ANALYZING THE MAXIMUM WIND POWER PENETRATION LEVEL AROUND KALPITIYA PENINSULA

Master of Science Dissertation

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DECLARATION

The work submitted in this dissertation is the result of my own investigation, except where otherwise stated.

It has not already been accepted for any degree, and is also not being concurrently submitted for any other degree.

UOM Verified Signature

T.R. Kothalawala
28/09/2010

I endorse the declaration by the candidate.

UOM Verified Signature

30/09/2010
Dr. J.P. Karunadasa

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Abstract

The Government of Sri Lanka has declared the importance of developing renewable energy in line with the national policy of maximizing indigenous sources and ensuring fuel diversity. Sri Lanka has exploited hydropower resources to almost its maximum economical potential. Only a limited number of small and medium scale hydropower plants are yet to be developed, and these are already in various stages of development. Therefore, the country is now clearly at a cross road as far as future generation is concerned.

Wind is one of the promising renewable energy options available for grid connected power. In addition, wind-mapping results for Sri Lanka shows a very good wind potential in Kalpitiya area.

This research covers the impact of wind integrations on the power system of Sri Lanka and analyzes the maximum wind penetration levels around Kalpitiya peninsula for the proposed years 2010, 2012, 2014 and 2016 transmission networks.

A steady state system analysis as well as a frequency and voltage stability analysis are used appropriately to figure out the wind penetration limits. Finally, a transient stability analysis is performed to confirm the stable operation of the wind integrated power systems.

The widely known power system simulation software package PSS®E is used to model wind turbines and perform steady state and stability analyses.

This research project concludes that 20MW; 70MW, 185MW and 220MW wind absorptions are feasible respectively in the years 2010, 2012, 2014 and 2016 at Puttlam GS/PS. Approximately 30% wind availability is considered for the steady state system analysis. In addition, 5% spinning reserve response on droop is assumed for year 2010 and 2012 and 10% spinning reserve response on droop is assumed for year 2012 and 2014.

Analyzing the most economical wind penetration limit with net work modifications is beyond the scope of this research and is open for further research study.

Acknowledgement

Thanks are due first to my supervisor, Dr. J.P. Karunadasa, for his great insights, perspectives, guidance and sense of humor. My sincere thanks also go to the officers in Post Graduate Office, Faculty of Engineering, University of Moratuwa, Sri Lanka for helping in various ways to clarify the things related to my academic work in time with excellent cooperation and guidance. Sincere gratitude is also extended to those who serve in the Department of Electrical Engineering office.

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This dissertation would not have been possible unless the understanding, encouragement and patience provided by my family. Therefore I owe my deepest gratitude to my family.

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Chapter 1

1. Introduction

1.1. Wind power status and challenges

Wind farms have become a familiar sight around the world for a wide variety of reasons including their economic, environmental, and social benefits. Unlike other forms of electricity generation where fuel is shipped to a processing plant, wind energy generates electricity at the source of fuel. Wind is a native fuel that does not need to be mined or transported, which take two expensive aspects of long-term energy costs. Though wind plants provide numerous advantageous over fossil fuel plants, wind power production introduces more uncertainty in operating a power system. It is technically possible to integrate very large amounts of wind capacity in power systems; the limits arising from how much can be integrated at socially and economically acceptable costs [1]. However, some studies reveal that the maximum wind penetration level is limited by the allowable frequency deviations [2], where in Sri Lankan point of view the allowable frequency deviation is stated as ±1% in the Electricity Act and strictly adhered during the system operations.

Induction generators are often used for wind power projects and they require adequate amount of reactive power compensation at the grid substations for excitation. Different types of wind turbine generators behave differently during transmission grid disturbances, so extensive modelling of the dynamic electromechanical characteristics of a new wind farm is required to ensure predictable stable behaviour during system faults.

The Government of Sri Lanka has declared the development of renewable energy to be of high priority, in line with the national policy of maximizing indigenous sources and ensuring fuel diversity. Sri Lanka has exploited hydropower resources to almost its maximum economical potential. Only a limited number of small and medium scale hydropower plants are yet to be developed, and these are already in various stages of development. Therefore, the country's increasing electricity demand in the future will have to be met with increased imports of fossil fuel. Wind is one of the promising renewable energy options available for grid connected power. A special standardized tariff for small wind power plants has been published by the Ministry of Power & Energy, Sri Lanka to encourage the development of wind power by the private sector. The extent of wind energy potential in Sri Lanka was identified during the Wind Resources Assessment Study conducted by the National Renewable Energy Laboratory of USA in 2002. The technical and economic feasibility of harnessing this resource for power generation to its maximum potential is required to be studied. The technical ability of the Sri Lankan Power System to absorb wind-based generation has been identified as a major concern in developing wind power.

This study is an attempt to model wind power plants around Kalpitiya area using doubly fed induction generators and analyzes the issues related to the above wind integration such as grid limitations, stability effects and voltage impacts. Adequate load flow and dynamic simulation models that are necessary to evaluate the impact on the power system due to the above wind integration will be carried out during this study.

The outcome of this study will be a figure for maximum amount of wind power, which can be integrated in to the power system around Kalpitiya area without disturbing the stability and reliability of the system. Further this study will identify the power system strengthening requirements to increase the wind power penetration level at the steady state.

1.2. Background study

1.2.1. World wind picture

At the end of year 2007, global installed capacity of wind-powered generators was 93.8 gigawatts. Wind energy is used in more than 70 countries [3]. Although wind produces around 1% of worldwide electricity requirement, it accounts for approximately 19% of electricity production in Denmark, 9% in Spain and Portugal, and 6% in Germany and the Republic of Ireland [4].

World interest on wind energy increased rapidly during the past few years. 19.7GW of wind energy were added to the system during year 2007 that was 27% growth compared to the total installed capacity in year 2006 (74MW) [4].

The total installed wind energy capacity and prediction (1997-2010) and Worldwide Wind Energy by Continents is illustrated in figure1.1 and figure 1.2.

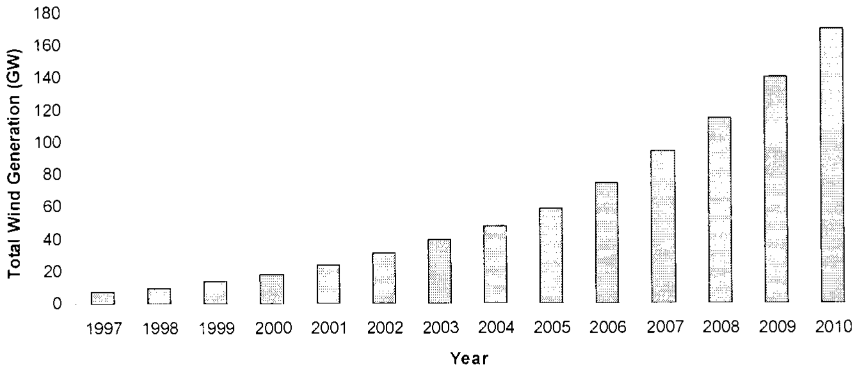

Figure 1.1: Worldwide wind energy by continents

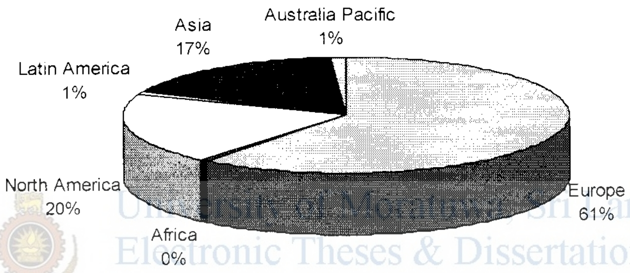

Figure 1.2 : Worldwide wind energy by continents

As the power sector is encouraged in moving towards green energy concept, the existing targets for wind power anticipate a quite high penetration in many countries.

1.2.2. Sri Lanka's power system

Ceylon Electricity Board (CEB), the state owned electricity utility established in 1969 is responsible for Power Transmission and most of the Generation and Distribution of electricity in Sri Lanka. At present Sri Lanka's power system consists of CEB owned medium and large hydro power plants of 1205MW and oil-fired thermal power plants of 548 MW. In addition, oil-fired thermal power plants of 720 MW capacity connected to the national grid are operated by the Independent Power Producers. The first coal-fired power plant (300 MW) is presently under construction. Apart from the above, small power plants of 172 MW , (mainly mini hydro) owned and operated by the private sector are connected to the 33kV distribution network as embedded generators [5]. CEB has issued letter of Intent to the private sector for the development of mini hydro and other embedded generators of about 200MW. Further, CEB has been operating a 3MW pilot wind power plant in the southern part of the country since 1999. Other wind power plants of 30MW are presently under construction by private developers in the north-western part of the country. In addition, proposals have been submitted to connect wind power plants of more than 100MW. Most of these wind farms are in the Kalpitiya peninsula in north western Sri Lanka. CEB operates a 220kV/132kV transmission network with a total length of approximately 2100 km [6]. Maximum demand so far met by the CEB is 1922MW with an annual generation 9900GWh.

1.2.3. Sri Lanka wind potential

In the Sri Lankan contest, the country is now clearly at a cross road as far as future power generation is concerned. The energy demand is increasing at around 6% per annum. Most of the energy generated is from imported fossil fuels. As the prices of petroleum based fossil fuels have been on the rise, the seriousness of the situation prompts the necessity of moving towards wind, the most promising and indigenous energy source available for future.

The wind-mapping results for Sri Lanka show many areas that are estimated to have good -to excellent wind resources (Refer Appendix A). These areas are concentrated largely in two major regions. The first is the northwestern coastal region from the Kalpitiya Peninsula north to Mannar Island and the Jaffna Peninsula. The second region is the central highlands in the interior of the country, largely in the Central Province and also in parts of Sabaragamuwa and Uva Provinces [7]. This report is basically focused on analyzing the wind penetration capability of the Sri Lankan power system around Kalpitiya Peninsula (Refer Appendix B for wind speed and power data at Narakkalliya site in Kalpitiya area).

1.2.4. Wind turbine generator technologies

A Wind Turbine Generator (WTG) typically consists of two or three blades connected to a hub to form the rotor assembly. The rotor hub connects to a shaft which turns a generator, usually through a gearbox. The electrical output of the generator is then fed to the grid either directly or through a system of power electronics that converts it to the correct grid frequency and voltage.

Three common technologies are used for wind turbine generators. The main differences between the three concepts are the generating system and the way in which the aerodynamic efficiency of the rotor is limited during high wind speeds. All wind turbines installed at present use one of the following systems, depicted in the figure 1.3.

(a). Squirrel cage induction generator
(b). Direct drive synchronous generator
(c). Doubly fed induction generator

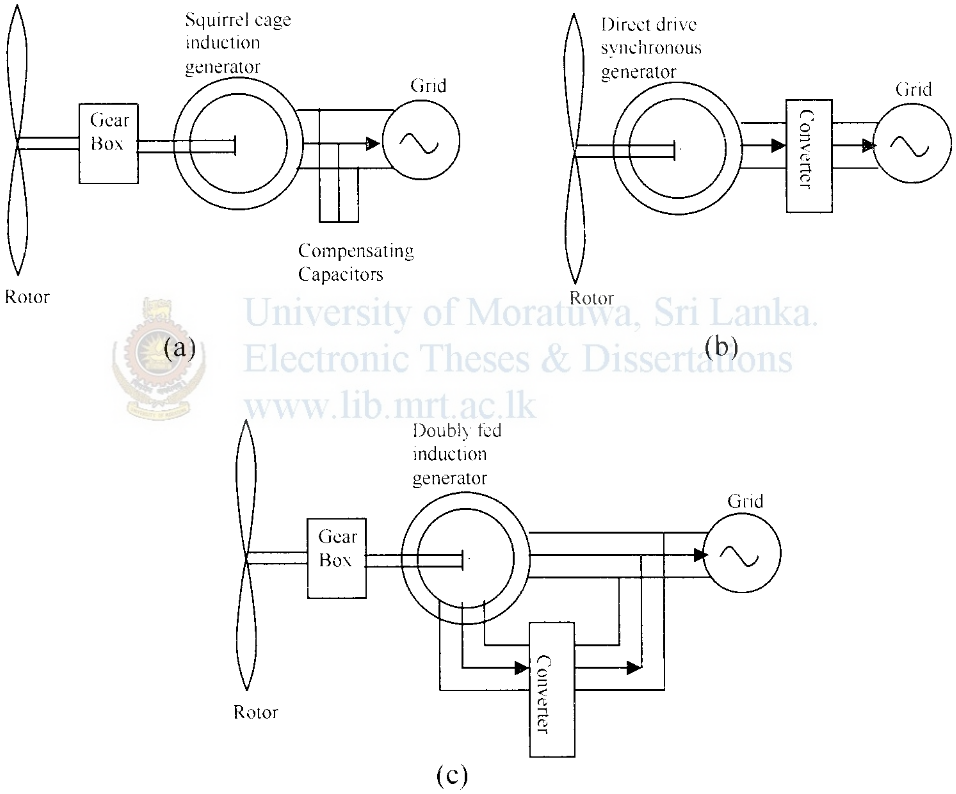

Figure 1.3: Generating systems used in wind turbines: (a) Squirrel cage induction generator, (b) Direct drive synchronous generator and (c) Doubly fed induction generator

The squirrel cage induction generator is the oldest technology, and it is a directly grid coupled conventional induction generator. The power delivered can be varied by varying the rotor speed and hence the slip, but those rotor variations are very small (approximately 1-2%). Therefore this wind turbine type is normally referred to as fixed speed turbines. This type of generators always consumes reactive power and in most cases the reactive power consumption is fully compensated by using capacitors. In addition, there exist semi variable speed systems where the rotor resistance of the squirrel cage induction generator is varied by using power electronics. By changing the rotor resistance, the torque/speed characteristic of the generator can be shifted and approximately 10% of speed variation is achievable at relatively low cost.

The other two generating systems depicted in figure 1.3 are variable speed systems. To achieve variable speed operation, the mechanical rotor speed and the electrical grid frequency should be decoupled. In doubly fed induction generator, the rotor is decoupled from the grid by using partially rated back to back voltage source converter and in direct drive synchronous generator, the generator is completely decoupled from the grid by power electronics converter [8].

1.2.5. Impacts of wind power on the power system

Impacts of wind power on the power system can be broadly divided into two sectors as local impacts and system wide impacts. The aspects coming under those sectors are depicted in the table below:

Local impacts	System wide impacts
1. Branch flows and node voltages	1. Dynamics and stability
2. Protection schemes, fault currents and switchgear ratings	2. Reactive power/ voltage control possibilities
3. Harmonics	3. Frequency control and dispatch of the remaining conventional units
4. Flicker	

Table 1-1: Local and system wide impacts of wind power

The first two aspects coming under local impacts should always be investigated when connecting new generating capacity to a power system, and the issues are therefore not specific for wind power [9].

The way in which wind turbines affect the voltages at nearby nodes varies with the wind turbine generator technology used. The induction generator with squirrel cage rotor cannot control its terminal voltage. Therefore, additional equipment such as capacitor banks or SVCs (Static Var Compensators) are necessary for voltage controlling. On the other hand, variable speed turbines have the capability of varying the reactive power at a given active power, rotor speed and terminal voltage, but the range over which the reactive power can be controlled depends on the size of the power electronic converter.

Direct drive variable speed turbines have an advantage here because they already have large converters and some extra capacity can be added to allow reactive power control at a marginal cost. However doubly fed induction generators already have an advantage of using small converters and adding converter capacity to control reactive power tends to cancel this advantage.

The contribution of wind turbines to the fault currents is also different in three main wind turbine types. Directly grid coupled squirrel cage induction generators contribute to the fault currents and rely on conventional protection schemes. DFIG also contributes to the fault currents, but is quickly disconnected when a fault occurs due to the sensitivity of power electronics used. Direct drive generators hardly contribute to the fault currents because the power electronic converter which the turbine is equipped with cannot carry a fault current.

The harmonic effects are important when generators are coupled to the grid through power electronic devices; therefore this is mainly applied to variable speed turbines. However, in case of modern power electronic converters with high switching frequencies, advanced control algorithms and filtering techniques, the harmonic issue should not be a major problem.

The flicker issue is typical to wind turbines due to the intermittent nature of the wind resource. The problem is critical for fixed speed turbine generators as it is not possible to store the turbulence of the wind in the form of rotational energy in the rotor. For a variable-speed turbine, the power fluctuations caused by wind variations can be more or less absorbed by changing the rotor speed and thus power variations originating from the wind conversion and the drive train can be reduced. Depending on the strength of the grid connection, the resulting power fluctuations can result in grid voltage fluctuations, which can cause unwanted fluctuations in bulb brightness.

As wind turbine generators use different technologies other than that of conventional synchronous generators, analyzing the impact of dynamics and stability of the power system become important. Adequate modelling of turbine generating systems is essential to investigate those impacts.

The second aspect coming under system wide impact is the reactive power and voltage control possibilities. Wind power affects the reactive power generation and voltage control possibilities in the system mainly for following reasons.

- Wind turbine generating systems have very limited capability to vary their reactive power output
- Wind power plants cannot be flexibly located compared to conventional thermal power plants from the perspective of grid voltage control
- Wind power plants are weakly coupled to the grid at low voltages and distance sites

Due to the above facts, a comprehensive analysis on power system voltage control possibilities should be conducted when integrating wind power plants in to the power system.

Since the prime mover of the wind power cannot be controlled, it impacts on the frequency control and the dispatch of the remaining conventional units in the power system. Further the variability of wind on long term (> 15 min.) tends to complicate the dispatch of conventional units by varying the demand curve to be matched by those generating units.

All the above discussed effects become more severe at high wind power penetrations. The topic of this dissertation is focused on quantifying the wind penetration level in a particular area of the power system based on the limit at which system wide effects start to occur.

1.3. Motivation

The Government of Sri Lanka has declared the development of renewable energy to be of high priority in line with the national policy of maximizing indigenous sources and ensuring fuel diversity.

At present a large number of wind power development proposals have been submitted to CEB in order to get the approval to connect into the national grid. A clear idea about the power system's capability of absorbing wind power is essential when granting permission to develop those wind farms. This study is an attempt to figure out the wind absorption capability of the Sri Lankan power system around Kalpitiya peninsula.

1.4. Research approach

The topic being investigated in the research project is the impact of large wind integration on the power system both in the steady state and the transient state. The outcome will be a quantified wind penetration level in a particular area of the power system based on the limit at which the adverse effects of wind power starts to occur on the power system. Note that, in this dissertation, the penetration level is defined as the amount of wind power that can be absorbed in to the grid at a particular point in a given year.

The study will narrow down to Kalpitiya peninsula and the reasons for this are described below.

Large numbers of wind power development proposals around this area have already been submitted to the utility and it is assumed that they should be served as first come first serve basis.

Out of other resource areas (mainly Mannar, Jaffna and Central Hills), only Mannar is located on the same wind line with Kalpitiya where the system frequency concerns have to be handled together. However the access to the national grid from Mannar sites is not developed yet and there are no proposals to extend the national grid towards Mannar sites up to year 2016. Hence this research omits the possibility of developing Mannar wind sites within the study period (2010-2016).

The penetration levels of the other locations can be separately treated based on the fact that their wind patterns do not coincide with the studied region. But, it may further complicate the dispatch schedules of the remaining conventional units and hence more attention needs to be paid on the power system operational aspects.

Out of the three common wind generating technologies, this dissertation use doubly fed induction generator (DIFG) technology to model wind turbine generators as it is the most popular technology at present. Further, the adverse effects of directly coupled induction generators such as severe voltage fluctuations and limitations in reactive power capabilities should be eliminated to comply with the grid code. Hence, the impact of directly grid coupled generators on the grid can be assumed more or less similar to the DIFGs after adopting the eliminating techniques such as static var compensators, soft starters and rotor resisters to damp out input variations, which become compliment to comply with the grid code.

In this research project, the widely known power system simulation software package PSS®E was used. This program contains dynamic simulation models for wind turbines that have been successfully used by numerous PSS®E users around the globe.

The first step was to use load flow simulations to investigate network limitations at the steady state. The next step was to investigate the impact of wind power on the power system dynamic behaviour. Finally, quantified grid absorption capabilities for the years 2010, 2012, 2014 and 2016 were identified by analyzing the steady state and the stability study results.

1.5. Dissertation outline

This dissertation reflects the research approach discussed above. In chapter 2, the DFIG model and the various control models used will be discussed in more detail. Further, the system configurations and modelling approach will also be discussed in the same chapter.

Steady state system analysis including load flow, contingency and transmission transfer limits will be discussed in chapter 3.

Chapter 4 will present the frequency stability analysis, while chapter 5 presents the voltage stability part.

Chapter 6 will reinvestigate the transient stability of the power system with proposed wind integrations in chapter 4&5.

In chapter 7, the conclusions of the research project are summarized and topics for further research are indicated.

Chapter 2

2. Wind Modelling

2.1. System configuration

Puttlam 132/33kV Grid Substation (GS) and Puttlam Power Station (PS) Switchyard were considered as the grid integration points for the wind power generated around Kalpitiya area as they are located in the vicinity of the wind sites. This study assumes that the wind power generated at various sites around Kalpitiya area will be taken in to Puttlam GS or Puttlam PS using 33kV feeders. This study uses GE 3.6 MW wind turbines to model wind machines. Relevant WTG data are depicted on table 2-1 [10].

Description	**Unit**	**Value**
Generator Rating	MVA	4
P_{max}	MW	3.6
P_{min}	MW	0.16
Q_{max}	Mvar	2.08
Q_{min}	Mvar	-1.55
Terminal voltage for 50 Hz	V	3300
X_{source}	p.u	0.8
Unit transformer rating	MVA	4
Unit transformer impedance	%	7
Unit transformer	X/R	7.5

Table 2-1: Data for GE 3.6 MW WTG model.

As the terminal voltage of the 3.6MW GE wind turbine for 50Hz system is 3.3kV, appropriately rated 3.3/33kV transformers were used for each WTG. The point of common coupling (PCC) was taken as 33kV for year 2010 system. The absorption capabilities were analyzed by considering both 220kV and 132kV voltage levels as PCC for year 2012, 2014 and 2016 systems. It was proposed that 33/220kV transformers at Puttlam coal power plant site be used to integrate wind power at 220kV level. The proposed system configuration is shown in figure 2.1.

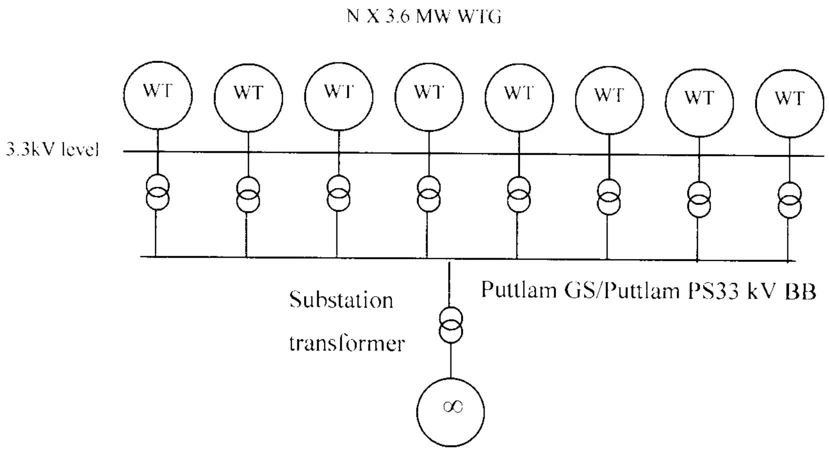

Figure 2.1: Proposed system configuration

2.2. Modelling in power flow

A wind turbine in power flow is treated as a conventional machine. Although the wind farm is made-up of a large number of individual wind generators, this study is based on a reasonable assumption. The assumption is that all machines parallel into a single equivalent large machine behind a single equivalent reactance. Such a model is shown in figure 2.2.

The GE 3.6 MW model which is used in this study is applicable to other vintage wind turbine generators as long as the basic principle of power conversion and control are the same [10].

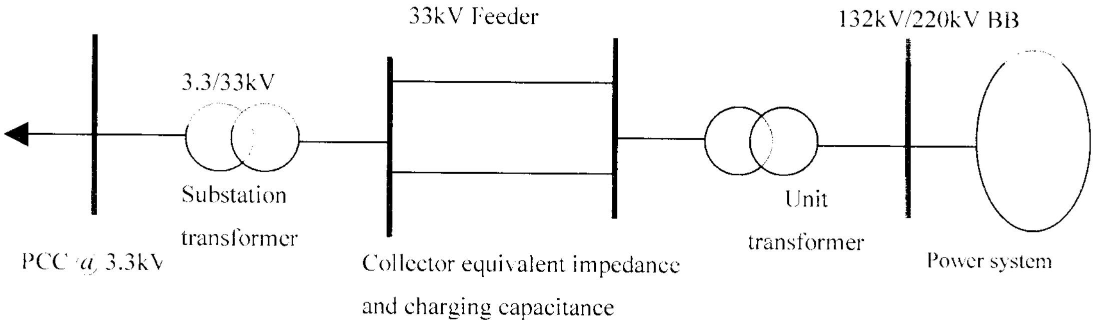

Figure 2.2: Simplified wind farm power flow model

2.3. Modelling for dynamics

The DIFG model used for this study has seven modules. They are:

1. Generator and converter module – GEWTG1
2. Electrical control module – GEWTE1

3. Shaft module - GEWTT
4. Pitch control module - GEWTP
5. Aerodynamic module - GEWTA
6. Active power control module – GEW1E1
7. Wind gust module - WGUSTC

Functional descriptions of each module is provided in the technical guide "Modelling of GE Wind Turbine Generators for Grid Studies", which is available with the software package. The connectivity diagram is shown in figure 2.3[11].

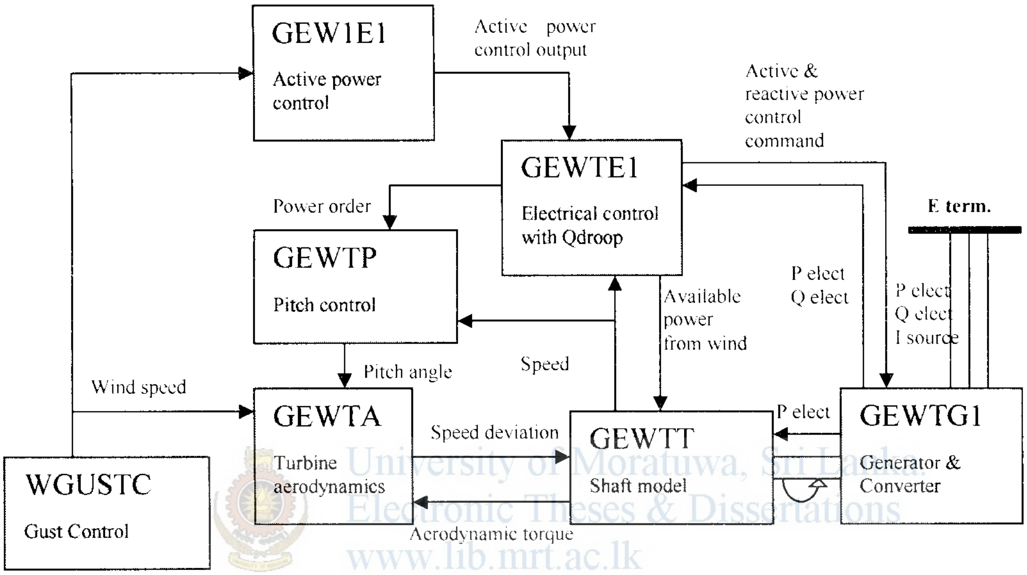

Figure 2.3: Connectivity diagram

Chapter 3

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3. Steady State System Analysis

3.1. Introduction

The objective of the steady state system analysis is to identify several wind absorption capability levels of the proposed transmission network.

This study was performed based on year 2012, 2014 and 2016 transmission networks proposed in "Long Term Transmission Development Plan 2008-2016" , prepared by the Transmission Planning unit of CEB .(Refer to appendix C and appendix D for the proposed year 2016 transmission map and the year 2016 single line diagram.)

The steady state system analysis was carried out only for 132kV level due to following reasons:

- Both 132kV transmission connections from Puttlam GS to New Chilaw/Madampe and New Anuradhapura have Lynx conductors, with low thermal ratings. Hence there is a possibility of achieving a steady state power transfer limit before stability limit.
- 220kV network around Puttlam PS has been planned to evacuate 900MW coal fired thermal power with approximately 750MW excess capacity. Therefore the possibility of achieving a steady state limit for wind penetration at 220kV level can be neglected.

Transmission Transfer Limit Analysis (TLTG) followed by a Load Flow Analysis were performed to identify the above stated wind power absorption capability levels.

3.2. Transmission Transfer Limit Analysis

Transmission Transfer Limit Analysis is a common approach used to find a limiting solution. It starts with a base case and calculates the sensitivity of flow in monitored elements or groups of elements to a variation in interchange. This technique is often referred to as a distribution factor technique. Once the sensitivity of elements is known, linear projections can be used to estimate permissible interchanges based on thermal limits. P1, P2 and P3 in figure 3.1 represent linear line flow functions of the net import. The horizontal line rating intersects P1 imposing a limit or net import restriction. The TLTG estimates the export limit of the specified subsystem using the above explained technique.

The above approach was initially used to identify 132kV transmission line capacity limitations related to wind power absorption at Puttlam GS.

In the beginning the power system was divided in to two sectors (Study & opposing systems shown in figure 3.2). The transmission lines connecting the two systems above were taken as the interface. Elements included in the study, opposing and interface systems are depicted in table 3-1.

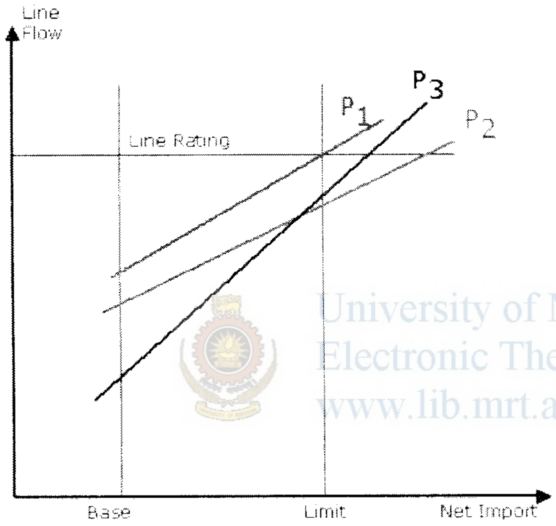

Figure 3.1: TLTG approach

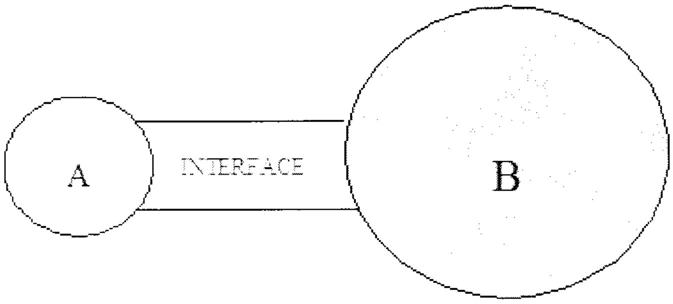

Figure 3.2 : Study system (A) opposing system (B) and interface used in TLTG

Study system [A]	Opposing system [B]	Interface
Puttlam 132kV BB Puttlam 33kV BBs	Rest of the power system BBs excluding BBs specified in A.	Puttlam –New Chilaw 132kV line Puttlam – Anuradhapura 132kV line Puttlam – Maho 132kV line

Table 3-1 : Study, opposing and interface elements for TLTG analysis

3.3. Load flow analysis

3.3.1. Load flow solution

Load flow solution is a solution of the network under steady state condition subjected to certain inequality constrains under which the system operates. These constrains can be in the forms of load nodal voltages, reactive power generation of the generators and the tap setting of a tap changing under load transformer etc.

Load flow solution is essential for designing a new power system as well as for extending existing power systems. This analysis requires the calculation of numerous load flows under both normal and contingency operating conditions.

3.3.2. Planning criteria

During the synthesis of transmission development plan, it is targeted to meet the planning criteria to ensure quality and reliable supply under normal operating conditions as well as under contingencies. The adopted contingency level for the planning purposes is N-1, i.e. outage of any one element of the transmission system at a time.

Under normal operating conditions, the equipment (transmission line, transformer and etc.) loading limit is considered as 100% of the respective thermal limit and under contingency situation the allowable equipment loading limit is considered as 120%.

The permitted voltage deviations at any live busbar of the network under normal and contingency conditions are depicted in the table below:

Voltage level	Allowable voltage variation (%)	
	Normal condition	N-1 condition
220 kV	±5%	-10% to +5%
132kV	±10%	±10%
33kV	±1%	±1%

Table 3-2: Allowable range of voltage variations

3.4. Steady state simulation procedure

Two system loading scenarios were considered during the steady state system analysis. They are the day peak and night peak loading scenarios.

Initially TLTG was performed only the for day peak scenario as this becomes more critical when considering branch thermal ratings (i.e. branch thermal ratings are fairly low during day time due to temperature effect). Several transfer limits were identified for each year with a set of network improvements during the TLTG analysis.

Then the load flow simulations were performed for both day peak and night peak loading scenarios to verify the results obtained during TLTG analysis.

Both normal and N-1 operating conditions were considered during the above analysis.

It was assumed that all transmission development proposals that are listed in the "Long Term Transmission Development Plan 2008-2016" would be implemented timely.

3.5. Results and conclusions

Power absorption capabilities identified using the above described method is listed in table 3-3.

Year	**Power absorption capability**		**Network modifications required**
	Level	**Amount (MW)**	
2010	1	50	None
	2	100	Upgrade Puttlam-Pannala 132kV line to operate at 75°C
			Upgrade Puttlam-Madampe 132kV line to operate at 75°C
2012	1	50	None
	2	180	Upgrade Puttlam-Pannala 132kV line to operate at 75°C
			Upgrade Puttlam-Madampe 132kV line to operate at 75°C
			Upgrade Habarana - Anuradhapura 132kV line to operate at 75°C
			Switch off Kelaniya - Kolonnawa 132kV line
2014	1	30	None
	2	190	Upgrade Puttlam - New_Chilaw 132kV line to operate at 75°C
			Upgrade Habarana - Anuradhapura 132kV line to operate at 75°C
	3	360	Re-string Puttlam - New_Chilaw 132kV line using Zebra
			Re-string Puttlam – Anuradhapura 132kV line using Zebra
			Upgrade Habarana - Anuradhapura 132kV line to operate at 75°C
2016	1	120	None
	2	280	Upgrade Puttlam - New_Chilaw 132kV line to operate at 75°C

Table 3-3: Steady state power absorption capability at Puttlam 132kV level

The absorption capabilities depicted in the table 3-3 can be released due to the intermittent nature of the wind resource. The common practice is to consider 20~30% wind resource availability for steady state analysis. Table 3-4 depicts the steady state wind power absorption capability at Puttlam 132kV level without modifying the proposed network and by considering approximately 30% wind availability.

Year	Wind Power Absorption Capability (MW)
2010	160
2012	160
2014	70
2016	400

Table 3-4: Steady state wind power absorption capability at Puttlam 132kV level

Sever steady state limitations were observed during year 2014. The absorption capability of year 2016 system is fairly high. This may be due to the retirement of the Heladanavi generator and the higher local power consumptions.

Chapter 4

4. Frequency Stability Analysis

4.1. Introduction

Section 1.2.4 described the impact of wind integration on the power system. In this chapter the impact of wind power on system frequency will be discussed in greater detail.

Frequency stability of the power system will be investigated under sudden wind farm outages during this chapter. Further, the system frequency behaviour will be presented following wind resource input variations.

4.2. Evaluate frequency stability limit

Since the prime mover of the wind power cannot be controlled, it impacts on the frequency control and the dispatch of the remaining conventional units in the power system. Therefore it is necessary to quantify the wind integration level where the adverse system wide frequency affects starts to occur.

4.2.1. Factors affecting the frequency stability

The frequency stability of the system primarily depends on the available spinning reserve, governor availability and their parameters, mechanical limit switch positions and power system strength at that operating point.

Note that, in this dissertation, the spinning reserve is defined as the percentage of excess amount of generation available from all synchronized units responsive on droop and ready to serve the additional demand, to the total load and losses being supplied.

Spinning reserve must be allocated to obey certain rules, usually set by the regulators.

Governor droop setting defines the active power participation factor of the machine for frequency changes. Lower droop setting results higher active power participation.

Power system strength for frequency variations was evaluated by using system frequency characteristic constant, K.

$$K = \frac{dp/p}{df}$$

Where;

dp : Outage capacity

p : Demand at outage in MW

df : Maximum frequency drop at outage.

4.2.2. Existing practice in frequency controlling

The allowable frequency deviation in Sri Lanka is stated as ±1% in the Electricity Act and strictly adhered during the system operations.

The current practice is to use a single frequency controlling machine under free governor mode with a lower droop setting to control the system frequency. However all other candidate units are keep at free governor mode with higher droop settings.

In addition, a load shedding scheme is used in system operations in order to protect the system from cascade collapses after large generator outages. Normally, the first load shedding frequency is considered as 48.75Hz and several load shedding stages are used according to the severity of the failure. The allowable outage capacity before initiating the load shedding scheme is determined by the system frequency characteristic constant, K.

4.2.3. Frequency stability limit for wind integration

This study concentrated into a small geographical area located in the same wind line. Therefore, following frequency limits are considered in order to assure a quality and reliable electricity supply to consumers and to minimize the power system operational issues

- The system frequency should be recovered without initiating load shedding schemes following total wind farm outages.
- Frequency fluctuations resulted due to anticipated wind speed variations should be within allowable ±1% limit.
- The maximum allowable wind ramp rate is limited to 10MW/min, as mentioned in the grid code [12].

4.3. Data and assumptions

This study is based on the transmission networks proposed in the "Long Term Transmission Development Plan 2008-2016" and assumes that all development proposals presented in the above plan would be implemented as per schedules.

The power system constants of the transmission lines and transformers and the constants for individual generation facilities were extracted from " Master Plan Study on the Development of Power Generation and Transmission System in Sri Lanka"[13]. The substation equipment data were taken from CEB data base.

Governor droop setting for all generators except the frequency controlling unit was set to 5% and the droop setting for frequency controlling unit was taken as 1.6% throughout this study.

System spinning reserve (reserve available in the units with governors) was maintained approximately at 5% for year 2010 and 2012, and about 10% spinning reserve was maintained for year 2014 and 2016.

The system frequency impact is severe at low loading conditions. Therefore the frequency stability analysis was carried out for off peak loading scenario. Off peak demand considered for each year is depicted in the table below:

Year	**Off peak demand(MW)**
2010	916
2012	1076
2014	1267
2016	1491

Table 4-1: System demand- off peak

4.4. Methodology and results

The frequency stability is considered as a system-wide impact. Therefore this section of the study does not present the local network arrangement. This section focuses on investigating an allowable generator outage capacity for each year, which does not initiate the first load shedding scheme.

Further, this part investigates the system frequency response that occurs due to anticipated wind input variations. However, it is not reasonable to apply the same wind input variation to all WTGs at the same time. Hence, to reduce the complexity of the study and to increase the validity of the result, this study uses only 70% of the full wind power range to simulate wind variations.

4.4.1. System analysis – Year 2010

A system frequency characteristic constant, K (refer section 4.2.1) for year 2010 off peak loading scenario was found as 5.2%MW/Hz after simulating number of generator outage simulations. Therefore, the capacity outage limit was calculated as 59MW for year 2010 off-peak scenario just before the activation of automatic load shedding scheme (scheduled to activate at 48.75 Hz).

4.4.2. System analysis – Year 2012

Several generator tripping simulations were carried out for year 2012 off peak loading scenario while keeping approximately 5% spinning reserve. System simulation results depicted that the capacity outage limit for year 2012 system is only 90 MW just before initiating the load shedding scheme. The system frequency response and mechanical power variation of the frequency controlling machine after 90MW generation outage is shown in figure 4.1.

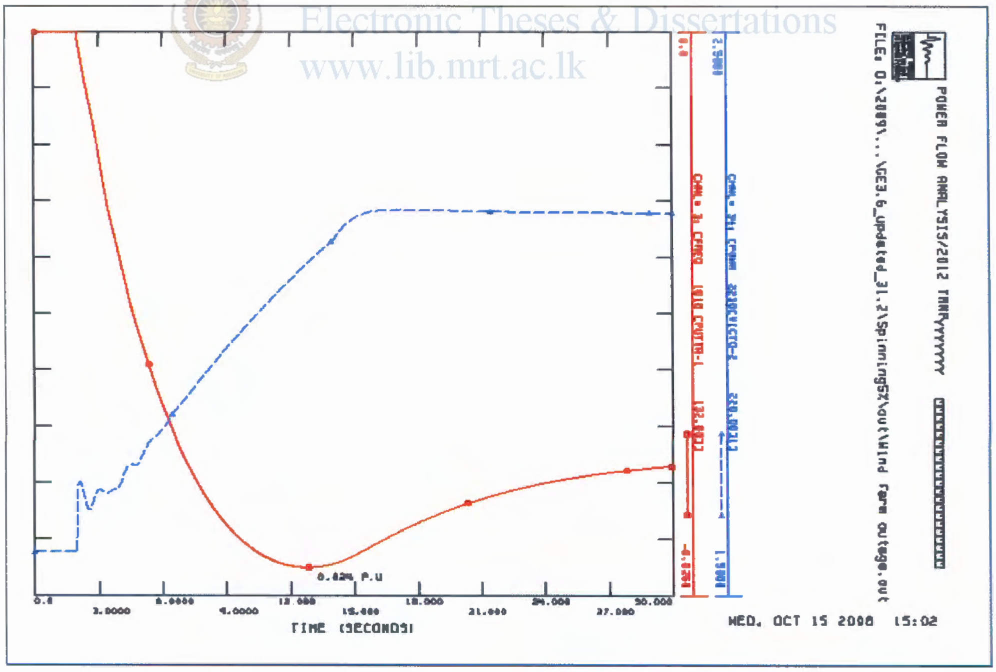

Figure 4.1: System response at 5% spinning reserve- off peak loading scenario-90MW generation outage

Year 2012 network under off peak loading condition with 90MW wind integration was tested against wind speed variations. The applied wind speed input variation, the observed mechanical power output variation of the largest wind farm and the observed system frequency variation are shown in figure 4.2. The rate of change of mechanical power output of the largest wind farm is shown on the same graph.

Results depict that the observed frequency variation is within the allowable ±1% limit.

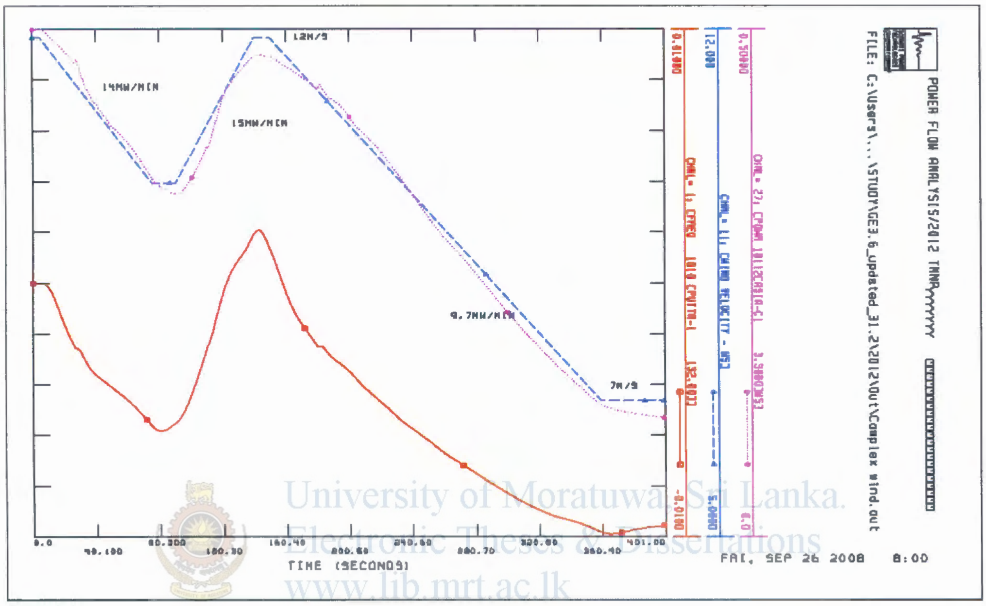

Figure 4.2: System frequency response for wind input variations – Year 2012 at 90MW wind integration level

4.4.3. System analysis – Year 2014

It has been found that the voltage fluctuation becomes the limiting factor for wind integration during year 2014. The capacity limit for voltage stability was obtained as 185MW. The voltage stability will be discussed in detail during the next chapter. Therefore this section discusses the frequency stability of the power system with 185MW wind integration.

The maximum frequency drop observed during the off peak scenario, following a sudden 185MW generation outage was only 1.6%. Year 2014 network under off peak loading condition with 185MW wind integration was tested against wind speed variations and it was found that the system frequency deviation remains within allowable ±1% limit (refer figure 4.3).

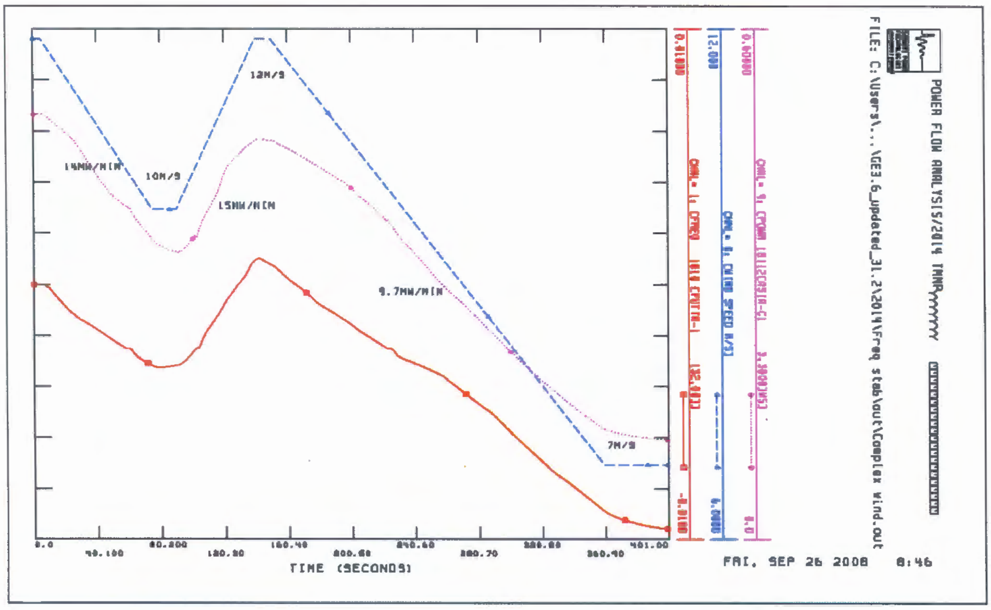

Figure 4.3: System frequency response for wind input variations – Year 2014 at 185MW wind integration level

4.4.4. System analysis – Year 2016

Frequency stability studies were carried out for year 2016 network against 220MW outage capacity. The limit 220MW was obtained from the voltage stability studies, which will be discussed in the next chapter.

The off peak frequency drop observed was only 2%, where the first load shedding is designed to be activated at 2.5% drop. Year 2016 network under off peak loading condition with 220MW wind integration was tested against wind speed variations and it was found that the system frequency deviation remains within allowable ±1% limit (refer figure 4.4).

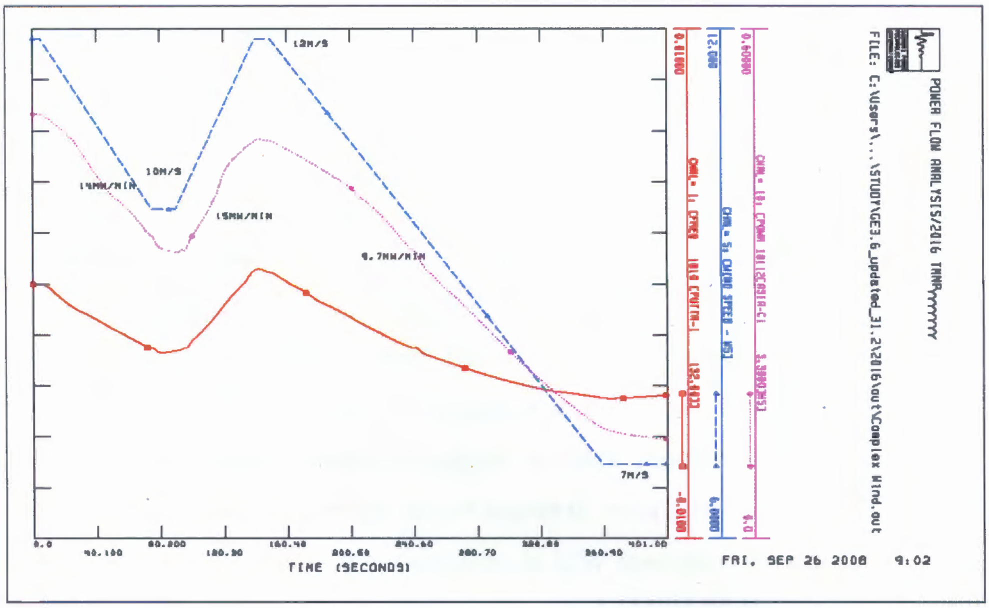

Figure 4.4: System frequency response for wind input variations – Year 2016 at 220MW wind integration level

Chapter 5

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5. Voltage Stability Analysis

5.1. Interfacing standards

Maximum capacity of a wind plant that can be connected to a power system is primarily determined by the electrical system and power quality considerations.

Various countries adopt various standards to limit renewable integrations and to ensure the power quality. A rough rule of thumb to control the power quality has been to keep the renewable power plant capacity in MW less than the grid line voltage in kV, if the grid is stiff .On a weak grid, however, only 10 or 20 % of this capacity may be allowed.

On the other hand, it is convenient to meet the power-quality requirements by limiting the total renewable power rating less than a few percent of the short circuit MVA of the grid at the proposed interface. The limit is generally 2% in developed countries and 5 % in developing countries [14].

Some countries adopt a limit on the step change in voltage a customer can cause when loading or unloading a generating unit. This limit is ±2% in Spain for wind generators.

5.2. Voltage stability limit

The voltage fluctuation observed at the point of common coupling (PCC) following a sudden wind farm failure and the grid short circuit level at the PCC were taken in to account to in determining the voltage stability limit for the network during this study.

Since there is no wind interface standard developed for Sri Lanka, the allowable maximum voltage fluctuation is limited to approximately 2% at the PCC and the obtained figure was compared with the grid short circuit level at the same point to obtain a wind integration limit at that point of the grid.

5.3. Methodology and results

The voltage stability is considered as a local impact. Therefore it is necessary to identify the system configuration for wind integration in order to perform voltage stability studies.

Initially proper system configurations were identified for each study year and then the voltage stability studies were carried out for the selected configurations in order to identify the voltage stability limit.

Since local impact highly depends on the local loads, both night peak and off peak loading scenarios were appropriately taken in to account during the voltage stability analysis.

5.3.1. System analysis – Year 2010

This part of the study aims at obtaining a voltage stability limit for wind integration to the proposed year 2010 network at existing Puttlam GS.

At present Puttalam GS consists of 2x31.5MVA transformers. Holcim cement factory is supplied with power using two dedicated 33kV feeders. Two transformers are operated separately. Year 2010 Puttlam GS arrangement is shown in the figure 5.1.

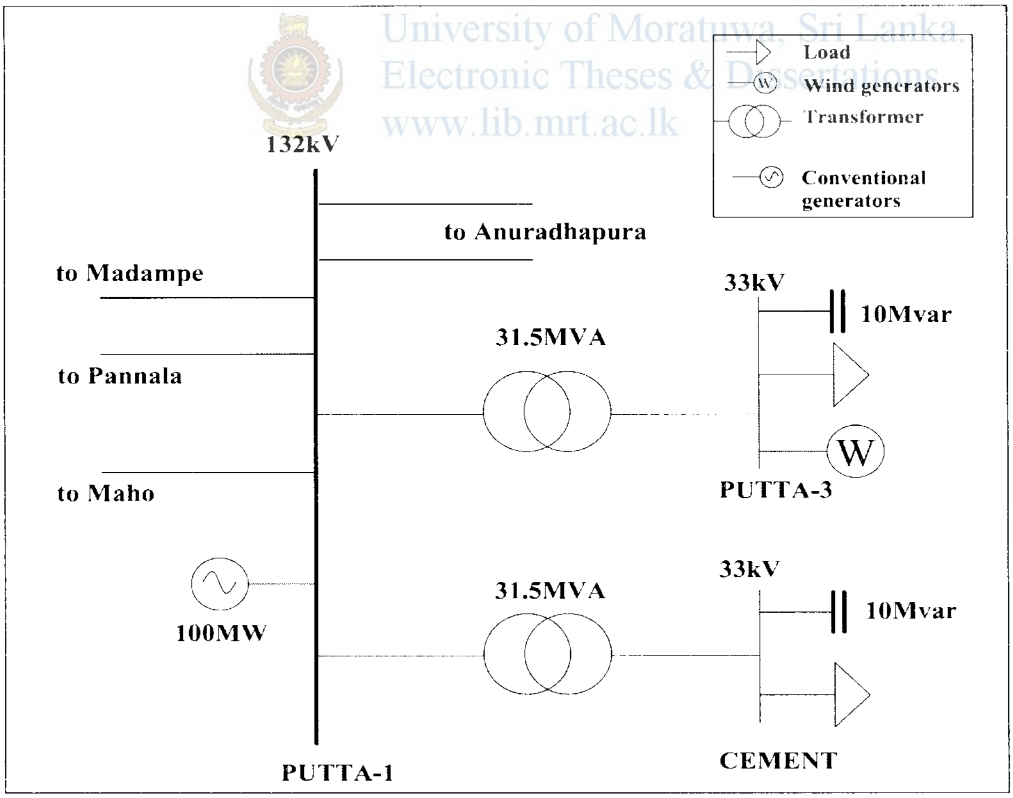

Figure 5.1: Proposed Puttlam GS arrangement for year 2010

The impact of wind additions on the 33kV level is analyzed by considering two wind integration levels. They are 20MW and 35MW. Results are summarized in table 5-1.

Busbar	**Observed voltage fluctuation**	
	kV	**% of nominal voltage**
CEMENT	0.165	0.5
PUTTA-3	0.132	0.4

20MW penetration level at night peak scenario

Busbar	**Observed voltage fluctuation**	
	kV	**% of nominal voltage**
CEMENT	0.066	0.2
PUTTA-3	0.755	2.3

20MW penetration level at off peak scenario

Busbar	**Observed voltage fluctuation**	
	kV	**% of nominal voltage**
CEMENT	0.198	0.6
PUTTA-3	0.363	1.1

35MW penetration level at night peak scenario

Busbar	**Observed voltage fluctuation**	
	kV	**% of nominal voltage**
CEMENT	0.066	0.2
PUTTA-3	1.419	4.3

35MW penetration level at off peak scenario

Table 5-1: Observed voltage fluctuations at 33kV level of Puttlam GS

Short-circuit level at Puttlam 33kV busbar is obtained as 258MVA. Wind integration level as a percentage of short circuit level is depicted in table 5-2.

Busbar	**Wind power as % of SCC**	
	Integration level 35MW	**Integration level 20MW**
PUTTA-3	13.6%	7.8%

Table 5-2: Wind power as a percentage of SCC – Year 2010

The maximum voltage fluctuation observed in the 33kV busbar is 4.3% following a sudden drop of 35MW wind plant. Around 2.3% variation can be observed following a sudden drop of 20MW wind farm. 20MW wind integration level is about 7.8% of SCC at PCC. Therefore the maximum wind absorption capability at 33kV level of the existing Puttlam GS is identified as 20MW for year 2010 when considering the voltage fluctuations.

5.3.2. System analysis – Year 2012

Voltage stability of the year 2012 network with wind additions into 132kV and 220kV levels was analyzed during this part of study. Year 2012 network arrangement around Puttlam area is depicted on figure 5.2.

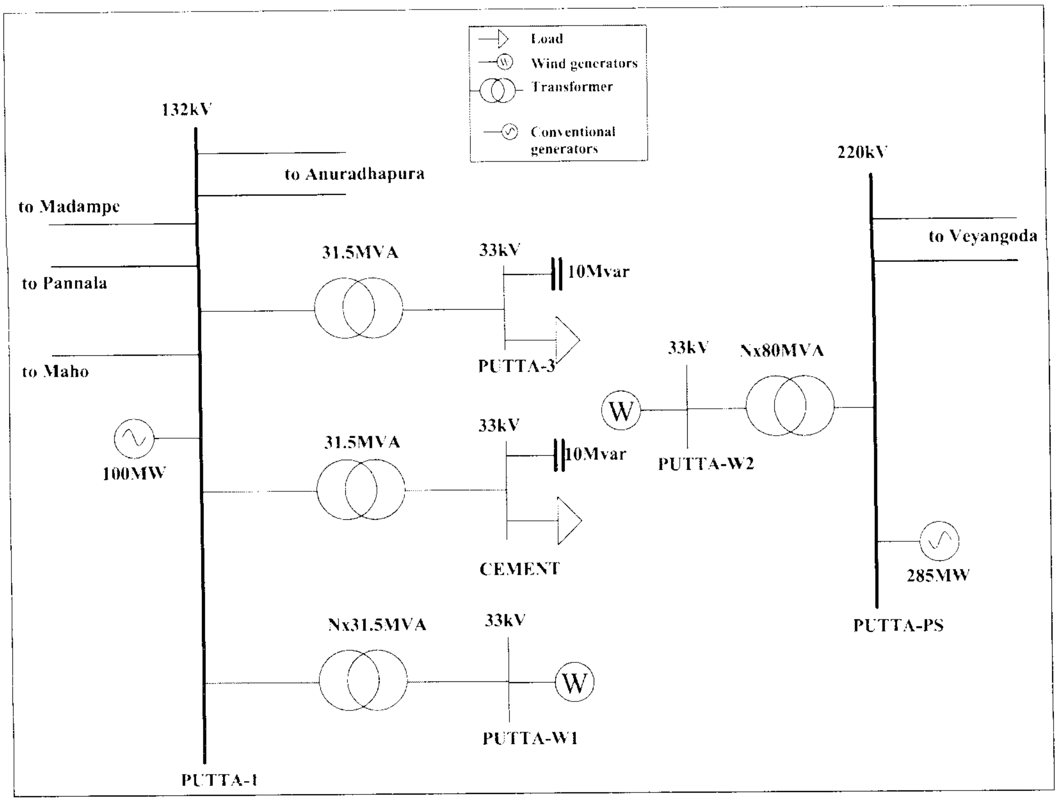

Figure 5.2 : Proposed network arrangement for year 2012

85MW and 80MW wind integrations were considered respectively at 132kV and 220kV levels and the results are summarized in the table below.

Loading scenario	Observed voltage fluctuation As % of nominal voltage
Night peak	1.4%
Off peak	1.8%

85MW wind absorption at 132kV level

Busbar	Observed voltage fluctuation As % of nominal voltage
Night peak	1.4%
Off peak	1.9%

80MW wind absorption at 220kV level

Table 5-3: Observed voltage fluctuations at 132kV and 220kV busbars at Puttlam- Year 2012.

SCC at Puttlam 132kV and 220kV busbars and the wind integration levels as a percentage of SCC are depicted in table 5-4.

Voltage level	SCC (MVA)	Wind capacity (MW)	Wind power as % of SCC
132kV	1075	85	7.9%
220kV	1486	80	5.4%

Table 5-4: Wind power as a percentage of SCC – Year 2012

Results depict that there is a possibility of a slight increase in wind penetration at 220kV level; however there is a frequency stability limit at 90MW. Therefore this study proposes limiting the total wind integration to 90MW and splitting that amount between the above two voltage levels such that 85MW at 132kV level and 80MW at 220kV level will not be exceeded.

5.3.3. System analysis – Year 2014

Voltage stability of the year 2014 network with wind additions in to 132kV and 220kV levels was studied in this section. The network arrangement is shown in figure 5.3. The results are summarized in table 5-5:

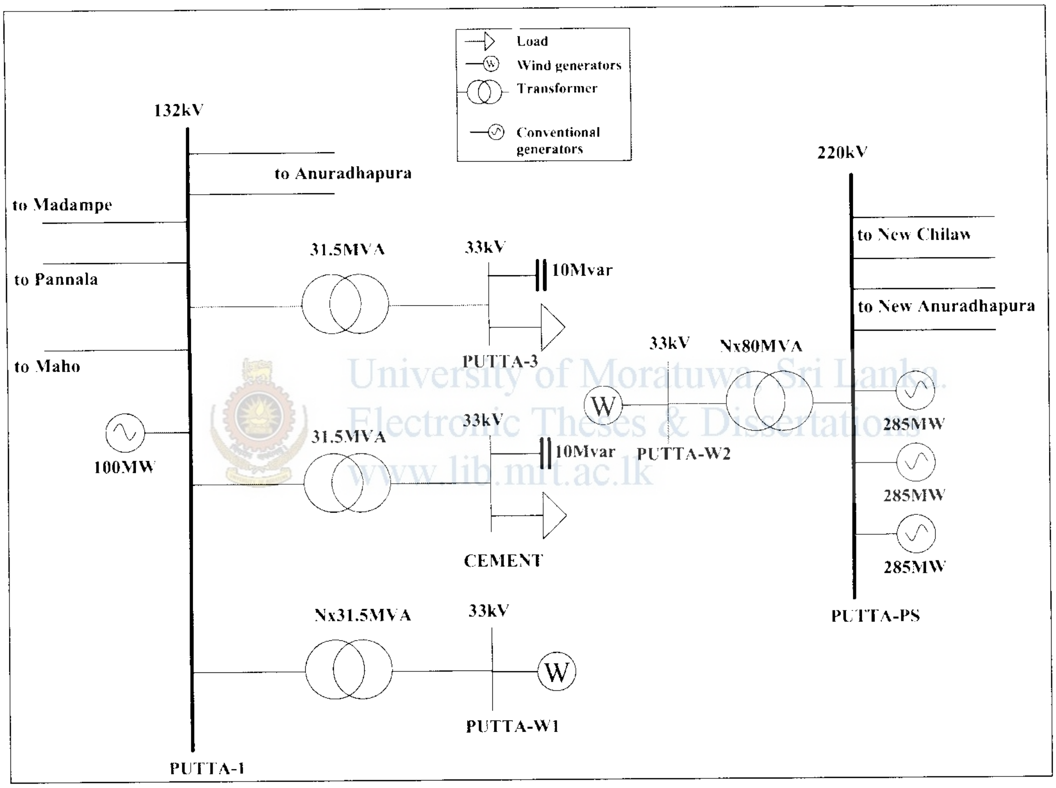

Figure 5.3 : Proposed network arrangement for year 2014

Voltage level	SCC (MVA)	Wind capacity (MW)	Observed voltage fluctuation As % of nominal voltage	Wind power as % of SCC
132kV	1738	90	1.8%	5.2%
220kV	3506	95	2.0%	2.7%

Table 5-5: Observed voltage fluctuations and SCC at 132kV and 220kV busbars at Puttlam- Year 2014.

Even though we observe only 1.8% voltage variation at 132kV level, there exist critical network limitations at 132kV network, which limits the absorption capability at 132kV level. This 90MW integration at 132kV level will only be feasible assuming 20% average continuous wind output, especially during day time.

5.3.4. System analysis – Year 2016

Voltage stability studies were carried out to year 2016 network. The network arrangement is shown in the figure 5.4. It has been found that 220MW of wind power can be integrated into year 2016 power system at Puttlam area. The summary of the voltage analysis is depicted in table 5.6.

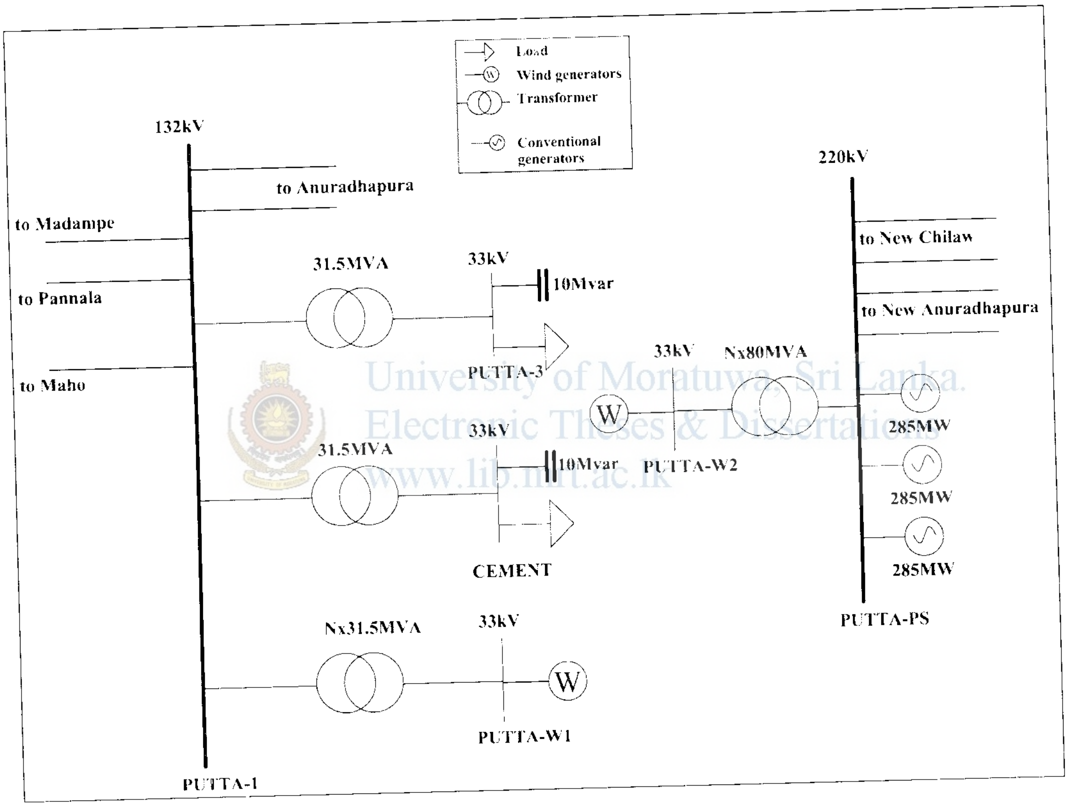

Figure 5.4 : Proposed network arrangement for year 2016

Voltage level	SCC (MVA)	Wind capacity (MW)	Observed voltage fluctuation As % of nominal voltage	Wind power as % of SCC
132kV	1486	90	2.0%	6.1%
220kV	3849	135	2.4%	3.4%

Table 5-6: Observed voltage fluctuations and SCC at 132kV and 220kV busbars at Puttlam- Year 2016.

There are no frequency stability or steady state violations observed for the above wind penetration levels. Therefore the wind interconnection limit at 132kV and 220kV levels at Puttlam substations is identified as 90MW and 135MW correspondingly for year 2016 network.

Chapter 6

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6. Transient Stability Analysis

6.1. Introduction

Transient stability studies determine the response of a power system to the occurrence of faults, tripping of a transmission line (with or without auto-reclosing), tripping of a generator, or load shedding.

The recovery of a power system subjected to a severe disturbance is of interest to both system planners and operators. Typically the system must be designed and operated in such a way that a specified number of credible contingencies do not result in failure of quality and continuity of power supply to the loads.

Transient stability studies are carried out during the transmission planning synthesis to ensure the stable operation of the power system. However this research study proposes to integrate considerable amount of wind power in to year 2012, 2014 and 2016 power systems proposed in the "Long Term Transmission Development Plan 2008-2016". Therefore it is necessary to reinvestigate the transient stability of the wind integrated power system.

This section will present the transient stability analysis of the year 2012, 2014 and 2016 power systems.

6.2. Stability criteria

Stability criteria should ensure the system stability during and after a system disturbance.

For all pertaining equipment in service, the system should remain stable in case of:

- Three-phase fault at any one overhead line terminal, cleared by the primary protection with successful and unsuccessful auto re-closing
- Loss of any one generation unit
- Load rejection by loss of any transformer

6.3. Transient stability studies year 2012, 2014 and 2016

6.3.1. Methodology

Transient system stability analysis was carried out for year 2012, 2014 and 2016 power systems. During the study, the transmission system was subjected to specific pre-identified transient system disturbances which are expected to be critical.

Studies were carried out under two switching sequences as given below.

I. Successful Re-closing : t=0 Fault occurs
t=120ms, fault cleared & circuit tripped
t=620ms, circuit re-closed

II. Unsuccessful Re-closing : t=0 Fault occurs
t=120ms, circuit tripped
t=620ms, circuit re-closed with fault
t=740ms circuit tripped

Following assumptions are made when carrying out stability studies.

- 5% spinning reserve is maintained in year 2012 while 10% spinning reserve is maintained in year 2014 and 2016.
- An automatic load shedding scheme is incorporated in the study in order to sustain the stability of the system.
- Typical exciter and governor models are included for all generators.

6.3.2. Transient stability results

The year 2012 network with 90MW wind integration was tested against severe system disturbances and confirms the system stability. The summary of the analysis is shown in table 6-1.

Fault	Location	Scenario		
		NP	DP	OP
Puttlam – Veyangoda 132kV line . 3-ph fault	Puttlam end	SS	SS	SS
Puttlam – Asia-w 132kV line. 3-ph fault	Power plant end	SS	SS	SS
Puttlam 285MW unit tripping	N/A	SS	SS	SSLS
Puttlam- Anuradhapura 132kV line. 3-ph fault	Puttlam end	SS	SS	SS
Heladanavi unit tripping	N/A	SS	SS	SS
Puttlam – New_Chilaw 132kV line. 3-ph fault	Puttlam end	SS	SS	SS
Wind farm tripping	N/A	SS	SS	SS

SS System Stable SSLS System Stable with Load Shedding

Table 6-1: System stability analysis results, year 2012

The year 2014 power system with 185MW wind integration at Kalpitiya area was also tested against severe system disturbances and it was found that the system is stable in the transient state. The results are depicted in the table below:

Fault	Location	Scenario		
		NP	DP	OP
Puttlam – New_Chilaw 220kV line . 3-ph fault	Puttlam end	SS	SS	SS
Puttlam- New Anuradhapura 220kV line . 3-ph fault	Puttlam end	SS	SS	SS
Puttlam 285MW unit tripping	N/A	SS	SS	SSLS
Puttlam- Anuradhapura 132kV line. 3-ph fault	Puttlam end	SS	SS	SS
Heladanavi unit tripping	N/A	SS	SS	SS
Puttlam – New_Chilaw 132kV line. 3-ph fault	Puttlam end	SS	SS	SS
Wind farm tripping	N/A	SS	SS	SS

SS System Stable SSLS System Stable with Load Shedding

Table 6-2: System stability analysis results, year 2014

Finally transient stability studies were carried out for year 2016 system. It has been observed that the system is stable in the transient state following critical system disturbances with 220MW wind integration at Puttlam GS/PS. Transient stability analysis results for year 2016 is given in table 2-3.

Fault	Location	Scenario		
		NP	**DP**	**OP**
Puttlam – New_Chilaw 220kV line . 3-ph fault	Puttlam end	SS	SS	SS
Puttlam- New Anuradhapura 220kV line . 3-ph fault	Puttlam end	SS	SS	SS
Puttlam 285MW unit tripping	N/A	SS	SS	SSLS
Puttlam- Anuradhapura 132kV line, 3-ph fault	Puttlam end	SS	SS	SS
Puttlam – New_Chilaw 132kV line, 3-ph fault	Puttlam end	SS	SS	SS
Wind farm tripping	N/A	SS	SS	SS

SS System Stable SSLS System Stable with Load Shedding

Table 6-3: System stability analysis results, year 2016

Chapter 7

7. Conclusions and Further Research Area

7.1. Conclusion

This research was basically focused on analyzing the impact of large wind integration on the power system both in the steady state and the transient state. Therefore the steady state , frequency stability and voltage stability studies were carried out for year 2010, 2012, 2014 and 2016 power systems to perform the above task and finally to quantify maximum wind absorption capabilities.

Chapter 1 contains a general introduction to this dissertation and to wind power technology. It highlights the necessity of wind absorption capability study for the Sri Lankan power system. Further this chapter concluded that this research can be narrowed down to Kalpitiya peninsula for the studied period.

Chapter 2 was devoted to present the wind power modelling techniques.

Steady state system analysis was carried out in chapter 3. The outcome of this exercise were steady state wind power absorption limits at Puttlam 132kV level without modifying the proposed network and by considering approximately 30% wind availability.

Frequency stability studies were carried out in chapter 4 to quantify the maximum wind absorption level where the adverse system wide frequency effects begin to occur.

Voltage stability studies were carried out in chapter 5 to analyze the impact of wind additions on the system voltage.

Finally a transient stability analysis was carried out in chapter 6 to confirm the stable operation of the power system with proposed wind integrations.

The outcome of this dissertation is depicted in table 6.1 and the decisive factors used during this dissertation are listed below:

- There should not be any load shedding schemes activated due to anticipated wind variations and system voltages & frequency should be recovered without any problem.
- Maintain 5% spinning reserve in year 2010 & 2012 and maintain 10% spinning reserve in year 2014 & 2016
- Maximum voltage fluctuation allowed at the Point of Common Coupling (PCC) should be limited to 2% of the nominal voltage.

Year	Steady state limit absorption capability (MW)	Transient stability limit			Proposed capacity at PCC (MW)		
		Absorption capability (MW)	Limiting factor	Operating condition	33kV	132kV	220kV
2010	160	20	Voltage	5% spinning reserve	20	-	-
2012	160	90	Frequency	5% spinning reserve	-	<85	<80
2014	70	185	Voltage	10% spinning reserve	-	90	95
2016	400	220	Voltage	10% spinning reserve	-	90	130

Table 7-1: Wind absorption capability of the Sri Lankan power system around Puttlam area

7.2. Further research area

The outcome of this research was a quantified wind penetration level around Kalpitiya peninsula based on the limit at which the adverse effects of the wind power begin to occur on the power system.

This study was carried out for the proposed years 2010, 2012, 2014 and 2016 power systems. The limits obtained from this study can be extended by applying various mitigation techniques such as introducing static var compensators and automatic generation control techniques.

In addition, wind absorption capability of the power system can be improved by maintaining high spinning reserves.

However introducing mitigating techniques and maintaining large spinning reserve involve considerable amount of cost. Therefore, analyzing the most economical wind absorption capability level of the power system associated with a proper economic evaluation is proposed as further research to this study.

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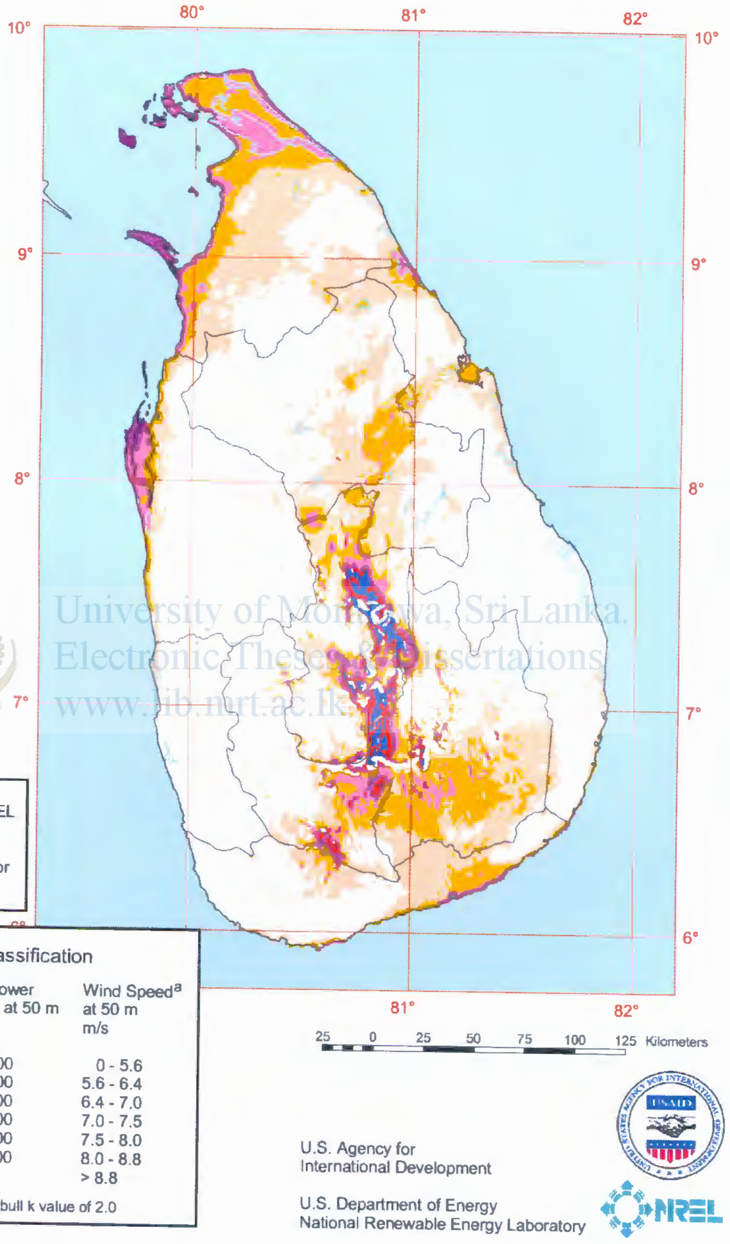
Abbreviations

CEB	Ceylon Electricity Board
DIFG	Doubly Fed Induction Generator
GE	General Electric
GS	Grid Substation
GS/PS	Grid Substation and Power Station
N/A	Not Applicable
PCC	Point of Common Coupling
PS	Power Station
PSS®E	Power System Simulator / Engineering
SCC	Short Circuit Capacity
SS	System Stable
SSLS	System Stable with Load Shedding
SVC	Static Var Compensators
WTG	Wind Turbine Generator

Appendix A: Sri Lanka Wind Resource Map



This map was produced by NREL with technical assistance from TrueWind Solutions and with funding from the U.S. Agency for International Development.

Wind Power Classification

Wind Power Class	Resource Potential	Wind Power Density at 50 m W/m²	Wind Speed[a] at 50 m m/s
1	Poor	0 - 200	0 - 5.6
2	Marginal	200 - 300	5.6 - 6.4
3	Moderate	300 - 400	6.4 - 7.0
4	Good	400 - 500	7.0 - 7.5
5	Excellent	500 - 600	7.5 - 8.0
6		600 - 800	8.0 - 8.8
7		> 800	> 8.8

[a] Wind speeds are based on a Weibull k value of 2.0

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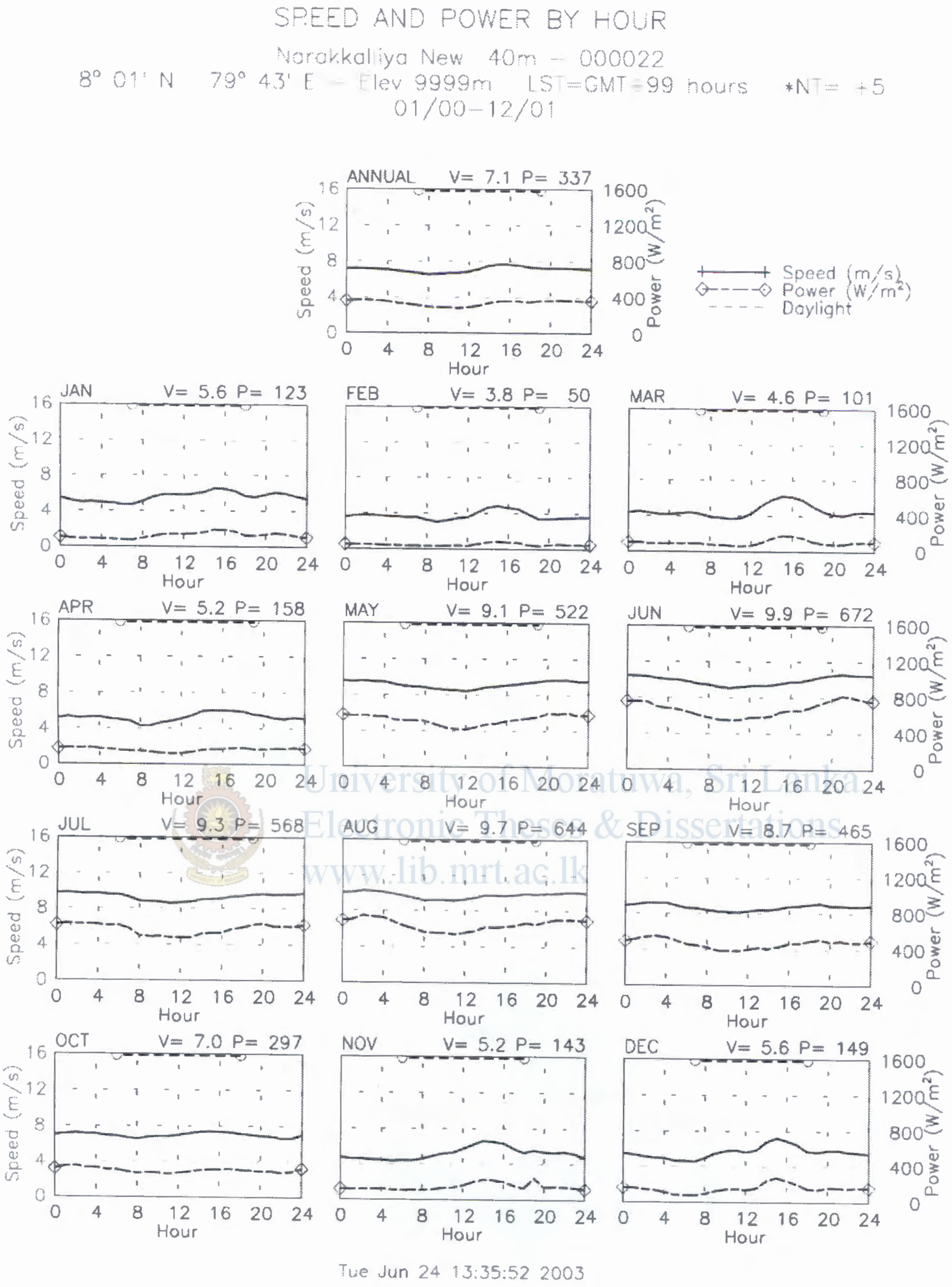
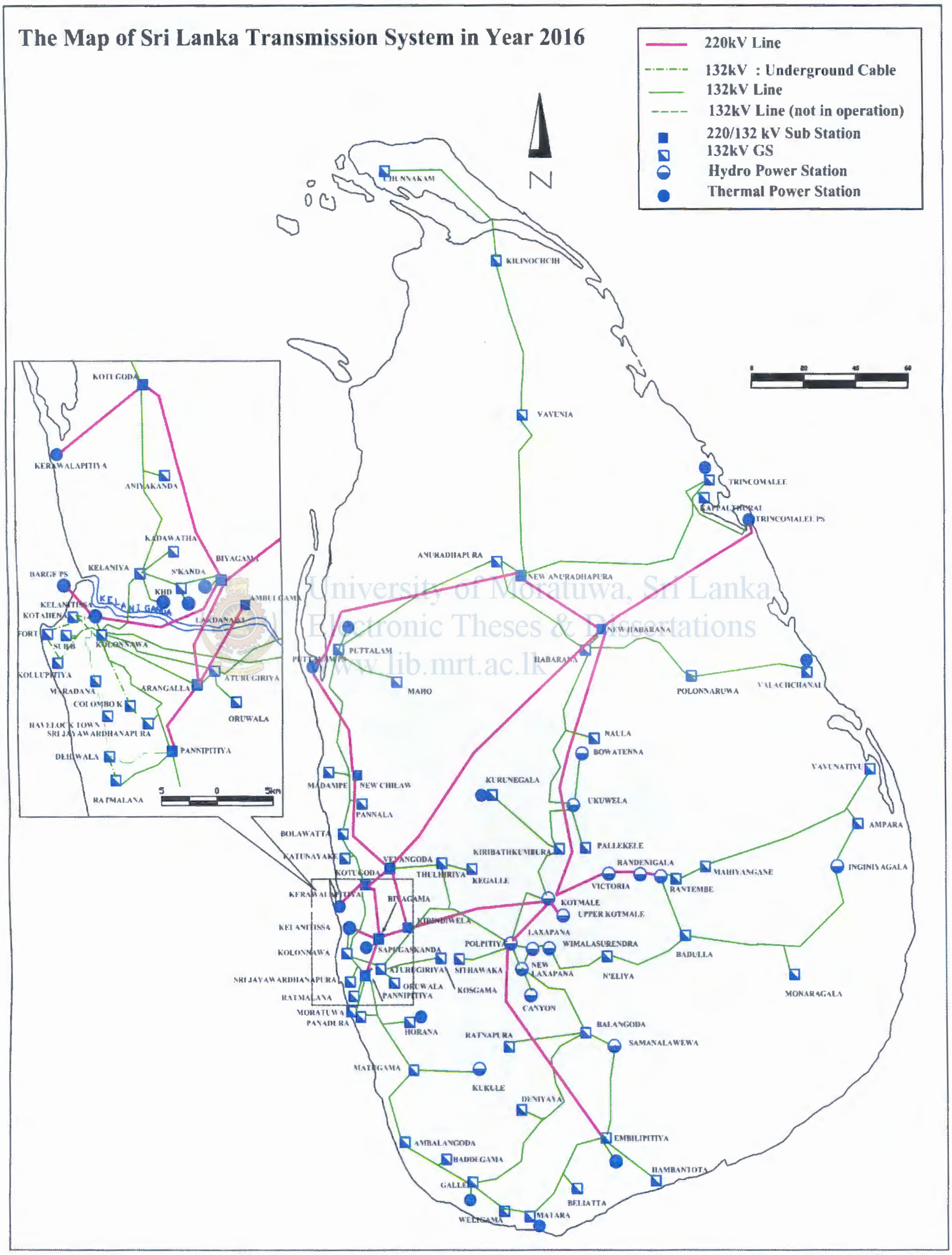
U.S. Department of Energy
National Renewable Energy Laboratory

Appendix B: Wind speed and power by hour at Narakkalliya site



Appendix C: Map of Sri Lanka Transmission System in Year 2016



Appendix D: Proposed Transmission Network – Year 2016