A SIMPLIFIED APPROACH TO EVALUATE THE RELIABILITY OF CONVENTIONAL GENERATION WITH WIND POWER

By

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A SIMPLIFIED APPROACH TO EVALUATE THE

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WITH WIND POWER

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CHAPTER I

INTRODUCTION

Harnessing renewable energy resources is gaining considerable momentum due to concerns regarding global warming, security of energy supplies and the associated economic and environmental impacts. This is especially evident in the case of wind electric conversion due to dramatic improvements in technologies and significant lowering of generation costs. Both on-shore and off-shore multi-megawatt size units are being installed globally in increasing numbers and the resulting growth in penetration levels has brought many technical and economic problems to light for serious consideration and research.

Electricity provides a crucial infrastructure for a nation's overall growth and development. Therefore, the power system is expected to generate and supply electricity continuously in the amount needed and at reasonable prices with nearly 100% reliability. However, the mismatch between power generation and load characteristics leads to the uncertainties in electric power supply. Achieving high reliability with excess of generation capacity with respect to load is not an optimal solution from economic point of view. Hence, probabilistic evaluations are carried out for the power systems during early planning and operating phases in order to achieve maximum possible reliability without exceeding economic constraints.

Until mid 1960's probabilistic evaluations of power systems were not done due to lack of data, lack of realistic reliability techniques and misunderstandings about the significance and meaning of such evaluations. All that changed since the major Northeast blackout of 1965 in the US [1]. On 9th November 1965, nearly 25 million people and approximately 80,000 square miles suffered from the loss of electricity for almost 12 hours. The states which were left without electric supply included Ontario in Canada and Massachusetts, Connecticut, New Hemisphere, Rhode Island, Vermont, New York and New Jersey in US. To prevent the repetition of such events in future, Reliability Councils were established in the US to define the standards, to share the information and to improve the co-ordination among power suppliers. Since then reliability evaluation has become a regular practice in power systems.

High energy demands resulting from the use of sophisticated electrical equipments and changing life style of human beings due to technological advances led to the installation of new power plants using coal, natural gas, nuclear etc. Increased use of polluting resources for generating electricity created issues such as green house gases, acid rains, increase in the percentage of atmospheric CO_2 and global warming. As a result, a need emerged to use renewable energy sources to generate grid-friendly electricity. Since the last few decades, electricity is being generated not only from conventional energy sources but also from eco-friendly energy sources such as wind and solar. Wind generated electricity has shown outstanding growth over the last two decades. Since 1980's generation cost of electricity from wind has reduced from US 38¢/kWh to US 4¢/kWh.

Some of the major contributors towards this development are advances in power electronic systems, advances in designing and manufacturing technologies, variable speed operation, increased ratings and better siting. Figure 1 shows the progress of global wind power capacity since 1997 and the capacity predictions up to the year of 2010 as estimated by World Wind Energy Association (WWEA) [2].

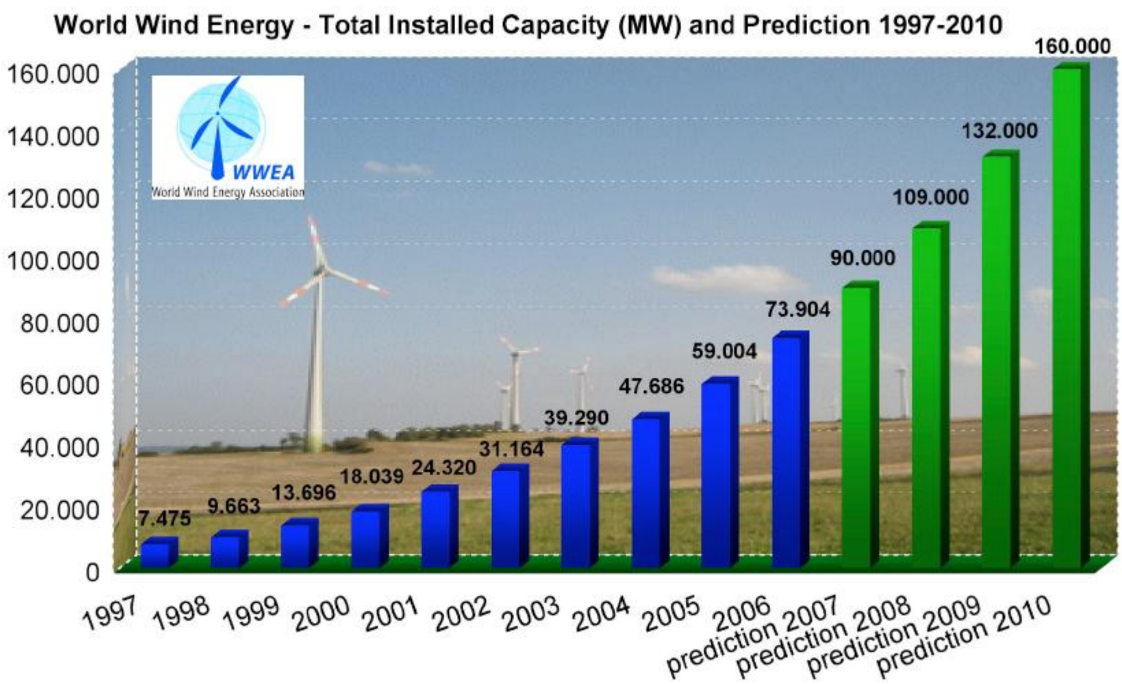

Figure 1: Global Wind Power Capacity – 1997 to 2010 [2]

In spite of extraordinary progress, wind electric conversion techniques face major issues due to variability of output and poor reliability. At present reliability evaluations are routinely performed not only for conventional power generation but also for wind-electric conversion. Researchers have presented many reliability techniques in the past involving probabilistic simulation, Markov models, quadratic modeling etc. [3-5]. However, early estimations of forced outage rates and expected power outputs of wind electric conversion systems (WECS) will prove useful in designing stages in order to adequately meet the grid load in the future. One such simplified approach is presented in this study. It mainly concentrates on the generation part of WECS and does not include the reliability aspects of transmission and distribution of energy. The results obtained are used to study the loss of load of a combined conventional and wind power system.

Chapter 2 reviews the progress of wind-electric conversion technology over the years. It also discusses the major impacts of penetration of wind-generated electricity into conventional power systems. A mathematical model of reliability of wind power using Weibull distribution function to characterize wind is developed in Chapter 3. Various key parameters which affect the availability of power output from wind electric conversion system are defined in this chapter. Chapter 4 applies the approach presented to a few study examples. Results are presented in tabular form along with the graphs of sensitivity analyses of key factors which affect the availability of power output from a wind turbine. The results obtained are used to determine the expected load loss of a combined conventional and wind-electric system with different levels of penetration of wind-generated electricity. In Chapter 5, the suggested simplified approach to evaluate the availability of wind power is summarized. It also provides concluding remarks for this study and discusses avenues to expand this work. Weibull distribution which is used to model the wind resource in this work and a MATLAB code for sensitivity analyses are documented in the Appendix section.

CHAPTER II

WIND POWER IN POWER SYSTEMS

Globally, wind-electric conversion continues to be the fastest growing renewable energy technology. This growth is primarily due to technological advances in structural analysis, design and manufacture of blades and the ability for variable speed operation facilitated by the employment of power electronics. However, the stochastic nature of the wind resource and consequently of the electrical output has significant reliability implications for system operation and planning. In this chapter, the progress of wind power over last few decades is reviewed in brief followed by its impacts on the power system operation and planning.

2.1 Review of Progress of Wind Power

Human beings have harnessed wind energy to enable them to accomplish various tasks such as sailing ships, grinding grain, pumping water and separating husk for several millennia. The advent of storage batteries in the mid 1800's and the simultaneous emergence of electricity usage, albeit in dc form, led to the development and use of small "windmills" with dc generators and battery energy storage in remote areas. This trend continued for many years in spite of the transformation of the electric power system to alternating current in the late 1800's since vast areas of the world had no access to grid connection [6].

Until the first oil embargo of 1973 and the ensuing energy crisis and steep increases in energy costs, interest in using wind generated electricity was very sporadic and confined to a few academic institutions. By this time, use of ac was so prevalent that feeding wind generated electrical energy into the grid posed a challenge because of the stochastic nature of the resource. Efforts to accomplish this ranged from developing innovative schemes to obtain a constant frequency output from a generator operating at variable speed [7] to employing sophisticated controls to maintain the rotational speeds of aeroturbines constant or very nearly constant in the presence of a constantly varying wind input.

The debate between constant-speed and variable-speed options raged on until the spectacular failures of MW-scale constant-speed systems in the US in the early 1980's. Improved aerodynamic models revealed that maintaining a constant speed resulted in undue stresses on the tower and other mechanical components (leading to their premature failure) and variable-speed operation obviated this problem in addition to extracting a larger fraction of the energy available in the wind over the full range of wind speed inputs. Coupled with advances in power electronic devices and power conversion technologies, all the modern MW-scale wind electric conversion systems of today utilize variable-speed operation with a variety of power conversion schemes to obtain utility-grade ac for insertion into the power-grid [8].

Figure 2 gives an idea of progress in the power ratings of wind turbines along with the increases in their rotor diameters and hub heights (hh) [9]. As a matter of fact, the enhancement in the power ratings of wind turbines is a direct result of efficient energy capture enabled by improved aerodynamic structures and flexibility in control and operating speeds aided by the advances in power electronics.

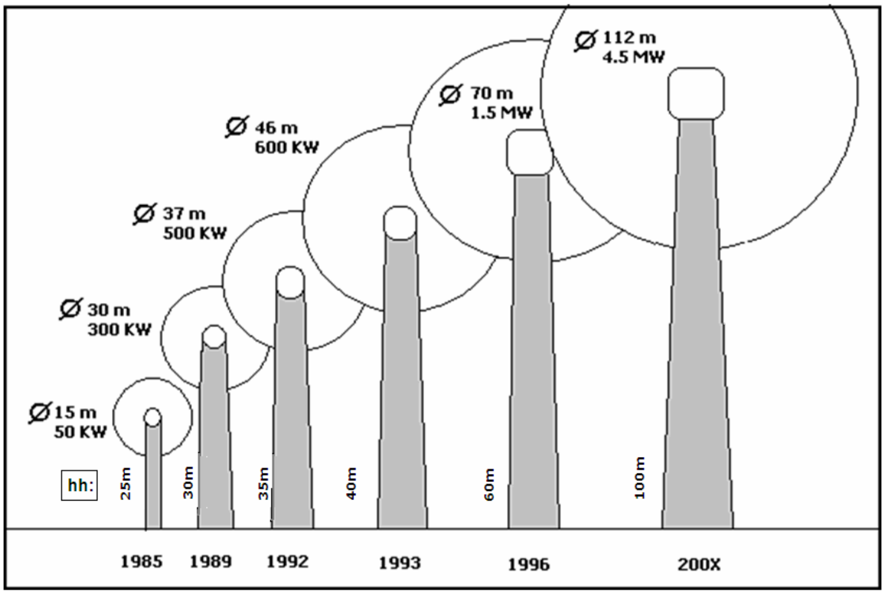

Figure 2: Wind Power Generation Progress Overview [9]

Energy credit and capacity credits are two of the important considerations associated with the economics of wind generated electricity. Energy credit refers to the rating of a continuously operating conventional power plant a wind power plant can replace in terms of the energy generated per year. It is typically expressed in the form of an "energy production factor" or "plant factor" k, defined as

$$k = \frac{kwh\ \ energy\ \ generated\ \ per\ \ year\ by\ the\ wind\ \ plant}{nameplate\ \ rating\ \ in\ \ kw \times 8760} \tag{2.1}$$

Capacity credit also refers to the rating of a continuously operating conventional power plant a wind plant can replace, but in terms of equivalent system reliability typically expressed in the form of loss of load probability (LOLP). Stochastic nature of the wind resource and the load demand influence capacity credit and makes it more stringent than the energy credit. Higher the penetration of wind-generated electricity into the power system, greater is the risk factor in relying on it due to the unpredictable nature of the wind resource and the load demand. The only way to evaluate a correct capacity credit and the allowable penetration level is to have accurate wind forecasting and detailed system modeling and simulation.

Wind energy is emerging as one of the centerpieces of the new economy. Improving plant factors, decreasing costs, longer lifetimes, technological advances in blades and structures, larger units and application of power electronics to realize variable speed operation are some of the key factors propelling its phenomenal growth. By 2002, world's wind power capacity reached 32,000 MW and it is expected to cross 90,000 MW by the end of 2007. While the cost of wind-generated electricity is declining steadily, the volatile prices of natural gas and fossil fuels are increasing rapidly. The cost of wind power is different at different locations due to a strong linkage between the amount of energy generated and the nature of wind resource available at a particular site. However, in the future, the cost effectiveness of wind power is predicted to depend more on dynamic and compliant design of the turbine than on its size or capacity.

By the end of year 2005, global wind energy installed capacity reached nearly 60,000 MW and the contribution of U.S. towards global wind energy exceeded 15%. Following the success of onshore wind electricity generation, offshore wind generation is also

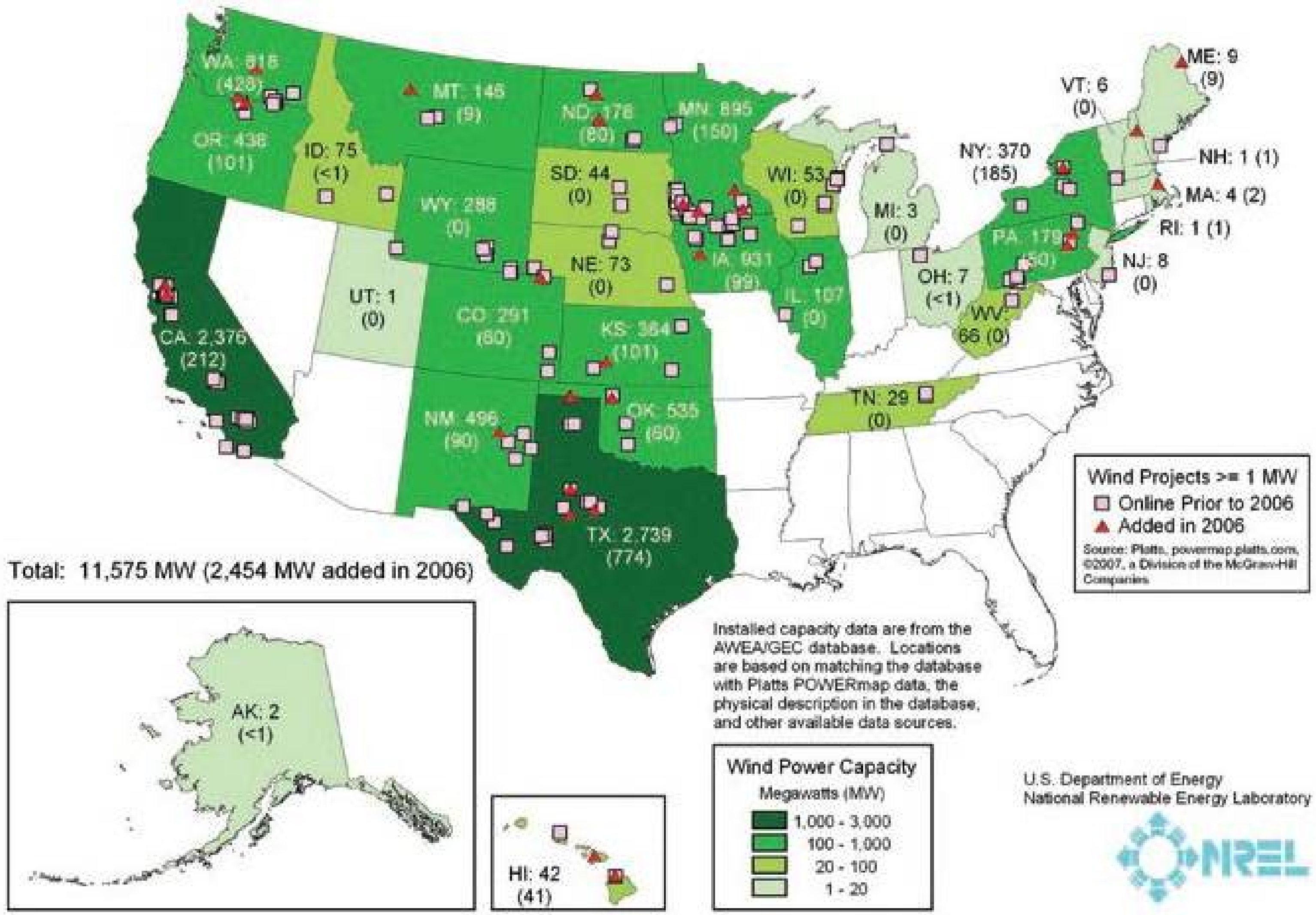

Figure 3: Progress of Wind Power in USA (2006) [10]

emerging as a powerful player. Offshore wind technology has the advantages of a strong and consistent wind resource, undersea cable installation and freedom from aesthetic issues such as visual pollution, noise levels and land-use concerns. Figure 3 shows the capacity of wind farms in different states of USA in 2006. The negative side of offshore development includes high investment costs, challenging construction and accessibility, severe environmental conditions due to corrosive salt water and potentially high capital and maintenance costs.

It is important to note that 32,000 MW of capacity in 2002 represented only 0.4% of the global installed capacity [11]. The fact that wind turbine reliability is affected by various factors making it incapable to carry major part of the system load over the year cannot be overlooked. Reliability of wind power can be improved not only with better turbine design, advanced technology and accurate forecasting of wind but also with improved planning in early stages. This study has made an attempt to suggest a simple approach to evaluate the reliability of WECS output during early planning stages. In the next section, impacts of the penetration of WECS output on the power system operation are discussed.

2.2 Impacts of Wind Power on Power Systems

As mentioned in the previous section, the penetration on wind-generated electricity into conventional power systems is increasing consistently. This has created several challenges for power system operators. Stochastic nature of wind resource has significant impacts on the availability and the quality of electric power generated from the wind. The addition of wind turbines into an existing power system affects the system operation in many ways depending upon the size and flexibility of the power system and the level of penetration of wind power into it. Power system has to satisfy customer's demands without failing. From the consumer's point of view, power system must satisfy the following requirements:

- Voltage level and frequency should be within acceptable limits.
- Power should be made available in required amount and at exactly the time consumer needs it.
- Power should be available at reasonable cost.

However, power system's ability to satisfy the above requirements will be limited by the penetration of wind-generated electricity due to its probabilistic nature. Electric power is available from a turbine only when the wind blows and as wind speed varies, the electric power output also varies causing variations in voltage, current and frequency at the point of common connection. These variations result in power fluctuations and additional requirements to satisfy customer demand thereby affecting the operating schedules of other power plants. Also, it may involve additional costs for balancing the system in terms of reserve requirements. The major impacts of penetration of wind generated electricity into existing power systems are discussed below in detail.

2.2.1 Power Quality

Electric power output is available from a wind turbine only for a certain range of wind speeds. Also, power available in wind is directly proportional to the cube of wind speed as given below.

$$P_{wind} = \frac{1}{2}\rho A V^3 \quad \text{watts} \qquad \ldots(2.2)$$

where

ρ = air density in kg/m^3

A = area of wind turbine rotor in m^2

V = wind speed in m/s

Hence, even a slight change in wind speed can have a significant impact on the amount of electric power output and on the overall power quality. The important measures of power quality are voltage level, frequency, harmonics, and ability to manage reactive power balance [12]. Impacts of probabilistic nature of wind resource on these crucial factors of power quality are briefly discussed below.

2.2.1.1 Voltage Level:

Stable voltage is required for normal operation of all electric equipment. Voltage fluctuations basically arise from fluctuating power as a result of varying wind speed. Such fluctuations may give rise to disturbances such as light flicker and low voltage. Variations in voltage are less prominent if the number of turbines connected to the grid is small. With large number of wind turbines connected to the grid such as a wind farm, every turbine generates electric power independently as they are subjected to wind resources having different characteristics at different times as a result of the large area of a wind farm. Hence, some of the high frequency fluctuations have a tendency to even out. Fixed speed wind turbines use pitch control to smooth out the power peaks, but they cannot smooth out high frequency power peaks quickly and efficiently. Variable speed wind turbines incorporate power electronic circuitry to obtain a steady voltage output by reducing the fluctuations.

2.2.1.2 Power Harmonics:

Use of power electronic circuitry in wind-electric conversion results in to high frequency power harmonics and could enhance existing harmonic distortion of voltage caused by the conventional power generation systems. The presence of harmonics in a voltage or current wave is an indication of inferior power quality. Different types of power generating devices produce harmonics with different characteristics. Also, loads connected to the grid such as power electronic equipment or non-linear loads may impact the harmonic nature of the grid voltage. Ultimately, harmonic distortion of voltage causes overheating and damage to equipment, faulty operation of protective relays and interference in communication lines. Modern power processing units use considerable amount of power electronics for efficient energy capture from the wind and hence care must taken to overcome resulting harmonic distortion.

2.2.1.3 System Frequency:

System frequency will be maintained only if the energy produced balances the energy consumed. If the energy produced is more than that consumed, for example, due to an increase in wind speed, then the system frequency will also increase and vice-versa. Unfortunately, since wind speed varies all the time, electrical energy produced by the wind turbine is never constant and causes variations in frequency and system voltage. When an active generating unit goes out of service due to a failure, system experiences a sudden loss of power. In such cases, reserves get connected to the grid to maintain the power supply to the connected loads. In such cases, voltage and frequency will vary for a certain time interval depending upon the time needed to switch in reserves if the available spinning reserves are not adequate. A power system with large number of wind turbines may face such situations frequently because wind turbines are disconnected from the grid in case of severe weather or mechanical failures or during an insufficient or oversupply of wind energy.

2.2.1.4 Reactive Power Balance:

The balance between active and reactive power is critical to maintain a proper voltage profile which should be maintained in a power system depending on the type of load connected to the grid. For capacitive loads system must absorb reactive power while, for inductive loads it should supply the same, thereby maintaining the power factor close to unity. Wind turbines often use asynchronous generators which are inductive in nature and absorb considerable amount of reactive power e.g. induction generators. Fixed or nearly constant speed wind turbines incorporating squirrel cage induction generators are provided with large capacitor banks to satisfy the reactive power requirements. But, due to the nearly constant speed operation they are less efficient and more prone to overstresses and their use is restricted to household and farm applications only. Variable speed wind turbines with doubly fed induction generators are most popular due to their flexible operation and high overall efficiency. They use efficient power electronic circuitry to achieve reactive power control. However, the use of power electronics results in additional costs and increases the harmonic distortion of system voltage.

The balance between different aspects of power quality can be maintained using different devices. Selection of the device will depend on the instantaneous penetration level of wind-generated electricity into the power system. At higher levels of penetration, use of additional sophisticated devices may become mandatory to maintain the power quality which will eventually increase the cost of generated electricity.

2.2.2 Power System Dynamics

2.2.2.1 Behavior under Dynamic Conditions:

Power system has to maintain its stability in case of sudden disturbances or changes such as faults, tripping of a generator, sudden loss or connection of a large load, changes in the mechanical power from a prime mover, etc. System voltage, current, frequency and rotor speeds experience momentary changes in their values during dynamic conditions. However, system regains its stability by adjusting itself to a new operating point without any loss of load.

Synchronous generators used in conventional power generation systems have inherent ability to adjust themselves to a new operating point within a short time interval during dynamic conditions. However, asynchronous generators popular in modern wind turbines lack this ability and depend on complex power electronic circuitry to remain connected to the grid during dynamic conditions. During fault occurrences, system experiences heavy current flow and large voltage dips. Consequently, turbine components are subjected to excessive electrical and mechanical stresses. In order to avoid any damage to its components, turbine is disconnected from the grid until the clearance of fault. In other words, wind turbines show a poor low voltage ride through (LVRT) capability during faults. Typically, a squirrel cage induction generator has extremely poor LVRT capability as compared to a doubly fed induction generator. Secondly, induction generators have less contribution towards short circuit capacity as compared to synchronous generators in conventional power plants. Consequently, system suffers from frequency imbalance, voltage drops and disturbances in its stability.

2.2.2.2 System Moment of Inertia:

"Moment of inertia of a system can be defined as the total amount of kinetic energy stored in all spinning turbines and rotors in the system" [13].

When the power generated is not equal to the power consumed, system absorbs energy from reserves, if present, or from the kinetic energy stored in the rotating masses of the turbines and generators. As a result, the turbine rotor speed decreases and hence the frequency. Systems with high moment of inertia can limit the rate of change of frequency thereby allowing sufficient response time to the controllers to overcome unbalance caused by frequency deviations. Fixed or nearly constant speed turbines contribute to overall moment of inertia of the system as they are directly connected to the grid. Variable speed wind turbines control the grid power independent of the mechanical power supplied by the wind to its rotor as shown in Figure 4 [14]. Power electronic converters decouple all the electrical quantities such as grid frequency and voltage from the mechanical quantities such as rotor speed. So, virtually DFIG offers zero inertia to the system. Use of energy storage systems becomes necessary for the systems with low moment of inertia. Also, it is observed that frequency changes are more when the turbine is subjected to large amount of wind energy. Hence, the risk of the system unbalance, instability, poor power quality and frequency variations is high at high penetration levels of wind energy.

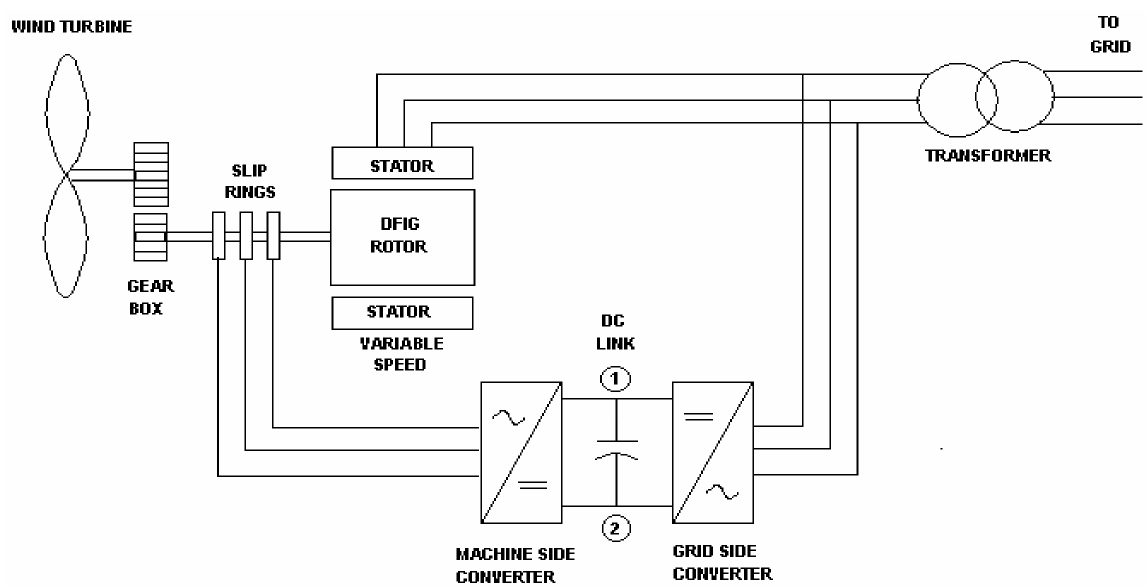

Figure 4: Wind-Electric Conversion with Doubly Fed Induction Generator [9]

2.2.3 Distribution Network Voltage Levels

In remote and isolated power systems, wind turbines are connected to the grid at locations where several consumers might be connected to the grid. In such cases, it is important to maintain the voltage and frequency at the point of common connection because any disturbance in their levels will directly affect the connected loads. Whether the wind turbine is active or inactive mainly depends on the wind speed. Also, the turbine power output varies with wind speed from time to time. In a situation where the load on the system is too high and electrical output from the turbine is comparatively low, the voltage at the point of common connection will have a considerably low value. This kind of situation is undesirable from power system stability point of view and may require additional arrangements to maintain the voltage level and frequency level at the common point of connection.

2.2.4 Losses

Losses mainly include generation, transmission and distribution losses. Depending on whether the wind farm is connected to the grid near or far away from the load, transmission and distribution losses will be less or more accordingly.

2.2.5 Economic Aspects

Although the cost of wind generated electricity has declined noticeably over the last few decades, significant amount of investment is involved in the manufacturing and installation of wind turbines. To overcome the limitations resulting from the stochastic nature of wind resource, wind farms are equipped with additional energy storage devices or reserves to ensure the continuity of supply to the connected loads. Also, the complex power electronic circuitry used in modern wind turbines contributes towards maintaining power quality. Use of these sophisticated controls increases the overall cost significantly. Existing transmission and distribution systems are designed based on conventional power generation techniques such as, hydro, thermal, gas, nuclear, coal-fired plants etc. Connecting wind power plants to these existing grids disturbs the operating schedules of conventional plants and may even result in overloading of transmission lines.

Redesigning the power system may improve the overall efficiency and stability, but it will also involve higher investments and will result in increased cost of electricity.

2.2.6 Some Additional Issues

Wind-electric conversion technology is becoming increasingly popular for its environmentally friendly (green) nature. Wind power can decrease the emission of CO_2 and other harmful gases by replacing conventional power plants such as coal-fired plants. However, this is possible only if the majority of power generation in a region is by air polluting coal-fired power plants. In a region where eco-friendly hydro and biomass plants dominate the power generation task, installation of wind power plants will not help to reduce the amount of CO_2, instead it could affect the stability of the existing power system.

With an increase in the penetration of wind-generated electricity into power system, the risk of loss of load and the loss of system balance increases. The risk at system level is directly proportional not only to LOLP but also to the consequences of the event [15]. So even with low LOLP, risk could be high due to the intermittent nature of wind speed. Secondly, even though non-conventional energy sources such as, wind and solar can satisfy the peak demands, no direct correlation exists between existence of load and availability of these energy sources. Operating schedules of different power plants are adjusted depending on the predictions made by wind forecasting techniques about the availability of wind during a certain time period. However, the predictions made by forecasting techniques are not accurate enough and uncertainties always exist, ultimately increasing the probability of an unscheduled shut down of the wind turbine subjected to very strong winds.

Wind turbine installations also cause some environmental issues such as avian mortality, visual pollution and noise which can be mitigated by proper siting of the plant and using advanced techniques for manufacturing turbine components such as blades. The low rotational speeds of large turbines tend to decrease avian mortality and noise levels.

To sum up, all the major issues are directly or indirectly caused by the stochastic nature of the wind resource. Although controlling the behavior of wind is out of our scope, it is possible to temper its impacts by deciding the penetration level of wind power into a power system based on early estimations of important parameters such as forced outage rates. Considering the ever increasing penetration levels of wind energy in most of the countries, developing such early estimation techniques is of high importance.

CHAPTER III

RELIABILITY OF WIND POWER

IEEE Reliability Society defines Reliability as follows:

"Reliability is a design engineering discipline which applies scientific knowledge to assure a product will perform its intended function for the required duration within a given environment."

Increased penetration of wind generated electricity into power systems makes the overall reliability of electric power supply a key factor in the success of wind-electric conversion system projects. Poor reliability of WECS units results in increased O&M cost, reduced system availability and it also directly affects the revenue from the project. Loss of load probability or LOLP is a well-known measure used to evaluate the reliability of electric power supply. With increasing penetration of wind generated electrical power into conventional power systems, LOLP will increase because the availability of electric power from WECS is not as high as from conventional units. Some of the crucial factors responsible for reduced availability of electric power from WECS are discussed in this chapter. A simplified method to evaluate the forced outage rate of electric power output from wind turbine is presented by including all the major factors affecting its availability.

3.1 Forced Outage Rate

Forced outage rate is one of the most important parameters in the estimation of component reliability. Components experience forced outage if emergency conditions related to a component force it out of service. The long-term probability of finding the component in the down state is called its 'forced outage rate' (FOR).

3.1.1 FOR of Conventional Generating Units

FOR of a generating unit is often termed as the 'unavailability' of that unit. By definition, it is the probability of finding the unit down on forced outage while operating under specified conditions at some distant time in the future. In the case of conventional generating units, emergency conditions may arise due to the stochastic nature of weather conditions, system behavior, customer demand or component failures. Also, load forecasting techniques constitute an important part of power system planning and operating decisions. But, these techniques cannot predict the load precisely, sometimes resulting in overloading and consequent loss of load.

If 'λ' and 'μ' are the constant failure and repair rates of a generating unit respectively, then from reliability studies its forced outage rate is given by,

$$FOR = \frac{\lambda}{\lambda + \mu} = \frac{\sum down\, time}{\sum down\, time + \sum up\, time} \quad \ldots (3.1)$$

Historical operational records of the unit are used to estimate the values of parameters, λ and μ [16]. Constant failure and repair rates imply exponentially distributed uptimes and downtimes. This is a commonly used assumption in reliability evaluations.

3.1.2 FOR of a Wind-Electric System:

The probability and frequency of forced outages of a wind-electric system are comparatively higher than those of a conventional generating unit. The stochastic nature of wind resource and mechanical failures of turbine components are responsible for forced outages of a wind-electric system resulting in zero output power. If sufficient reserve is not available, the power system may not be able to meet the grid load, thereby increasing the loss of load probability (LOLP). One possible way to decrease the loss of load is to have early estimates of WECS reliability and its expected power output and design the system accordingly.

Similar to a conventional generating unit, it is possible to arrive at an FOR for a wind-electric system. Characteristics of the wind resource, output curve of a WECS and mechanical failure data for a similar wind-electric system, operating in a wind regime having similar characteristic parameters, can be used as input data for calculating FOR of WECS. Estimates of FOR, availability and expected power output of WECS thus obtained can be used to evaluate the expected loss of load of a combined conventional and wind-electric system. Studies of this kind will simplify the decision making process at the early planning stages of introducing wind power as a generation option.

3.2 WECS Output Characteristics-Factors Affecting Availability of Electric Output

Figure 5 shows a typical curve for power output from a WECS. Wind-electric system starts generating electric power at a wind speed known as 'cut-in speed' (V_{ci}). It produces rated power (P_r) output above 'rated wind speed' (V_r) as shown in Figure 4. Wind turbine continues to produce the rated output till the wind speed reaches the 'cut-out' value (V_{co}). Beyond V_{co}, the turbine is completely shut down to avoid any damage to its components.

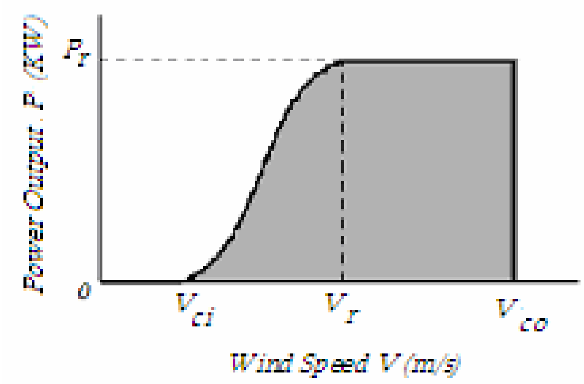

Figure 5: WECS Power Output Curve

Clearly, electric power output is available from a turbine only for a certain range of wind speeds. Secondly, mechanical failures resulting from severe weather conditions or aging of components force the turbine out of service. Hence, the probabilistic nature of wind resource and component failures are of high importance while estimating the availability of WECS. The major factors affecting the availability of WECS and in turn the availability of its power output are listed below:

1. Electric power is available from a WECS only for wind speeds between V_{ci} and V_{co}.
2. Only wind speeds only in the range from V_r to V_{co} generate rated electric power.

3. Non-linearity of the power curve from V_{ci} to V_r results in a variable power output less than the rated output.
4. Severe weather conditions exert excessive electrical and mechanical stresses on the system components leading to mechanical failures. In addition, normal wear and tear and fatigue will cause some components to fail. Serious mechanical failures result in turbine shutdown and consequently the unavailability of power output until repair is completed.
5. Wind turbine is disconnected from the grid beyond V_{co} in order to avoid excessive electrical and mechanical stresses on system components.

As a result, the expected power output from WECS is always less than its rated power output. A realistic assessment of WECS output can be made by including all the factors listed above in an appropriate manner. The nonlinearity present in the power curve for wind speeds between V_{ci} to V_r can be included by approximating it by a straight line as discussed in the next section. Since all the estimations and evaluations are probabilistic, this approximation is not expected to have any major influence on the results.

3.3 Approximation of WECS Power Output Curve

Figure 6 shows the approximated power output curve of a wind-electric system. The non-linear part of the curve between V_{ci} and V_r is approximated by a straight line. Thus, the equation for power output becomes

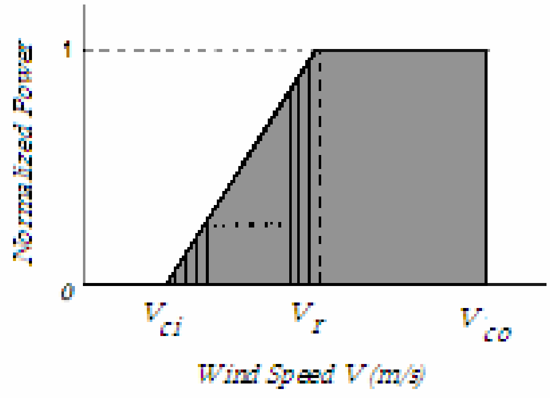

Figure 6: Approximated Power Output Curve

$$P = \begin{cases} P_r\left(\dfrac{V - V_{ci}}{V_r - V_{ci}}\right) & for\ V_{ci} \le V \le V_r \\ P_r & for\ V_r \le V \le V_{co} \\ 0 & elsewhere \end{cases}$$

… (3.2)

Using P_r as the base value, equation (3.2) can be normalized as

$$P = \begin{cases} \left(\dfrac{V - V_{ci}}{V_r - V_{ci}}\right) & for\ V_{ci} \le V \le V_r \\ 1 & for\ V_r \le V \le V_{co} \\ 0 & elsewhere \end{cases}$$

… (3.3)

3.4 Overall Forced Outage Rate of WECS Output

All the factors that affect the availability of wind-electric systems must be quantified to include their effects on the FOR value for WECS [17]. For this purpose, wind resource is modeled using Weibull Distribution as given in the Appendix A.

3.4.1 Quantification of the Factors Affecting Availability:

(1) *Wind Availability Factor* (P_{WA}): It is defined as the probability that wind speed is between cut-in and cut-out values.

$$Wind\ Availability\ Factor = P\left(V_{ci} \le V \le V_{co}\right) = P_{WA}$$

$$\therefore P_{WA} = \exp\left[-\left(\frac{V_{ci}}{\alpha}\right)^{\beta}\right] - \exp\left[-\left(\frac{V_{co}}{\alpha}\right)^{\beta}\right] \qquad \dots (3.4)$$

(2) *Constant Power Output Factor* (P_{Const}): Since rated power output results for wind speeds between V_r and V_{co}, the expected normalized power output in this speed range will be the probability of the wind speed lying in this speed range. Hence,

$$P_{Const} = \exp\left[-\left(\frac{V_r}{\alpha}\right)^{\beta}\right] - \exp\left[-\left(\frac{V_{co}}{\alpha}\right)^{\beta}\right] \qquad \dots (3.5)$$

(3) *Variable Power Output Factor* (P_{Var}): Expected value of normalized power output over the speed range from V_{ci} to V_r can be calculated as follows:

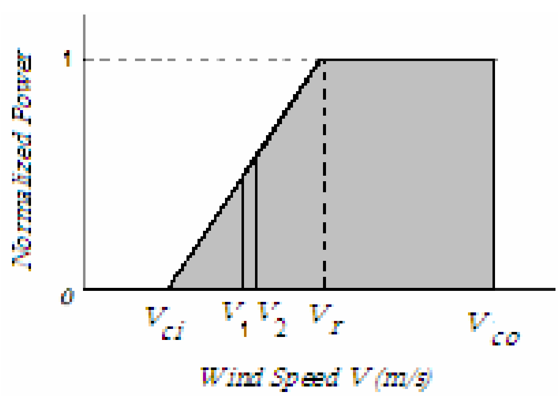

Figure 7: Expected Power Output Calculation for Variable Portion

The region from V_{ci} to V_r is divided into n small intervals as shown in Figure 6. Probability that the wind speed is between any two values, say V_1 and V_2 (Figure 7), will be

$$a_1 = P\left(V_1 \le V \le V_2\right) = \exp\left[-\left(\frac{V_1}{\alpha}\right)^{\beta}\right] - \exp\left[-\left(\frac{V_2}{\alpha}\right)^{\beta}\right] \quad \text{… (3.6)}$$

Then, the expected normalized power output over the speed range from V_1 to V_2 will be,

$$E\left(P_{1,2}\right) = a_1 * \frac{\left(\frac{V_1 + V_2}{2}\right) - V_{ci}}{(V_r - V_{ci})} \quad \text{… (3.7)}$$

Summation of the expected normalized power outputs calculated in this way for each small interval in the variable part will yield the expected normalized power output for the region from V_{ci} to V_r. Thus,

$$P_{Var} = \sum E(P_{1,2}) \quad \text{… (3.8)}$$

(4) *Factor for mechanical failures* (P_{Mech}): Forced outage rate for a mechanical component with a constant failure rate of 'λ' per hour and a mean repair time of 'r' hours is given by,

$$forced\ outage\ rate \cong \lambda r \quad \text{… (3.9)}$$

Wind turbine consists of several mechanical components as shown in Figure 8 with different failure and repair rates. With a serious failure of any one component, the wind turbine goes out of service. Therefore, from reliability point of view of all the components can be seen to be logically in series as shown in Figure 9. Then, the FOR of mechanical system will be a summation of individual component FORs [18].

$$FOR_{Mech} = \sum_i \lambda_i r_i \qquad \text{… (3.10)}$$

Hence,

$$P_{Mech} = 1 - FOR_{Mech} \qquad \text{… (3.11)}$$

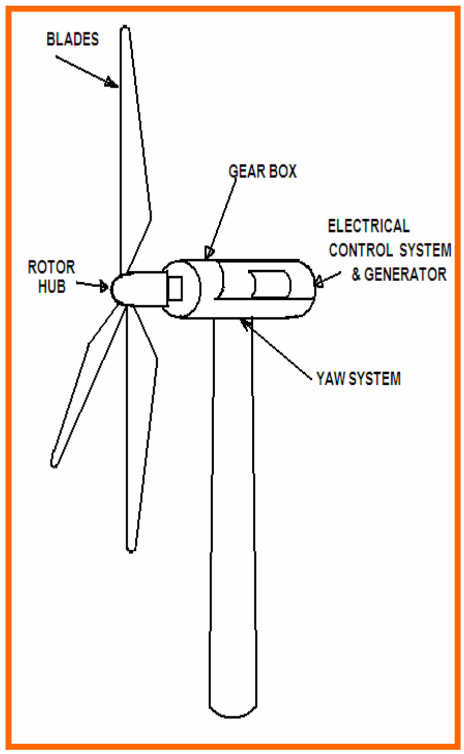

Figure 8: Wind Turbine Components

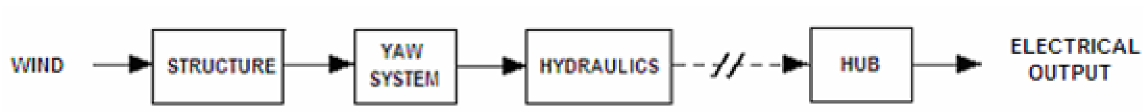

Figure 9: Series Reliability Model

3.4.2 Reliability Model of WECS:

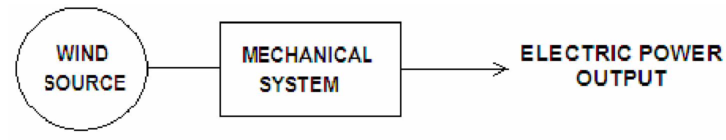

Figure 10: Series Reliability Model for WECS

Availability of power output from WECS depends on availabilities of wind resource and mechanical system. Hence, the overall reliability model for WECS will be a series model as shown in Figure 10. Also, for variable part of the power output curve, the expected power output from WECS is less than the rated power output by a factor defined earlier. This factor must be included appropriately [19]. Collecting all the factors discussed above, the reliability R for a WECS can be expressed as

$$R = P_{WA} * E\left(P\right) * P_{Mech} \qquad \ldots (3.12)$$

where
$$E(P) = P_{Var} + P_{Const} \qquad \ldots (3.13)$$

Then, the overall forced outage rate for the WECS output will be

$$FOR_{Pow} = 1 - R \qquad \ldots (3.14)$$

3.5 Summary

A method to determine the forced outage rate for wind-generated electricity is developed based on an approximated power output curve for WECS and failure and repair rates of mechanical components. Using Weibull probability density function and cumulative distribution function equations; general key factors are defined and expressed mathematically. Sensitivities of these factors for different parameters are examined in detail in the next chapter. Also, the FOR value is used to evaluate the generation reliability of power systems containing both conventional and wind generation.

CHAPTER IV

STUDY EXAMPLES

In this chapter, the concepts of FOR and expected power output of WECS are applied to assess the influence of the penetration of wind power into a conventional generation system. In particular, LOLP is employed to quantify the influence. Published failure data for wind power systems operating in Sweden are used in the example studies. Sensitivity of expected power output and wind availability factor to the Weibull parameters characterizing wind resource and design parameters such as cut-in and cut-out wind speeds is studied and the results are presented in graphical form.

4.1 FOR and Expected Power Output of WECS

For the study, three different wind regimes, labeled as low, moderate and high with their corresponding Weibull parameters as listed in Table 1 are chosen [20]. Values of cut-in, rated and cut-out wind speeds are chosen as 3.6 m/s, 8 m/s and 21 m/s respectively (1 mile/hr $\approx$ 2.24 m/s). Table 2 lists failure data for various components taken from published literature [21].

Table 3 lists the values of expected power output, wind availability factor, WECS reliability and FOR for the three different wind regime using the same component failure data. It can be seen that expected power output ranges from 31% to 87% of the rated power depending on the wind regime. As expected, better wind regimes yield higher values of expected power output, higher unit reliability and lower FOR values. In particular, the FOR values are significantly larger than the corresponding values for conventional generators.

Wind Speed	α (m/s)	β
Low	5.07	1.31
Moderate	9.7	2.00
High	15.55	3.10

Table 1. Wind Specific Data

Component	Failure Rate (yr^{-1})	Repair Time (hrs/yr)	MTTR (hrs)
Structure	0.006	0.6	100.00
Yaw System	0.026	6.6	253.85
Hydraulics	0.061	2.6	42.62
Mechanical Brakes	0.005	0.6	120.00
Gears	0.045	11.6	257.78
Sensors	0.054	2.7	50.00
Drive Train	0.004	1.2	300.00
Controls	0.050	9.2	184.00
Electric System	0.067	7.2	107.46
Generator	0.021	4.5	214.29
Blades	0.052	4.7	90.38
Hub	0.001	0.0	0.00

Table 2. Component Failure Data [17]

Wind Speed	Low	Moderate	High
E(P)	0.3159	0.6867	0.8709
P_{WA}	0.5265	0.8621	0.9118
FOR_{Mech}	0.0059	0.0059	0.0059
R	0.1653	0.5885	0.7892
FOR_{Pow}	0.8347	0.4115	0.2108

Table 3. Results

4.2 Sensitivity Analyses

Although the general nature of the relationship of the expected power output and wind availability factor to wind parameters, cut-in speed and cut-out speed are known, a simple study was undertaken to quantify these relationships. The results are presented in Figures 11-22 for all the three chosen wind regimes.

As the scale factor α increases, the mean wind speed also increases and wind speed approaches cut-out region for very high values of α. Accordingly, the expected power output and wind availability factor show a steady growth initially but a slight reduction for higher values of α as shown in Figures 11-13. Figure 14 and Figure 15 show a steady rise in expected power output and wind availability factor with increasing β at moderate and high wind speeds. However, as β increases, the spread of Weibull density function curve decreases indicating less variation in the wind speed. So, at low wind speeds and high β values, the turbine continues to generate power in the variable part of the power curve for a longer time thereby decreasing the expected power output as shown in Figure 16. Figures 17-19 show that with increasing V_{ci}, the expected power output increases while the wind availability factor decreases. As V_{ci} increases, the variable power output is available over a smaller speed range and the turbine generates the rated electric power for most of the time. Hence, the wind availability factor decreases while the average power over the operational wind speed range increases. With increasing V_{co}, the operational wind speed range increases and hence, rated power is available over a larger range of wind speed. Therefore, the wind availability factor and expected power output both increase with increasing V_{co} as shown in Figures 20-22.

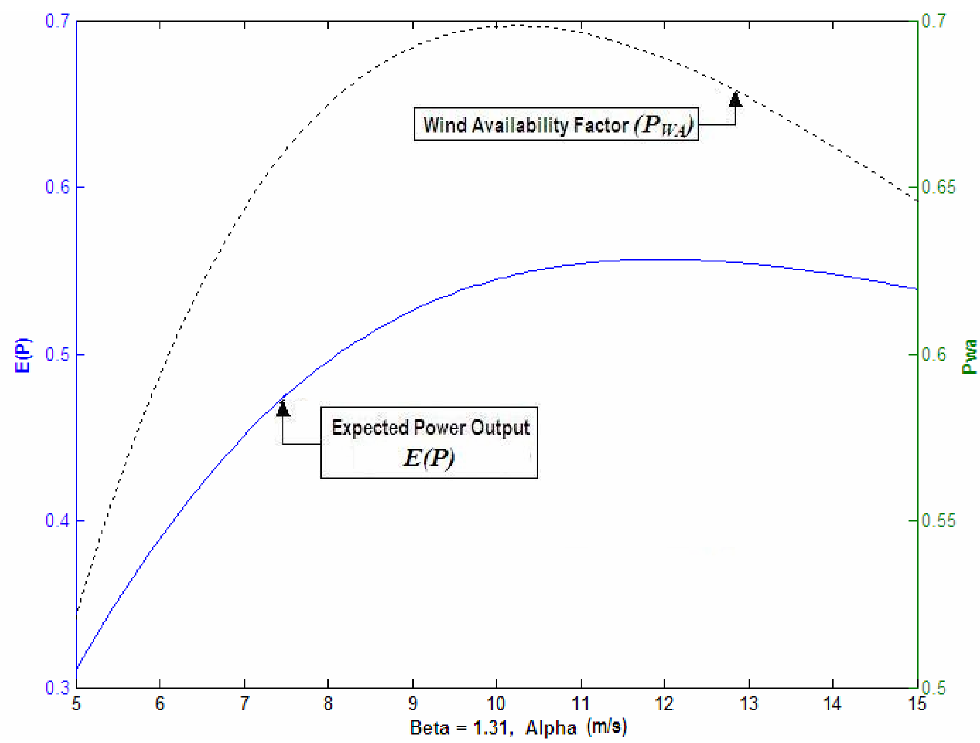

Figure 11: β = 1.31, Varying α

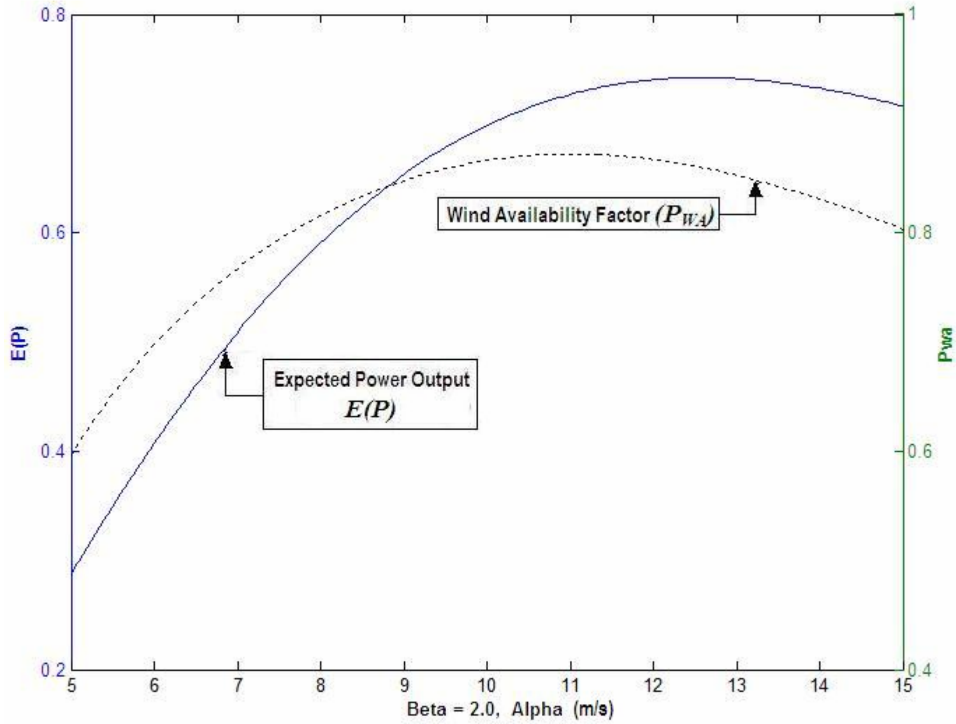

Figure 12: β = 2.0, Varying α

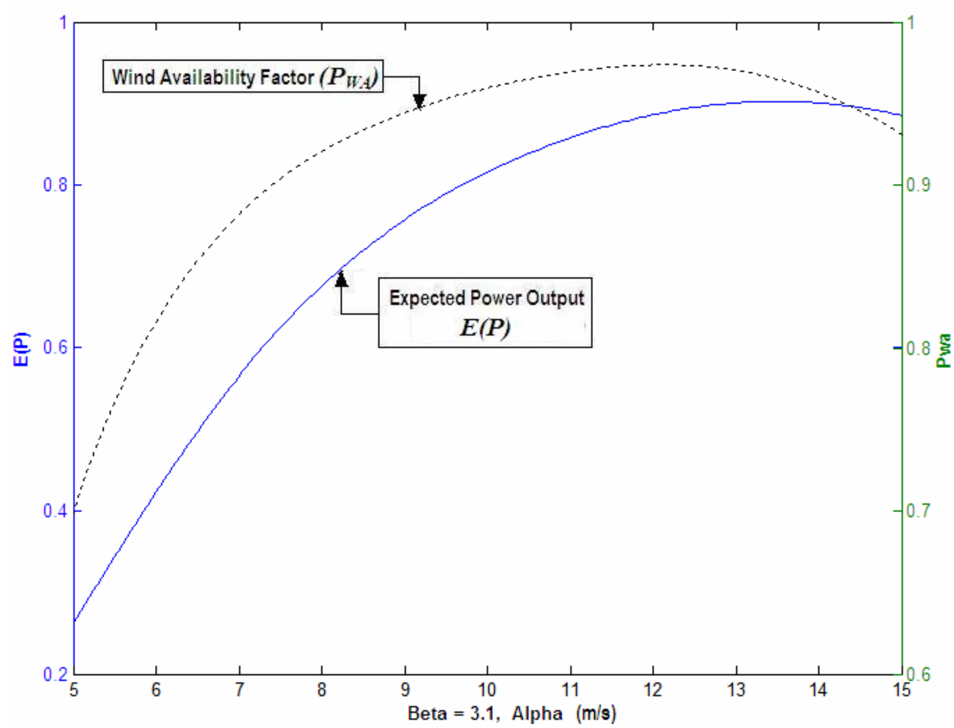

Figure 13: β = 3.1, Varying α

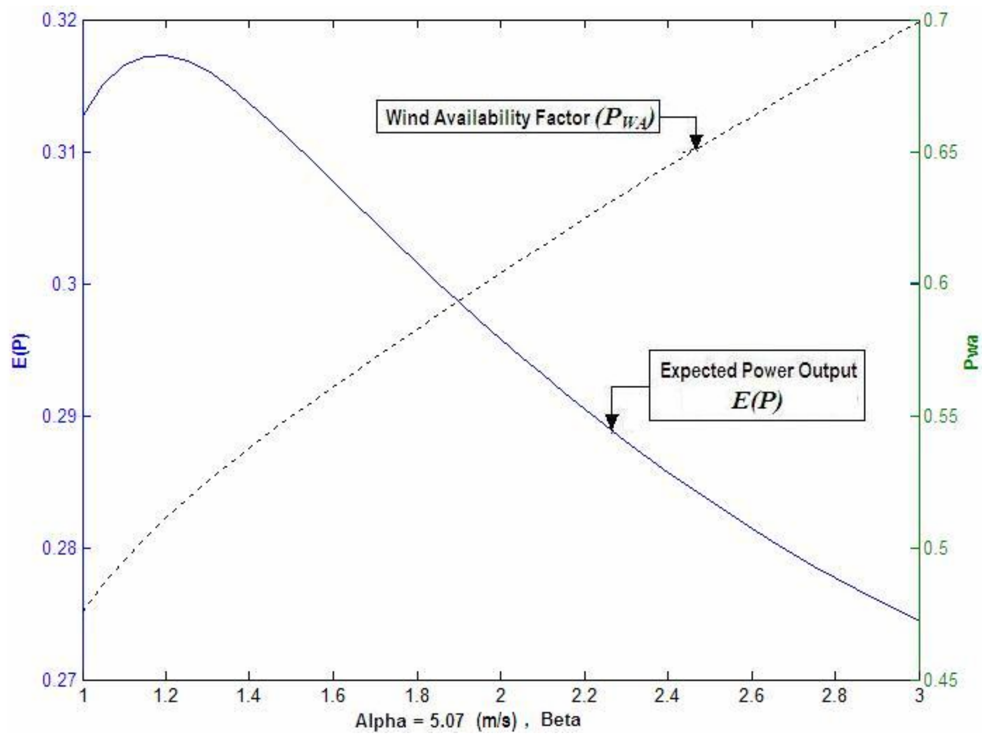

Figure 14: Low Wind Speed -Varying β constant α

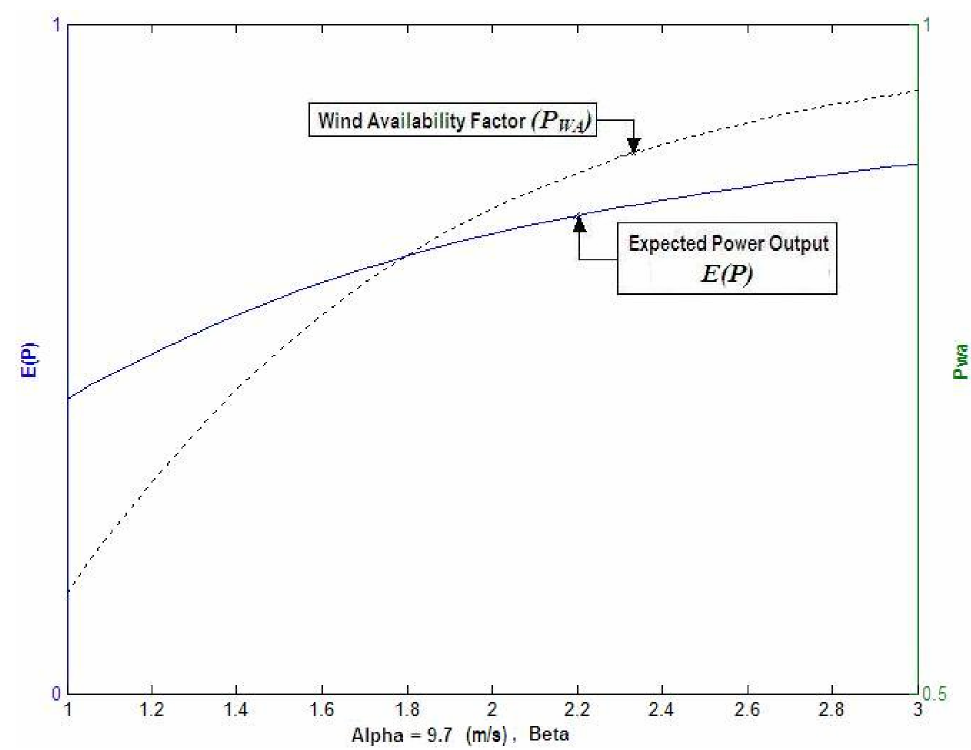

Figure 15: Moderate Wind Speed – Varying β constant α

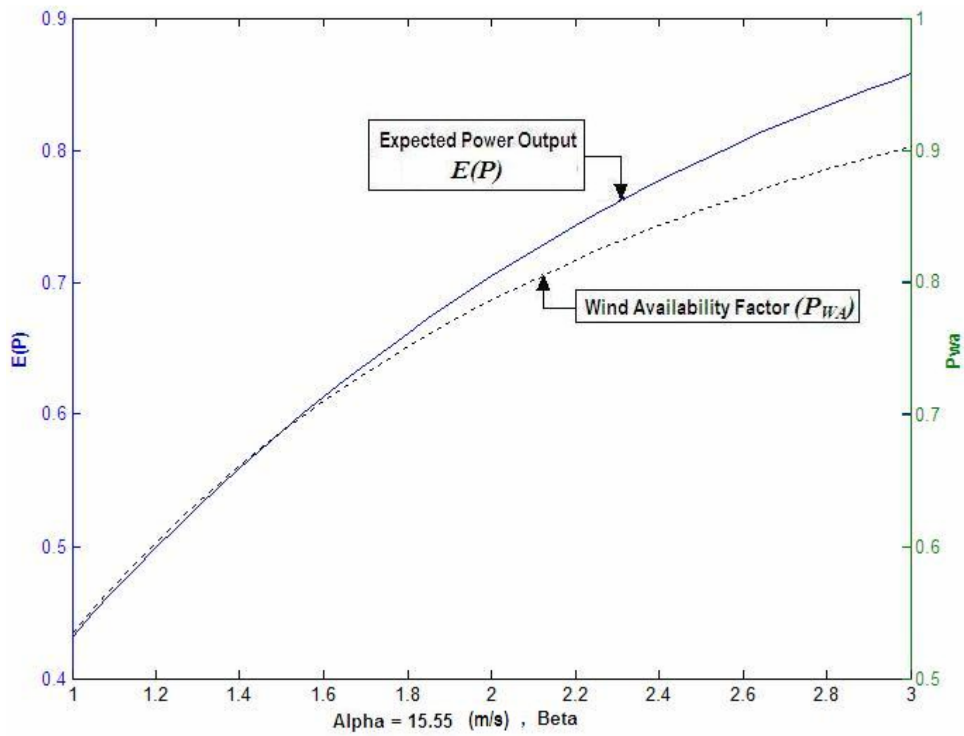

Figure 16: High Wind Speed –Varying β constant α

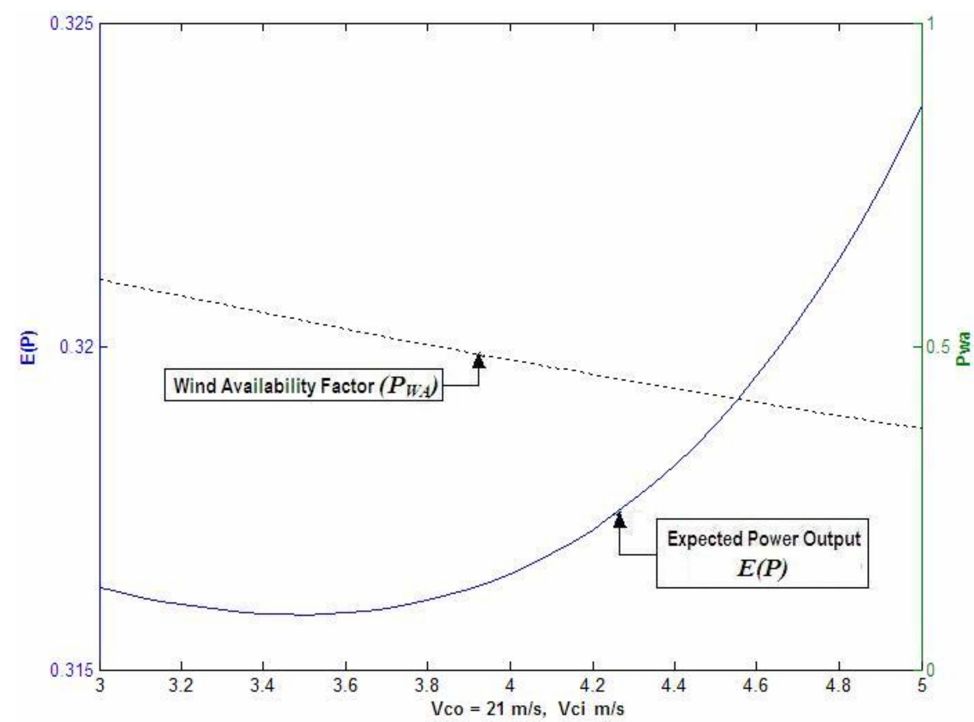

Figure 17: Low Wind Speed -Varying V_{ci} constant V_{co}

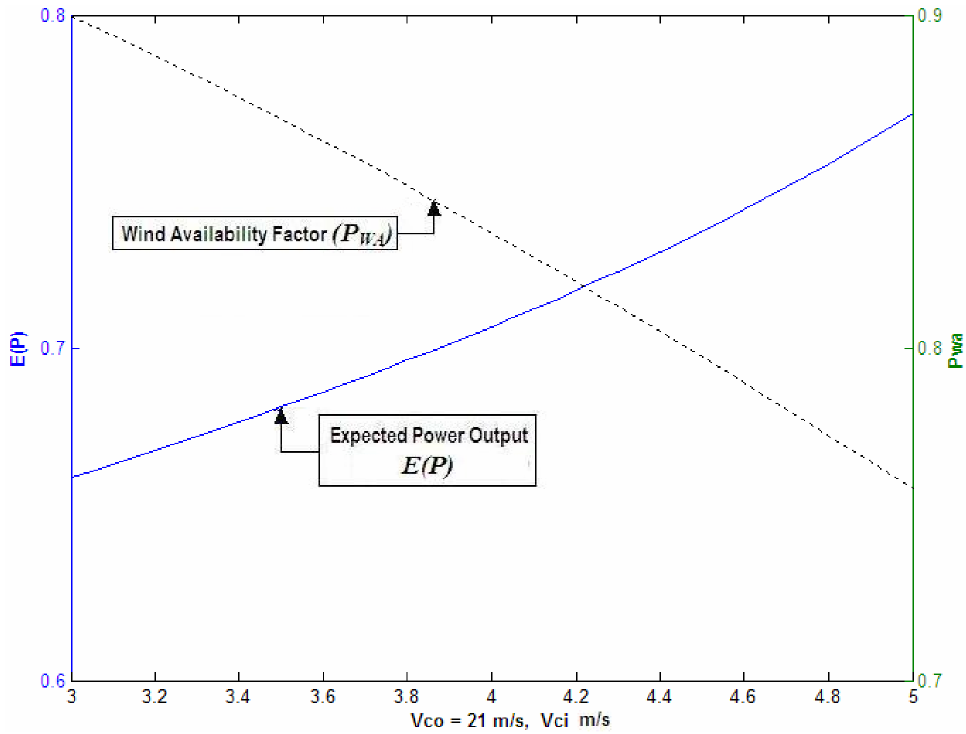

Figure 18: Moderate Wind Speed – Varying V_{ci} constant V_{co}

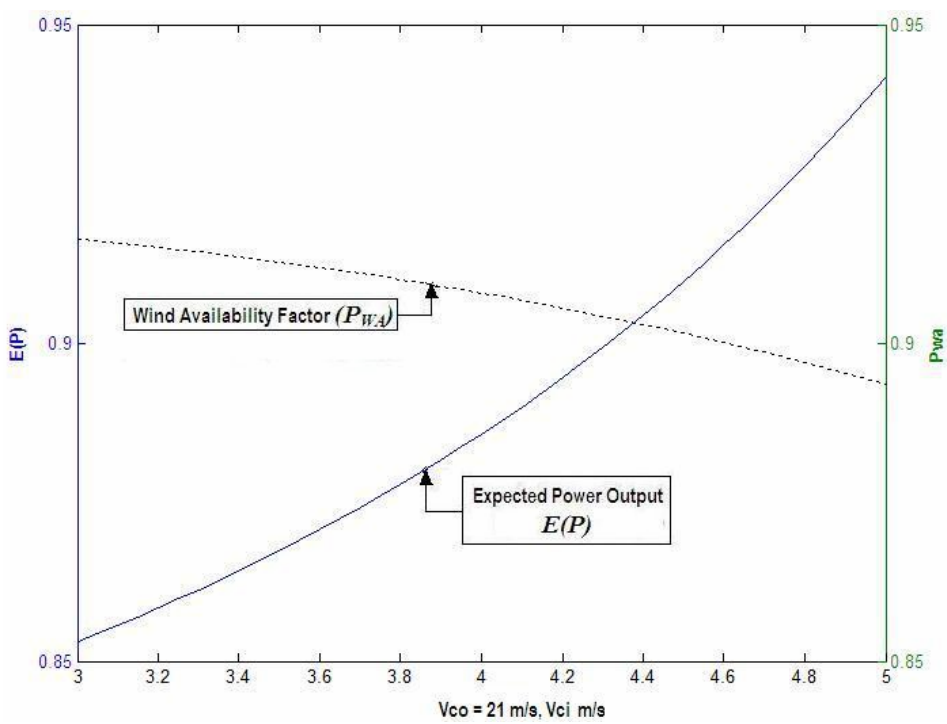

Figure 19: High Wind Speed –Varying V_{ci} constant V_{co}

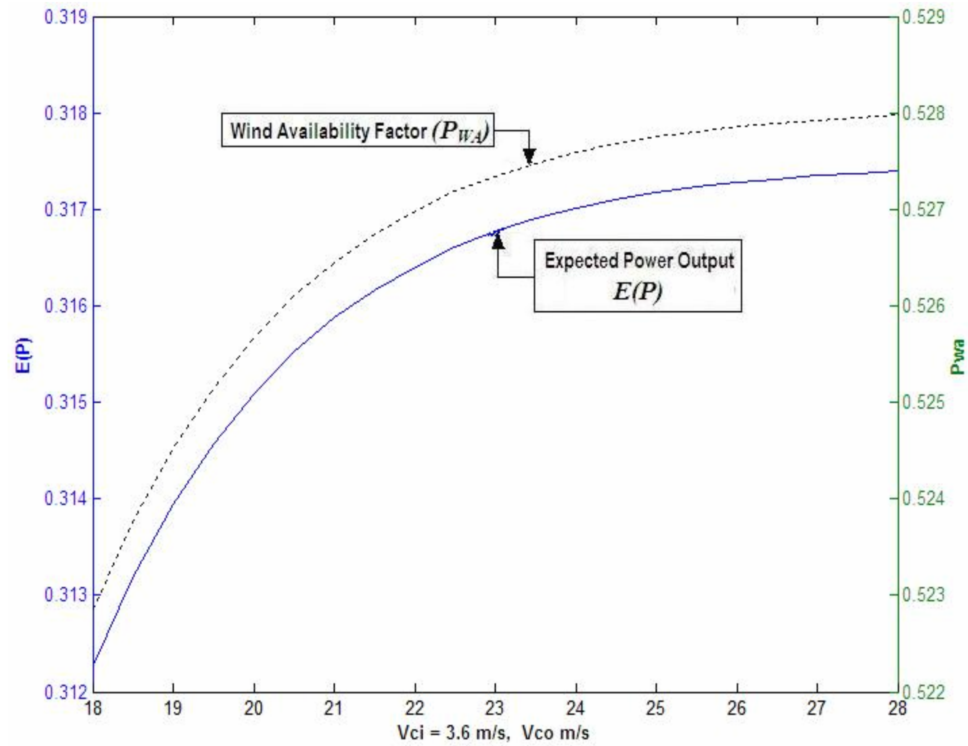

Figure 20: Low Wind Speed -Varying V_{co} constant V_{ci}

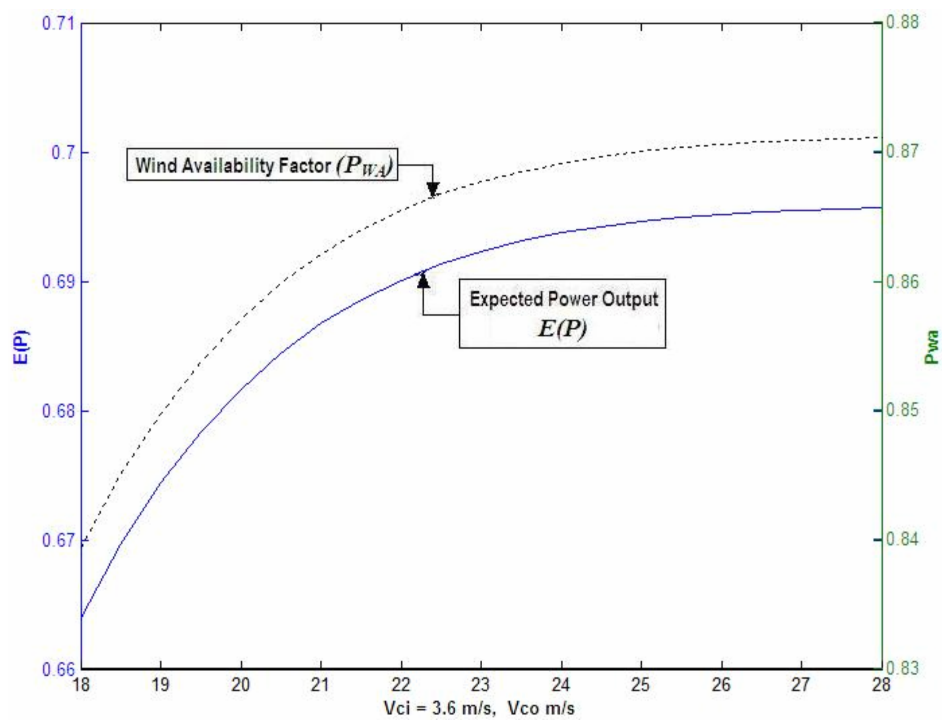

Figure 21: Moderate Wind Speed –Varying V_{co} constant V_{ci}

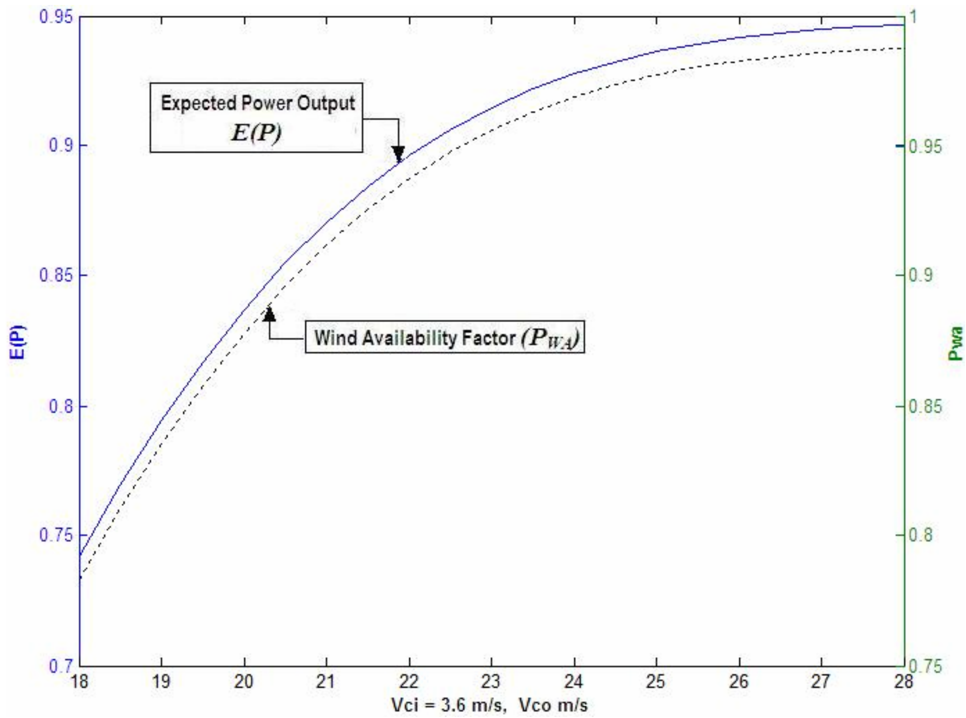

Figure 22: High Wind Speed –Varying V_{co} constant V_{ci}

4.3 Hybrid System Study using WECS FOR Values

Using the FOR values of WECS power output listed in Table 3, expected loss of load is calculated for a hybrid system consisting of different combinations of conventional generators and WECS generators.

i) Consider a system shown in Figure 23 consisting of three conventional coal fired generators and one WECS. All generators have a rating of 1 MW each. The forced outage rate of coal fired plant is taken as 0.02 and the system load is assumed to be 3 MW.

α	5.07
β	1.31
FOR_G	0.02
FOR_{POW}	0.8347

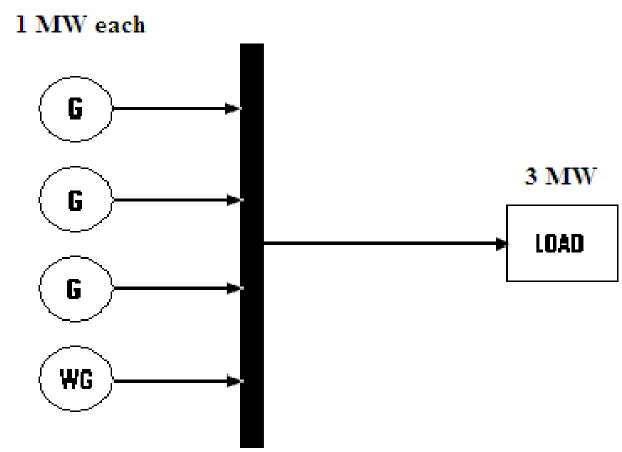

Figure 23: LOLP Study of a Hybrid System – One WECS Generator

Capacity In (MW)	Capacity Out (MW)	Individual Probability	Load Loss (MW)
4	0	0.1556	0
3	1	0.7951	0
2	2	0.0483	1
1	3	9.83e-4	2
0	4	6.68e-6	3

Table 4. Sample Calculations of LOLP - One WECS Generator

For selected values of α and β (α = 5.07, β = 1.31) the probabilities of load loss (LOLP) are calculated as given in Table 4. Then, the expected loss of load of this system is equal to 0.0503 MW as calculated below.

Expected Load Loss *= (1) (0.0483) + (2) (9.83e-4) + (3) (6.68e-6)*

= 0.0503 MW

ii) Now, using the same FOR and wind specific data but replacing one of the three coal fired generators by an additional WECS as shown in Figure 24, the probabilities of load loss are calculated as given in Table 5. It is observed that with an additional WECS generator the expected load loss has increased to 0.7356 MW.

$$\textbf{\textit{Expected Load Loss}} = (1)\,(0.68) + (2)\,(0.0274) + (3)\,(2.79e\text{-}4)$$

$$= \mathbf{0.7356\ MW}$$

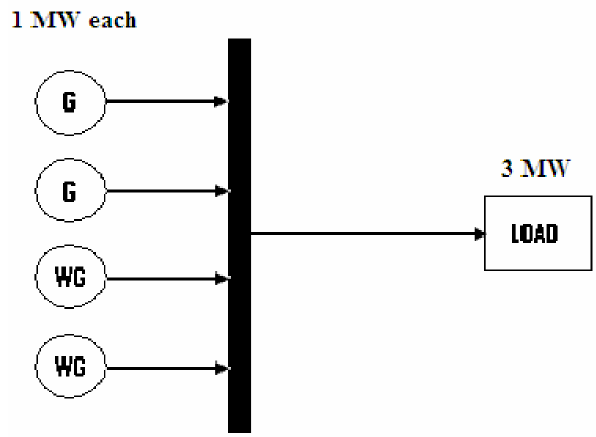

Figure 24: LOLP Study of a Hybrid System - Two WECS Generators

Capacity In (MW)	Capacity Out (MW)	Individual Probability	Load Loss (MW)
4	0	0.0262	0
3	1	0.2661	0
2	2	0.6800	1
1	3	0.0274	2
0	4	2.79e-4	3

Table 5. Sample Calculations of LOLP- Two WECS Generators

Following this approach, the expected values of loss of load are calculated for different combinations of conventional coal-fired generators and wind-electric generators and the results are tabulated in Table 6. Clearly, the expected load loss has shown significant rise in its values with an increase in the number of WECS generators or in other words, at high penetration levels of wind generated electricity into power system [22].

# of Coal-Fired Plant Generators	# of WECS Generators	E(Load Loss) MW With Different Wind Speeds		
		Low	**Moderate**	**High**
4	0	0.00236	0.00236	0.00236
3	1	0.0503	0.0254	0.0136
2	2	0.7356	0.1956	0.06
1	3	1.53	0.4543	0.134
4	1	0.00195	0.00099	0.00053
5	0	7.84e-5	7.84e-5	7.84e-5

Table 6. Expected Load Loss of a Hybrid System at different Penetration Levels

CHAPTER V

SUMMARY AND CONCLUDING REMARKS

6.1 Summary and Concluding Remarks

With the phenomenal global growth of wind farms feeding electric power into utility grids, their impact on the overall system operation is becoming increasingly important at several levels. The stochastic nature of wind and consequently of the electrical output has significant reliability implications for system operation and planning. Preliminary long-range planning will benefit by the availability of simpler models, to be followed by detailed analyses and studies. This study has presented a simple approach to evaluate the forced outage rate of the electrical output from a wind-electric conversion system that could be used in the early stages of planning with wind energy in the generation mix.

The approach considers the nature of wind and its availability, output characteristics of typical wind-electric conversion systems and hardware failure models. The resulting values of reliability and forced outage rate are used to estimate the expected loss of load of a combined generation system with different combinations of coal-fired plants and WECS generators having a rating of 1 MW each and with a system load of 3 MW. Results clearly indicate a significantly higher expected load loss at higher penetration levels of wind power into the system which is unacceptable. Hence, early estimations of loss of load will be helpful in power system scheduling and reserve planning in order to meet the demand on the grid. Also, the acceptable level of penetration of wind generated electricity into the power system can be assessed by incorporating its FOR value into conventional reliability evaluation techniques used to assess generation capacity.

In addition to being simple, the approach is general enough to consider units of any rating and any location. In spite of the approximations made, the results reveal the influences of all the major design factors such as cut-in speed, cut-out speed and Weibull parameters. These influences are presented graphically for different wind speed data. Graphs show the behavior of wind availability factor and expected normalized power output from a wind turbine when different key parameters are varied. Approximating the non-linear part of the power curve to a straight line does not affect the forced outage rate values significantly. The usefulness of the key factors obtained using approximated power curve has been illustrated by hybrid generation system study examples.

6.2 Scope for Future Work

The study presented has assumed a constant wind specific data throughout and has not included the variations in the Weibull characteristic parameters over time. Usually, the scale and shape parameters vary with seasonal changes. The effect of seasonal changes can be covered with slight modifications to the approach presented. This study assumes a constant load whereas in a practical scenario, the load also varies stochastically. The impact of variable load on the expected load loss values is left for future work. In order to obtain more accurate results, different turbine design parameters can be included in this study which requires further work.

The approach presented can also be used as an initial step in reserve planning. Since we have the forced outage rate values of wind-generated electricity, they can be utilized to determine effective load carrying capability (ELCC) of wind capacity. The results of ELCC will decide how much capacity of wind power is equivalent to the conventional generation capacity maintained in the reserve margin. Similar kind of study has been done by Electric Reliability Council of Texas, Inc. (ERCOT) for the year 2008 [23]. According to ERCOT report, by replacing 550 MW of pulverized coal capacity with the overall wind capacity of 6300 MW the same value of LOLP can be reached. Hence, the ELLC of wind energy is 8.7% of the installed wind capacity which can be counted in the reserve margin calculations. Future studies should take into account the approach presented in the ERCOT report as it will allow the eco-friendly wind power to replace the polluting coal-fired plants without crossing the reliability standards.

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APPENDIX A

WEIBULL DISTRIBUTION TO MODEL WIND RESOURCE

Weibull distribution has been used in the presented study to model the wind resource. It is one of the most widely used probability distributions for wind resource. It is a two parameter distribution namely, a "scale parameter" (α) having unit m/s and a "shape parameter" (β). Figures A.1 and A.2 show the "Probability Density Function" (pdf) and the "Cumulative Distribution Function" (CDF) respectively.

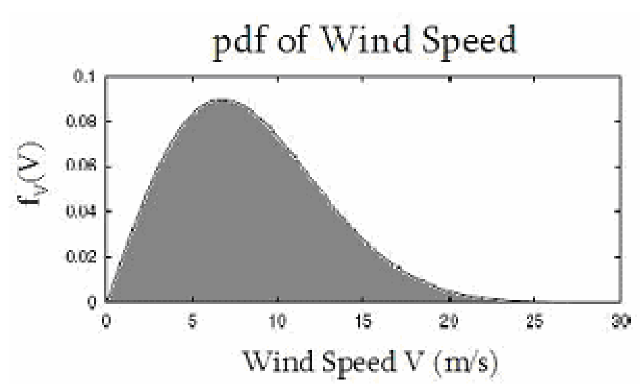

Figure A.1: Weibull Probability Density Function

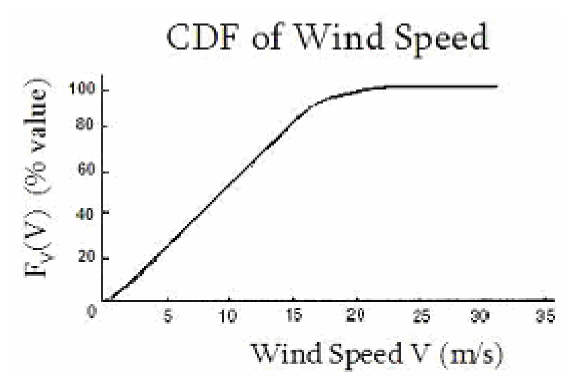

Figure A.2: Weibull Cumulative Distribution Function

Weibull Cumulative Distribution Function:

$$F(V) = 1 - \exp\left[-\left(\frac{V}{\alpha}\right)^{\beta}\right] \qquad \ldots A.1$$

Weibull Probability Density Function:

$$f(V) = \frac{\beta * V^{\beta-1}}{\alpha^{\beta}} \exp\left[-\left(\frac{V}{\alpha}\right)^{\beta}\right] \qquad \ldots A.2$$

where,

V = wind speed (m/s)

Hence, using CDF function the probability that the wind speed V m/s is between any two values say V_1 and V_2 can be written as,

$$\begin{aligned} P(V_1 \le V \le V_2) &= F(V_2) - F(V_1) \\ &= \exp\left[-\left(\frac{V_1}{\alpha}\right)^{\beta}\right] - \exp\left[-\left(\frac{V_2}{\alpha}\right)^{\beta}\right] \end{aligned} \qquad \ldots A.3$$

The expected value of Weibull distribution is given by,

$$\begin{aligned} \mu = E[V] &= \int_0^{\infty} V * f(V)\, dV \\ \therefore E[V] &= \alpha * \Gamma\left(1 + \frac{1}{\beta}\right) \end{aligned} \qquad \ldots A.4$$

where μ is called the first moment of random variable V i.e. wind speed and Γ is the gamma function given by,

$$\Gamma(x) = \int_0^{\infty} V^{x-1} e^{-V}\, dV \qquad \ldots A.5$$

The variance of Weibull distribution is

$$Var[V] = \sigma^2 = \int_0^{\infty} V^2 f(V)\, dV - \mu^2 \qquad \ldots A.6$$

where σ is known as 'standard deviation'. By substituting values of *f(V)* and μ we get

$$Var[V] = \sigma^2 = \alpha^2 \left[\Gamma\left(1 + \frac{2}{\beta}\right) - \Gamma^2\left(1 + \frac{1}{\beta}\right) \right] \qquad \ldots A.7$$

Using the equations above, the mean or expected value and variance of wind speed V for different values of α and β are calculated as follows:

For $\alpha = 5.07$ m/s and $\beta = 1.31$,

E [V] ≈ 4.7 m/s (= 10.528 miles/hr), Variance ≈ 13 m^2/s^2

For $\alpha = 9.70$ m/s and $\beta = 2.00$,

E [V] ≈ 8.6 m/s (= 19.264 miles/hr), Variance ≈ 20 m^2/s^2

For $\alpha = 15.55$ m/s and $\beta = 3.1$,

E [V] ≈ 14 m/s (= 31.36 miles/hr), Variance ≈ 24 m^2/s^2

In this way the mean wind speed can be determined for a particular location provided the scale and shape parameters of Weibull distribution are known. The graph in Figure A.3 shows the variations of the scale parameter α with respect to mean wind speed E[V] for different values of β.

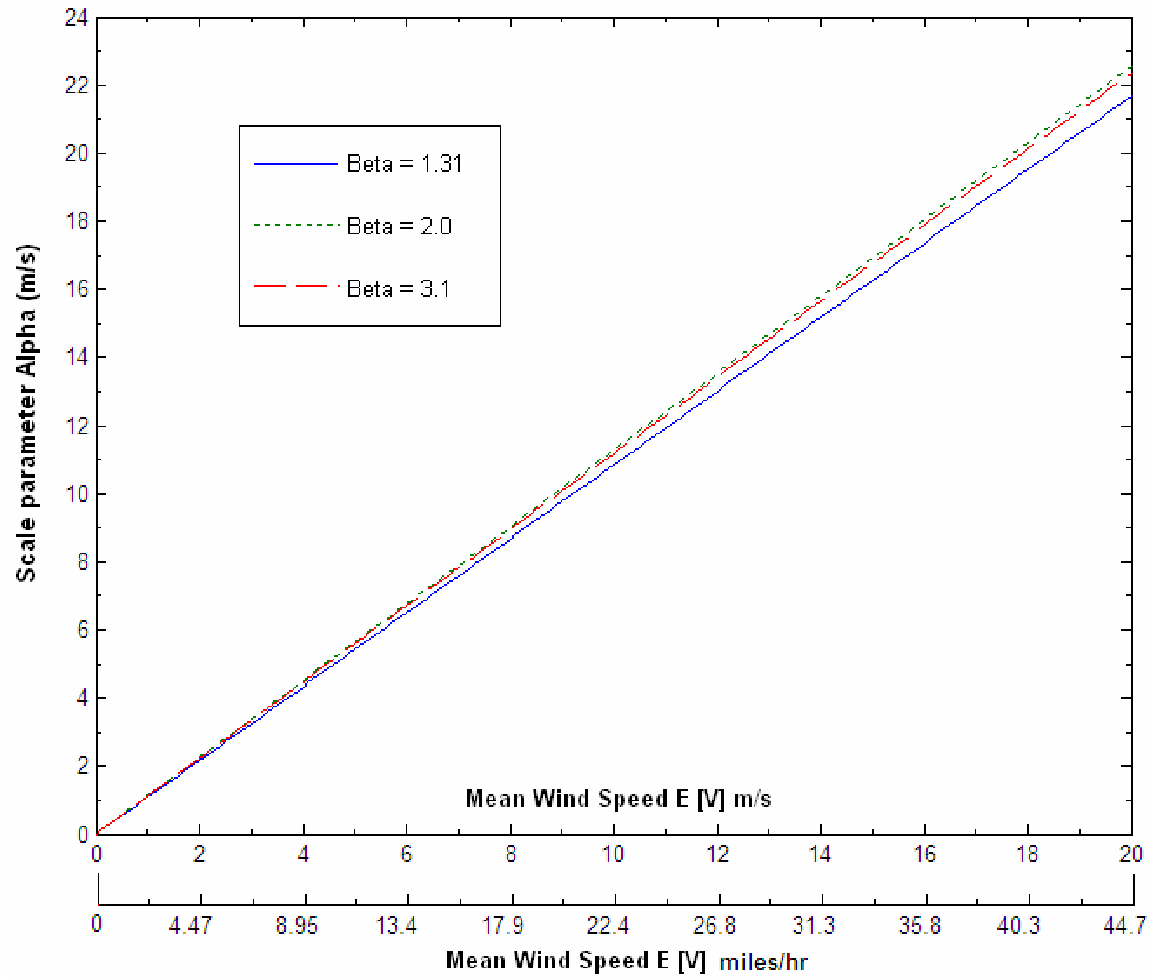

Figure A.3: Scale Parameter vs. Mean Wind Speed

APPENDIX B

MATLAB CODE FOR SENSITIVITY ANALYSES

B.1 Program Listing

```
function[] = FOR(Alpha,Beta,Vci, Vr, Vco, FailuresPerYear, RepairHoursPerFailure)

Interval = (Vr-Vci)/50;

V = Vci;

for k = 1:50

    V_New = V + Interval;

    Probability(k,:) = exp(-(V/Alpha)^Beta) - exp(-(V_New/Alpha)^Beta);

    Power(k,:) = (((V_New + V)/2)-Vci)/(Vr-Vci);

    V = V_New;

end


%%%Calculate different factors affecting availability of WECS output

Variable_Output_Factor = Probability' * Power;

Constant_Output_Factor = exp(-(Vr/Alpha)^Beta) - exp(-(Vco/Alpha)^Beta);

Exp_Pow_Output = Variable_Output_Factor + Constant_Output_Factor;

Wind_Availability_Factor = exp(-(Vci/Alpha)^Beta) - exp(-(Vco/Alpha)^Beta);

Failure_Rates = FailuresPerYear./8760;
```

```
FOR_Mech = RepairHoursPerFailure * Failure_Rates';

Reliability_Power = Wind_Availability_Factor * (1-FOR_Mech) * Exp_Pow_Output;

FOR_Power = 1 - Reliability_Power;


%%%Plot graphs of sensitivity analyses

 %%%Varying Alpha

Count = 1;

for Alpha_New = 5:0.05:15

    V = Vci;

    for k = 1:50

        V_New = V + Interval;

        Probability(k,:) = exp(-(V/Alpha_New)^Beta) - exp(-(V_New/Alpha_New)^Beta);

        Power(k,:) = (((V_New + V)/2)-Vci)/(Vr-Vci);

        V = V_New;

    end

    Variable_Output_Factor = Probability' * Power;

    Constant_Output_Factor = exp(-(Vr/Alpha_New)^Beta)

                                              – exp(- (Vco/Alpha_New)^Beta);

    Exp_Pow_Output1(Count,:) = Variable_Output_Factor + Constant_Output_Factor;

    Wind_Availability_Factor1(Count,:) = exp(-(Vci/Alpha_New)^Beta)

                                                              – exp(-(Vco/Alpha_New)^Beta);

    Count = Count + 1;

end
```

```
Alpha_New = 5:0.05:15;

subplot(4,1,1),[AX,H1,H2]

= plotyy(Alpha_New,Exp_Pow_Output1,Alpha_New,Wind_Availability_Factor1,'plot');

xlabel('Alpha')

set(get(AX(1),'Ylabel'),'String','E(P)')

set(get(AX(2),'Ylabel'),'String','Pwa')


%%%Varying Beta

Count = 1;

for Beta_New = 1:0.05:3

    V = Vci;

    for k = 1:50

        V_New = V + Interval;

        Probability(k,:) = exp(-(V/Alpha)^Beta_New) - exp(-(V_New/Alpha)^Beta_New);

        Power(k,:) = (((V_New + V)/2)-Vci)/(Vr-Vci);

        V = V_New;

    end

    Variable_Output_Factor = Probability' * Power;

    Constant_Output_Factor = exp(-(Vr/Alpha)^Beta_New)

                                        - exp(-(Vco/Alpha)^Beta_New);

    Exp_Pow_Output2(Count,:) = Variable_Output_Factor + Constant_Output_Factor;

    Wind_Availability_Factor2(Count,:) = exp(-(Vci/Alpha)^Beta_New)

                                                        - exp(-(Vco/Alpha)^Beta_New);
```

```
    Count = Count + 1;

end

Beta_New = 1:0.05:3;

subplot(4,1,2),[AX,H1,H2] =

plotyy(Beta_New,Exp_Pow_Output2,Beta_New,Wind_Availability_Factor2,'plot');

xlabel('Beta')

set(get(AX(1),'Ylabel'),'String','E(P)')

set(get(AX(2),'Ylabel'),'String','Pwa')


%%%Varying Vci

Count = 1;

for Vci_new = 3:0.05:5

    V = Vci_new;

    for k = 1:50

        V_New = V + Interval;

        Probability(k,:) = exp(-(V/Alpha)^Beta) - exp(-(V_New/Alpha)^Beta);

        Power(k,:) = (((V_New + V)/2)-Vci_new)/(Vr-Vci_new);

        V = V_New;

    end

    Variable_Output_Factor = Probability' * Power;

    Constant_Output_Factor = exp(-(Vr/Alpha)^Beta) - exp(-(Vco/Alpha)^Beta);

    Exp_Pow_Output3(Count,:) = Variable_Output_Factor + Constant_Output_Factor;
```

```
    Wind_Availability_Factor3(Count,:) = exp(-(Vci_new/Alpha)^Beta)
                                        - exp(-(Vco/Alpha)^Beta);
    Count = Count + 1;
end
Vci_new = 3:0.05:5;
subplot(4,1,3),[AX,H1,H2] =
plotyy(Vci_new,Exp_Pow_Output3,Vci_new,Wind_Availability_Factor3,'plot');
xlabel('Vci')
set(get(AX(1),'Ylabel'),'String','E(P)')
set(get(AX(2),'Ylabel'),'String','Pwa')

%%%Varying Vco
Count = 1;
for Vco_new = 18:0.5:28
    V = Vci;
    for k = 1:50
        V_New = V + Interval;
        Probability(k,:) = exp(-(V/Alpha)^Beta) - exp(-(V_New/Alpha)^Beta);
        Power(k,:) = (((V_New + V)/2)-Vci)/(Vr-Vci);
        V = V_New;
    end
    Variable_Output_Factor = Probability' * Power;
    Constant_Output_Factor = exp(-(Vr/Alpha)^Beta) - exp(-(Vco_new/Alpha)^Beta);
```

```
    Exp_Pow_Output4(Count,:) = Variable_Output_Factor + Constant_Output_Factor;
    Wind_Availability_Factor4(Count,:) = exp(-(Vci/Alpha)^Beta)
                                          - exp(-(Vco_new/Alpha)^Beta);
    Count = Count + 1;
end
Vco_new = 18:0.5:28;
subplot(4,1,4),[AX,H1,H2] =
plotyy(Vco_new,Exp_Pow_Output4,Vco_new,Wind_Availability_Factor4,'plot');
xlabel('Vco')
set(get(AX(1),'Ylabel'),'String','E(P)')
set(get(AX(2),'Ylabel'),'String','Pwa')

%%%Output results
Exp_Pow_Output
Wind_Availability_Factor
FOR_Mech
Reliability_Power
FOR_Power
```

B.2 User Instructions

User needs to run the MATLAB program by giving following command in the "Command Window".

FOR(Alpha,Beta,Vci, Vr, Vco, Failures, RepairHoursPerFailure)

Following are the codes snippets of the input data at different wind speeds for above command.

```
%%%%%%%%%%%%%%%%%LOW WIND SPEED%%%%%%%%%%%%%%%
Alpha = 5.07;
Beta = 1.31;
Vci = 3.6;
Vr = 8;
Vco = 21;
Failures = [0.006 0.026 0.061 0.005 0.045 0.054 0.004 0.05 0.067 0.021 0.052 0.001];
RepairHoursPerFailure
        = [100 253.85 42.62 120 257.78 50 300 184 107.46 214.29 90.38 0];
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%MODERATE WIND SPEED%%%%%%%%%%%%%%%
Alpha = 9.7;
Beta = 2.0;
Vci = 3.6;
Vr = 8;
Vco = 21;
Failures = [0.006 0.026 0.061 0.005 0.045 0.054 0.004 0.05 0.067 0.021 0.052 0.001];
RepairHoursPerFailure
        = [100 253.85 42.62 120 257.78 50 300 184 107.46 214.29 90.38 0];
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
%%%%%%%%%%%%%%%%%HIGH WIND SPEED%%%%%%%%%%%%%%%
Alpha = 15.55;
Beta = 3.12;
Vci = 3.6;
Vr = 8;
Vco = 21;
Failures = [0.006 0.026 0.061 0.005 0.045 0.054 0.004 0.05 0.067 0.021 0.052 0.001];
RepairHoursPerFailure
    = [100 253.85 42.62 120 257.78 50 300 184 107.46 214.29 90.38 0];
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

VITA

RASHMI RAMESH NAGARKAR

Candidate for the Degree of

Master of Science

Thesis: A SIMPLIFIED APPROACH TO EVALUATE THE RELIABILITY OF CONVENTIONAL GENERATION WITH WIND POWER

Major Field: Electrical Engineering

Biographical:

Education: Received the degree of Bachelor of Engineering (B.E.) in Electrical Engineering from Pune University, Maharashtra, India, June 2004; fulfilled requirements for the Master of Science Degree at Oklahoma State University with major in Electrical Engineering in December, 2007.

Experience: Research Assistant, Electrical Engineering Department, Oklahoma State University, 2006-2007; Software Engineer, Geometric Software Solutions Ltd., Pune, India from June 2004 to November 2005.

Professional Memberships: IEEE Student Member 2007.
IEE Student Member 2002.

Name: Rashmi Nagarkar　　Date of Degree: December, 2007

Institution: Oklahoma State University　　Location: Stillwater, Oklahoma

Title of Study: A SIMPLIFIED APPROACH TO EVALUATE THE RELIABILITY OF CONVENTIONAL GENERATION WITH WIND POWER

Pages in Study: 62　　Candidate for the Degree of Master of Science

Major Field: Electrical Engineering

Scope and Method of Study: The purpose of this study is to develop a simplified method to evaluate the reliability of electric power output from a combined conventional and wind electric conversion system (WECS). The progress of wind-electric conversion technology and impacts of its penetration into existing power systems have been reviewed in the initial part of this study. Wind turbine gives a variable power output due to stochastic nature of the wind input which complicates the task of determining the availability of WECS output. The study presented provides a simplified reliability model for the output of a WECS for the use in the reliability evaluation of a hybrid generation system. The method can be extended to include the effect of turbine design parameters and seasonal changes with a few modifications. The approach can be used in reserve capacity planning in which coal-fired plants will be replaced by WECS which requires further study.

Findings and Conclusions: The approach centers around the determination of an effective Forced Outage Rate (FOR) for a WECS. This FOR is used along with corresponding values for conventional generation units to evaluate the overall generation reliability. Sensitivity of the FOR value for several key parameters are studied using MATLAB 7.1 program. As expected, FOR values for WECS are significantly larger than those for conventional units. This leads to a larger Loss of Load Probability (LOLP) for the combined system. This study and the ensuring results will be beneficial at the initial stages of generation planning with WECS.

ADVISER'S APPROVAL: Dr. R. G. Ramakumar