INFLUENCE OF WIND REGIME ON THE SECURITY OF POWER SYSTEMS WITH WIND ELECTRIC GENERATION

By

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INFLUENCE OF WIND REGIME ON THE SECURITY OF POWER SYSTEMS WITH WIND ELECTRIC GENERATION

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I dedicate my thesis to my grandparents with love.

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CHAPTER 1

Introduction

1.1 Background

The cost of energy has increased significantly in the last ten years due to increasing demand and decreasing reserves of fossil fuels. All this have led to an increased interest in renewable energy resources. Global growth in the demand for electricity is especially high and new ways of generating it continues to interest engineers and scientists. Indiscriminate burning of fossil fuels and lack of environmental cleanup in many parts of the world result in many adverse effects such as global warming and ecological imbalance. Use of fossil fuels results in emission of greenhouse gases, permitting incoming solar radiation to reach the surface of the earth unhindered but restricting the outward flow of infrared radiation. Greenhouse effect is a warming of the earth's surface and lower atmosphere that tends to intensify with an increase in atmospheric concentration of carbon dioxide and other greenhouse gases such as methane. Other undesirable effects include long-term climatic changes, stronger hurricanes and rise of ocean water levels. An increase in atmospheric concentrations of other trace gases such as chlorofluorocarbons (Freons), nitrous oxide, and methane, due again largely to human activity, may also aggravate greenhouse conditions. Therefore there is an imminent need for “clean” generation technologies which reduce harmful emissions and use the already existing natural renewable resources.

1.2 Trends in Wind Generation technologies:

Of all the renewable energy resources available, wind energy is the most popular form in use for electricity production at present [1]. Wind turbines mounted on towers capture the energy in moving air and convert it into rotary mechanical energy and then to electricity. The rated capacity of the turbines depends mainly on the diameter of the chosen rotor. Table 1 below shows the approximate rated capacities for some rotor diameters.

Table 1. Rotor diameter and ratings of wind turbines [2]

Rotor Diameter (m)	Rated Capacity (MW)
50	0.75
66	1.5
85	2.5
100	3.5
120	5.0

An Off-shore wind turbine in Arklow, Ireland is shown in Figure 1

Figure 1. Off-shore 3.6 MW 100m diameter GE turbines off the coast of Arklow, Ireland (Robert Thresher, NREL)

An on-shore wind turbine in Nebraska is shown in Figure 2.

Figure 2. On-shore 1.5 MW 72m diameter system in Nebraska (Tennessee Valley Infrastructure Group)

The available turbine technologies are improving each year. This improvement in technology is shown below for each decade [2]:

→ 1980s

- Structurally stiff
- 3 bladed – upwind yaw-driven
- Constant speed and 2 speed
- Stall regulated/tip brakes or full-span pitch controlled
- Fiberglass blades
- Geared transmission
- Induction generator
- Steel truss or tube tower

→ 1990s

- Structurally stiff
- 3 bladed – upwind yaw-driven
- Variable speed and constant speed
- Special airfoils – NREL
- Stall regulated and pitch controlled
- Planetary transmission
- Induction generator
- Large size to reduce COE

→ Future Innovation

- Scale to larger size
- Advanced blade materials and manufacturing
- Low speed direct drive generators

- Custom power electronics (high efficiency)
- Feedback control of drive train and rotor loads
- More flexible structurally
- O&M reduction features

The turbines can be located on-shore or off-shore. Wind-electric conversion systems occupy minimum land area and the land around them can be used for other purposes. The available wind turbines can be classified into small, intermediate and large wind turbines based on their generation capacities [2].

- Small scale wind turbines are the turbines the turbines that have generation capacities upto 10 kW. The generated power from these turbines are generally used for household purposes, farming and remote applications such as charging batteries, pumping water, ice making, etc.
- Intermediate scale wind turbines are the turbines that have generation capacities between 10 kW and 500 kW. The power generated from these turbines is generally used to empower small villages, in hybrid systems and as distributed power resources.
- Large scale wind turbines are the turbines that have generation capacities between 500 kW and 6 MW. These turbines are generally used as central station wind farms, distributed power resources and offshore wind generation stations.

Wind systems have gained wide popularity in recent times for their potential use as distributed energy resources, the primary disadvantage being that their outputs are highly site specific and intermittent. Initially, constant speed wind systems were used. Almost all of them failed due to excessive stresses on the rotating and supporting components. However, the trend now is towards variable speed systems owing to the facts that variable speed systems operate with high energy capture and low drive-train loads. Advanced power electronics is used to operate wind systems at constant voltage and constant frequency output and at desired power factors.

1.3 Security analysis of a power system

Power system reliability, once mainly the domain of planning and operating engineers within the utility, now must involve a diverse group of people. With all the restructuring and other changes faced by the power industry, reliability has been the hot topic of discussion for a considerable time. This has also been a stalling factor for initiating changes in the industry, making changes to proceed very cautiously.

Reliability is considered as a combination of two main components [3]:

1. Security
2. Adequacy

Definitions for these two terms as given by the North American Electric Reliability Council (NERC) are [3]:

Security: It is the ability of electric systems to withstand disturbances such as electric short circuits or unanticipated loss of system elements.

Adequacy: It is the ability of electric systems to supply the aggregate electrical demand and energy requirements of customers at all times, taking into account scheduled and reasonably expected unscheduled outage of system elements.

In an existing network, a disturbance such as sustained overload, collapse of voltage or transient instability may result in blackouts. To maintain the reliability level at an acceptable value even during individual component outages, a large safety margin is built-in and it is calculated by considering all possible uncertainties. A strong system is operated with large safety margin and the resulting reliability is obviously very high. This method of maintaining reliability is called the deterministic method. But now as the power world transforms from regulated to a competitive market, economics start to play an important role. The cost of delivered energy is always a deciding factor along with supply reliability for the consumer. This has increased the pressure on engineers and planners and large security margins can no longer be maintained. [3]

Due to these reduced security margins, insertion of wind generated electric power into the power system may easily take the system into insecure states. Hence it is absolutely necessary to perform a thorough security analysis of the system before a decision is made on aspects such as the point of insertion of wind, the maximum capacity that can be installed at that point, etc. A simple method to evaluate security with wind is discussed in this work.

> “In the operational context, most control centers are currently adapting load flow techniques for the steady-state security analysis of contingencies to determine whether the system is secure or insecure. In the real time environment, it is hardly feasible to perform exhaustive contingency testing to determine how well the system, in its present state, can withstand these contingencies. The performance index contains all line flows normalized by their limits. These normalized flows are raised to an even power, thus, the use of absolute magnitude of flows is avoided.” [13]

Hence the lines that are loaded above a pre-selected safe level are in alert or emergency conditions and they should be given importance in any security analysis. With several lines loaded above their safe levels, the system will be less able to handle any unanticipated loss of equipment and/or changes in loads and other disturbances. In short, the system will be less secure.

CHAPTER 2

Literature Review

2.1 Types of Renewable Energy Resources

The entire world currently depends on coal, oil and natural gas for most of the energy needs. As they are non-renewable, when they become less abundant, their cost will go higher and higher. On the contrary, renewable energy resources such as wind, biomass and insolation are replenished on a regular basis.

The main types of renewable energy resources available are: [4]

- Insolation
- Wind Energy
- Hydro Power
- Biomass
- Geothermal Energy
- Ocean, Tidal and Wave Power

2.1.1 Insolation

Solar radiation incident on the earth's surface is called insolation. The incident energy is in two forms: photons and thermal. Solar cells, also known as photovoltaic (PV) devices, convert the incident photons (that have sufficient energy) directly into electricity. A solar cell is a suitably designed large area P-N junction diode with external connections.

Many Solar cells are systematically combined to form PV arrays to obtain kW/MW scale outputs at practical voltages. The main advantages of PV systems are no moving parts, silent operation, long lifetime, no recurring fuel costs, environmentally benign operation and high power output to weight ratio. The primary disadvantage is the high cost of cells.

2.1.2 Wind Energy

This is the most popular form of renewable energy resource in use for electricity production at present. Wind turbines mounted on towers capture the energy in moving air and convert it into rotary mechanical energy and then to electricity. The turbines can be located on-shore or off-shore. Wind-electric conversion systems occupy minimum land area and the land around them can be used for other purposes. Small wind turbines can be used for simple applications such as pumping of water and grinding grain. However, for utility-scale electric power generation, several large (70m or larger rotor diameter) wind turbines are installed in groups to form wind farms.

Wind systems have gained wide popularity in recent times for their potential use as distributed energy resources, the primary disadvantage being that their outputs are highly site specific and intermittent. Initially, constant speed wind systems were used. Almost all of them failed due to excessive stresses on the rotating and supporting components. However, the trend now is towards variable speed systems owing to the facts that variable speed systems operate with high energy capture and low drive-train loads. Advanced power electronics is used to operate wind systems at constant voltage and constant frequency output and at desired power factors.

2.1.3 Hydropower

Electricity produced from the potential energy of stored water is hydropower. Water is generally stored in elevated reservoirs and when released, flows through a turbine causing it to spin. This spin of the turbine drives a generator and allows generation of electricity. Currently, hydropower is the largest renewable energy source in use, generating around 10% of the total electrical energy in the U.S and much higher percentages in several countries around the world. [6]

The second type of hydropower plant called a pumped storage plant, which can store and release large quantities of energy as required. When power flows from grid, the generators act as motors and pump water from a lower level to a higher level. When power is needed, the stored water is allowed to flow back through the turbine and generators to produce electricity.

2.1.4 Biomass

The world-wide consumption of wood is approximately 2.8 to 3 Billion tons annually. 15% of this consumption is by the energy sector. More than 50% of the wood consumption world-wide is accounted for energy purposes. In developing countries, firewood is the primary source of fuel. Due to its high percentage of usage and due to the poor efficiency of utilization, the demand for firewood is increasing exponentially. The direct result of firewood usage is clearing of large forest areas and shrinking of the carbon dioxide sink.

Presently, the US biopower industry has 1000 plants, each of 20 MW capacity. The estimated capacity of biopower in the rest of the world is around 20,000-25,000 MW. [4]

2.1.5 Geothermal Energy

Electricity produced from the heat stored in the crust of the earth is geothermal energy. Much beneath the earth's crust, high temperatures exist and deeper down, molten rock called magma exists. Technological advances to date do not allow production of electricity from magma which is a very abundant resource.

Temperatures within the earth increase with depth at an average rate of about 25°C/km [5]. Spatial variations of the thermal energy within the deep crust and mantle of the earth give rise to concentrations of thermal energy near the surface of the earth that can be used as an energy resource. Heat is transferred from the deeper portions of the earth by conduction of heat through rocks, by the movement of hot magma towards the surface, and by deep circulation of water. The thermal energy retrieved is used in a slightly modified thermal power plant to generate electricity.

2.1.6 Ocean, Tidal and Wave energy

Two forms of energy are available in ocean waters. Thermal energy due to the heating of the surface and mechanical energy produced by waves and tides. Almost three fourths of the earth is covered with water. Much more of the Sun's heat is captured by ocean waters than by land surface. This generates a temperature gradient between the surface water and deep water which can be harnessed using a heat engine to generate electricity.

Mechanical energy available in the oceans is due to waves and tides. While tides occur due to the gravitational forces between the moon and the earth, waves are due to the effect of wind on the surface of ocean waters.

The main difference between the two kinds of energies available from ocean waters is that ocean thermal energy is fairly constant while ocean mechanical energy is highly site specific and intermittent, much like wind energy.

2.2 The ascent of wind energy

Wind energy is renewable, abundant, environmentally benign and can be converted easily to rotary mechanical energy for coupling to an electrical generator to generate electricity. The turbines can be located either on shore or off shore. In many parts of the world, capability to locate off shore is an attractive feature.

Table 2 shows current and future cost estimates for power generation from the main renewable energy resources.

Due to the low existing and next generation costs for power generation by wind and due to its high potential for use as a distributed generation source, wind energy has gained significant prominence among all the renewables. Technological advances such as large diameter rotors, variable speed operation, sophisticated power electronic systems and ingenious construction and installation techniques have accelerated this trend.

Table 2: Estimated generation costs [4]

Resource	Current cost (U.S. Cents/kWh)	Next Generation cost (U.S. Cents/kWh)
Photovoltaics	20-30	12-15
Biopower	7-15	4-6
Wind Energy	4-6	2-4
Geothermal Energy	5-8	3-5

As the level of penetration of wind electric conversion systems into conventional power systems increases, their impact on the overall reliability and security of power delivery should be assessed in detail. This is a very complex problem since a multitude of factors interact to varying degrees in real time. This paper focuses on one specific aspect – namely the impact on security. Simplified approach based on a "security index" is used to arrive at some general conclusions on the nature and factors influencing the overall security**.**

2.3 Wind Turbine Generators

A GE 1.5s wind turbine rated at 1.5 MW is considered in this study. This is one of the most widely used wind turbine at present. It has active yaw, pitch regulated, has an asynchronous generator and employs power/torque control capability. A bedplate drive train design is used in its construction and all nacelle components are assembled on a common structure which provides more durability. Elastrometric elements are used to support the generator and gearbox to minimize noise. Three important wind speeds generally define the wind turbine output characteristic [6].

- **Cut-in wind speed:** speed at which the turbine starts to generate power.

- **Rated wind speed:** speed at which the turbine reaches rated power.
- **Cut-out wind speed:** speed at which the turbine is shut down to keep mechanical loads and generator power from reaching dangerous levels.

Power curves for GE 1.5sl and 1.5s units are shown in Figure 1. The power generated at a particular wind speed can be read directly from the graph.

For the units considered,

Cut-in speed is 4m/s

Rated speed is 12m/s

Cut-out speed is 25m/s [7]

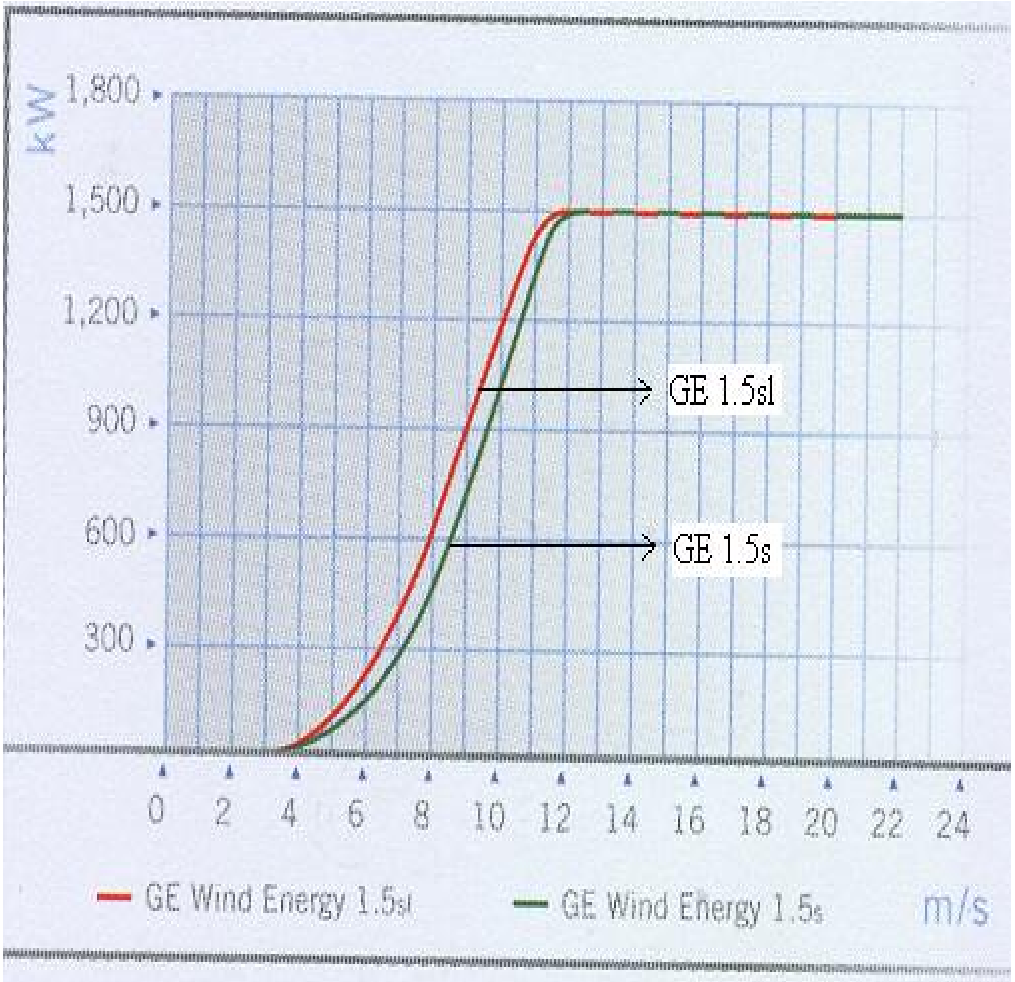

Figure 3: Power curve for GE 1.5sl/1.5s [7]

2.4 Reliability test system (RTS 79)

The reliability test system, originally formulated in 1979, is a standard system to perform bench mark studies on existing and new reliability evaluation techniques. This is a single area system and has the core data and system parameters necessary for composite reliability evaluation. The system was upgraded once in 1986 into a two area system and was named as RTS–86 and again in 1996 into a three area system and was called RTS–96. One of the important requirements of a test system is that it should represent, as much as possible, all the different technologies and configurations that could be encountered in a real-world system [8]. Since its publication in 1979, it has been used to report results in many IEEE and international journals involving reliability evaluation. A one-line diagram of the system is shown in Figure 2.

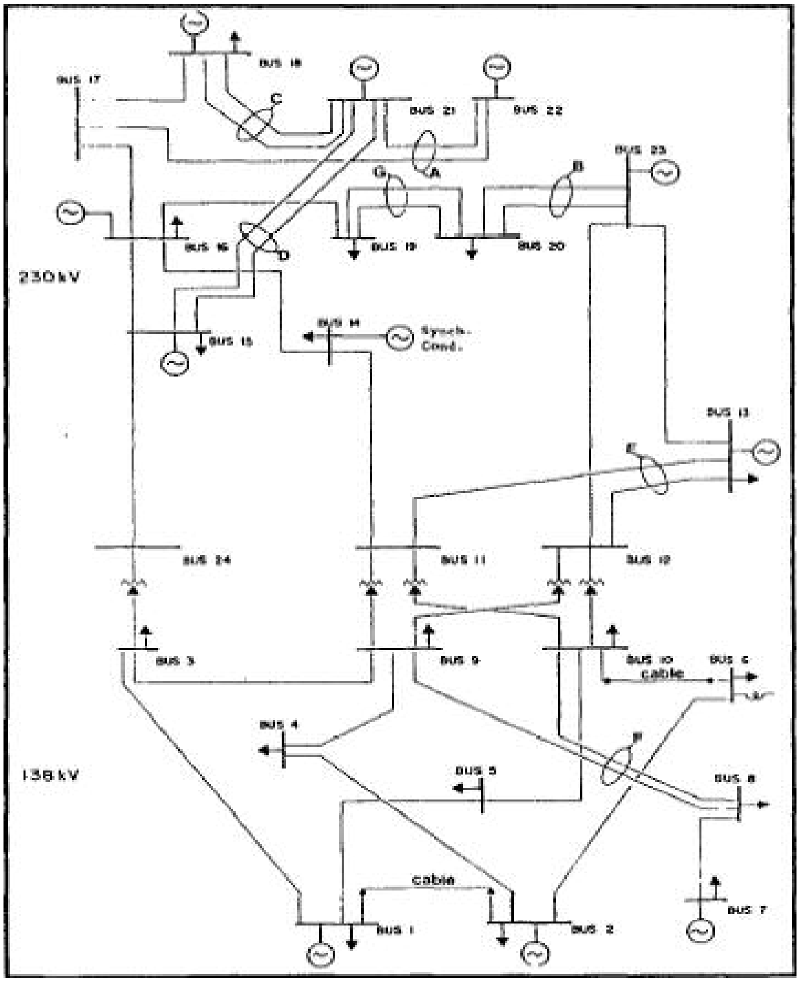

Figure 4: Single line diagram of RTS-79 test system [8]

Bus data for the test system is tabulated in Table 3.

Table 3: IEEE RTS-79 Bus Data [8]

Bus Number	Bus Name	Bus type	Base kV
101	Abel	3	138
102	Adams	2	138
103	Adler	1	138
104	Agricola	1	138
105	Alken	1	138
106	Alber	1	138
107	Alder	2	138
108	Alger	1	138
109	Ali	1	138
110	Allen	1	138
111	Anna	1	230
112	Archer	1	230
113	Arne	2	230
114	Arnold	2	230
115	Arthur	2	230
116	Asser	2	230
117	Aston	1	230
118	Astor	2	230
119	Attar	1	230
120	Attila	1	230
121	Attlee	2	230
122	Aubrey	2	230
123	Austen	2	230
124	Avery	1	230

Bus Type:

1 – Load bus (no generation)
2 – Generator bus
3 – Swing bus

The assumed generation at various busses is tabulated in Table 4.

Table 4: Real and reactive generations at each bus [8]

Bus Number	MW generation	MVAR generation
1	660	-50
2	192	-50
7	30	0
13	594	0
14	0	-50
15	215	-50
16	155	-50
18	400	-50
21	400	-50
22	300	-60
23	600	-125

The real power generation at bus number 14 is ‘Zero’ because it is a synchronous condenser and cannot generate any real power.

Table 5 shows the load data assumed in the simulation study.

Table 5: Assumed Real and Reactive loads at buses [8]

Bus Number	MW load	MVAR load
1	108	22
2	40	20
3	180	37
4	36	7.5
5	100	20
6	88	20
8	80	20
9	120	22
10	45	10
13	175	40
14	175	35
15	317	64
16	100	20
18	333	68
19	181	37
20	128	26

The transmission branch data for the network is given in Table 6.

Table 6: Transmission branch data [8]

From Bus	To Bus	L (km)	R (pu)	X (pu)	B (pu)	Tr (pu)
1	2	4.8	0.003	0.014	0.461	0
1	3	88.5	0.055	0.211	0.057	0
1	5	35.4	0.002	0.085	0.023	0
2	4	53.1	0.033	0.127	0.034	0
2	6	80.5	0.05	0.192	0.052	0
3	9	49.9	0.031	0.119	0.032	0
3	24	0	0.02	0.084	0.000	1.015
4	9	43.5	0.027	0.104	0.028	0
5	10	37	0.023	0.088	0.024	0
7	8	25.8	0.016	0.061	0.017	0
8	9	69.2	0.043	0.165	0.045	0
8	10	69.2	0.043	0.165	0.045	0
9	11	0	0.02	0.084	0.000	1.03
9	12	0	0.02	0.084	0.000	1.03
10	11	0	0.02	0.084	0.000	1.015
10	12	0	0.02	0.084	0.000	1.015
11	13	53.1	0.006	0.048	0.1	0
11	14	46.7	0.005	0.042	0.088	0
12	13	53.1	0.006	0.048	0.1	0
12	23	107.8	0.012	0.097	0.203	0
13	23	96.6	0.011	0.087	0.182	0

14	16	43.5	0.005	0.059	0.082	0
15	16	19.3	0.002	0.017	0.036	0
15	21	54.7	0.006	0.049	0.103	0
15	21	54.7	0.006	0.049	0.103	0
15	24	57.9	0.007	0.052	0.109	0
16	17	29	0.003	0.026	0.055	0
16	19	25.8	0.003	0.023	0.049	0
17	18	16.1	0.002	0.014	0.03	0
17	22	117.5	0.014	0.105	0.221	0
18	21	29	0.003	0.026	0.055	0
18	21	29	0.003	0.026	0.055	0
19	20	44.3	0.005	0.04	0.083	0
19	20	44.3	0.005	0.04	0.083	0
20	23	24.1	0.003	0.022	0.046	0
20	23	24.1	0.003	0.022	0.046	0
21	22	75.6	0.009	0.068	0.142	0

Where,

L is the length of transmission line in miles

Tr is the Transformer off-nominal turns ratio

Off-nominal turns ratio:

Generally, for a transformer, the ratio of the voltage bases selected on the two sides is equal to the ratio of the voltage ratings of the windings. However, in some cases, it is impossible to select voltage bases in this manner. To overcome this situation, a per-unit model of a transformer whose voltage ratings are not in proportion to the selected base voltages can be developed. Such a transformer is said to have an ‘off-nominal turns ratio’. [9]

Non-zero values are Tr are for transmission lines and zero indicates transmission line.

CHAPTER 3

Modeling the wind resource

Wind is highly site specific and variable. It has instantaneous, minute-by-minute, hourly, diurnal, seasonal and annual variations. It also depends on other factors such as terrain and the above ground height of measurement. A given wind speed data, for a specific location and height, can be modeled effectively by either a Weibull distribution or a Rayleigh distribution. The standard Rayleigh distribution is the most simple probability distribution to model wind speed as it is a single parameter distribution and needs only the mean wind speed to complete the model. The Weibull distribution is an improvement over the Rayleigh distribution and requires the knowledge of two parameters – scale parameter α and shape parameter β. By manipulating these two parameters, a very good fit of observed/measured data can be achieved.

3.1 Weibull distribution function

Wind speed v is a continuous random variable and it can be modeled by the density function f(v) where [10]

$$f(v) = \frac{(\beta v^{\beta-1})}{(\alpha^{\beta})} \exp[-(\frac{v}{\alpha})^{\beta}] \qquad \mathbf{(1)}$$

If the mean (m_v) and standard deviation (σ_v) of wind speed are known, then the parameters α and β can be found using the following equations [11, 12].

$$m_v = \alpha\Gamma(1 + \frac{1}{\beta}) \qquad \mathbf{(2)}$$

$$\left(\frac{\sigma_v}{m_v}\right)^2 = \left[\frac{\Gamma(1+\frac{2}{\beta})}{\Gamma^2(1+\frac{1}{\beta})}\right] - 1 \qquad (3)$$

Once α and β are known, the corresponding distribution function F(v) can be expressed as

$$F(v) = 1 - \exp\left[-\left(\frac{v}{\alpha}\right)^{\beta}\right] \qquad (4)$$

The probability of the wind speed being between two values a and b can be found from the equation

$$P(a \le v \le b) = F(b) - F(a) \qquad (5)$$

Equation 4 can be plotted for different values of α and β to illustrate the influence of these parameters on the distribution function.

3.2 Effect of α on distribution function

Figure 5-8 illustrates the influence of the scale parameter α on the distribution function for a fixed β. The scale parameter has a significant influence on the distribution. With a constant β value, larger values of α correspond to larger values of mean wind speeds and the distribution skews more and more towards higher wind speeds.

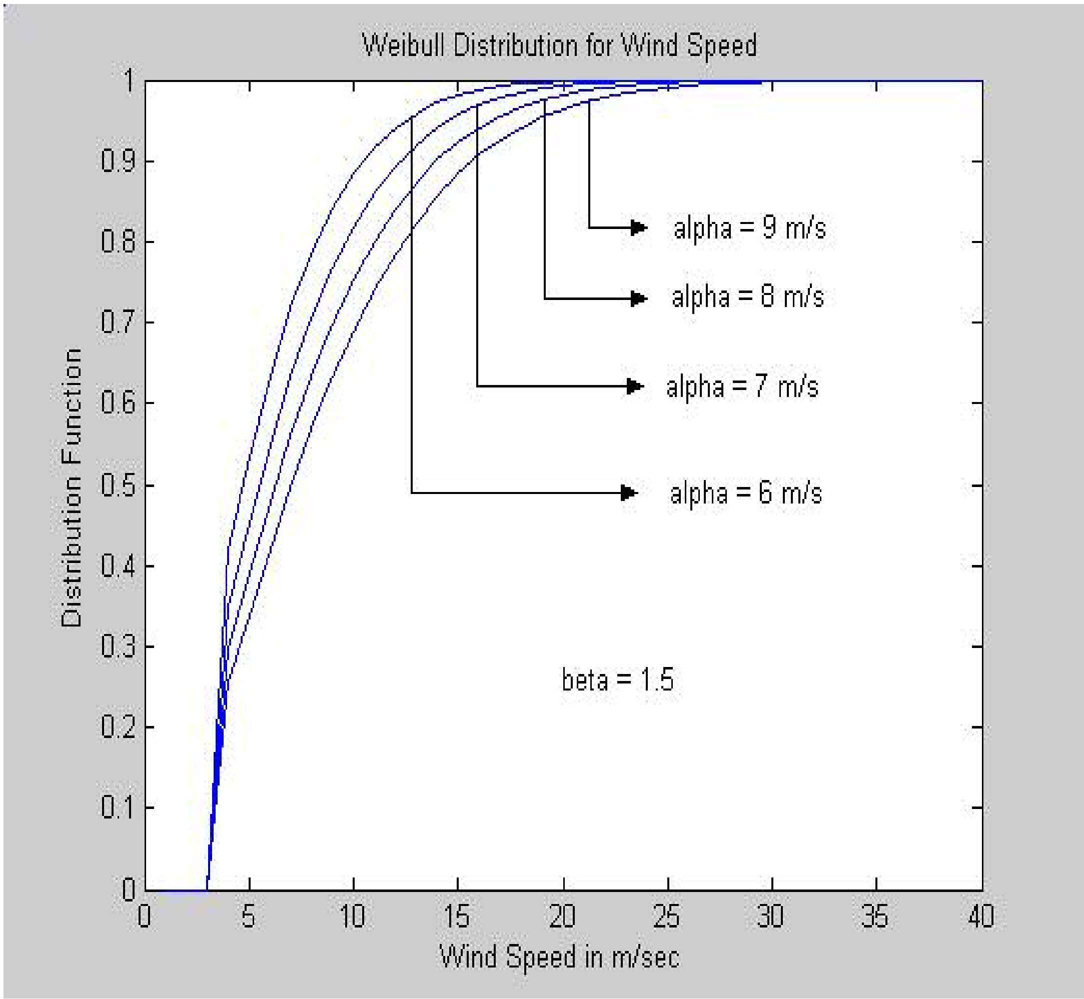

Figure 5: Effect of scale parameter (α) on the distribution function for β = 1.5

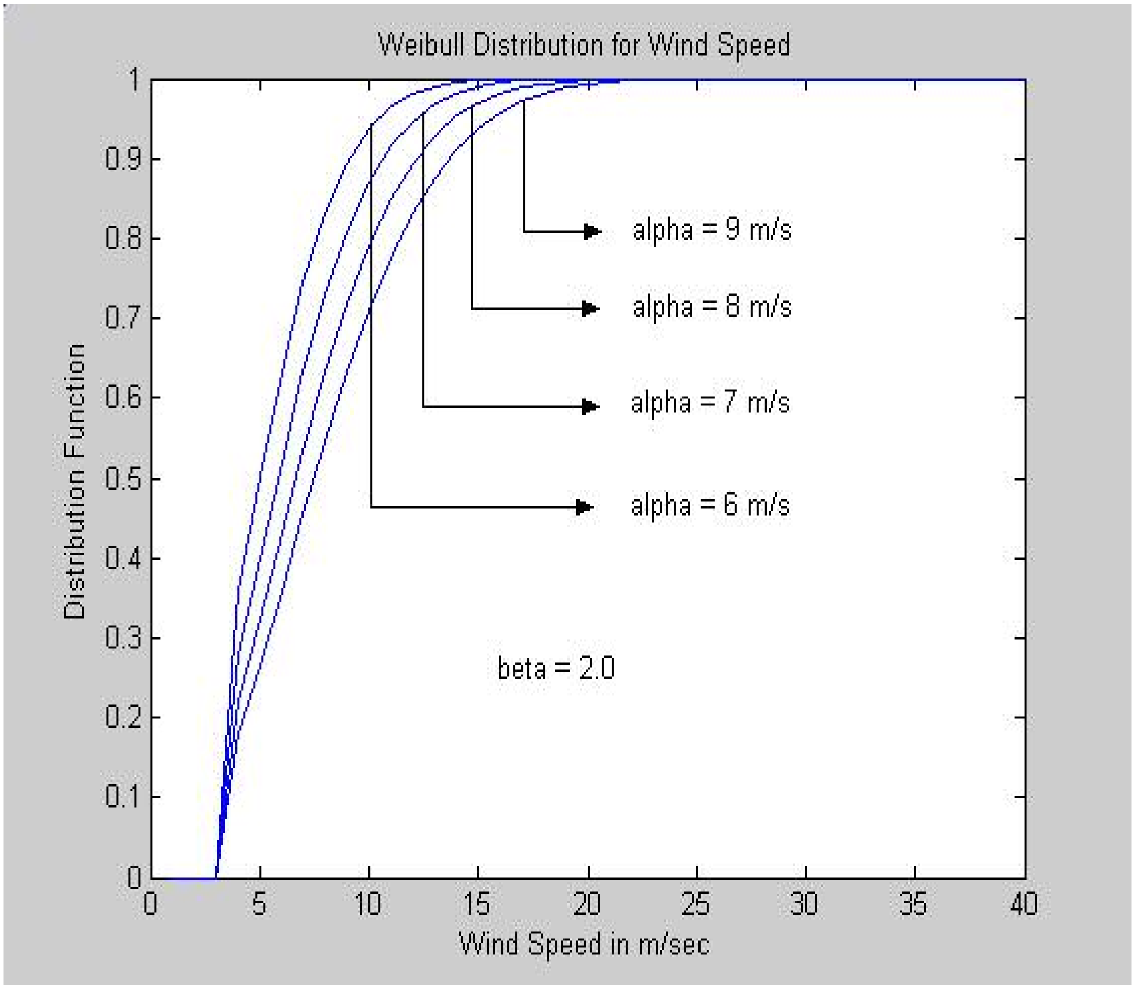

Figure 6: Effect of scale parameter (α) on the distribution function for β = 2.0

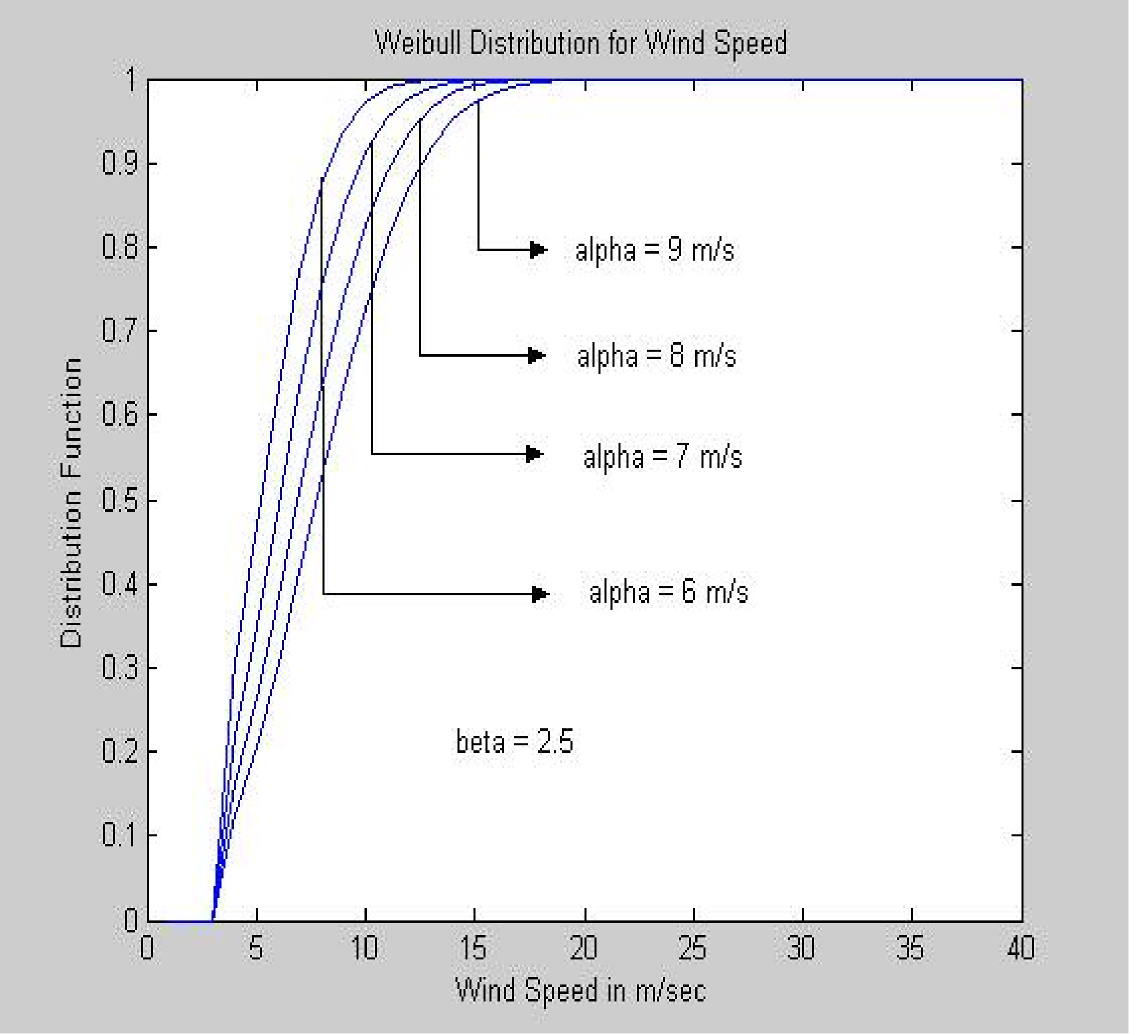

Figure 7: Effect of scale parameter (α) on the distribution function for β = 2.5

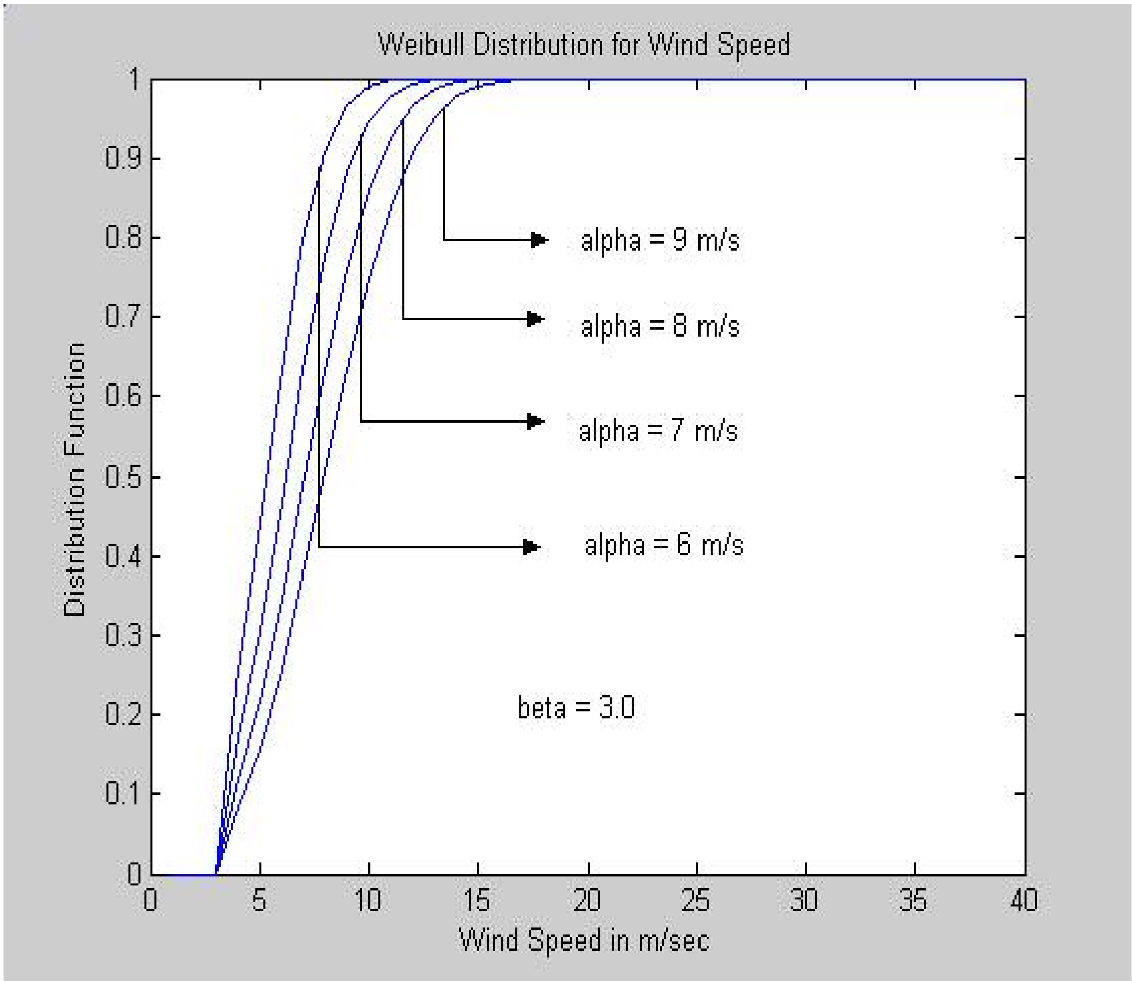

Figure 8: Effect of scale parameter (α) on the distribution function for β = 3.0

3.3 Effect of β on distribution function

Figures 9 - 12 show the influence of shape parameter β on the distribution function for a given α. Clearly, the influence is not significant. Smaller β values tend to skew the function somewhat to the right over a wider range of wind speeds.

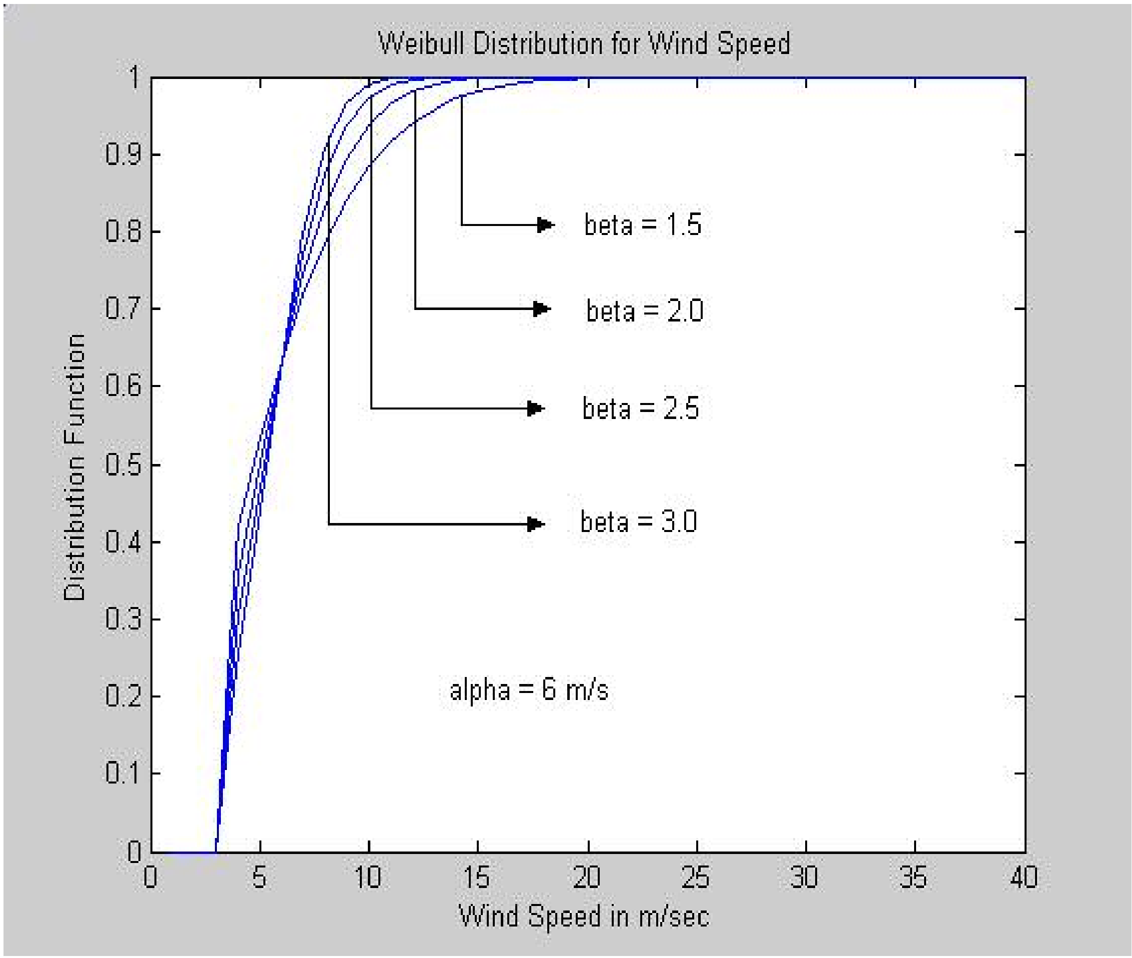

Figure 9: Effect of the shape parameter (β) on the distribution function for α = 6 m/s

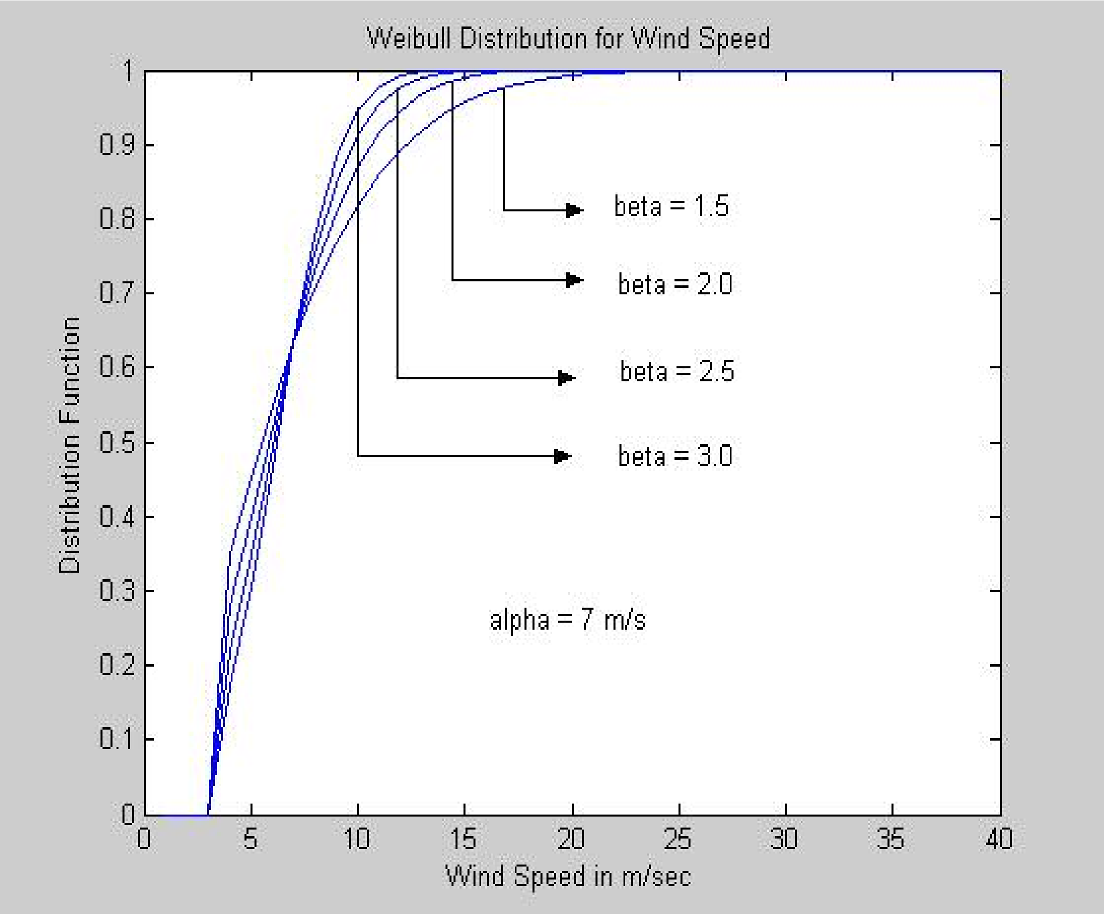

Figure 10: Effect of the shape parameter on the distribution function for α=7 m/s

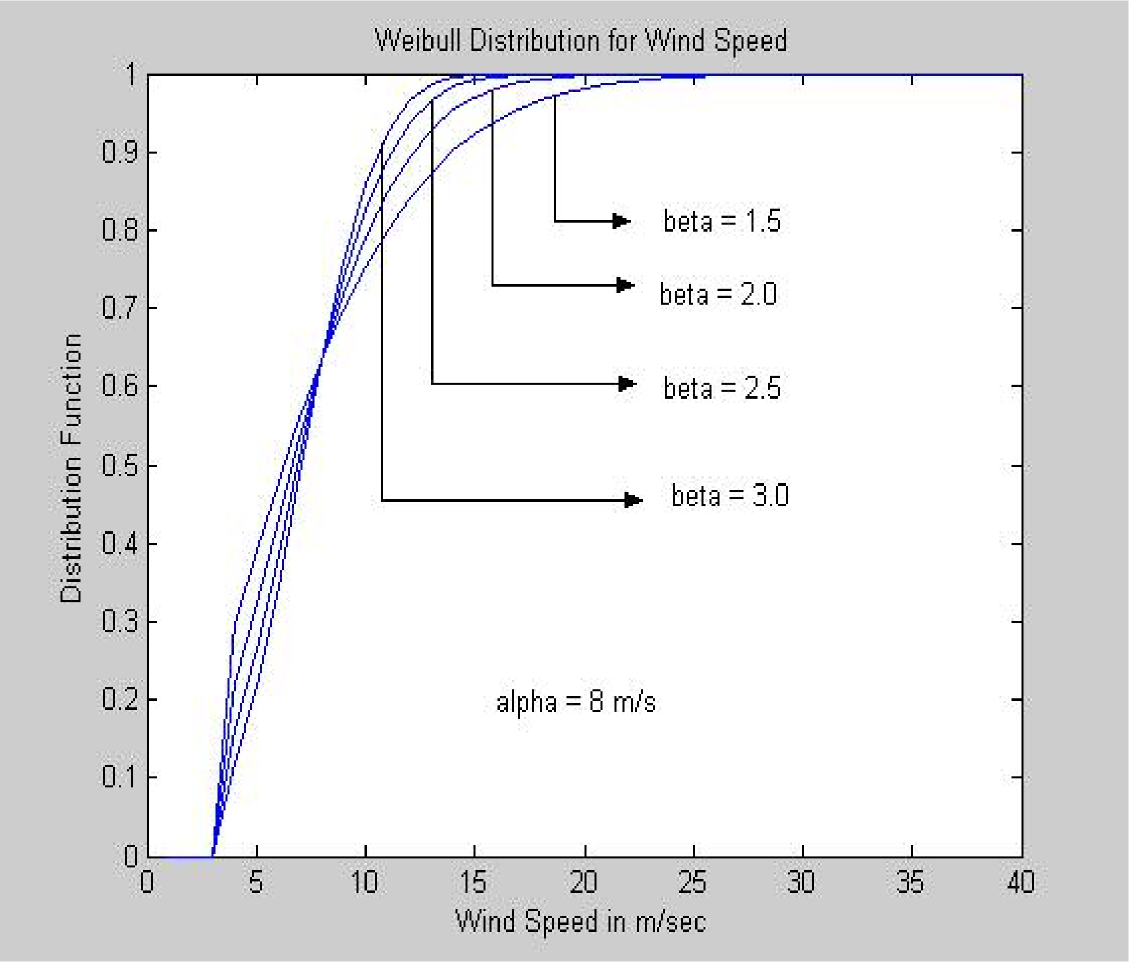

Figure 11: Effect of the shape parameter (β) on the distribution function for α=8 m/s

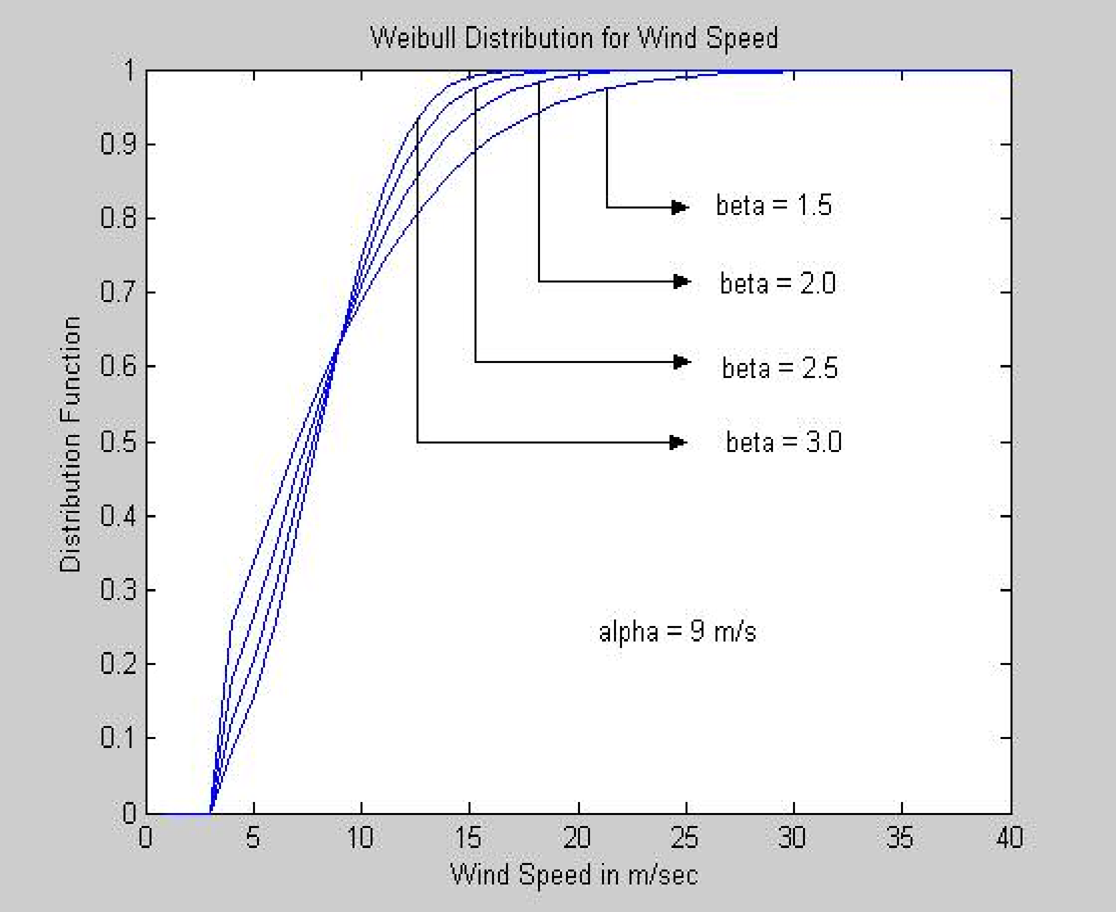

Figure 12: Effect of the shape parameter (β) on the distribution function for α=9 m/s

CHAPTER 4

Simulation Procedure

As the penetration of wind energy systems into conventional power systems increases, the following questions need to be examined:

- Impact on overall reliability
- Impact on overall security
- Impact on power quality
- Impact on stability
- Impact on economics
- Potential environmental impacts

This work studies the impact of introducing wind generation into a conventional power system on the overall security of the system by employing a simplified approach based on line loadings.

A power system is considered to be in one of four states, namely: normal, alert, emergency or restorative. It is desired that the power system remain in normal state all the time. However, this is unrealistic and as there are no distinct delineations between states, many rules of thumb are used as per convenience for demarcation. In this study, all the lines that are loaded 75% of rated or less are considered to be in normal state. This percentage is chosen arbitrarily for study purposes to illustrate the simplified approach. Any other value could be chosen based on circumstances. In real world, the percentage can vary based on the application and the system specifications. All the other lines are considered to be in alert state and the index representing the system performance is calculated accordingly.

After running load flow studies on the system, any one of the following three methods can be used to formulate a performance index based on the lines that are in alert or in emergency states for security evaluations.

1. Pick out the lines that have power flows higher than 75% of their rated capacities. Assign weighting factors depending on the importance of lines making sure that the sum of the factors is unity. Use this information in formulating the performance index.
2. Alternatively, pick out the lines that carry more than 75% of their rated capacities, calculate the ratios of real power flows to capacities square them (to give more significance to the lines that carry more than 100% of their rated capacity over the lines that carry between 75% to 100% of their capacity) and add.
3. Another way is to consider all the lines, calculate the square of the ratios of actual real power flows to their ratings, assign impact factors of 0 for the lines with flows less than 75% of their ratings and 1 for lines with flows greater than 75% of their ratings and add.

The second and third methods give the same result for the performance index. The third method is used in this thesis. Obviously, in this method, the impact factors will not add up to 1 as the factor is either a 1 or a 0.

Three kinds of performance indices have been defined for a system.

- Real power performance index
- Reactive power performance index
- Voltage-reactive power performance index

Though any one of the above three indices can be used in simplified security evaluations, the real power performance index is used here.

The expression for the real power performance index for the system using the third method mentioned above is given in Equation 6. [13]

$$PI = \sum_{k=1}^{L} W_k \left(\frac{P_k}{P_k^{\lim}}\right)^2 \qquad \textbf{(6)}$$

where,

k = line being considered

L = total number of lines in the system

W_k = impact factor for line k (zero or one)

P_k = real power flowing in line k

P_k^{lim} = maximum limit on real power for line k

Impact factor (W_k):

The impact factor for a line is taken as '0' if the line is loaded 75% or less and is taken as '1' otherwise. As mentioned earlier, this percentage is arbitrary and can be chosen based on the application. In general, the impact factor indicates the importance of the state of that part of the system for the overall security of the system.

The real power flowing in a line is obtained from simulation of the model of the RTS 79 system that is built using Power World simulation software and the maximum limit on real power of each line is obtained from the specifications table for RTS 79.

It is seen that higher the performance index, larger the number of lines that are in alert condition and hence lesser the security of the system. Therefore, the inverse of the performance index can be taken as the security index (SI) for the system. The goal will then be to achieve as high a value as possible for the SI, given as [14]:

$$SI = \frac{1}{PI} \tag{7}$$

Since the wind input is stochastic, the SI is a continuous random variable that can be described by a suitable distribution function.

Power World simulator 8.0 is used in the simulation results reported in this paper. The simulator uses the Newton-Raphson method to perform load flow analysis. It is highly user friendly and has all the basic electrical components built in it. These components can be conveniently dragged and dropped in to build a system. It has the capability for serious engineering analysis and is also so interactive and graphical that it can be used to explain power system operations to non-technical audiences. All the data of RTS 79 related to generators, busses, transformers and loads are entered when prompted in the **‘Edit Mode’**. By entering the ‘**Run Mode’,** the overall status of the system can be viewed. At this stage, all the lines that are overloaded are shown in ‘**Red’** indicating that they are in alert state. All the other lines in normal state are indicated in blue.

In the run mode, all the data related to the system such as power flow list, Y-Bus and outage information can be viewed from the case information option. From the power flow list, the real power flowing though all the lines is substituted in Equation 6 and the performance index is calculated for the system as a whole. The inverse of this performance index gives the security index (SI) for the system.

The standard reliability test system drawn using the Power World simulator is shown in Figure 13 in the ‘Edit Mode’.

A wind field farm with 50 turbines, each with a generation capacity of 1.5 MW is employed in the study. Hence, the maximum wind generation available is 75 MW.

The conventional generator at bus number 7 rated at 30 MW is replaced by the wind farm in the simulation model and security index is evaluated for regular intervals of wind speed values. Since the wind input is random (stochastic), the cumulative output of the wind farm is also random and the corresponding security index will be a random variable. Thus the security index can also be represented by a suitable distribution function.

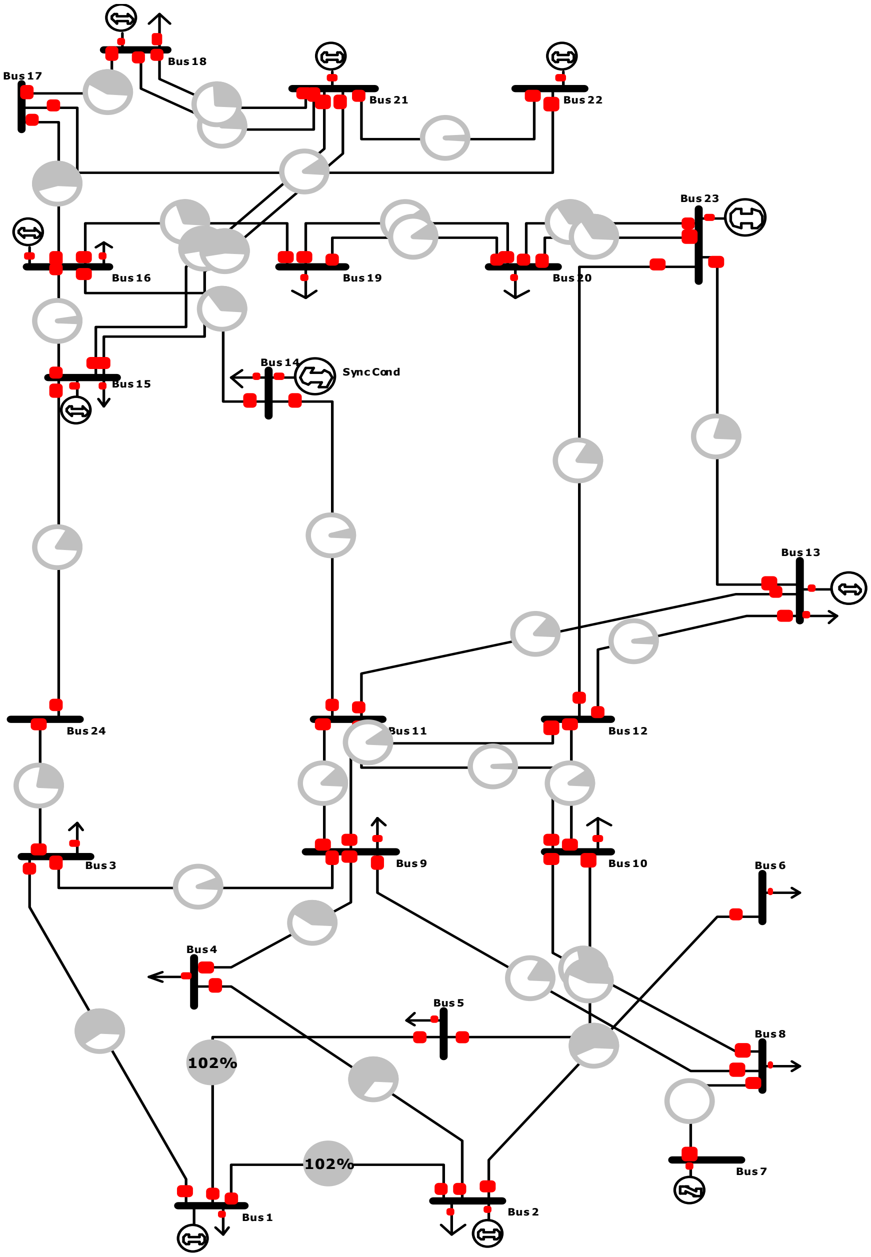

Figure 13: Simulated version of RTS 79 (in Edit mode)

Assuming everything else is unchanging except the wind input, the steps for obtaining the distribution function for the security index are as follows [14]:

- For each value of α and β, the Weibull distribution function is plotted using Equation 4.
- After obtaining the distribution function, the probability of the wind speed being between two values a and b is found using Equation 5. Wind speed values are divided into equal intervals of 1 m/s from Zero to the cut-out speed. Probabilities for each of the intervals are calculated
- The power output of the wind farm for each interval is found corresponding to the mid-point of each interval from the power curve shown in Figure 3. This generation value is entered in the generator dialogue box for bus number 7 in the simulation diagram shown in Figure 11 and power flow list is obtained.
- Real power flows in the lines are substituted in Equation 6 and the performance index of the system is evaluated. The inverse of the performance index is the security index corresponding to the midpoint wind speed. Probability of this SI value is taken as the probability of the corresponding wind speed interval.
- The cumulative distribution function of security index is plotted using these values with security index on x-axis and cumulative probability on y-axis.

As discussed earlier, the security index is a good indicator of the security of the system with wind generation. Higher the value of the security index, better the system security. Hence, a high value of security index is desirable.

CHAPTER 5

Results and Discussion

Following the procedure discussed in the previous section, probability distribution function for the security index is obtained and plotted for various combinations of α, β and penetration levels. Two of these three parameters are assumed to be constant at a time and the effect of the third parameter is evaluated and plotted as families of curves. Corresponding to a particular value of the security index, the probability that the index is less than or equal to that value can be read off the distribution function. Since it is desirable to have as high a value as possible for the security index, it is desirable to have as low a value as possible for the probability read off the distribution function. Therefore, the combination that yields the lowest value of the cumulative probability is the most desirable from the security viewpoint.

The total generation and load data for the simulated system are given below:

5.1 Generation:

Total real power generation: 3591 MW (with a maximum wind generation of 75 MW included)

Total reactive power generation: 535 MVAR

Therefore, with 60 MW of wind generation, the penetration percentage is (75x100)/3516 or 2.13.

5.2 Load:

Total real load: 2206 MW

Total reactive load: 468.5 MVAR

The system power factor is assumed to be 0.98.

Wind generated electricity is assumed to be injected at unity power factor.

5.3 Comments on the results presented in graphical form:

Since higher values of SI indicate better system security (based on the definition used), we will look for the probability of the SI being above a pre-selected value to be as high as possible.

In other words, the probability of SI being less than or equal to the pre-selected value should be as low as possible.

Thus, for a pre-selected value of security index (along the x-axis), the curve that gives the lowest value of cumulative probability corresponds to the most secure system as per the definition.

The influence of the following factors on the security index is considered in this work.

- Effect of scale parameter (α)
- Effect of shape parameter (β)
- Effect of penetration level of wind electric generation at a selected location.
- Effect of location of wind electric generation within the system.

5.4 Effect of α on security index:

The effect of scale parameter α on the SI is shown in Figures 14-17 for different values of β and wind generation level of 75 MW.

Based on the earlier discussion, wind regime with highest value of α yields the most secure system. Moreover, the security of the system increases with increasing α values. This is anticipated, as security of the system increases with increasing mean wind speed and the scale parameter α is directly proportional to mean wind speed for a given value of shape parameter β.

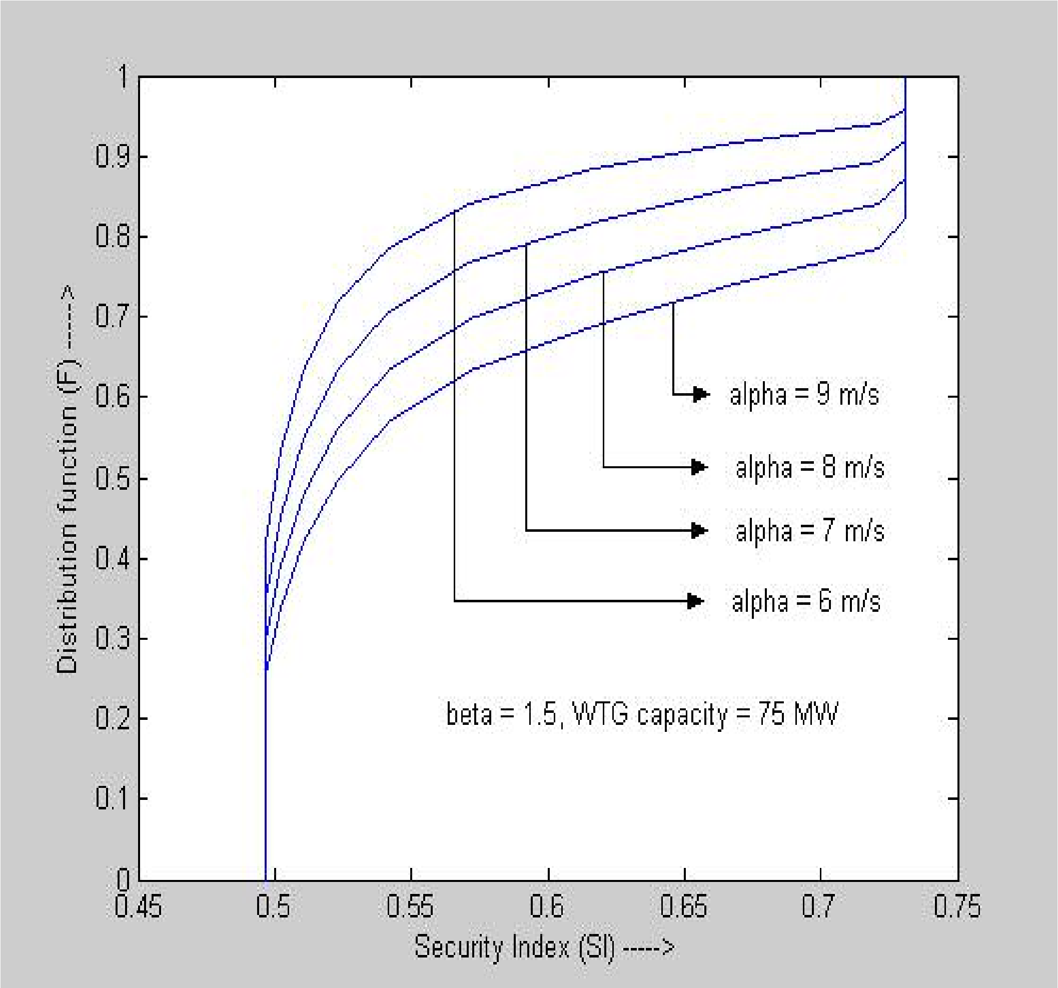

Figure 14: Effect of α on security index for β=1.5, WTG capacity = 75 MW

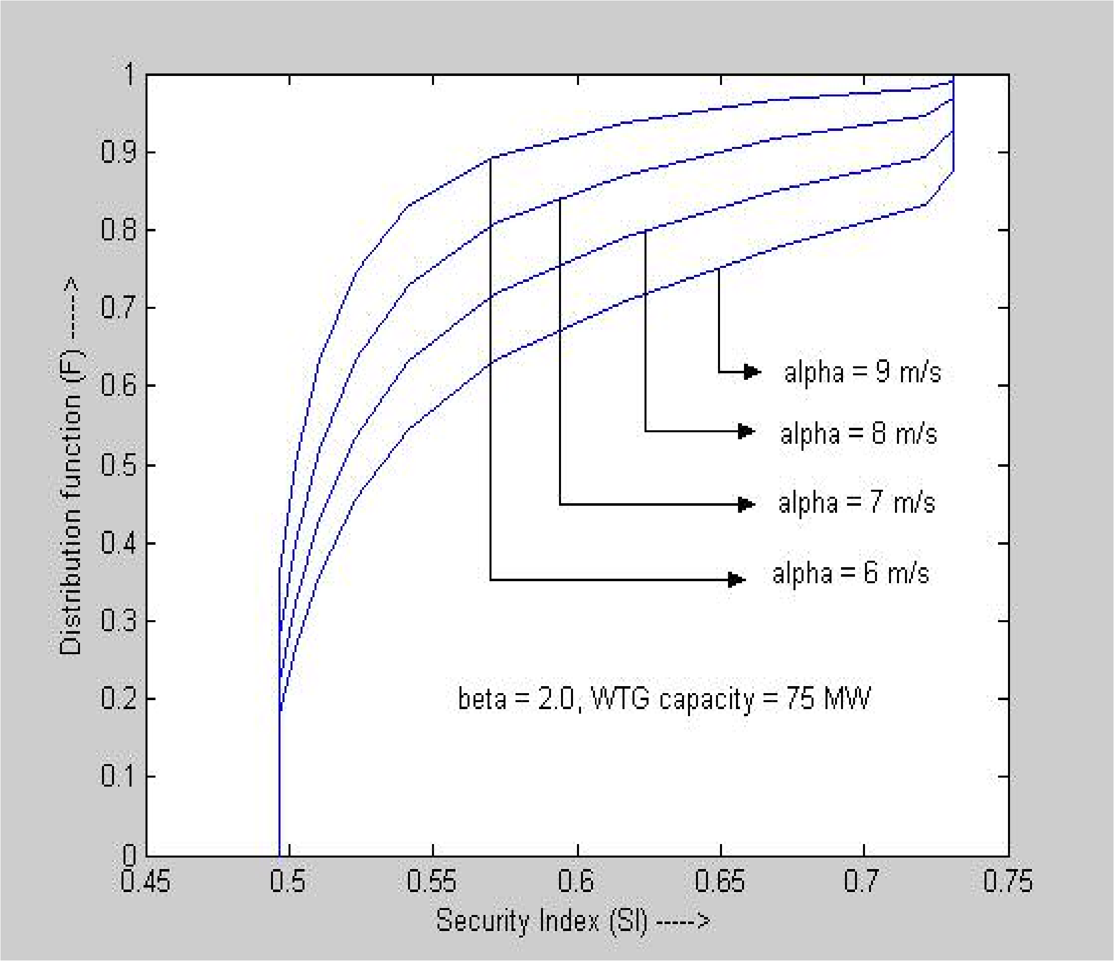

Figure 15: Effect of α on security index for β = 2.0, WTG capacity = 75 MW

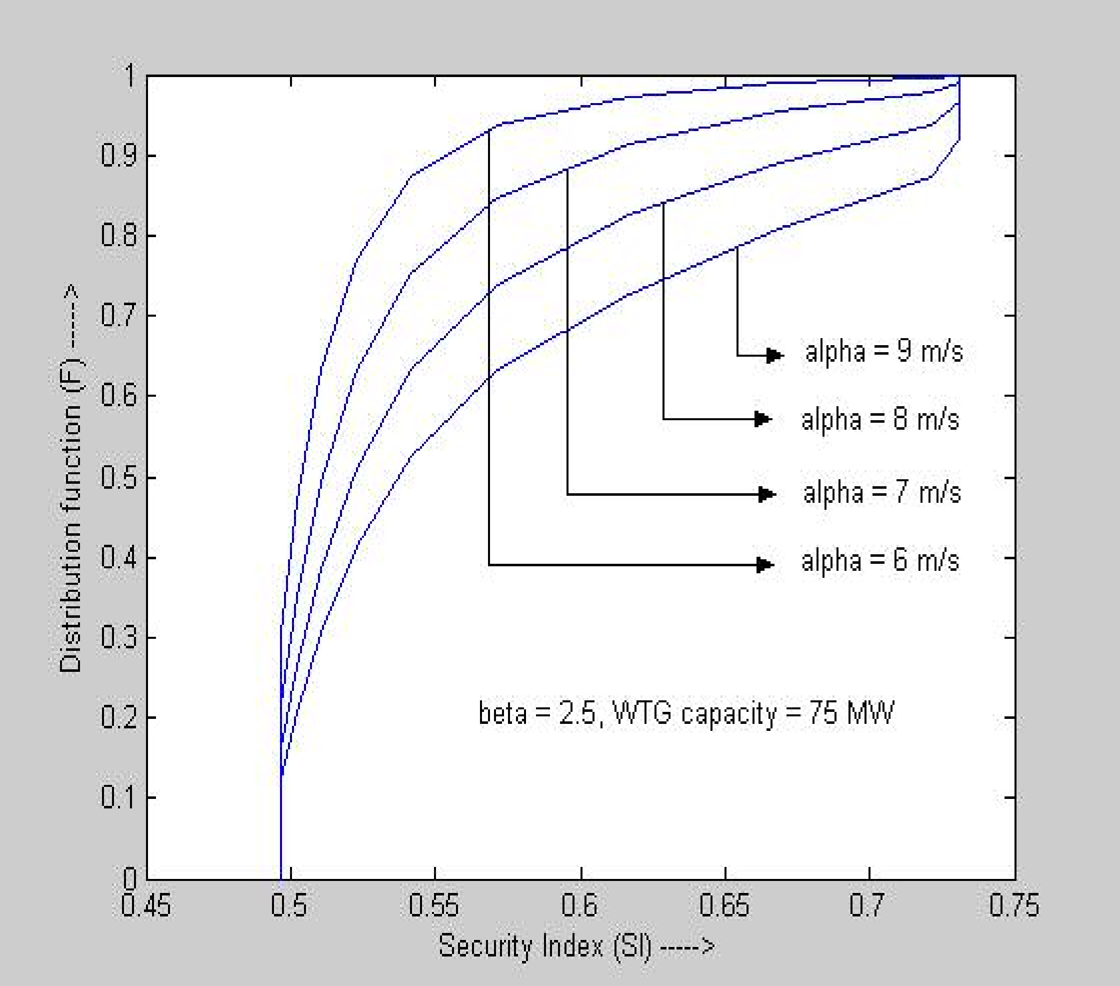

Figure 16: Effect of α on security index for β = 2.5, WTG capacity = 75 MW

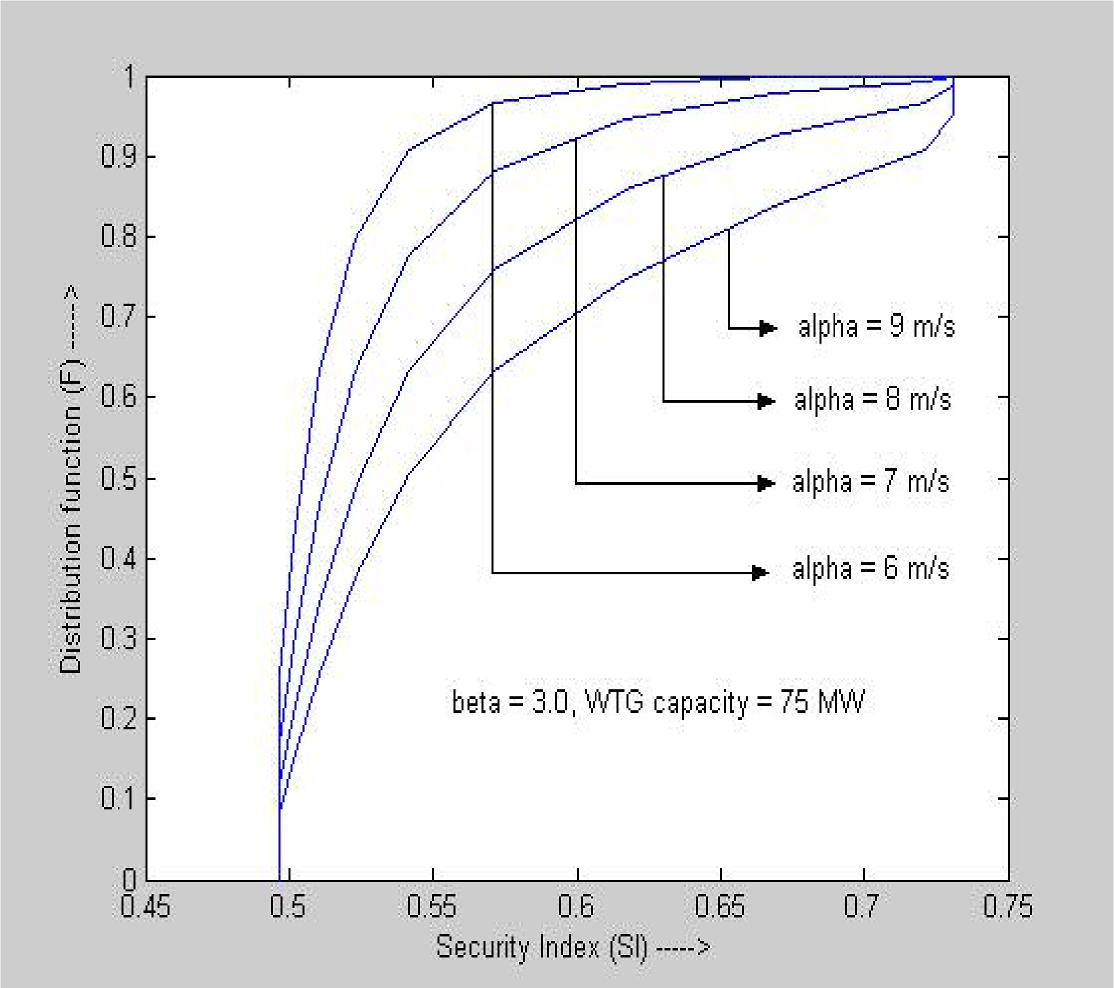

Figure 17: Effect of α on security index for β = 3.0, WTG capacity = 75 MW

5.5 Effect of β on security index:

The effect of shape parameter β on the security index is shown in Figures 18-21 for different values of α and injected wind generated electrical power of 45 MW.

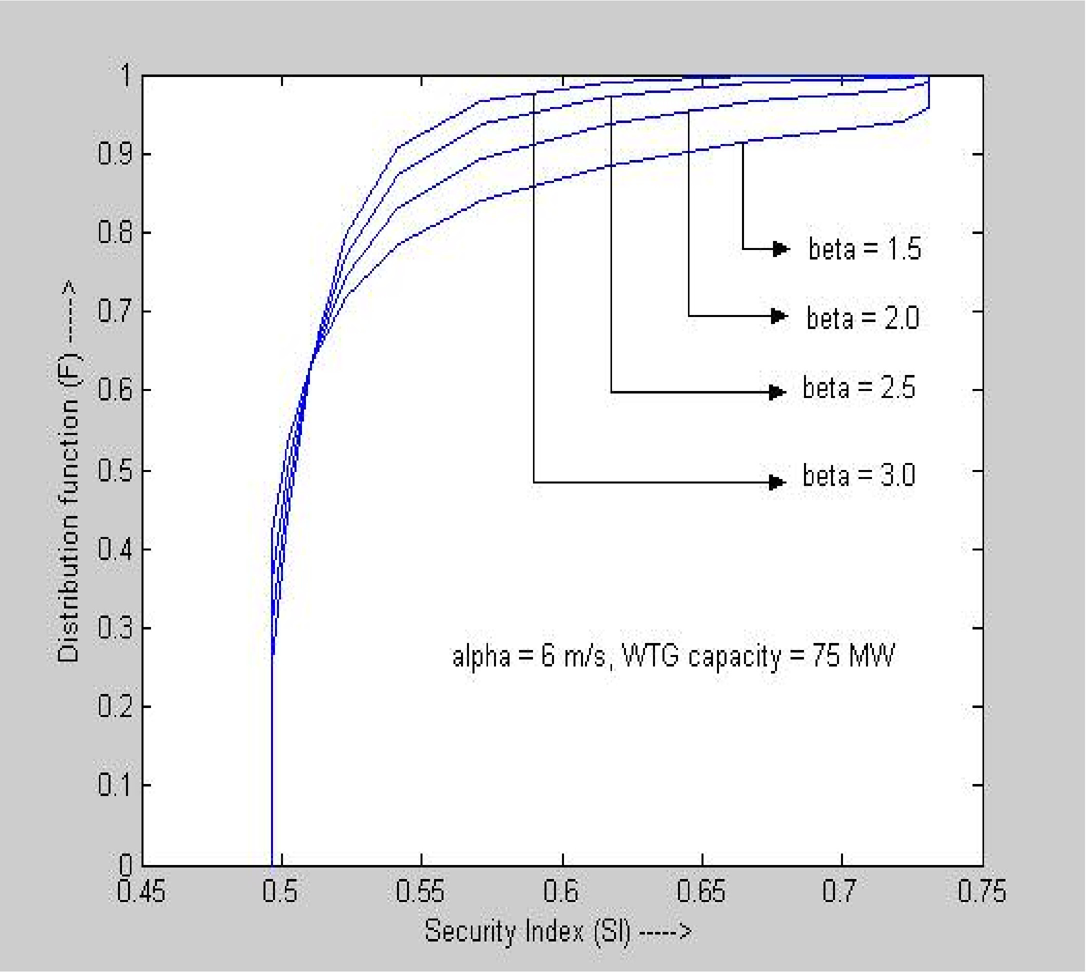

Figure 18: Effect of β on security index for α = 6 m/s and WTG capacity = 75 MW

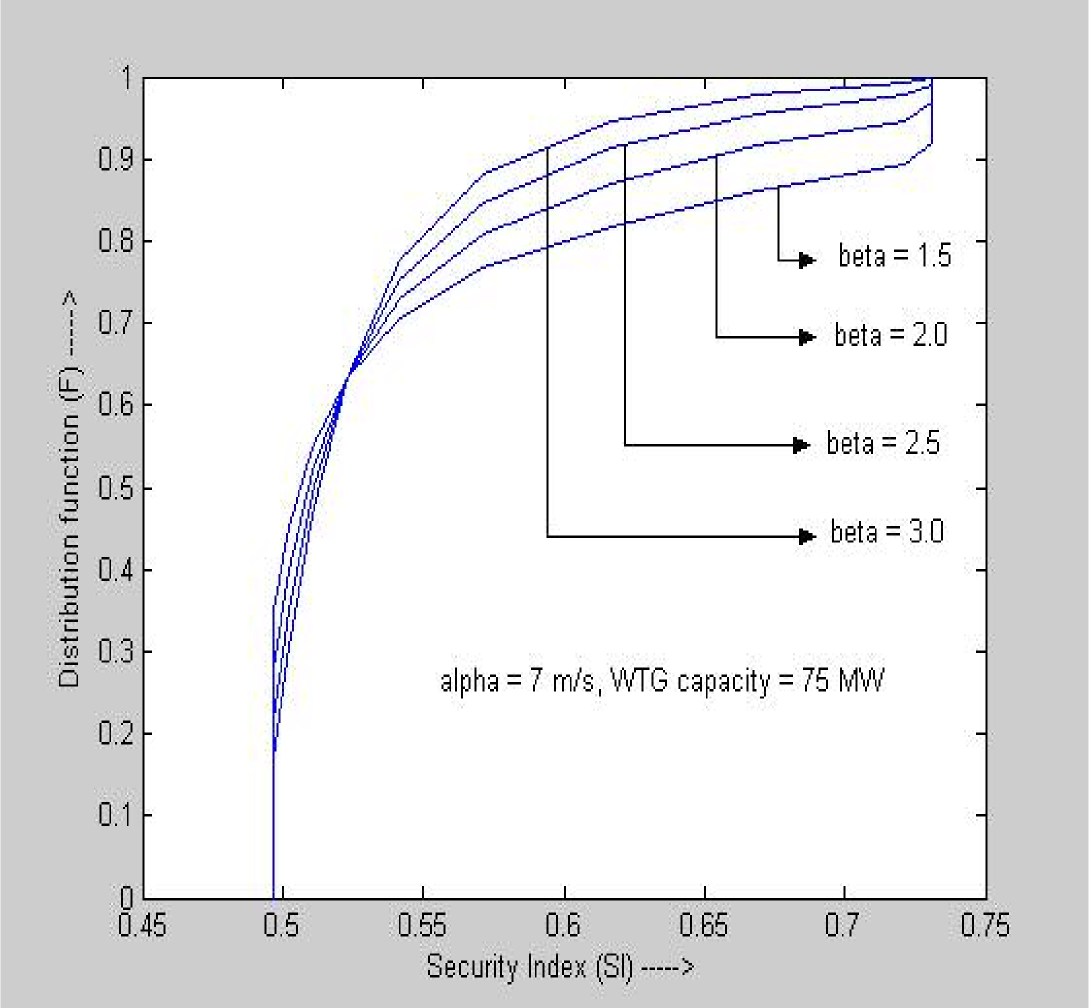

Figure 19: Effect of β on security index for α = 7 m/s and WTG capacity = 75 MW

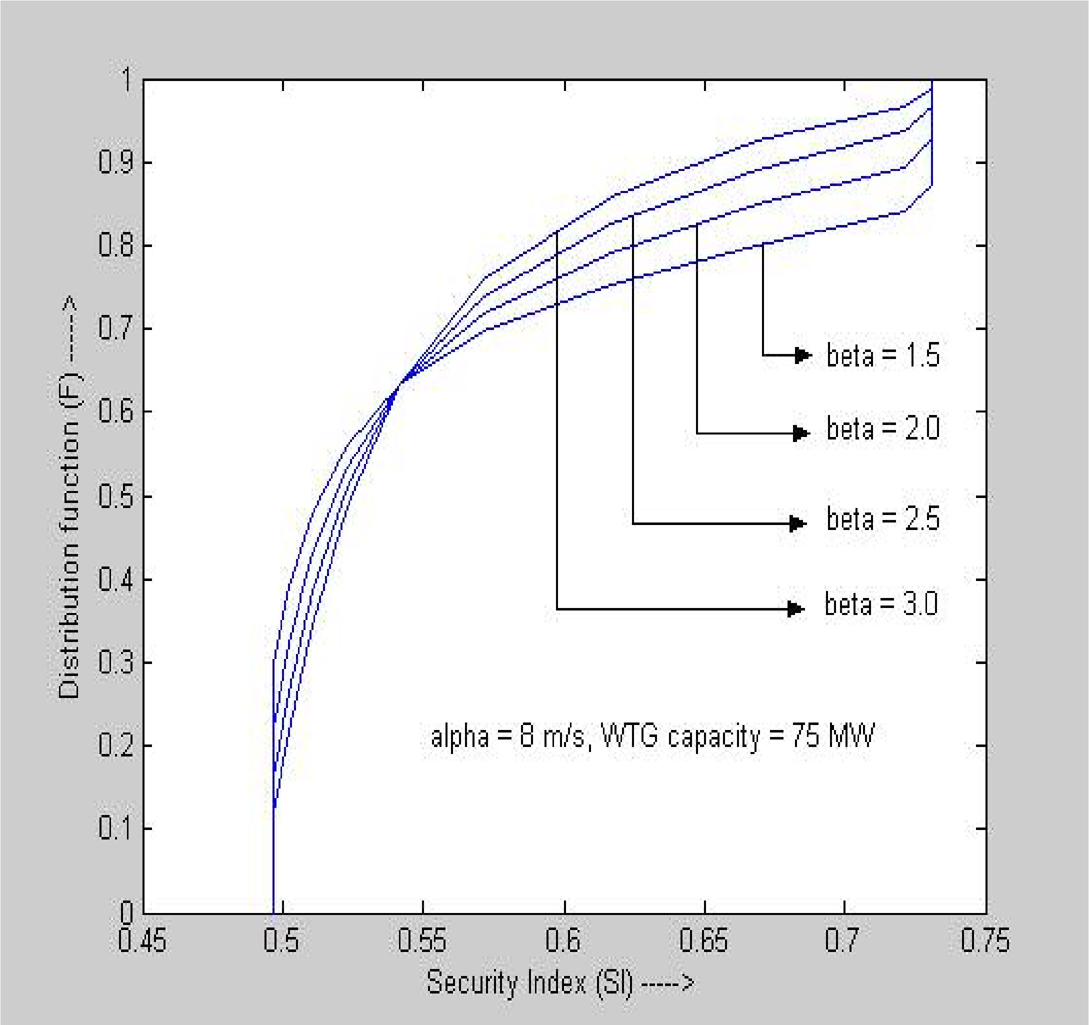

Figure 20: Effect of β on security index for α = 8 m/s and WTG capacity = 75 MW

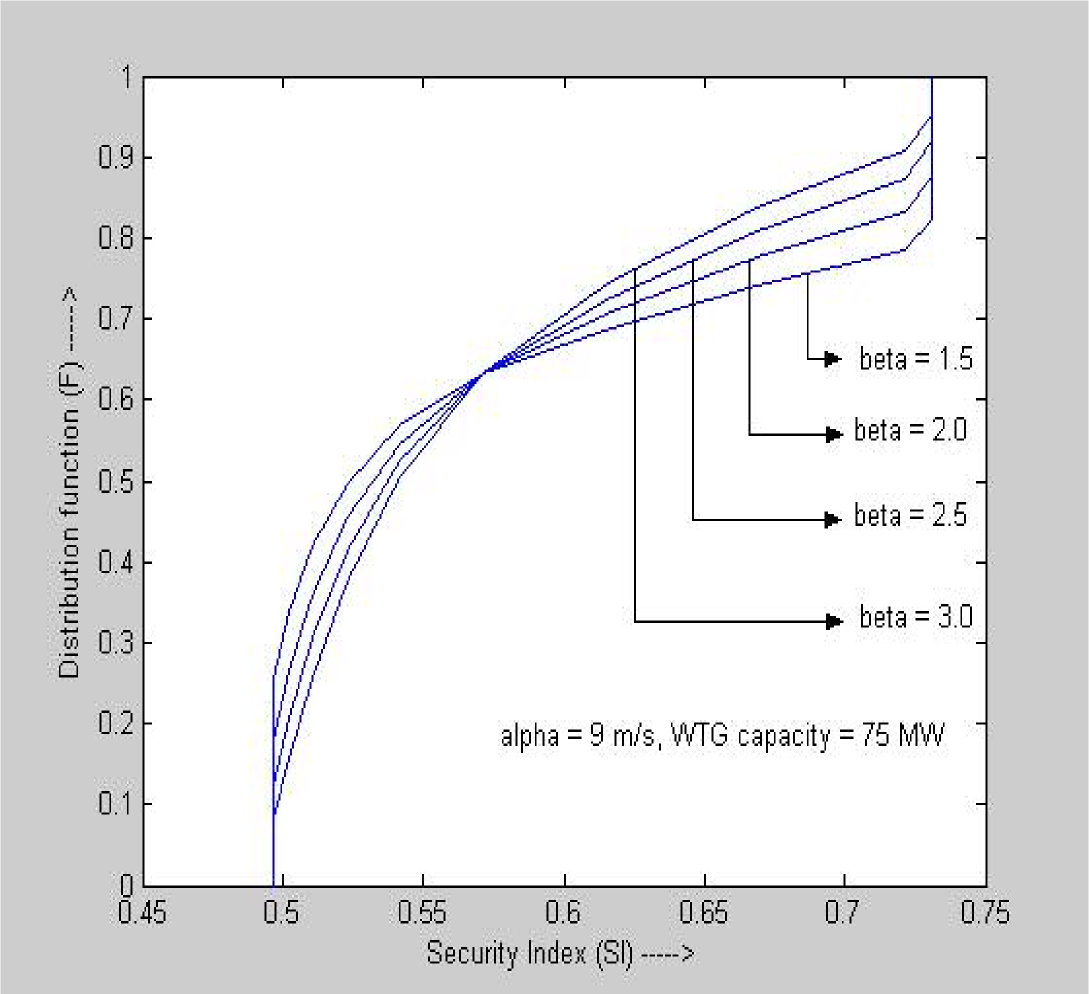

Figure 21: Effect of β on security index for α = 9 m/s and WTG capacity = 75 MW

In this case, the wind regime with the smallest value of β represents a more secure system. Security of the system increases with decreasing β. The increase is more and more pronounced as the β value decreases because, as can be seen, the difference between the curves for β = 1.5 and β = 2.0 is greater than the difference between the curves for β = 2.5 and β = 2.0. This is a direct consequence of the fact that smaller values of β tend to increase the probability of higher wind speeds (see Figures 9 - 12) for a given mean wind speed.

5.6 Effect of penetration level on security index:

The effect of penetration levels on the security index is shown in Figure 22 for α = 9 m/s and β = 2.0.

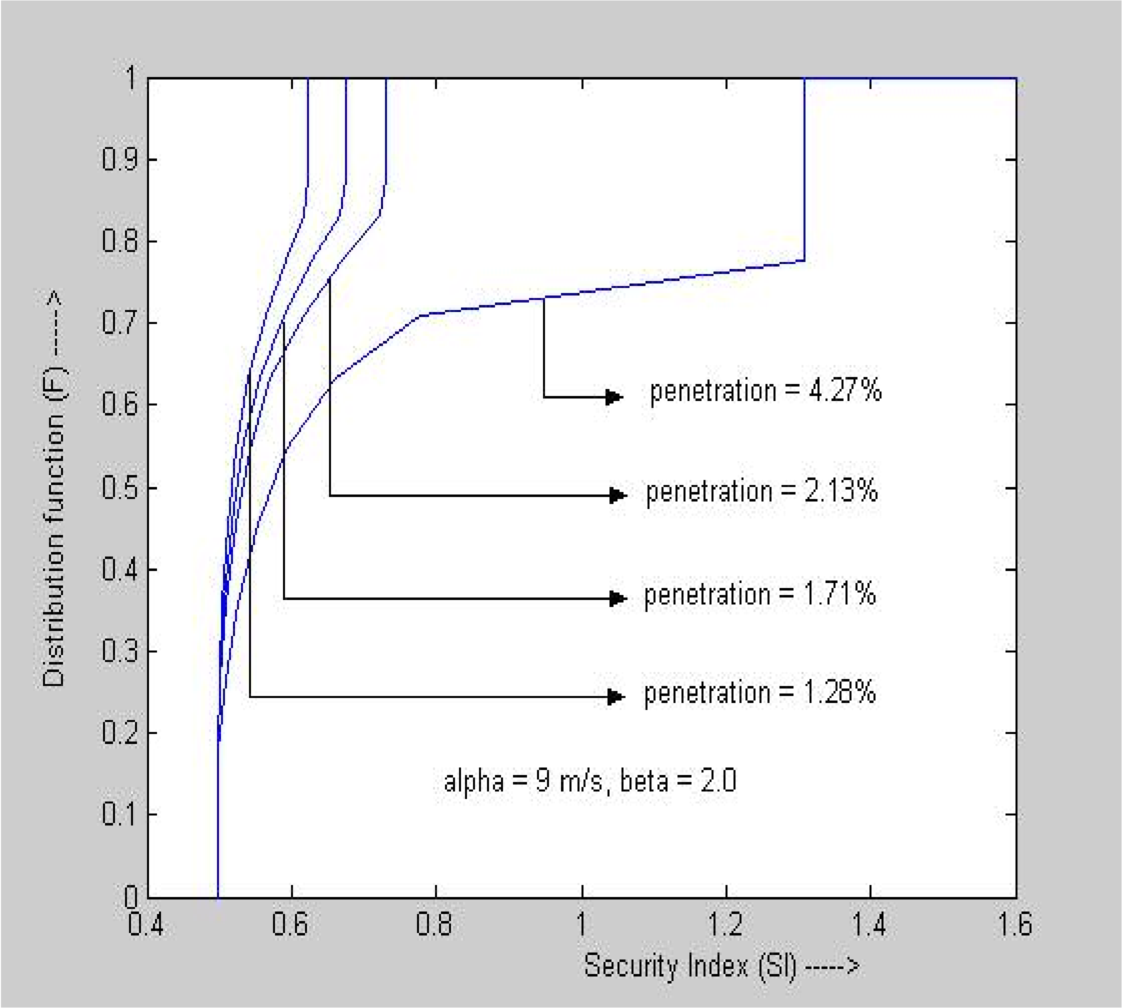

Figure 22: Effect of penetration level on security index

To study the effect of wind power penetration on the security index, total wind turbine electrical output is decreased from 60 MW (1.7% penetration) to 45 MW (1.3% penetration) and then to 30 MW (0.84% penetration) and simulations were performed for each case. It is seen that as penetration level increases, the security of the system increases. This is anticipated, as the generation at bus number 7 increases with increasing penetration levels. While this is true for the case studied, it may not always be valid. Depending on the location of the wind farm in the system, ratings of the lines around the wind farm and the location of the loads, increased wind power output may overload some of the lines, leading to a reduction of the security index at high penetration levels.

5.7 Effect of location on security index:

In order to study the influence of location on the security index, a wind farm with a total capacity of 150 MW was assumed at Bus no.7 first and then at Bus no.16. The wind farm is assumed to replace the conventional generation at these buses. They are 60 MW at Bus no.7 and 155 MW at Bus no.16. These two locations were chosen because they had the smallest and the second smallest conventional generators. In both cases, an α value of 8 m/s and a β value of 2 were chosen for the purpose of this study. An examination of Figure 23 shows that for most of the range of security index values, location 1 at Bus no.7 is a better choice than location 2 at Bus no.16. There are many other loose ends that need to be tied before making any clear statements in this regard. However, it is obvious that the simple approach presented in this thesis can be used to decide between different suitable locations for establishing wind farms.

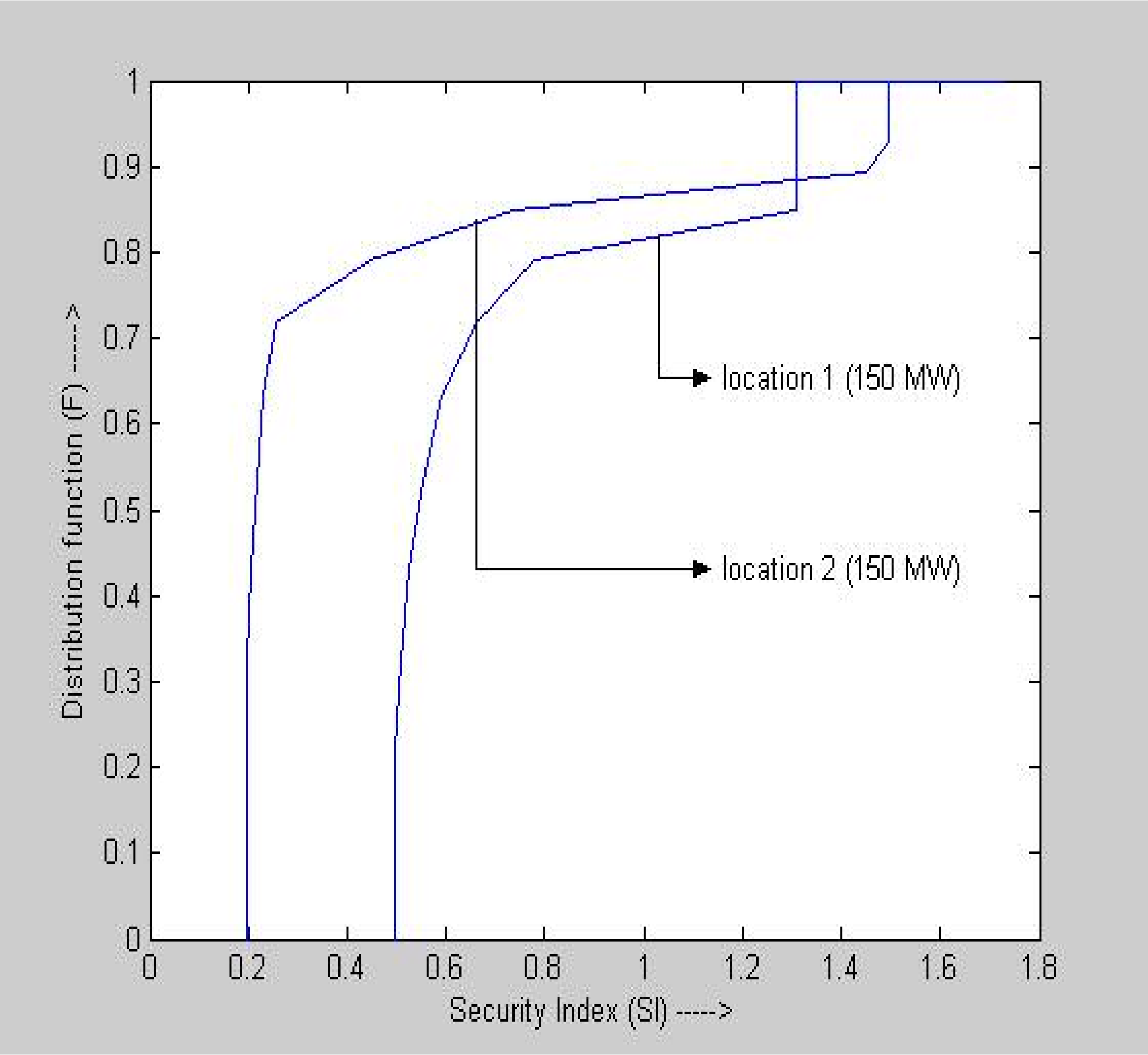

Figure 23: Effect of location on security index for α = 8 m/s and β = 2

CHAPTER 6

Summary and Conclusions

6.1 Summary

A simplified approach for evaluating the security of a power system with wind generation is presented. Globally, wind has become the fastest growing renewable energy resource for electric power generation. Competitive generation costs and advancing turbine technology coupled with the use of variable speed option and power electronics are some of the reasons for this impressive growth. Turbines are getting larger and more efficient at a rapid rate. Megawatt-scale units (1.5 to 2 MW) are becoming the standard and several larger (up to 5 MW) units are in various stages of development. Due to the inherent variability of the resource, the question of how the overall security of a power system will be affected by the insertion of wind generation needs to be studied. Obviously, the nature and extent of the influence will depend on several factors such as wind regime, turbine design, level of penetration, time dependence of load, etc. An approach based on "security index" is considered in this work. The standard (24 bus) reliability test system is used in the study. Results are presented in the form of probability distribution functions (pdf) for the security index obtained using the PDF of wind speed distributions and output characteristics of wind generation systems. Influences of scale and shape parameters of the wind speed distribution are considered in detail. The simulations are done using Power World Simulator 8.0 and the variations in probability distribution function and the system security are obtained graphically. Based on the simulation results, some conclusions are drawn about the influence of wind electric generators and wind regimes on the security of a power system.

6.2 Conclusions

Based on the security index used in this study, it is seen that a high value of SI (or a low value of PI) indicates a highly secure system.

For a highly secure system, the following parameters are desired:

- A high value of scale parameter
- A low value of shape parameter
- A high value of penetration level of wind generation

The security index used is only one of the many possible choices. Irrespective of the choice, the index is a continuous random variable and can be represented by its distribution function. Once the choice is made, the procedure discussed in this work can be employed to study the influence of various parameters on the security of power systems with wind electric generation. In particular, the penetration level at which security starts to deteriorate (based on the selected index) can be estimated by repeated simulations of the system. Also, this approach can assist in deciding between different suitable locations for establishing wind farms.

6.3 Scope for future work

While all the conclusions are intuitively obvious, the effect of the location of the wind farm within the system has not been studied in sufficient detail. Also, correlation between the time dependence of load and wind availability is another major topic that requires further study.

For a detailed investigation, several different security indices must be employed and the results should be analyzed. Instead of replacing conventional generation by wind as done in this study, wind generation can be added to the existing system and the analysis can be performed to assess its impacts.

Wind farms can be located only at sites with good wind regimes which depend on many factors involving geography and terrain. The simple approach presented in this work can be used to identify upper bounds for penetration levels at a given site based on the security index. In addition, if more than one good wind site is available, this procedure can be used to make a suitable choice.

BIBLIOGRAPHY

[1] Johansson, T.B. et al. “Renewable energy – sources for fuels and electricity”. *Island press*, 1993.

[2] Schreck, S. 2003. Trends in wind energy technology. *Proceedings of the Energy information dissemination program, Report # 34.* Oklahoma State University, Stillwater, OK.

[3] McCalley, J.D. Vittal, V. Abi-Samra, N. “An overview of risk based security assessment” in *IEEE Power Engineering Society Summer Meeting, 1999.* Vol.1, 18-22 July 1999 pp.173 – 178.

[4] Iyer, H.S. “Priority based approach for operation of rural energy centers”, Masters thesis in *Oklahoma State University,* 2004.

[5] www.renewableenergyaccess.com

[6] Manwell, J.F. McGowan, J.G. Rogers A.L “Wind Energy Explained: Theory, Design and Application” John Wiley & sons Ltd. 2003.

[7] GE Wind Energy Handout on 1.5sl/1.5s wind turbine specifications, 2003.

[8] The IEEE Reliability Test System - 1996

“A report prepared by the Reliability Test System Task Force of the application of Probability Methods Subcommittee” in *IEEE Transactions on Power Systems*, Vol. 14, NO. 3, August 1999

[9] Glover, J.D. Sarma, M.S. “Power System analysis and design”, Brooks/Cole, 2002.

[10] Ramakumar, R. “Engineering Reliability: Fundamentals and Applications”, Prentice Hall Publishers, 1993.

[11] Deshmukh, R.G. “A Probabilistic study of wind-electric conversion systems from the point of view of reliability and capacity credit”, Doctoral thesis in *Oklahoma State University,* 1979.

[12] Deshmukh, R.G. Ramakumar, R. “Reliability Analysis of combined wind-electric and conventional generation systems” in *Solar Energy*, Vol. 28, No.4, pp. 345-352, 1982

[13] Ejebe,G.C. Wollenberg, B.F. “Automatic Contingency Selection” in *IEEE transactions on Power Apparatus and Systems*, Vol. PAS-98, No.1 Jan/Feb 1979.

[14] Yekkirala, S. Ramakumar, R. 2005. “A simplified approach to assess the security of power systems containing wind electric generation”, in *The 38th annual frontiers of power conference.*

[15] Farghal, S.A. Abdel Aziz, M.R. “Generation expansion planning including the renewable energy sources” in *IEEE Transactions on Power Systems* vol.3, Issue 3, Aug. 1988 pp.816 – 822

[16] Brey, J.J. Castro, A.;Moreno, E. Garcia, C. “Integration of renewable energy sources as an optimised solution for distributed generation” in *IECON 02 [IEEE 2002 28th Annual Conference of the Industrial Electronics Society* Volume 4, 5-8 Nov. 2002 pp.3355 - 3359

[17] Peng Wang. Billinton, R. “Reliability benefit analysis of adding WTG to a distribution system” in *IEEE Transactions on Energy Conversion*. Vol.16, Issue 2, June 2001 pp.134 – 139.

[18] Papazoglou, T.M. Gigandidou, A. “Impact and benefits of distributed wind generation on quality and security in the case of the Cretan EPS” in *Quality and Security of Electric Power Delivery Systems, 2003. CIGRE/PES 2003. CIGRE/IEEE PES International Symposium.* 8-10 Oct. 2003 pp.193 – 197.

[19] Billinton, R. Guang Bai "Adequacy evaluation of generation systems including wind energy" in *Canadian Conference on Electrical and Computer Engineering, 2002. IEEE CCECE 2002*. vol.1, 12-15 May 2002 pp.24 - 29

[20] Dai, Y. McCalley, J.D. Abi-Samra, N. Vittal, V. "Annual risk assessment for overload security" in *IEEE Transactions on Power Systems,* Vol.16, Issue 4, Nov. 2001 pp.616 – 623

[21] Fischl, R. Chow, J.C. "On the probabilistic evaluation of indices for power system security assessment" in *IEEE International Conference on Man and Cybernetics Systems, 1992.,* vol.1 18-21 Oct. 1992 pp.768 – 773.

[22] Billinton, R. Allan, R.N. "Reliability Evaluation of Power Systems", Pitman Advanced Publishing Program, 1984.

[23] Ramakumar, R. "Electricity from Renewable Energy: A timely option", Keynote Address in *National Seminar on Renewable Energy Sources – Electric Power Generation*, Pune, Maharashtra, India. August 31 – September 1, 2001.

APPENDIX

1. Matlab Code for the Weibull distribution graph

```
function []=   eibull()
alpha=[];
beta=[];
i=1;
while i==1
   i=input(‘Enter a value other than 1 to discontinue  :     ‘);
   if i==1
   x=input(‘Enter the value of alpha              :’);
   y=input(‘Enter the value of beta               :’);
   alpha=[alpha x];
   beta=[beta y];
   end
end
s=size(alpha);
display(‘ *****************************Weibull Distribution
Values***********************’);
for i=1:s(2)
for n=1:40
   if n < 4
      F(n)=0;
      v(n)=n;
   else
```

```
          a=power((n/alpha(i)),beta(i));
        F(n)= 1-exp(-a);
        v(n)=n;
    end
end
disp(‘alpha       beta’);
disp([alpha(i) beta(i)]);
disp(‘-----------------------------------------------------------------------------------‘);
disp(‘Windspeed   Distribution Function value’);
disp(‘-----------------------------------------------------------------------------------‘);
disp([v’ F’]);
disp(‘-----------------------------------------------------------------------------------‘);
plot(v,F,’b’)
hold on
end
xlabel(‘Wind Speed in m/sec’)
ylabel(‘Distribution Function’)
title(‘Weibull Distribution for Wind Speed’);

end
```

2. Matlab code for Performance Index calculation

```
function []=performanceindex()
i=1;
while i==1
   i=input('Enter a value other than 1 to discontinue  :     ');
   if i==1
      alpha=input('Enter the value of alpha              :');
      beta=input('Enter the value of beta               :');
      for n=1:40
         if n < 4
            F(n)=0;
            v(n)=n;
         else
            a=power((n/alpha(i)),beta(i));
            F(n)= 1-exp(-a);
             v(n)=n;
         end
      end
      n=1;
      p=1;
      for m=1:1:24
         y(n)=F(m+1)-F(m);
         if n>1
         y(n)=y(n)+y(n-1);
         end
         % y(n)=y(n);
         n=n+1;
      end
```

```
    x=input('Enter the inverse Performance index values in array format  :');
    x
    y
    plot(x,y)
    hold on
    xlabel('Security Index (SI) ----->');
    ylabel('Distribution function (F) ----->');
    %title( ['alpha= ',alpha,'beta=',beta]);

  end
end
end
```

VITA

Sarada Yekkirala

Candidate for the Degree of

Master of Science

Thesis: INFLUENCE OF WIND REGIME ON THE SECURITY OF POWER SYSTEMS WITH WIND ELECTRIC GENERATION.

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Experience: Research Assistant at Oklahoma State University from August 2003 to December 2005.

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Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of study: INFLUENCE OF WIND REGIME ON THE SECURITY OF POWER SYSTEMS WITH WIND ELECTRIC GENERATION

Pages in study: 58 Candidate for the Degree of Master of Science

Major Field: Electrical and Computer Engineering

Abstract: Technological advances, coupled with variable speed operation, have made wind electric conversion the fastest growing electric power generation utilizing renewable energy resources. Variability of wind input and the associated variability in the electrical outputs of wind electric conversion systems feeding power to a conventional distribution system will affect the overall reliability and security of power supply. The influence of wind regime on the security of a distribution system quantified using a simple security index is investigated. Different wind regimes are considered by varying the scale and shape parameters defining the Weibull distribution. The security index itself becomes a random variable and it is presented in terms of a distribution function. Based on simulation results, certain conclusions are drawn as to the suitability of different wind regimes for wind electric conversion in terms of their influence on system security. Varying penetration levels are considered in the study using a standard 24 bus reliability test system. This simple approach can be used to select between two suitable wind farm sites based on system security as defined.

Advisor: Dr. R. G. Ramakumar