E. T. Jauch "*Maximizing Automatic Reverse Power Operations With LTC Transformers and Regulators*" IEEE Power Engineering Society Inaugural Conference and Exposition, South Africa, 2005, pp, 449-454

39. Commissioner for Energy Regulation website, "*Group Processing Approach for Renewable Generator Connection Applications*" Published by Commission for Energy Regulation (CER), Available [Online]: http://www.cer.ie [Accessed: Jul, 5, 2006]

40. Airtricity Services Available on National Tool Website [Online] "*http://www.ntr.ie/companies/wind-energy/services.asp"* ,[Accessed: Jul 10, 2006]

41. IEEE-RTS Task Force of APM Subcommitte, "IEEE Reliability Test System" IEEE PAS, Vol-98. No. 6, Nov./ Dec 1989, pp. 2047-2054

APPENDIX A: NETWORK DIAGRAMS

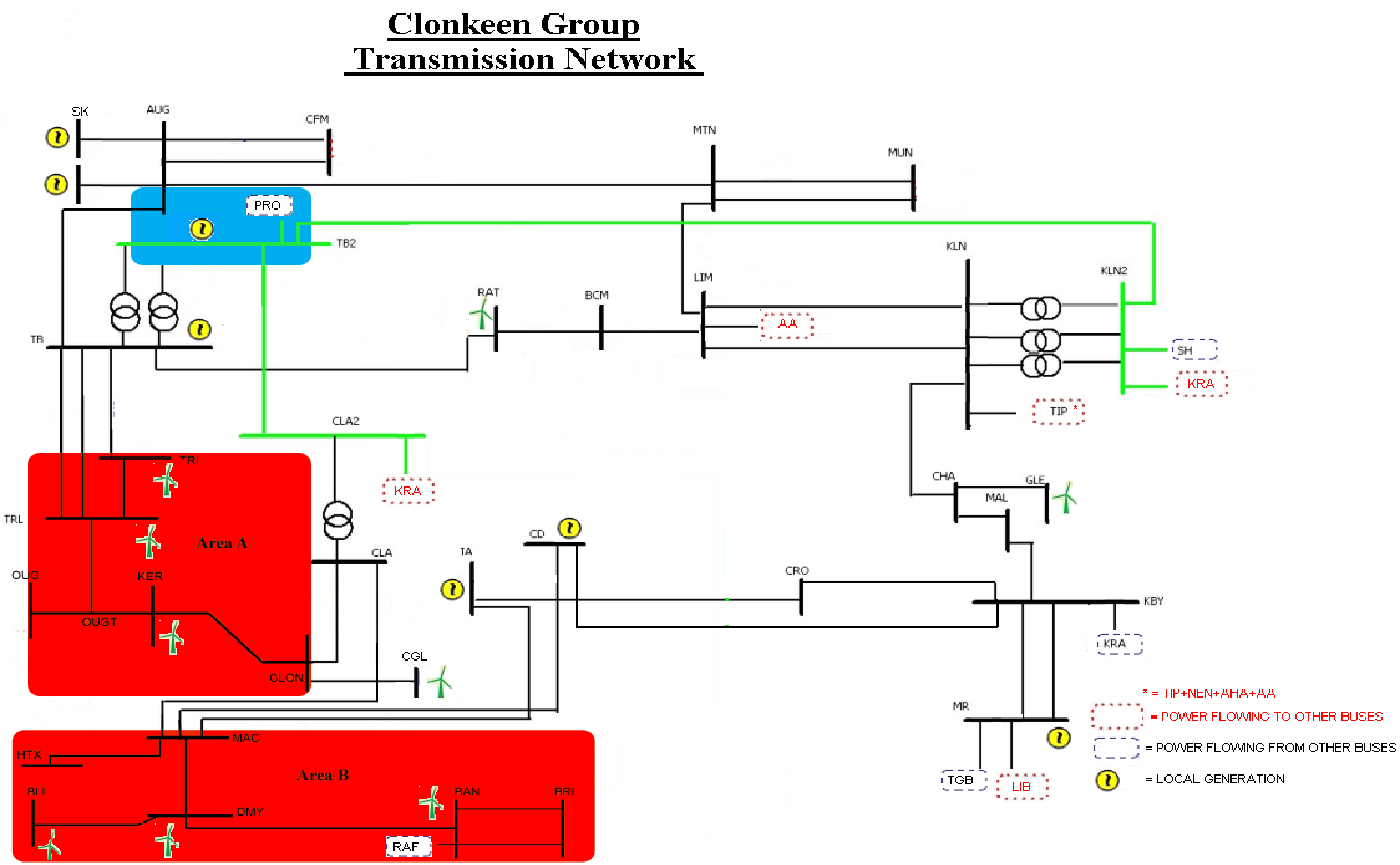


Figure 65: Clonkeen Group Transmission Network

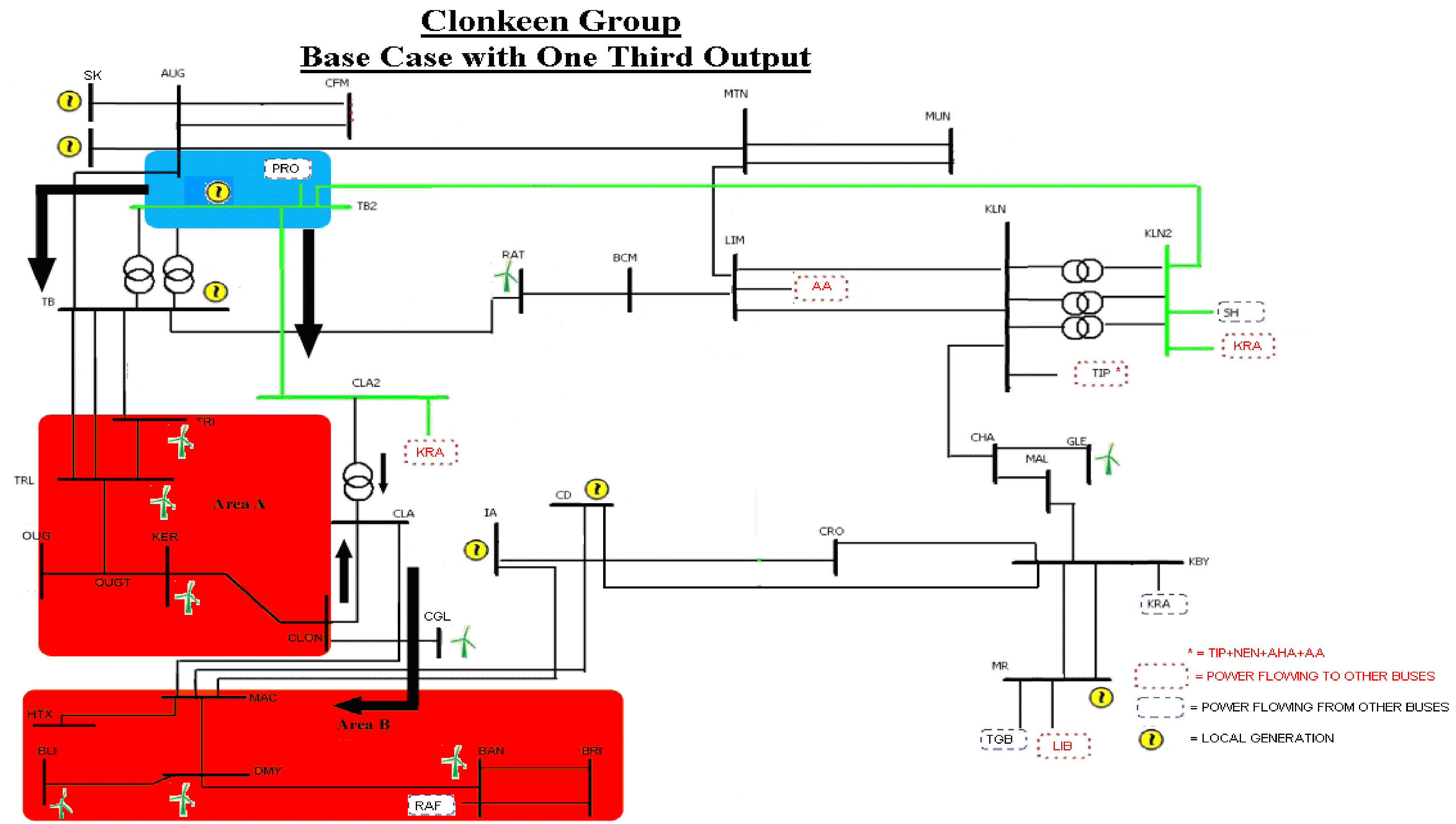


Figure 66: Base Case with One Third Wind Generation

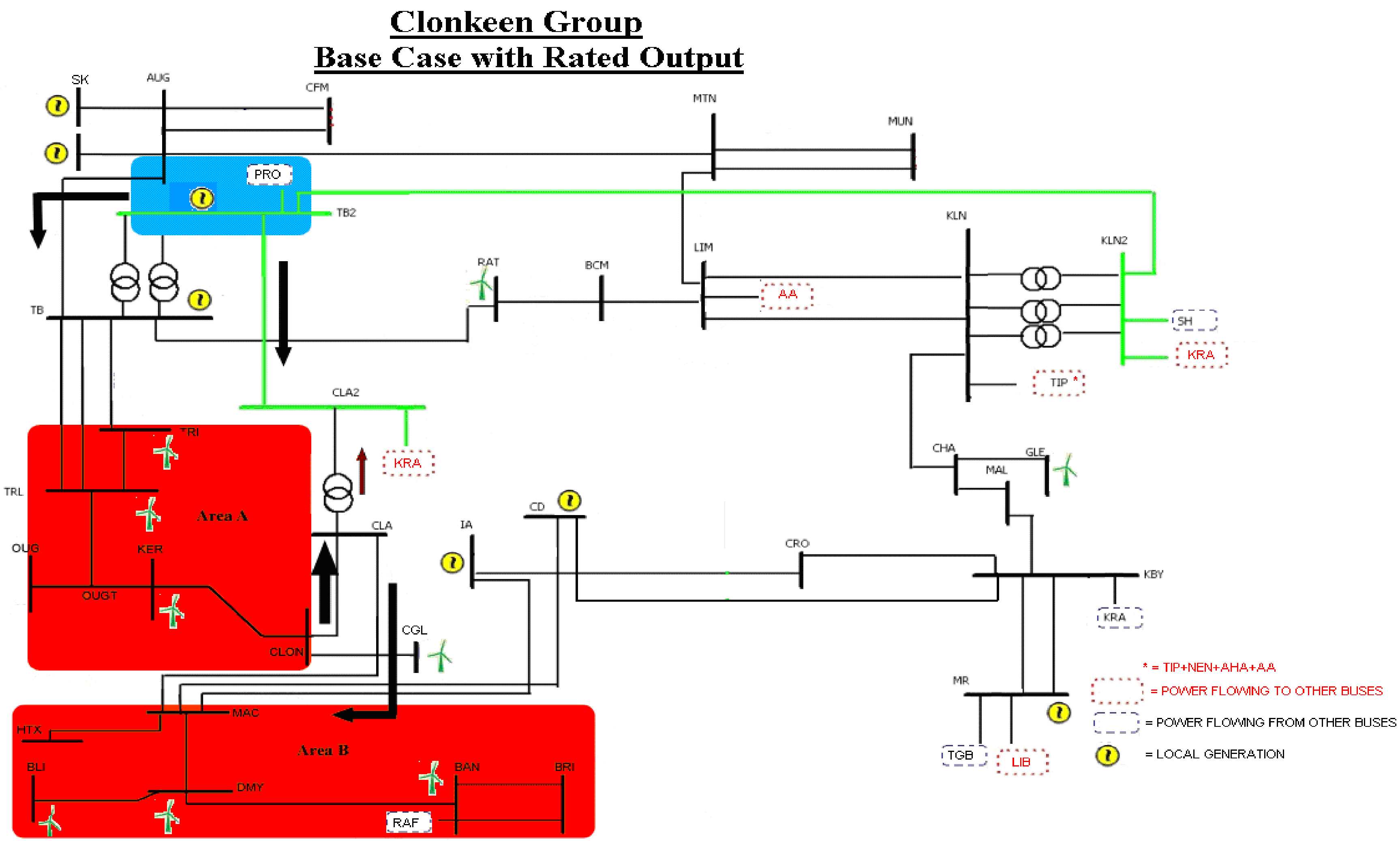


Figure 67: Base Case with Rated Wind Generation

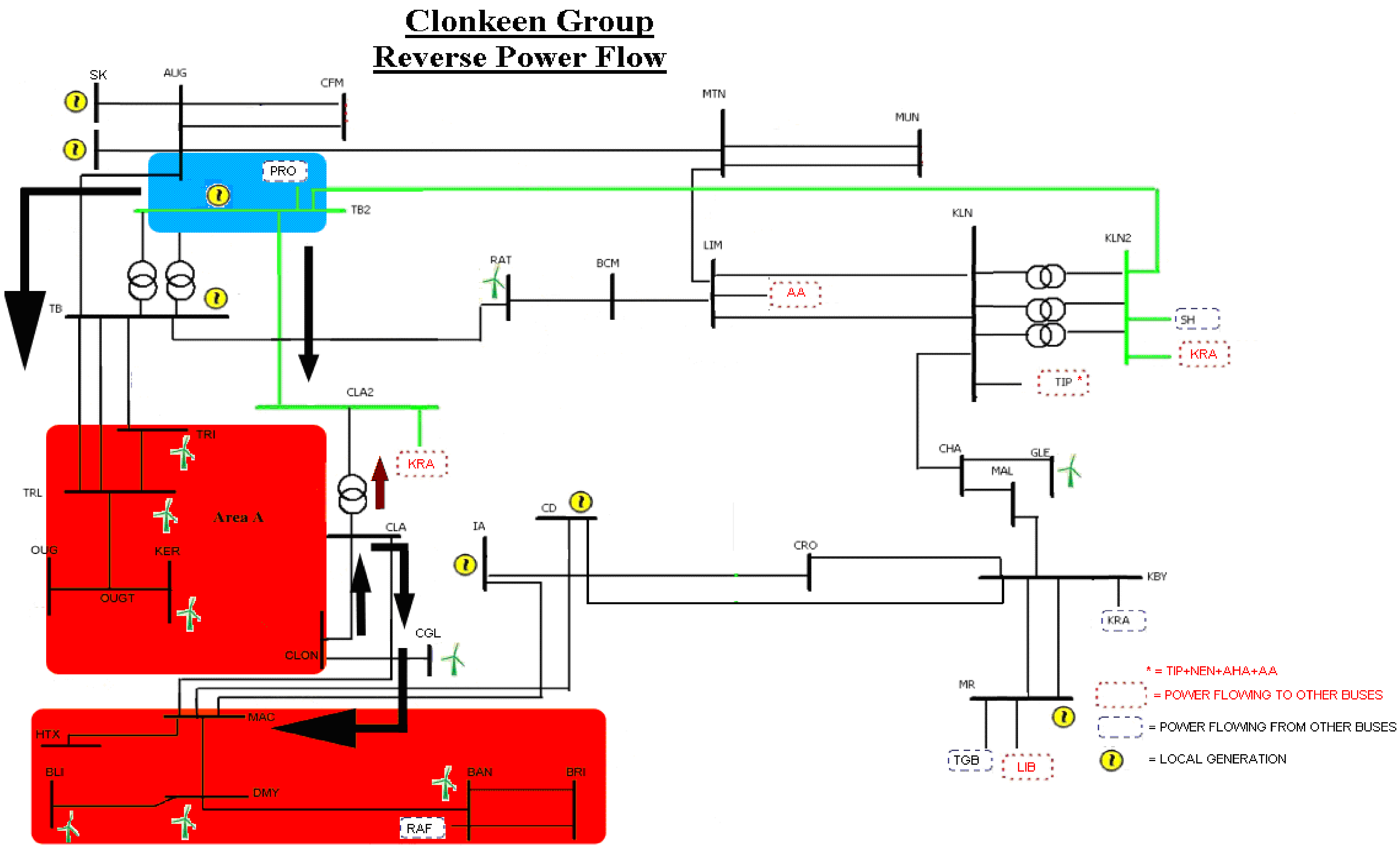


Figure 68: Contingency Case Reverse Power Flow

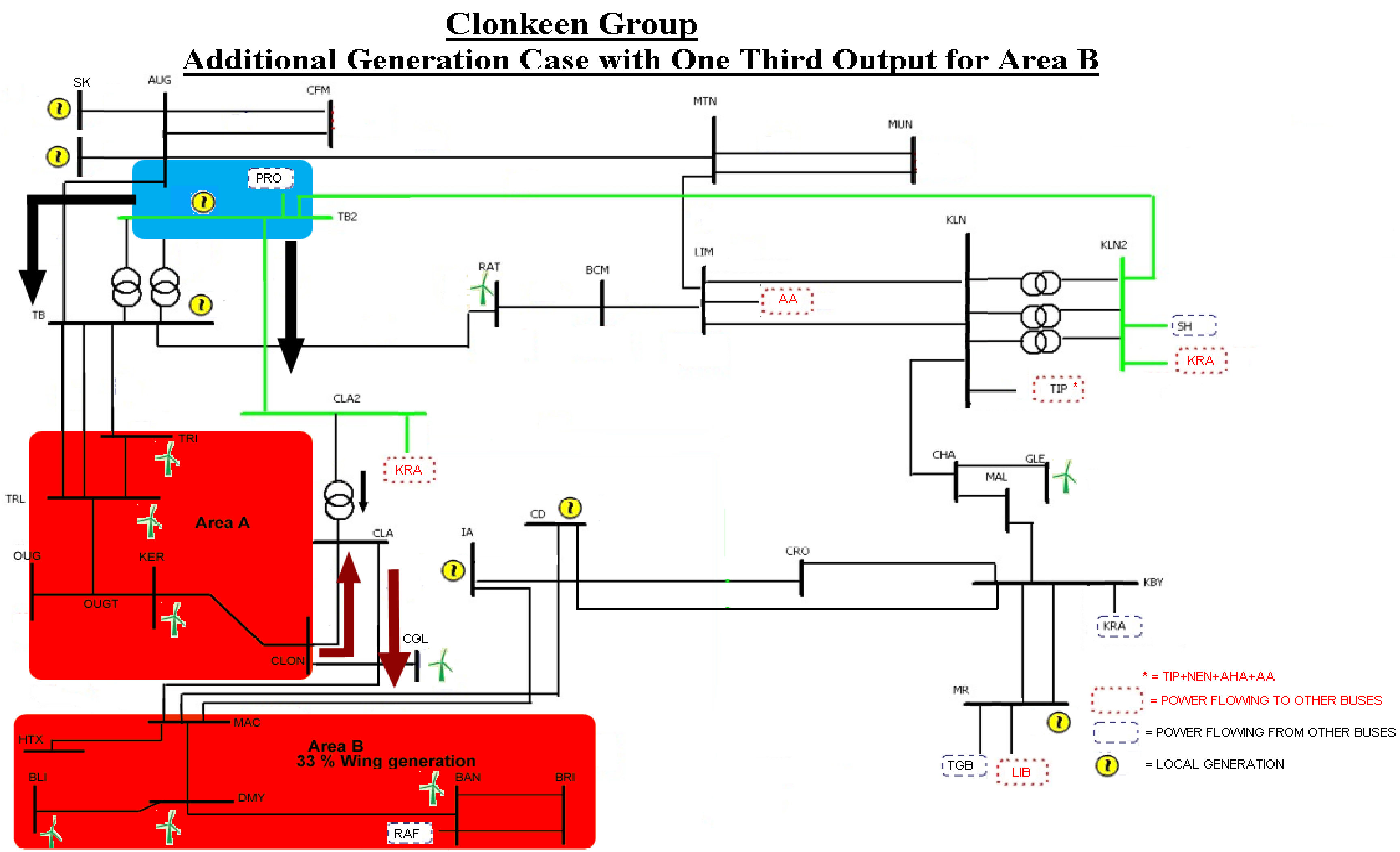


Figure 69: Additional Generation Case with One Third Output for Area B

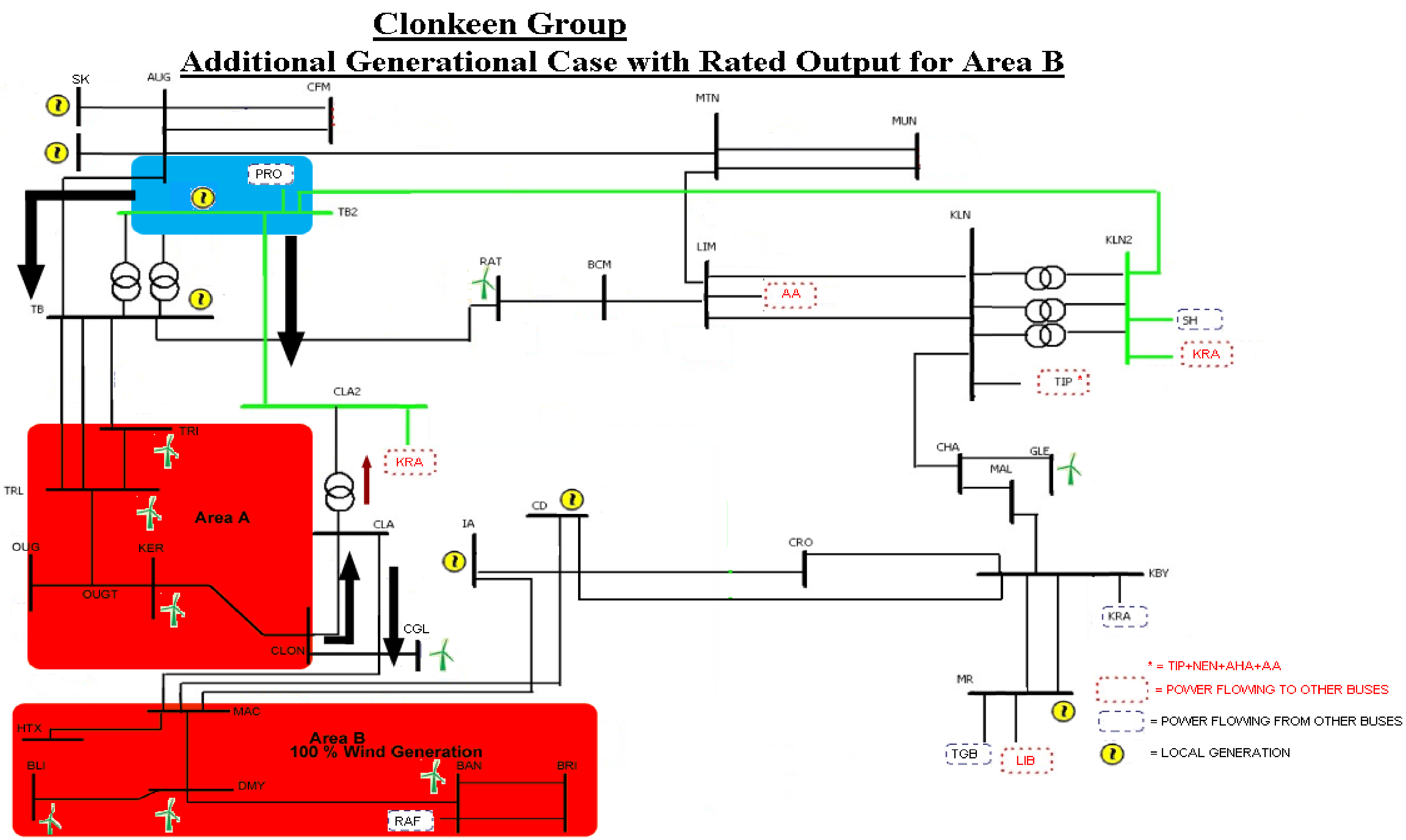


Figure 70: Additional Generation Case with Rated Output for Area B Only

Figure 71: Irish Transmission Network

APPENDIX B: BASE CASE LINE FLOW RESULTS

SUMMER NIGHT VALLEY 2008 BASE CASE

TABLE 4
ONE THIRD WIND GENERATION

LINE REPORT

Branch	From	To	P pu	Q pu	S pu
1	AUGHINISH 110	CASTLEFARM 110	0.220	0.083	0.235
2	AUGHINISH 110	CASTLEFARM 110	0.220	0.083	0.235
3	AUGHINISH 110	MONETEEN 110	0.405	0.304	0.507
4	AUGHINISH 110	SEALROCK_1 110	-0.440	-0.298	0.531
5	AUGHINISH 110	SEALROCK_2 110	-0.440	-0.298	0.531
6	AUGHINISH 110	TARBERT 110	0.034	0.126	0.131
7	BALLYCUMMIN 110	LIMERICK 110	0.118	-0.057	0.131
8	BALLYCUMMIN 110	RATHKEALE 110	-0.142	0.031	0.145
9	BALLYLICKEY 110	DUNMANWAY 110	0.066	-0.012	0.067
10	BANDON 110	BRINNY 110	0.021	0.007	0.022
11	BANDON 110	BRINNY 110	0.021	0.007	0.022
12	BANDON 110	DUNMANWAY 110	-0.101	0.019	0.103
13	CARRIGADROHID 110	KILBARRY 110	0.113	0.007	0.113
14	CARRIGADROHID 110	MACROOM 110	-0.113	0.119	0.164
15	CHARLEVILLE 110	GLENLARA 110	-0.086	0.032	0.091
16	CHARLEVILLE 110	KILLONAN 110	-0.083	-0.089	0.122
17	CHARLEVILLE 110	MALLOW 110	0.117	-0.038	0.123
18	CLASHAVOON 110	CLONKEEN 110	-0.290	0.197	0.351
19	CLASHAVOON 110	MACROOM 110	0.364	-0.066	0.370
20	CLASHAVOON 220	TARBERT 220	-0.579	-0.112	0.589
21	CLONKEEN 110	KNOCKEARAGH 110	0.094	0.194	0.215
22	CLONKEEN 110	COMMAGEARLAHY 110	-0.389	0.001	0.389
23	COOLROE 110	INNISCARRA 110	-0.115	-0.078	0.139
24	COOLROE 110	KILBARRY 110	0.089	0.038	0.097
25	DUNMANWAY 110	MACROOM 110	-0.082	-0.079	0.113
26	HARTNETTS CROSS 110	MACROOM 110	-0.031	-0.014	0.034
27	INNISCARRA 110	MACROOM 110	-0.115	0.036	0.121
28	KILBARRY 110	MARINA 110	0.112	-0.036	0.118
29	KILBARRY 110	MARINA 110	0.112	-0.036	0.118
30	KILBARRY 110	MALLOW 110	-0.066	0.103	0.123
31	KILLONAN 110	LIMERICK 110	-0.054	0.126	0.137
32	KILLONAN 110	LIMERICK 110	-0.043	0.095	0.104
33	KILLONAN 220	TARBERT 220	-0.543	-0.478	0.723
34	KNOCKEARAGH 110	OUGTRAGHT 110	-0.065	-0.186	0.197
35	LIMERICK 110	MONETEEN 110	-0.251	-0.222	0.335
36	MONETEEN 110	MUNGRET 110	0.073	0.037	0.082
37	MONETEEN 110	MUNGRET 110	0.077	0.037	0.085
38	OUGHTRAGH 110	OUGTRAGHT 110	-0.106	-0.088	0.138
39	RATHKEALE 110	TARBERT 110	-0.193	-0.139	0.238
40	TARBERT 110	TRIEN 110	0.129	0.002	0.129
41	TARBERT 110	TRALEE 110	0.067	0.074	0.099
42	TARBERT 110	TRALEE 110	0.055	0.075	0.093
43	TRALEE 110	OUGTRAGHT 110	0.174	0.265	0.317
44	TRIEN 110	TRALEE 110	0.018	0.162	0.163

TRANSFORMER REPORT

Branch	From	To	P pu	Q pu	S pu
1	CLASHAVOON 220	CLASHAVOON 110	0.074	0.133	0.152
2	KILLONAN 220	KILLONAN 110	0.073	-0.025	0.077
3	KILLONAN 220	KILLONAN 110	0.072	-0.026	0.077
4	KILLONAN 220	KILLONAN 110	0.147	-0.048	0.155
5	TARBERT 220	TARBERT 110	0.205	0.075	0.218
6	TARBERT 220	TARBERT 110	0.205	0.075	0.218

TABLE 5
RATED WIND GENERATION

LINE REPORT

Branch	From	To	P pu	Q pu	S pu
1	AUGHINISH 110	CASTLEFARM 110	0.220	0.083	0.235
2	AUGHINISH 110	CASTLEFARM 110	0.220	0.083	0.235
3	AUGHINISH 110	MONETEEN 110	0.360	0.342	0.496
4	AUGHINISH 110	SEALROCK_1 110	-0.440	-0.330	0.550
5	AUGHINISH 110	SEALROCK_2 110	-0.440	-0.330	0.550
6	AUGHINISH 110	TARBERT 110	0.080	0.153	0.172
7	BALLYCUMMIN 110	LIMERICK 110	0.118	-0.026	0.121
8	BALLYCUMMIN 110	RATHKEALE 110	-0.142	0.000	0.142
9	BALLYLICKEY 110	DUNMANWAY 110	0.249	-0.092	0.265
10	BANDON 110	BRINNY 110	0.021	0.007	0.022
11	BANDON 110	BRINNY 110	0.021	0.007	0.022
12	BANDON 110	DUNMANWAY 110	-0.072	0.005	0.072
13	CARRIGADROHID 110	KILBARRY 110	0.171	-0.019	0.172
14	CARRIGADROHID 110	MACROOM 110	-0.171	0.332	0.374
15	CHARLEVILLE 110	GLENLARA 110	-0.318	0.125	0.341
16	CHARLEVILLE 110	KILLONAN 110	0.262	-0.221	0.343
17	CHARLEVILLE 110	MALLOW 110	0.005	0.000	0.005
18	CLASHAVOON 110	CLONKEEN 110	-0.634	0.328	0.714
19	CLASHAVOON 110	MACROOM 110	0.137	-0.164	0.214
20	CLASHAVOON 220	TARBERT 220	-0.008	-0.175	0.175
21	CLONKEEN 110	KNOCKEARAGH 110	0.473	0.053	0.476
22	CLONKEEN 110	COMMAGEARLAHY 110	-1.130	0.236	1.154
23	COOLROE 110	INNISCARRA 110	-0.169	-0.054	0.178
24	COOLROE 110	KILBARRY 110	0.143	0.014	0.144
25	DUNMANWAY 110	MACROOM 110	0.262	-0.221	0.343
26	HARTNETTS CROSS 110	MACROOM 110	-0.031	-0.014	0.034
27	INNISCARRA 110	MACROOM 110	-0.170	0.072	0.184
28	KILBARRY 110	MARINA 110	0.112	-0.036	0.118
29	KILBARRY 110	MARINA 110	0.112	-0.036	0.118
30	KILBARRY 110	MALLOW 110	0.045	0.063	0.078
31	KILLONAN 110	LIMERICK 110	-0.030	0.087	0.092
32	KILLONAN 110	LIMERICK 110	-0.023	0.065	0.069
33	KILLONAN 220	TARBERT 220	-0.248	-0.523	0.578
34	KNOCKEARAGH 110	OUGTRAGHT 110	0.371	-0.367	0.522
35	LIMERICK 110	MONETEEN 110	-0.206	-0.260	0.332
36	MONETEEN 110	MUNGRET 110	0.073	0.037	0.082
37	MONETEEN 110	MUNGRET 110	0.077	0.037	0.085
38	OUGHTRAGH 110	OUGTRAGHT 110	-0.106	-0.088	0.138
39	RATHKEALE 110	TARBERT 110	-0.113	-0.131	0.173
40	TARBERT 110	TRIEN 110	-0.183	0.044	0.188
41	TARBERT 110	TRALEE 110	-0.191	0.164	0.252
42	TARBERT 110	TRALEE 110	-0.200	0.134	0.240
43	TRALEE 110	OUGTRAGHT 110	-0.251	0.471	0.534
44	TRIEN 110	TRALEE 110	-0.216	0.272	0.347

TRANSFORMER REPORT

Branch	From	To	P pu	Q pu	S pu
1	CLASHAVOON 220	CLASHAVOON 110	-0.497	0.196	0.534
2	KILLONAN 220	KILLONAN 110	-0.001	-0.007	0.007
3	KILLONAN 220	KILLONAN 110	-0.001	-0.007	0.007
4	KILLONAN 220	KILLONAN 110	-0.001	-0.015	0.015
5	TARBERT 220	TARBERT 110	-0.269	0.154	0.311
6	TARBERT 220	TARBERT 110	-0.269	0.154	0.311

SUMMER 2008 BASE CASE

TABLE 6
ONE THIRD WIND GENERATION

LINE REPORT

Branch	From	To	P pu	Q pu	S pu
1	AUGHINISH 110	CASTLEFARM 110	0.220	0.083	0.235
2	AUGHINISH 110	CASTLEFARM 110	0.220	0.083	0.235
3	AUGHINISH 110	MONETEEN 110	0.966	0.281	1.006
4	AUGHINISH 110	SEALROCK_1 110	-0.700	-0.271	0.750
5	AUGHINISH 110	SEALROCK_2 110	-0.700	-0.271	0.750
6	AUGHINISH 110	TARBERT 110	-0.007	0.095	0.096
7	BALLYCUMMIN 110	LIMERICK 110	0.245	-0.078	0.257
8	BALLYCUMMIN 110	RATHKEALE 110	-0.315	0.052	0.319
9	BALLYLICKEY 110	DUNMANWAY 110	-0.027	0.029	0.040
10	BANDON 110	BRINNY 110	0.021	0.007	0.022
11	BANDON 110	BRINNY 110	0.021	0.007	0.022
12	BANDON 110	DUNMANWAY 110	-0.042	-0.008	0.043
13	CARRIGADROHID 110	KILBARRY 110	0.115	0.006	0.115
14	CARRIGADROHID 110	MACROOM 110	-0.085	0.090	0.124
15	CHARLEVILLE 110	GLENLARA 110	-0.007	-0.054	0.055
16	CHARLEVILLE 110	KILLONAN 110	-0.287	0.002	0.287
17	CHARLEVILLE 110	MALLOW 110	0.151	-0.044	0.157
18	CLASHAVOON 110	CLONKEEN 110	-0.277	0.189	0.336
19	CLASHAVOON 110	MACROOM 110	0.756	-0.146	0.770
20	CLASHAVOON 220	TARBERT 220	-1.373	-0.049	1.374
21	CLONKEEN 110	KNOCKEARAGH 110	0.107	0.187	0.216
22	CLONKEEN 110	COMMAGEARLAHY 110	-0.389	0.001	0.389
23	COOLROE 110	INNISCARRA 110	-0.168	-0.079	0.185
24	COOLROE 110	KILBARRY 110	0.056	0.039	0.068
25	DUNMANWAY 110	MACROOM 110	-0.350	0.048	0.353
26	HARTNETTS CROSS 110	MACROOM 110	-0.089	-0.014	0.090
27	INNISCARRA 110	MACROOM 110	-0.118	0.037	0.124
28	KILBARRY 110	MARINA 110	0.187	-0.058	0.196
29	KILBARRY 110	MARINA 110	0.187	-0.058	0.196
30	KILBARRY 110	MALLOW 110	0.049	0.110	0.120
31	KILLONAN 110	LIMERICK 110	-0.099	0.190	0.214
32	KILLONAN 110	LIMERICK 110	-0.077	0.145	0.164
33	KILLONAN 220	TARBERT 220	-1.453	-0.306	1.485
34	KNOCKEARAGH 110	OUGTRAGHT 110	-0.337	-0.041	0.339
35	LIMERICK 110	MONETEEN 110	-0.748	-0.131	0.759
36	MONETEEN 110	MUNGRET 110	0.098	0.037	0.105
37	MONETEEN 110	MUNGRET 110	0.102	0.037	0.108
38	OUGHTRAGH 110	OUGTRAGHT 110	-0.202	-0.088	0.220
39	RATHKEALE 110	TARBERT 110	-0.574	-0.041	0.576
40	TARBERT 110	TRIEN 110	0.473	-0.038	0.474
41	TARBERT 110	TRALEE 110	0.327	-0.005	0.327
42	TARBERT 110	TRALEE 110	0.311	0.028	0.312
43	TRALEE 110	OUGTRAGHT 110	0.549	0.135	0.565
44	TRIEN 110	TRALEE 110	0.224	0.070	0.235

TRANSFORMER REPORT

Branch	From	To	P pu	Q pu	S pu
1	CLASHAVOON 220	CLASHAVOON 110	0.479	0.070	0.484
2	KILLONAN 220	KILLONAN 110	0.253	-0.005	0.253
3	KILLONAN 220	KILLONAN 110	0.251	-0.008	0.251
4	KILLONAN 220	KILLONAN 110	0.505	-0.001	0.505
5	TARBERT 220	TARBERT 110	0.852	0.006	0.852
6	TARBERT 220	TARBERT 110	0.852	0.006	0.852

TABLE 7
RATED WIND GENERATION

LINE REPORT

Branch	From	To	P pu	Q pu	S pu
1	AUGHINISH 110	CASTLEFARM 110	0.220	0.083	0.235
2	AUGHINISH 110	CASTLEFARM 110	0.220	0.083	0.235
3	AUGHINISH 110	MONETEEN 110	0.918	0.311	0.969
4	AUGHINISH 110	SEALROCK_1 110	-0.700	-0.296	0.760
5	AUGHINISH 110	SEALROCK_2 110	-0.700	-0.296	0.760
6	AUGHINISH 110	TARBERT 110	0.041	0.116	0.123
7	BALLYCUMMIN 110	LIMERICK 110	0.243	-0.053	0.248
8	BALLYCUMMIN 110	RATHKEALE 110	-0.313	0.027	0.314
9	BALLYLICKEY 110	DUNMANWAY 110	0.156	-0.052	0.164
10	BANDON 110	BRINNY 110	0.021	0.007	0.022
11	BANDON 110	BRINNY 110	0.021	0.007	0.022
12	BANDON 110	DUNMANWAY 110	-0.003	-0.026	0.026
13	CARRIGADROHID 110	KILBARRY 110	0.175	-0.020	0.176
14	CARRIGADROHID 110	MACROOM 110	-0.145	0.258	0.295
15	CHARLEVILLE 110	GLENLARA 110	-0.241	0.045	0.245
16	CHARLEVILLE 110	KILLONAN 110	0.063	-0.142	0.156
17	CHARLEVILLE 110	MALLOW 110	0.035	0.001	0.035
18	CLASHAVOON 110	CLONKEEN 110	-0.618	0.327	0.699
19	CLASHAVOON 110	MACROOM 110	0.512	-0.200	0.550
20	CLASHAVOON 220	TARBERT 220	-0.788	-0.108	0.795
21	CLONKEEN 110	KNOCKEARAGH 110	0.490	0.047	0.493
22	CLONKEEN 110	COMMAGEARLAHY 110	-1.130	0.242	1.156
23	COOLROE 110	INNISCARRA 110	-0.224	-0.053	0.231
24	COOLROE 110	KILBARRY 110	0.112	0.013	0.113
25	DUNMANWAY 110	MACROOM 110	0.005	-0.113	0.113
26	HARTNETTS CROSS 110	MACROOM 110	-0.089	-0.014	0.090
27	INNISCARRA 110	MACROOM 110	-0.175	0.071	0.189
28	KILBARRY 110	MARINA 110	0.187	-0.058	0.196
29	KILBARRY 110	MARINA 110	0.187	-0.058	0.196
30	KILBARRY 110	MALLOW 110	0.164	0.065	0.176
31	KILLONAN 110	LIMERICK 110	-0.072	0.155	0.171
32	KILLONAN 110	LIMERICK 110	-0.056	0.118	0.130
33	KILLONAN 220	TARBERT 220	-1.148	-0.369	1.206
34	KNOCKEARAGH 110	OUGTRAGHT 110	0.101	-0.244	0.264
35	LIMERICK 110	MONETEEN 110	-0.701	-0.167	0.721
36	MONETEEN 110	MUNGRET 110	0.098	0.037	0.105
37	MONETEEN 110	MUNGRET 110	0.102	0.037	0.108
38	OUGHTRAGH 110	OUGTRAGHT 110	-0.202	-0.088	0.220
39	RATHKEALE 110	TARBERT 110	-0.493	-0.043	0.494
40	TARBERT 110	TRIEN 110	0.148	0.009	0.148
41	TARBERT 110	TRALEE 110	0.056	0.084	0.101
42	TARBERT 110	TRALEE 110	0.044	0.084	0.095
43	TRALEE 110	OUGTRAGHT 110	0.106	0.328	0.344
44	TRIEN 110	TRALEE 110	-0.019	0.179	0.180

TRANSFORMER REPORT

Branch	From	To	P pu	Q pu	S pu
1	CLASHAVOON 220	CLASHAVOON 110	-0.106	0.129	0.167
2	KILLONAN 220	KILLONAN 110	0.176	0.007	0.176
3	KILLONAN 220	KILLONAN 110	0.175	0.004	0.175
4	KILLONAN 220	KILLONAN 110	0.351	0.019	0.352
5	TARBERT 220	TARBERT 110	0.354	0.059	0.359
6	TARBERT 220	TARBERT 110	0.354	0.059	0.359

WINTER 2008 BASE CASE

TABLE 8
ONE THIRD WIND GENERATION

LINE REPORT

Branch	From	To	P pu	Q pu	S pu
1	AUGHINISH 110	CASTLEFARM 110	0.220	0.083	0.235
2	AUGHINISH 110	CASTLEFARM 110	0.220	0.083	0.235
3	AUGHINISH 110	MONETEEN 110	1.190	0.540	1.307
4	AUGHINISH 110	SEALROCK_1 110	-0.750	-0.406	0.853
5	AUGHINISH 110	SEALROCK_2 110	-0.750	-0.406	0.853
6	AUGHINISH 110	TARBERT 110	-0.131	0.107	0.169
7	BALLYCUMMIN 110	LIMERICK 110	0.324	0.156	0.360
8	BALLYCUMMIN 110	RATHKEALE 110	-0.410	-0.188	0.451
9	BALLYLICKEY 110	DUNMANWAY 110	-0.016	0.024	0.029
10	BANDON 110	BRINNY 110	0.021	0.007	0.022
11	BANDON 110	BRINNY 110	0.021	0.007	0.022
12	BANDON 110	DUNMANWAY 110	-0.117	0.026	0.120
13	CARRIGADROHID 110	KILBARRY 110	0.254	-0.054	0.259
14	CARRIGADROHID 110	MACROOM 110	-0.174	0.202	0.266
15	CHARLEVILLE 110	GLENLARA 110	0.024	-0.348	0.349
16	CHARLEVILLE 110	KILLONAN 110	-0.387	0.105	0.401
17	CHARLEVILLE 110	MALLOW 110	0.084	-0.146	0.169
18	CLASHAVOON 110	CLONKEEN 110	-0.339	0.201	0.394
19	CLASHAVOON 110	MACROOM 110	0.856	-0.277	0.900
20	CLASHAVOON 220	TARBERT 220	-1.769	-0.141	1.774
21	CLONKEEN 110	KNOCKEARAGH 110	0.043	0.211	0.216
22	CLONKEEN 110	COMMAGEARLAHY 110	-0.389	-0.015	0.390
23	COOLROE 110	INNISCARRA 110	-0.362	-0.018	0.362
24	COOLROE 110	KILBARRY 110	0.262	-0.070	0.271
25	DUNMANWAY 110	MACROOM 110	-0.322	0.036	0.324
26	HARTNETTS CROSS 110	MACROOM 110	-0.111	-0.018	0.112
27	INNISCARRA 110	MACROOM 110	-0.174	0.067	0.186
28	KILBARRY 110	MARINA 110	-0.120	0.035	0.125
29	KILBARRY 110	MARINA 110	-0.120	0.035	0.125
30	KILBARRY 110	MALLOW 110	0.197	0.242	0.312
31	KILLONAN 110	LIMERICK 110	-0.142	0.017	0.143
32	KILLONAN 110	LIMERICK 110	-0.111	0.010	0.111
33	KILLONAN 220	TARBERT 220	-2.031	-0.172	2.038
34	KNOCKEARAGH 110	OUGTRAGHT 110	-0.334	-0.014	0.334
35	LIMERICK 110	MONETEEN 110	-0.959	-0.325	1.013
36	MONETEEN 110	MUNGRET 110	0.098	0.037	0.105
37	MONETEEN 110	MUNGRET 110	0.102	0.037	0.108
38	OUGHTRAGH 110	OUGTRAGHT 110	-0.279	-0.134	0.310
39	RATHKEALE 110	TARBERT 110	-0.864	0.062	0.866
40	TARBERT 110	TRIEN 110	0.513	-0.031	0.514
41	TARBERT 110	TRALEE 110	0.385	-0.018	0.386
42	TARBERT 110	TRALEE 110	0.367	0.021	0.368
43	TRALEE 110	OUGTRAGHT 110	0.625	0.160	0.645
44	TRIEN 110	TRALEE 110	0.299	0.037	0.302

TRANSFORMER REPORT

Branch	From	To	P pu	Q pu	S pu
1	CLASHAVOON 220	CLASHAVOON 110	0.518	-0.044	0.520
2	KILLONAN 220	KILLONAN 110	0.302	0.146	0.336
3	KILLONAN 220	KILLONAN 110	0.301	0.141	0.333
4	KILLONAN 220	KILLONAN 110	0.597	0.303	0.669
5	TARBERT 220	TARBERT 110	1.144	-0.008	1.144
6	TARBERT 220	TARBERT 110	1.144	-0.008	1.144

TABLE 9
RATED WIND GENERATION

LINE REPORT

Branch	From	To	P pu	Q pu	S pu
1	AUGHINISH 110	CASTLEFARM 110	0.220	0.083	0.235
2	AUGHINISH 110	CASTLEFARM 110	0.220	0.083	0.235
3	AUGHINISH 110	MONETEEN 110	1.141	0.548	1.266
4	AUGHINISH 110	SEALROCK_1 110	-0.750	-0.419	0.859
5	AUGHINISH 110	SEALROCK_2 110	-0.750	-0.419	0.859
6	AUGHINISH 110	TARBERT 110	-0.082	0.124	0.149
7	BALLYCUMMIN 110	LIMERICK 110	0.319	0.162	0.357
8	BALLYCUMMIN 110	RATHKEALE 110	-0.405	-0.194	0.449
9	BALLYLICKEY 110	DUNMANWAY 110	0.167	-0.057	0.176
10	BANDON 110	BRINNY 110	0.021	0.007	0.022
11	BANDON 110	BRINNY 110	0.021	0.007	0.022
12	BANDON 110	DUNMANWAY 110	-0.085	0.011	0.086
13	CARRIGADROHID 110	KILBARRY 110	0.309	-0.076	0.318
14	CARRIGADROHID 110	MACROOM 110	-0.229	0.359	0.426
15	CHARLEVILLE 110	GLENLARA 110	-0.216	-0.130	0.252
16	CHARLEVILLE 110	KILLONAN 110	-0.043	0.031	0.053
17	CHARLEVILLE 110	MALLOW 110	-0.020	-0.035	0.041
18	CLASHAVOON 110	CLONKEEN 110	-0.676	0.340	0.757
19	CLASHAVOON 110	MACROOM 110	0.611	-0.321	0.690
20	CLASHAVOON 220	TARBERT 220	-1.186	-0.205	1.203
21	CLONKEEN 110	KNOCKEARAGH 110	0.429	0.068	0.434
22	CLONKEEN 110	COMMAGEARLAHY 110	-1.130	0.227	1.153
23	COOLROE 110	INNISCARRA 110	-0.413	0.005	0.413
24	COOLROE 110	KILBARRY 110	0.313	-0.093	0.326
25	DUNMANWAY 110	MACROOM 110	0.026	-0.120	0.123
26	HARTNETTS CROSS 110	MACROOM 110	-0.111	-0.018	0.112
27	INNISCARRA 110	MACROOM 110	-0.226	0.098	0.246
28	KILBARRY 110	MARINA 110	-0.120	0.035	0.125
29	KILBARRY 110	MARINA 110	-0.120	0.035	0.125
30	KILBARRY 110	MALLOW 110	0.301	0.130	0.328
31	KILLONAN 110	LIMERICK 110	-0.112	0.004	0.113
32	KILLONAN 110	LIMERICK 110	-0.088	0.000	0.088
33	KILLONAN 220	TARBERT 220	-1.729	-0.245	1.746
34	KNOCKEARAGH 110	OUGTRAGHT 110	0.108	-0.220	0.245
35	LIMERICK 110	MONETEEN 110	-0.912	-0.343	0.974
36	MONETEEN 110	MUNGRET 110	0.098	0.037	0.105
37	MONETEEN 110	MUNGRET 110	0.102	0.037	0.108
38	OUGHTRAGH 110	OUGTRAGHT 110	-0.279	-0.134	0.310
39	RATHKEALE 110	TARBERT 110	-0.779	0.054	0.780
40	TARBERT 110	TRIEN 110	0.185	0.019	0.186
41	TARBERT 110	TRALEE 110	0.111	0.071	0.132
42	TARBERT 110	TRALEE 110	0.097	0.077	0.124
43	TRALEE 110	OUGTRAGHT 110	0.177	0.352	0.394
44	TRIEN 110	TRALEE 110	0.053	0.146	0.156

TRANSFORMER REPORT

Branch	From	To	P pu	Q pu	S pu
1	CLASHAVOON 220	CLASHAVOON 110	-0.065	0.020	0.068
2	KILLONAN 220	KILLONAN 110	0.226	0.145	0.269
3	KILLONAN 220	KILLONAN 110	0.226	0.141	0.266
4	KILLONAN 220	KILLONAN 110	0.446	0.297	0.536
5	TARBERT 220	TARBERT 110	0.637	0.034	0.638
6	TARBERT 220	TARBERT 110	0.637	0.034	0.638

APPENDIX C: MATLAB AND LSFS RESULTS

BUSES NAME AND NUMBER

TABLE 10

Buses Names and Number

NO	NAME	P(load)	Q(load)	P(gen)	Q(gen)	Voltage	B(cap)
1	AUGHINISH 110	0	0	0	0	1.0757	0
2	BALLYCUMMIN 110	7	2.6	0	0	1.04188	0
3	BALLYLICKEY 110	12.5	3.8	9.8	4.3	1.0383	0
4	BANDON 110	32.6	13.8	32.8	4.5	1.03911	16.2
5	BRINNY 110	4.2	1.5	0	0	1.0389	0
6	CARRIGADROHID 110	0	0	3	6.6	1.0514	0
7	CASTLEFARM 110	44	16.8	0	0	1.07463	0
8	COMMAGEARLAHY 110	0	0	14.9	8.9	1.0405	0
9	CHARLEVILLE 110	14.3	9.6	0	0	1.0325	0
10	CLONKEEN	0	0	0	0	1.0382	0
11	CLASHAVOON 110	0	0	0	0	1.05127	0
12	CLASHAVOON 220	89.4	2.1	0	0	1.04087	0
13	COOLROE 110	11.2	4	0	0	1.04924	0
14	DUNMANWAY 110	35.4	13.5	7.3	-4	1.04928	16.2
15	GLENLARA 110	0	0	0.7	1	1.03443	0
16	HARTNETT'S CROSS 110	8.9	1.4	0	0	1.0505	0
17	INNISCARRA 110	0	0	5	12.3	1.0522	0
18	KILBARRY 110	84.4	36.7	99.7	46	1.047	0
19	KNOCKEARAGH 110	47.6	19.5	3.3	-2.2	1.0194	0
20	KILLONAN 110	89.2	40.3	0	0	1.0501	0
21	KILLONAN 220	88.8	29.2	44.3	33.1	1.0289	0
22	LIMERICK 110	81.5	40.4	0	0	1.0426	0
23	MACROOM 110	10.6	1.2	0	0	1.0512	0
24	MALLOW 110	19.8	8	0	0	1.03221	0
25	MARINA 110	40.6	11.3	3.2	18.3	1.04727	0
26	MONETEEN 110	0	0	0	0	1.04714	0
27	MUNGRET 110	20	7.4	0	0	1.04695	0
28	OUGHTRAGH 110	20.2	8.8	0	0	1.0264	0
29	OUGTRAGHT 110	0	0	0	0	1.033	0
30	RATHKEALE 110	30.1	10	4.5	3	1.042078	0
31	SEALROCK 110	0	0	70	25.1	1.0757	0
32	SEALROCK 110	0	0	70	25.1	1.0757	0
33	TARBERT 110	0	0	0	0	1.057	0
34	TARBERT 220	0	0	493.1	12.7	1.065	0
35	TRIEN 110	28.6	11	4.2	1.1	1.0391	33.6
36	TRALEE 110	46.4	17.7	16.2	2.7	1.04683	32.9

PSS/E AND MATLAB RESULT COMPARISION

TABLE 11

	Lines		Mat Lab Solution				PSS/E Solution		Difference	
BUS	From	To	P	Q	S	Rating	P	Q	P	Q
			pu	pu	pu	pu	pu	pu	pu	pu
1	1	7	0.22	0.083	0.235	0.51	0.22	0.085	0	-0.002
	1	7	0.22	0.083	0.235	0.51	0.22	0.085	0	-0.002
	1	26	0.968	0.279	1.007	1.37	0.96	0.22	0.008	0.059
	1	31	-0.7	-0.269	0.749	1.2	-0.7	-0.274	0	0.005
	1	32	-0.7	-0.269	0.749	1.2	-0.7	-0.274	0	0.005
	1	33	-0.009	0.092	0.093	1.52	-0.005	0.174	-0.004	-0.082
2	2	22	0.246	-0.081	0.259	1.07	0.228	-0.14	0.018	0.059
	2	30	-0.316	0.055	0.321	1.07	-0.298	0.114	-0.018	-0.059
3	3	14	-0.027	0.029	0.04	1.07	-0.027	0.025	0	0.004
4	4	5	0.021	0.007	0.022	0.68	0.021	0.006	0	0.001
	4	5	0.021	0.007	0.022	0.68	0.021	0.007	0	0
	4	14	-0.04	-0.009	0.041	1.07	-0.043	-0.007	0.003	-0.002
5	5	4	-0.021	-0.007	0.022	0.68	-0.021	-0.006	0	-0.001
	5	4	-0.021	-0.008	0.023	0.68	-0.021	-0.007	0	-0.001
6	6	18	0.098	0.013	0.099	1.07	0.132	-0.002	-0.034	0.015
	6	23	-0.068	0.068	0.096	1.07	-0.102	0.067	0.034	0.001
7	7	1	-0.22	-0.084	0.235	0.51	-0.22	-0.085	0	0.001
	7	1	-0.22	-0.084	0.235	0.51	-0.22	-0.085	0	0.001
8	8	10	0.149	0.079	0.169	1.87	0.149	0.086	0	-0.007
9	9	15	-0.007	-0.054	0.055	1.07	-0.007	-0.031	0	-0.023
	9	20	-0.319	0.017	0.32	0.72	-0.375	-0.006	0.056	0.023
	9	24	0.183	-0.058	0.192	0.72	0.232	-0.063	-0.049	0.005
10	10	11	0.152	-0.146	0.211	1.07	0.167	-0.149	-0.015	0.003
	10	8	-0.149	-0.081	0.17	1.87	-0.149	-0.086	0	0.005
	10	19	-0.003	0.227	0.227	1.07	-0.018	0.237	0.015	-0.01
11	11	10	-0.15	0.14	0.205	1.07	-0.167	0.149	0.017	-0.009
	11	23	0.721	-0.116	0.73	1.87	0.792	-0.135	-0.071	0.019
12	12	34	-1.465	-0.04	1.465	4.31	-1.508	-0.046	0.043	0.006
13	13	17	-0.152	-0.086	0.175	1.07	-0.184	-0.077	0.032	-0.009
	13	18	0.04	0.046	0.061	1.07	0.072	0.036	-0.032	0.01
14	14	3	0.027	-0.039	0.047	1.07	0.027	-0.025	0	-0.014
	14	4	0.04	0.001	0.04	1.07	0.043	0.007	-0.003	-0.006
	14	23	-0.348	0.046	0.351	1.07	-0.351	0.049	0.003	-0.003
15	15	9	0.007	0.045	0.045	1.07	0.007	0.031	0	0.014
16	16	23	-0.089	-0.014	0.09	1.07	-0.086	-0.014	-0.003	0
17	17	13	0.153	0.084	0.174	1.07	0.184	0.077	-0.031	0.007
	17	23	-0.103	0.029	0.107	1.07	-0.135	0.048	0.032	-0.019
18	18	6	-0.098	-0.024	0.101	1.07	-0.132	-0.002	0.034	-0.022
	18	13	-0.04	-0.05	0.064	1.07	-0.072	-0.036	0.032	-0.014
	18	25	0.187	-0.058	0.196	1.11	0.185	-0.025	0.002	-0.033
	18	25	0.187	-0.058	0.196	1.11	0.185	-0.025	0.002	-0.033
	18	24	0.017	0.125	0.126	0.72	-0.032	0.13	0.049	-0.005
19	19	10	0.005	-0.231	0.231	1.07	0.018	-0.237	-0.013	0.006
	19	29	-0.448	0.015	0.448	1.07	-0.462	0.024	0.014	-0.009
20	20	9	0.325	-0.017	0.326	0.72	0.375	0.006	-0.05	-0.023
	20	22	-0.101	0.193	0.217	1.07	-0.089	0.228	-0.012	-0.035
	20	22	-0.079	0.147	0.167	0.86	-0.069	0.175	-0.01	-0.028
21	21	34	-1.484	-0.299	1.514	4.31	-1.551	-0.286	0.067	-0.013
22	22	2	-0.246	0.075	0.257	1.07	-0.228	0.14	-0.018	-0.065
	22	20	0.101	-0.194	0.219	1.07	0.089	-0.228	0.012	0.034
	22	20	0.079	-0.156	0.175	0.86	0.069	-0.175	0.01	0.019

	22	26	-0.75	-0.129	0.761	1.37	-0.74	-0.073	-0.01	-0.056
23	23	6	0.068	-0.068	0.096	1.07	0.102	-0.067	-0.034	-0.001
	23	11	-0.719	0.123	0.729	1.87	-0.792	0.135	0.073	-0.012
	23	14	0.353	-0.044	0.356	1.07	0.351	-0.049	0.002	0.005
	23	16	0.089	0.012	0.09	1.07	0.086	0.014	0.003	-0.002
	23	17	0.103	-0.034	0.108	1.07	0.135	-0.048	-0.032	0.014
24	24	9	-0.182	0.053	0.19	0.72	-0.232	0.063	0.05	-0.01
	24	18	-0.016	-0.133	0.134	0.72	0.032	-0.13	-0.048	-0.003
25	25	18	-0.187	0.056	0.195	1.11	-0.185	0.025	-0.002	0.031
	25	18	-0.187	0.056	0.195	1.11	-0.185	0.025	-0.002	0.031
26	26	1	-0.953	-0.211	0.976	1.37	-0.96	-0.22	0.007	0.009
	26	22	0.753	0.138	0.765	1.37	0.74	0.073	0.013	0.065
	26	27	0.098	0.037	0.105	0.45	0.098	0.037	0	0
	26	27	0.102	0.037	0.108	0.45	0.098	0.037	0.004	0
27	27	26	-0.098	-0.037	0.105	0.45	-0.098	-0.037	0	0
	27	26	-0.102	-0.037	0.108	0.45	-0.098	-0.037	-0.004	0
28	28	29	-0.202	-0.088	0.22	1.07	-0.202	-0.088	0	0
29	29	19	0.455	-0.008	0.455	1.07	0.462	-0.024	-0.007	0.016
	29	28	0.203	0.086	0.22	1.07	0.202	0.088	0.001	-0.002
	29	36	-0.658	-0.078	0.662	1.07	-0.68	-0.084	0.022	0.006
30	30	2	0.32	-0.055	0.325	1.07	0.298	-0.114	0.022	0.059
	30	33	-0.576	-0.044	0.578	1.2	-0.559	-0.031	-0.017	-0.013
31	31	1	0.7	0.262	0.747	1.2	0.7	0.274	0	-0.012
32	32	1	0.7	0.262	0.747	1.2	0.7	0.274	0	-0.012
33	33	1	0.009	-0.105	0.106	1.52	0.005	-0.174	0.004	0.069
	33	30	0.587	0.066	0.591	1.2	0.559	0.031	0.028	0.035
	33	35	0.514	-0.044	0.516	1.2	0.523	-0.171	-0.009	0.127
	33	36	0.367	-0.017	0.367	0.93	0.368	-0.08	-0.001	0.063
	33	36	0.35	0.02	0.35	1.37	0.357	-0.039	-0.007	0.059
34	34	12	1.487	0.065	1.488	4.31	1.508	0.046	-0.021	0.019
	34	21	1.501	0.327	1.536	4.31	1.551	0.286	-0.05	0.041
35	35	33	-0.509	0.052	0.512	1.2	-0.523	0.171	0.014	-0.119
	35	36	0.265	0.052	0.27	1.07	0.273	0.043	-0.008	0.009
36	36	33	-0.359	0.019	0.36	0.93	-0.368	0.08	0.009	-0.061
	36	33	-0.345	-0.021	0.345	1.37	-0.357	0.039	0.012	-0.06
	36	29	0.665	0.09	0.671	1.07	0.68	0.084	-0.015	0.006
	36	35	-0.263	-0.055	0.269	1.07	-0.273	-0.043	0.01	-0.012

LFSF RESULT COMPARISION COMMAGEARLAHY 110KV

TABLE 12

LFSF Based on Phase Angle Change

LINE REPORT

Branch	From	To	Actual P(pu)	LFSF P(pu)	Diff P(pu)
1	AUGHINISH 110	CASTLEFARM 110	0.220	0.221	0.001
2	AUGHINISH 110	CASTLEFARM 110	0.220	0.221	0.001
3	AUGHINISH 110	MONETEEN 110	0.960	0.977	0.018
4	AUGHINISH 110	SEALROCK_1 110	-0.700	-0.693	0.007
5	AUGHINISH 110	SEALROCK_2 110	-0.700	-0.693	0.007
6	AUGHINISH 110	TARBERT 110	-0.000	-0.074	-0.074
7	BALLYCUMMIN 110	LIMERICK 110	0.239	0.256	0.017
8	BALLYCUMMIN 110	RATHKEALE 110	-0.309	-0.342	-0.033
9	BALLYLICKEY 110	DUNMANWAY 110	-0.027	-0.036	-0.009
10	BANDON 110	BRINNY 110	0.021	0.022	0.001
11	BANDON 110	BRINNY 110	0.021	0.022	0.000
12	BANDON 110	DUNMANWAY 110	-0.040	-0.052	-0.012
13	CARRIGADROHID 110	KILBARRY 110	0.167	0.193	0.026
14	CARRIGADROHID 110	MACROOM 110	-0.137	-0.175	-0.038
15	CHARLEVILLE 110	GLENLARA 110	-0.007	0.003	0.010
16	CHARLEVILLE 110	KILLONAN 110	-0.186	-0.252	-0.066
17	CHARLEVILLE 110	MALLOW 110	0.050	0.075	0.025
18	CLASHAVOON 110	CLONKEEN 110	-0.661	-0.694	-0.033
19	CLASHAVOON 110	MACROOM 110	0.856	0.993	0.137
20	CLASHAVOON 220	TARBERT 220	-1.089	-1.340	-0.250
21	CLONKEEN 110	COMMAGEARLAHY 110	-1.144	-1.147	-0.003
22	CLONKEEN 110	KNOCKEARAGH 110	0.458	0.432	-0.027
23	COOLROE 110	INNISCARRA 110	-0.217	-0.241	-0.023
24	COOLROE 110	KILBARRY 110	0.105	0.122	0.017
25	DUNMANWAY 110	MACROOM 110	-0.348	-0.396	-0.048
26	HARTNETTS CROSS 110	MACROOM 110	-0.089	-0.091	-0.002
27	INNISCARRA 110	MACROOM 110	-0.168	-0.199	-0.031
28	KILBARRY 110	MARINA 110	0.187	0.190	0.003
29	KILBARRY 110	MARINA 110	0.187	0.190	0.003
30	KILBARRY 110	MALLOW 110	0.149	0.143	-0.007
31	KILLONAN 110	LIMERICK 110	-0.092	-0.092	0.001
32	KILLONAN 110	LIMERICK 110	-0.072	-0.072	0.000
33	KILLONAN 220	TARBERT 220	-1.361	-1.557	-0.196
34	KNOCKEARAGH 110	OUGTRAGHT 110	0.009	-0.027	-0.037
35	LIMERICK 110	MONETEEN 110	-0.742	-0.745	-0.004
36	MONETEEN 110	MUNGRET 110	0.098	0.098	0.000
37	MONETEEN 110	MUNGRET 110	0.102	0.102	0.000
38	OUGHTRAGH 110	OUGTRAGHT 110	-0.202	-0.206	-0.004
39	RATHKEALE 110	TARBERT 110	-0.569	-0.624	-0.055
40	TARBERT 110	TRIEN 110	0.349	0.400	0.051
41	TARBERT 110	TRALEE 110	0.208	0.247	0.039
42	TARBERT 110	TRALEE 110	0.194	0.240	0.046
43	TRALEE 110	OUGTRAGHT 110	0.197	0.263	0.067
44	TRIEN 110	TRALEE 110	0.102	0.136	0.034

TABLE 13
LFSF Based on Line Flow Change

LINE REPORT

Branch	From	To	Actual P(pu)	LFSF P(pu)	Diff P(pu)
1	AUGHINISH 110	CASTLEFARM 110	0.220	0.220	-0.000
2	AUGHINISH 110	CASTLEFARM 110	0.220	0.220	-0.000
3	AUGHINISH 110	MONETEEN 110	0.960	0.961	0.001
4	AUGHINISH 110	SEALROCK_1 110	-0.700	-0.700	-0.000
5	AUGHINISH 110	SEALROCK_2 110	-0.700	-0.700	-0.000
6	AUGHINISH 110	TARBERT 110	-0.000	-0.002	-0.002
7	BALLYCUMMIN 110	LIMERICK 110	0.239	0.240	0.001
8	BALLYCUMMIN 110	RATHKEALE 110	-0.309	-0.310	-0.001
9	BALLYLICKEY 110	DUNMANWAY 110	-0.027	-0.027	-0.000
10	BANDON 110	BRINNY 110	0.021	0.021	0.000
11	BANDON 110	BRINNY 110	0.021	0.021	-0.000
12	BANDON 110	DUNMANWAY 110	-0.040	-0.040	0.000
13	CARRIGADROHID 110	KILBARRY 110	0.167	0.172	0.005
14	CARRIGADROHID 110	MACROOM 110	-0.137	-0.142	-0.005
15	CHARLEVILLE 110	GLENLARA 110	-0.007	-0.007	-0.000
16	CHARLEVILLE 110	KILLONAN 110	-0.186	-0.191	-0.005
17	CHARLEVILLE 110	MALLOW 110	0.050	0.055	0.005
18	CLASHAVOON 110	CLONKEEN 110	-0.661	-0.662	-0.001
19	CLASHAVOON 110	MACROOM 110	0.856	0.865	0.009
20	CLASHAVOON 220	TARBERT 220	-1.089	-1.097	-0.008
21	CLONKEEN 110	COMMAGEARLAHY 110	-1.144	-1.144	-0.000
22	CLONKEEN 110	KNOCKEARAGH 110	0.458	0.456	-0.002
23	COOLROE 110	INNISCARRA 110	-0.217	-0.222	-0.005
24	COOLROE 110	KILBARRY 110	0.105	0.110	0.005
25	DUNMANWAY 110	MACROOM 110	-0.348	-0.348	0.000
26	HARTNETTS CROSS 110	MACROOM 110	-0.089	-0.089	-0.000
27	INNISCARRA 110	MACROOM 110	-0.168	-0.172	-0.004
28	KILBARRY 110	MARINA 110	0.187	0.187	-0.000
29	KILBARRY 110	MARINA 110	0.187	0.187	-0.000
30	KILBARRY 110	MALLOW 110	0.149	0.144	-0.005
31	KILLONAN 110	LIMERICK 110	-0.092	-0.094	-0.002
32	KILLONAN 110	LIMERICK 110	-0.072	-0.073	-0.001
33	KILLONAN 220	TARBERT 220	-1.361	-1.365	-0.004
34	KNOCKEARAGH 110	OUGTRAGHT 110	0.009	0.005	-0.004
35	LIMERICK 110	MONETEEN 110	-0.742	-0.743	-0.001
36	MONETEEN 110	MUNGRET 110	0.098	0.098	-0.000
37	MONETEEN 110	MUNGRET 110	0.102	0.102	0.000
38	OUGHTRAGH 110	OUGTRAGHT 110	-0.202	-0.202	-0.000
39	RATHKEALE 110	TARBERT 110	-0.569	-0.570	-0.001
40	TARBERT 110	TRIEN 110	0.349	0.350	0.001
41	TARBERT 110	TRALEE 110	0.208	0.210	0.002
42	TARBERT 110	TRALEE 110	0.194	0.196	0.002
43	TRALEE 110	OUGTRAGHT 110	0.197	0.202	0.005
44	TRIEN 110	TRALEE 110	0.102	0.104	0.002

LFSF RESULT COMPARISION FOR TWO BUSES GENERATION CHANGE

TABLE 14
COMMAGEARLAHY 110kV AND KNOCKEARAGH 110kV

LINE REPORT

Branch	From	To	Actual P(pu)	LFSF P(pu)	Diff P(pu)
1	AUGHINISH 110	CASTLEFARM 110	0.220	0.220	-0.000
2	AUGHINISH 110	CASTLEFARM 110	0.220	0.220	-0.000
3	AUGHINISH 110	MONETEEN 110	0.966	0.967	0.000
4	AUGHINISH 110	SEALROCK_1 110	-0.700	-0.700	-0.000
5	AUGHINISH 110	SEALROCK_2 110	-0.700	-0.700	-0.000
6	AUGHINISH 110	TARBERT 110	-0.007	-0.008	-0.001
7	BALLYCUMMIN 110	LIMERICK 110	0.245	0.245	-0.000
8	BALLYCUMMIN 110	RATHKEALE 110	-0.315	-0.315	0.000
9	BALLYLICKEY 110	DUNMANWAY 110	-0.027	-0.027	-0.000
10	BANDON 110	BRINNY 110	0.021	0.021	0.000
11	BANDON 110	BRINNY 110	0.021	0.021	-0.000
12	BANDON 110	DUNMANWAY 110	-0.042	-0.042	0.000
13	CARRIGADROHID 110	KILBARRY 110	0.137	0.136	-0.001
14	CARRIGADROHID 110	MACROOM 110	-0.107	-0.106	0.001
15	CHARLEVILLE 110	GLENLARA 110	-0.007	-0.007	-0.000
16	CHARLEVILLE 110	KILLONAN 110	-0.243	-0.245	-0.002
17	CHARLEVILLE 110	MALLOW 110	0.107	0.109	0.002
18	CLASHAVOON 110	CLONKEEN 110	-0.446	-0.439	0.008
19	CLASHAVOON 110	MACROOM 110	0.800	0.797	-0.002
20	CLASHAVOON 220	TARBERT 220	-1.248	-1.254	-0.006
21	CLONKEEN 110	KNOCKEARAGH 110	0.101	0.105	0.004
22	CLONKEEN 110	COMMAGEARLAHY 110	-0.559	-0.558	0.001
23	COOLROE 110	INNISCARRA 110	-0.189	-0.187	0.002
24	COOLROE 110	KILBARRY 110	0.077	0.075	-0.002
25	DUNMANWAY 110	MACROOM 110	-0.350	-0.350	0.000
26	HARTNETTS CROSS 110	MACROOM 110	-0.089	-0.089	-0.000
27	INNISCARRA 110	MACROOM 110	-0.139	-0.138	0.001
28	KILBARRY 110	MARINA 110	0.187	0.187	-0.000
29	KILBARRY 110	MARINA 110	0.187	0.187	-0.000
30	KILBARRY 110	MALLOW 110	0.092	0.090	-0.002
31	KILLONAN 110	LIMERICK 110	-0.099	-0.099	0.000
32	KILLONAN 110	LIMERICK 110	-0.078	-0.078	-0.000
33	KILLONAN 220	TARBERT 220	-1.408	-1.410	-0.002
34	KNOCKEARAGH 110	OUGTRAGHT 110	-0.127	-0.136	-0.010
35	LIMERICK 110	MONETEEN 110	-0.748	-0.749	-0.000
36	MONETEEN 110	MUNGRET 110	0.098	0.098	-0.000
37	MONETEEN 110	MUNGRET 110	0.102	0.102	0.000
38	OUGHTRAGH 110	OUGTRAGHT 110	-0.202	-0.202	-0.000
39	RATHKEALE 110	TARBERT 110	-0.575	-0.575	-0.000
40	TARBERT 110	TRIEN 110	0.396	0.400	0.003
41	TARBERT 110	TRALEE 110	0.254	0.257	0.003
42	TARBERT 110	TRALEE 110	0.239	0.242	0.004
43	TRALEE 110	OUGTRAGHT 110	0.333	0.343	0.010
44	TRIEN 110	TRALEE 110	0.149	0.153	0.003

UPEC 07 POWER ENGINEERING CONFERENCE

PAPER

INVESTIGATION OF NETWORK CONSTRAINTS IN TRANSMISSION NETWORKS WITH SIGNIFICANT WIND GENERATION CAPACITY

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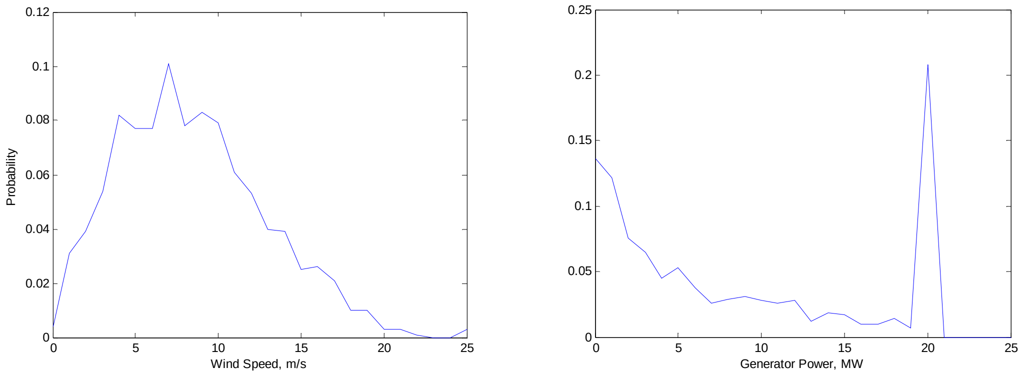
ABSTRACT

Ireland has seen the rapid increase in the level of wind generation over the past 10 years, from an installed capacity of less than 10MW in 1993 to a current level of over 500MW (February 2006). This has led to significant challenges to system operators, network planners, generation owners and wind developers. Previous work by the Electrical Power Engineering Research Group at DIT has looked at the incorporation of high levels of wind energy penetration into generation adequacy assessment calculations **Error! Reference source not found.**. This paper looks at the problems associated with integrating wind capacity into transmission networks.

With significant increases in wind capacity, the development of the networks can lag the rate at which new generation capacity is installed. The task of planning and developing a network in such a context is particularly challenging when multiple and diverse wind farm developers are seeking to advance projects rapidly. This can lead to a requirement that wind generation output be constrained to ensure that critical parts of the associated shared network do not become overloaded.

In assessing the impact of wind generation on transmission network capacity, one approach is to investigate the critical conditions, for example, under minimum or maximum load conditions. These critical conditions might be further defined by specifying minimum or maximum generation levels from wind capacity. One specific critical condition might be with minimum load conditions and maximum wind generation.

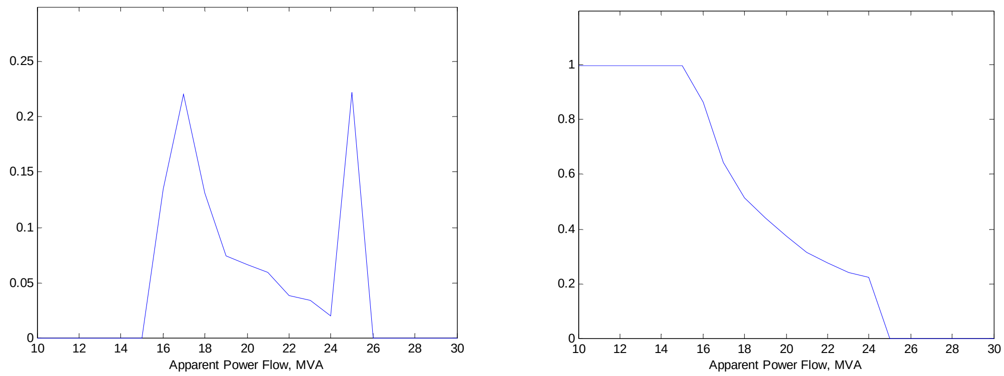
A probabilistic approach on the other hand would recognize that the wind generation, and to some extent the load, is stochastic in nature. Thus the potential might certainly exist for overload on specific lines, or for a reversal in power flow for specific network elements, but the probability of such an occurrence is also an important consideration.



(a) (b)

Figure 1 Probability Density Function for (a) Wind Speed (b) Generator Power Output

This paper investigates the probability distribution of power flow in transmission networks with a significant penetration of wind generation. The typical distribution of wind speeds (based on a Rayleigh distribution) is shown in Fig. 1(a). The resultant probability distribution of active power output for a 20MW wind generator with a rated wind speed of 12m/s and a cut-out wind speed of 20m/s is shown in Fig. 1(b). This wind generation output is then coupled with a load flow model of the network to determine the probability distribution of the power flow on specific lines. In particular, this information can be utilized to determine the probability of overload. Fig. 2 shows the probability density function and the cumulative probability distribution of the power flow on a line close to the point of connection of the wind generation. As can be seen, the probability of the power flow exceeding a level of 24MVA is 23% in this case.



(a) (b)

Figure 2 Line Power Flow (a) Probability Density Function for (b) Cumulative Distribution Function

The analysis presented above represents a Monte Carlo simulation of the wind generation/load/network combination. For large networks requiring simulation over considerable periods (possibly years in the case of planning studies) the computational requirements can be excessive because of the need for solution of the load flow problem for each hour of the simulation. The second part of this paper considers the accuracy of applying DC load flow approaches in determining generation participation factors to determine power flow on specific lines.

REFERENCES

[1] W. Carr and M.F. Conlon, “Simulation of Wind Speed Records for Use in Generation Adequacy Assessment Calculation”, accepted for the *40th Universities Power Engineering Conference*, University College Cork, September 2005

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