A PROBABILISTIC STUDY OF GRID-CONNECTED WIND ELECTRIC CONVERSION SYSTEMS

By

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CHAPTER I

INTRODUCTION

1.1 Background

Electrical Energy is regarded as one of the prime forms of energy due to its versatility of application. It can be converted to any other desirable form of energy with ease. Indices such as generation capacity, electrical energy consumption, energy reserves, etc. are used in determining the strength of national economy and prosperity. At the same time, they also lead to significant greenhouse gas emissions and water and soil contamination. Government, non-government and environmental organizations have taken due note of this and have instituted regulatory policies, public awareness efforts and research projects to mitigate the impacts. Another major consequence is the rapid exhaustion of non-renewable resources such as coal, oil, natural gas, etc. which took millions of years to form through the process of fossilization. . All these factors indicate the necessity of the development of techno-economical and environmentally friendly technologies of electric power generation. However, it is certain that the electrical load demands, current as well as future, will need an array of such technologies, to satisfy. Research and development is concentrated towards developing them so as to maintain highly reliable electric supply as per national standards with minimum environmental impacts. This implies optimum usage of non-renewable as well as renewable resources for generation, since renewable resources alone will not suffice in the foreseeable future.

Forerunners amongst renewable resources are wind energy, insolation, tidal energy, and geothermal energy in addition to the well-known hydropower. However, all of these are direct or indirect derivatives of solar energy. On the regulatory front, many countries collectively and individually have established measures regarding policies and investment. Prime examples of this are the newly popular terms "carbon footprint" and "carbon trade". As mentioned in [1], "a "carbon footprint" is the total amount of CO_2 and other greenhouse gases, emitted over the full life cycle of a process or product" and "carbon trade" is an incentive mechanism provided to control emission of carbon products. A widely used method in determining the carbon footprint is life cycle assessment (LCA). None of the methods of electricity generation are totally carbon free because CO_2 is emitted either during operation or manufacturing of equipments or both. Environmental Protection Agency (EPA) is an active regulatory body which has been instrumental in the United States for assigning the limits on gas emissions of various utility as well non-utility processes and thus regulating greenhouse gas levels [2].

1.2 Role of Non Renewable Energy Resources

Fossil fuels such as coal, natural gas and oil used for generation of electricity are termed as non-renewable energy resources. These resources are formed due to the action of heat, pressure, moisture and other environmental parameters on biodegradable matter, over a very long period of time. Concerns over the depletion of the reserves of fossil fuels have been expressed by experts for several decades. These resources can also be considered as capacity reserves, since electrical energy can be generated using these as per requirement. Base load demands are almost (except nuclear power plants) supplied by consuming these resources. As per [3], CO_2 emission for the year 2008 from the electric power sector in the U.S. was 2,359.1 million metric tonnes, for the generation of 4,119,388,000 MWh. The generation included approximately 9% renewable energy penetration, mostly hydroelectric. The carbon footprint for generation from renewable resources is far less as compared to the generation from non-renewable resources. Thus, the two primary concerns with the usage of the non-renewable resources are fast depletion which leads to high cost and harmful impacts on the environment are countered.

1.3 Stimulants for Utilization of Renewable Energy Resources

Stimulating factors for the usage of renewable energy resources have been technological progress and constructive policies and programs implemented at community as well national levels. One of the prominent global initiatives was the ‘Kyoto Protocol’ announced on 11th December 1997 which sets limits on the greenhouse gas emissions for the participating 32 industrialized nations. The guiding principle for this protocol was ‘common but differentiated responsibilities’ which led to mechanisms, such as, emission trading, clean development mechanism, and joint implementation as per [4]. Many developed nations such as United States, Germany, United Kingdom, etc. and developing countries such as India, Brazil, etc. have their own renewable energy policy standards. These policies encourage renewable energy assimilation at micro as well as macro levels into the electric network. United States’ vision of 20% electricity from renewable sources by 2020 will lead to significant reductions in greenhouse gas emissions, and on a global stage will pave the way for other nations to adopt similar policies. On the technological front, the major issue in the assimilation of electrical energy from renewable resources in the electric grids is the inherent variability of the inputs, requiring power conditioning. For example, solar cells convert the sunlight projected onto its surface into a variable dc supply, which cannot be directly injected into the grid. Highly efficient power electronic inverters have been developed for conversion from variable dc to ac of suitable quality and provide the electrical interface needed between the grid and cells. Advanced concepts in electrical interfacing of renewable energy sources using power electronic systems have been discussed in the literature [5-6]. In brief, environmental concerns coupled with technological advances have propelled renewable energy technologies into the forefront and promise to play a major role in modern electric energy system.

1.4 Wind Energy and Its Status

Wind energy is one of the most abundantly available energy resources and it has been utilized since ancient times. Windmills were employed in farms for water pumping purposes in earlier times and now the same ideology in conjunction with an electrical generator is used to generate electricity. Wind electric conversion systems (WECS) are commercially available in a variety of ratings for residential as well as commercial purposes. Power ratings of these systems range from 5 kW to as much as 6 MW. Small wind is a designated term for wind turbines installed on a residential level (10 kW or less), whereas large wind implies large wind turbines (about 1-6 MW) for commercial purposes. A collection of wind turbines at a suitable location is known as a wind farm. They are classified on the basis of the location namely, onshore and offshore wind farms. Offshore wind farms have wind turbines installed over shallow ocean beds whereas onshore wind farms have installations over land. Typically, offshore wind farms have wind turbines with larger ratings due to larger availability of wind resource off the shores. Both developing and developed nations are rapidly investing in wind energy installations at suitable on and offshore sites. Currently, the United States ranks first in installed wind energy capacity with a total installation of 38, 478 MW in 2009 [7]. In countries such as Denmark, the relative penetration of wind energy is larger as compared to the United States due to smaller grid size, lower energy requirement, and strong transmission ties with neighboring countries. Projections of future wind energy installations indicate a significant rise, although similar trends in harnessing other renewable resources are also expected. The electric grid of the future will have a mix of energy injected from myriad different technologies, all managed in an optimum manner. Though, one hurdle in large scale penetration of wind energy is the variability of wind and its unavailability at times of heavy load demands. Significant research and development activities are underway around the world under the overarching term “Smart Grid” to handle all such issues.

1.5 Objective

The objective of this study is to establish a framework for a probabilistic power and energy exchange in electric networks with constant and variable generation. The scope of the study includes getting an overall picture of a system with a configuration of a wind farm connected to an electrical load and grid through an electrical interface. Variability in the wind speed-power output characteristic between cut-in wind speed and rated wind speed of a wind electric conversion is introduced, and its impacts are investigated. The relation between power output and wind speed considered here are linear, square, cubic, fourth and fifth order. Finally, the collective power output of a wind farm is expressed as a single random variable, which is modeled by probability density function. The interaction is quantified by energy exchanges under specific operating conditions. Load density function is modified as per demand side management techniques so as to simulate an environment similar to a smart grid.

1.6 Organization of Thesis

A short overview of the remaining sections of the thesis is given below:

Chapter II: Literature Review: documents the results of the literature review done prior and during the study. Review of basic concepts of probability and random variables is also included.

Chapter III: Model Development: deals with the mathematical formulation of the power output of a wind electric conversion system. Detailed nature of the density function is explained. Model is extended to obtain a density function for the collective power output of multiple systems.

Chapter IV: Application to a Practical Case: describes the details of the wind farm, electric grid and interface with load. Also, description of the load density function and its data is explained. Impact of variability in output characteristics in the interval between cut-in and rated wind speeds is investigated.

Chapter V: Smart Grid-A Distant Vision: explains the need for modernization of the existing electric grid. Also, deals with the various technologies involved for the objectives. An analytical exercise is performed to demonstrate the effectiveness of smart grid.

Chapter VI: Discussion of Results: discusses all the major findings of the study. It also explains the trends of energy exchanges obtained under different load conditions.

Chapter VII: Concluding Remarks and Future Scope: sums up the entire study, and draws some final remarks. Scope for further work is also outlined.

CHAPTER II

REVIEW OF LITERATURE

2.1 Random Variables

Outcomes of statistical experiments can have numerical or non-numerical forms. Simple coin toss experiment will have expected outcomes as heads or tails, or a random quality check of transistors will have outcome as standard or defective item and so on. Clearly, these statistical experiments have non-numerical outcomes. But, these outcomes will follow certain pattern which is a complex function of experimental conditions and the procedure involved. In a broad sense, "a variable which eludes predictability in assuming its different possible values is called a random variable" [8]. Mathematical and scientific investigations can be made more explicit if such outcomes are expressed as numerical values. Hence, there needs to be a link between non-numerical outcomes and the real line. For every outcome ∂, associating a real number $X(\partial)$ will lead to a correspondence rule between the outcomes and real line. Such a correspondence subject to specific constraints is called a random variable [9]. Thus, random variable can be perceived as a mapping between outcomes of an experiment to the real line. The domain and range of random variables are all possible outcomes (sample space) and their correspondingly mapped real numbers. Classic examples of random variables are wind speeds, insolation, traffic flow, stock prices, etc.

2.1.1 Modeling Random Variables: As explained in section 2.1, random variables are functions which map outcomes to the real line. "Variables produced by the interplay of a complex system of causes exhibit irregular variations which are, to all intents and purpose, random" serves as textbook definition of random variables [8]. This irregularity and pattern of changes can be sufficiently explained by using probability and functions of probability. Probability distribution function (PDF) and probability density functions (pdf) are the two basic functions used to model a random variable. They form an integro-differential pair and provide all the necessary information about a random variable to explain its nature.

Mathematically, the probability distribution function (PDF) is defined as:

$F_X(\partial) = P[X \leq \partial] = P_X[(-\infty, \partial)]$

where X is the random variable; ∂ is a dummy variable for X; $F_X(\partial)$ is the probability distribution function for X.

Properties of probability distribution function (PDF) [9]:

1. Values of any distribution function at positive and negative infinity are $F_X(\infty) = 1$ and $F_X(-\infty) = 0$ respectively.
2. The distribution function is a non-decreasing function i.e. for $\partial_1 \leq \partial_2$ will imply $F_X(\partial_1) \leq F_X(\partial_2)$.

3. $F_X(\partial)$ is continuous from the right. i.e. $F_X(\partial) = \lim_{\xi \to 0} F_x(\delta + \xi)$, $\xi > 0$.

A density function, if it exists, is the derivative of the distribution function. In other words, probability density function is the slope of the distribution function. Mathematically,

$$f_X(\partial) = \frac{d\mathrm{Fx}(\partial)}{d\partial}$$

Properties of probability density function (pdf) [9]:

1. $f_X(\partial) \geq 0$.
2. The area under a density function curve is always unity.
3. $F_X(\partial) = \int_{-\infty}^{\partial} f\mathrm{x}(\partial) = P[X \leq \partial]$
4. $F_X(\partial_1) - F_X(\partial_2) = \int_{-\infty}^{x1} f\mathrm{x}(\partial)d\delta - \int_{-\infty}^{x2} f\mathrm{x}(\partial)d\delta = \int_{x1}^{x2} f\mathrm{x}(\partial)d\delta = P[\partial_1 < X \leq \partial_2]$.

where X is the random variable; ∂ is a dummy variable for X; $f_X(\partial)$ is the probability density function for X.

Random variables are classified on the basis of existence of derivative of the distribution functions (PDF). If a PDF $F_X(\partial)$ is a continuous function of ∂ such that the derivative exists at every point, then the random variable (∂) is continuous. Whereas if the PDF $F_X(\partial)$, has a staircase form with discontinuities then the random variable (∂) is discrete. If a distribution forms an arithmetic progression, then the random variable is of lattice type. A random variable is of mixed type if its distribution is neither continuous nor exhibits staircase pattern [10].

2.2 Wind Energy Resource

2.2.1 Origin of Wind: Wind can be best interpreted as the motion of air. Two prime causes of the movement of air molecules are uneven heating of the surface of earth by the sun and the rotation of earth. The uneven heating of the earth's surface causes differential pressure leading to air circulation. These can be attributed as macro level causes of wind, though there are many local factors such as terrain which influence wind and its patterns. Air envelopes play a dual role as both reflector and an absorber while interacting with insolation. Either of these roles is dominant depending upon the location of the envelopes and time of the day. During the daytime, an air envelope over land surface acts as a dominant reflector whereas an envelope over water surface as a dominant absorber. This results in lighter air over land surface and heavier air over water surface. Lighter air rises above and is replaced by the heavier air, thus setting up wind currents. The whole mechanism is reversed at night time with the roles of air envelope exactly reversed. It is also worthwhile to note that cooling rate of water is lower as compared to land which also influences the strength and duration of wind currents. "On a broader scale, large circulating streams of air are generated by the more intense heating of the earth's surface near the equator than at the poles. The hot air from tropical regions rises and moves in the upper atmosphere toward the poles, while cool surface winds from the poles replace the warmer tropical air" [11]. The rotation of earth has an impact on the direction of wind currents. Colder winds from the polar regions have a natural tendency to move westwards whereas the warmer air to move eastwards on account of their inertia. This leads to a clockwise air circulation in low pressure zones (northern hemisphere) and an anti-clockwise air circulation in high pressure zones (southern hemisphere) [11]. Thus, wind is one of the most abundant and freely available energy resources on earth.

2.2.2 Historical Applications of Wind Energy: Usage of wind turbines dating back to the seventeenth century B.C. has been testified by historians and archaeologists. One of the earliest mentions about wind mills with horizontal axis and four sails is from the third century B.C. by the Hero of Alexandria. Persian civilizations used vertical axis wind turbines for applications of farming and water pumping in the mid seventeenth century [12]. Earliest mention about English wind turbines is dated 1191 A.D., while other countries used them during the sixteenth century. Basic application for all these wind turbines was either milling or grinding of grains, and so were more often referred to as wind mills. These machines were noisy, mechanically inefficient, bulkier, and tedious to maintain. First ever material optimized and efficient machines were introduced by the Dutch civilization, as their design involved optimizing aerodynamic parameters related to efficiency. Dutch travelers and migrants installed this developed type of wind turbine in the U.S. by the mid-eighteenth century. By the nineteenth century, a further developed version of this wind turbine named "*American Mutliblade Wind Turbine*" was built for efficient water pumping over grazing lands. Approximately 6.5 million of such turbines were installed during 1880 to 1930, for livestock and farming, with some still functioning satisfactorily [13].

2.2.3 Wind Electricity Generation: Denmark was the birthplace of wind turbines generating electricity in 1890, with several hundred units commissioned in a few decades with power ratings ranging from 5 kW to 25 kW. Commercialization of wind turbines for electricity generation in the U.S. occurred in the year 1925, with Wincharger (200 W to 1200 W) and Jacobs (1500 W to 3000

W) as the market leaders. The cost of electricity generation from wind energy followed a very interesting pattern; a decrease in the cost starting in 1940 till 1970, wherein it dipped to 3 cents/kWh and then it rose sharply thereafter. The reduction in cost was compensated by rising cost of the equipment and maintenance [13]. The era of large wind turbines began in the late 1960s on account of the various issues related to Arab Oil Embargo and hazards associated with nuclear electricity generation. It was spurred by innovative projects sponsored by the U.S. DOE which involved very simple machines such as 100 kW NASA MOD-0 through to the extremely modernized 3.2 MW Boeing MOD-5B. Other prime factors for successful resurgence of wind turbines were variable-speed operation, improved blade materials and structures, and the introduction effective electricity and renewable energy portfolios such as the Public Utility Regulatory Policy Act of 1978 and its amendments [14]. One of the most recent initiatives is ‘20% Wind Energy by 2020’ by the U.S. DOE, gives an account of the advantages of wind energy, technical issues, economics, federal policies and measures undertaken to achieve the objective [15]. Germany and China rank second and third respectively in wind energy installations with capacities 25,777 MW and 25,104 MW respectively [16].

2.3 Intermittency-An Inherent Quality

An inherent characteristic of wind is its variability. Variability has prime importance as energy associated with wind varies as the cube of its speed. Wind is variable on a temporal as well as spatial scale over a wide range. Temporal variation implies time variation of the wind at the same location. For a wind regime, wind speeds and its pattern for any period of study will be certainly different than a similar dataset from another comparable study period. Temporal variability of wind can be based on a wide range of time scales starting from instantaneous to seconds to as long as seasonal to annual scales. Long term variations of wind speed patterns are fairly complicated in nature and cannot be forecasted with great accuracy, as compared to short term variations. Abrupt variations in wind measured on seconds time scale are termed as “gusts and turbulences”. Spectrum graphs are employed to study temporal variations of wind speeds. Spatial variation of wind implies difference in wind speeds and patterns at different locations observed at the same time. Large wind streams are dictated by the latitude of the locations as it determines the insolation. On a micro scale, local topography plays a dominant role in determining the wind speed and patterns. These factors include humidity, roughness of terrain, presence of water bodies, presence of mountain slopes and valleys, etc [17]. Roughness of the surface plays a dominant role in the dynamics of local wind speed and its pattern. Surfaces are assigned roughness class to account for their impact on wind dynamics, e.g. a roughness class of high value of 3 to 4 indicates presence of multiple obstacles such as buildings, trees, etc. For offshore wind farms, it can be ignored as ocean surface has zero roughness class such that the surface is absolutely smooth. Wind shear formula has been formulated to provide resultant wind speed values taking into account the roughness class of the surface. In short, variability is an inseparable part of wind energy and it needs significant technical attention as electricity generated from it will also be variable.

2.4 Wind Speed Modeling

A wind farm development project can be briefly divided into the following phases:

1. Initial site selection
2. Project feasibility assessment (includes wind resource assessment)
3. Preparation and submission of the planning application
4. Construction
5. Operation
6. Decommissioning and land reinstatement [17].

These steps involve an in-depth analysis of the characteristics of the potential sites with respect to economics, local topography, and matching wind profiles to site profile. Historical wind data may not necessarily be always applicable for site selection; since such data is obtained and processed for meteorological purposes. Short term wind variations (turbulences) are associated with the structural strength and control functions of WECS whereas the long term wind characteristics are related to gross energy yield and capacity factor [18]. Statistical models for wind speeds are employed so as to assess performance, determine energy yields, potential site assessment and so on.

The data obtained from the measurement centers set up at potential sites need appropriate processing and data analysis in order to be useful for analysis and to draw conclusions. One year wind speed data of a potential site is usually sufficient to determine a suitable wind speed distribution with the help of extrapolation. Distribution obtained in such a manner suffices any planning studies with an acceptable accuracy. To simplify, frequency distribution is grouped along with the number of hours, which indicates the velocity range and its time duration [14].

Two of the most commonly used standard distributions to represent wind speeds are Rayleigh distribution and Weibull distribution.

2.4.1 Rayleigh Distribution: It is a one-parameter model widely used to represent wind speeds due to its simple nature. It requires knowledge of only the mean wind speed of the regime. The density and distribution functions are given below:

$$f(x; \sigma) = \frac{x}{\sigma^2} \times e^{-\left(\frac{x}{2\sigma^2}\right)} \tag{2.1}$$

$$F(x; \sigma) = 1 - e^{-\left(\frac{x}{2\sigma^2}\right)} \tag{2.2}$$

where, x is the random variable representing wind speed, σ is the mode of the distribution. The relation between the mean and mode is given as:

$$\text{mean} = \sigma \times \sqrt{\pi/2}\ .$$

Larger value of mode is desirable and it implies the wind regime has high wind speeds. Figures 2.1and 2.2 show Rayleigh density and distribution functions for different mode values respectively.

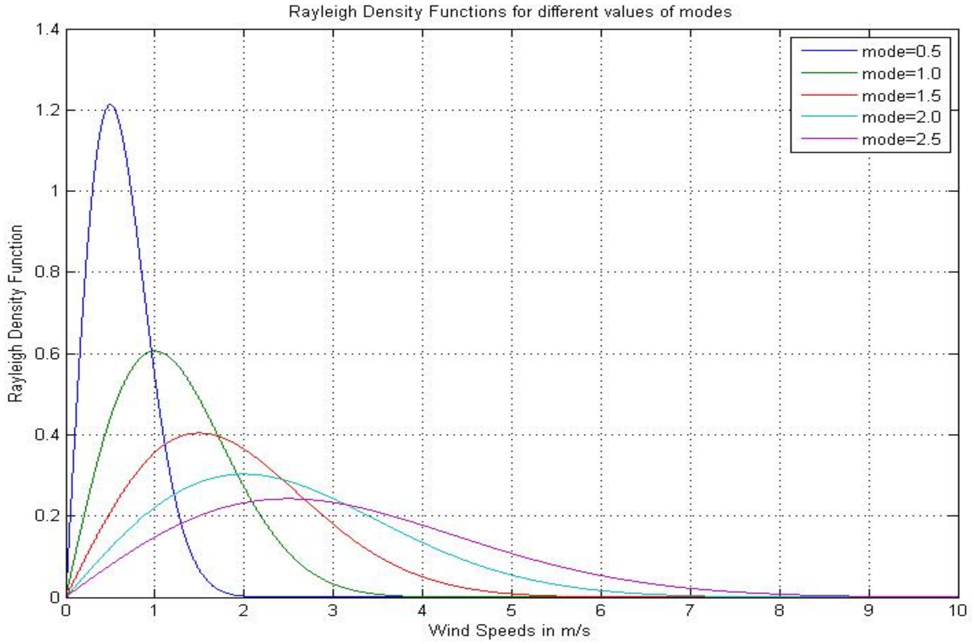


Figure 2.1: Rayleigh density function for different values of mode of the distribution

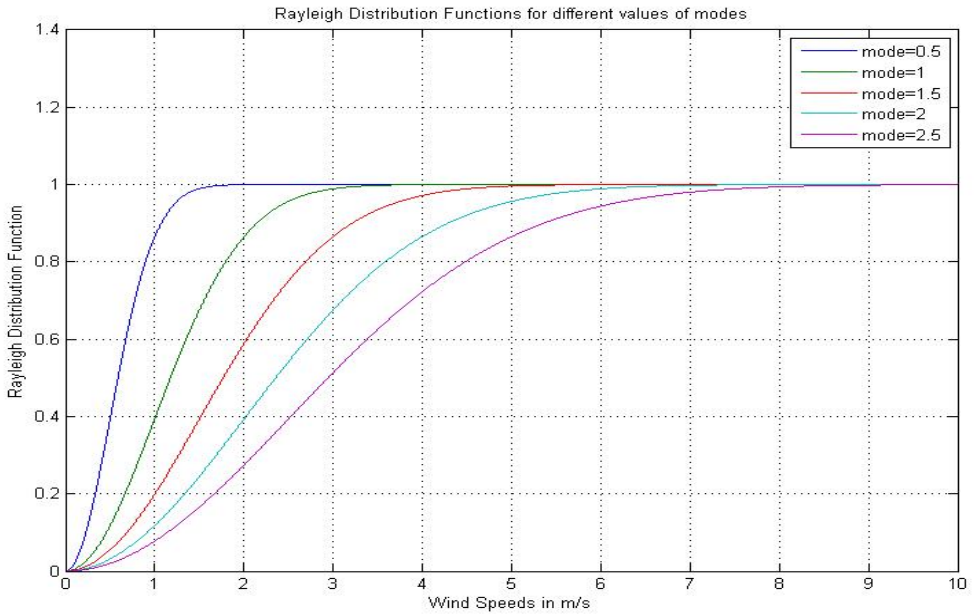


Figure 2.2: Rayleigh distribution functions for corresponding values of mode of the distribution

2.4.2 Weibull Distribution: It is a two parameter distribution with α as the scale parameter and β as the shape parameter. Scale and shape parameters are functions of both mean and standard deviation of the distribution. Scale parameter is directly proportional to the mean wind speed, so it indicates how windy the regime is. Shape parameter indicates the variability of the wind speed samples from the mean value. It is one of the most widely used distributions because of its flexibility with two parameters to fit wind speed data. The associated density and distribution functions are given by equations 2.1 and 2.2 respectively :

$$\mathrm{f(v)} = \left(\frac{\beta}{\alpha\hat{}\beta}\right) \times \mathrm{v}^{\beta-1}\mathrm{e}^{\left[-\left(\frac{\mathrm{v}}{\alpha}\right)^{\beta}\right]} \qquad (2.3)$$

$$\mathrm{F(v)} = 1 - \mathrm{e}^{\left[-\left(\frac{\mathrm{v}}{\alpha}\right)^{\beta}\right]} \qquad (2.4)$$

where v is the wind speed random variable; α and β are the scale and shape parameters respectively. Estimation of scale and shape parameters from mean and standard deviation of the wind speed measurements is a tedious process. Equations 2.5 and 2.6 give the respective relations for mean and standard deviation with the two Weibull parameters [14]:

$$\mu = \alpha \times \Gamma\left(1 + \frac{1}{\beta}\right) \qquad (2.5)$$

$$\sigma^2 = \mu^2 \times \left[\frac{\Gamma(1+\frac{2}{\beta})}{\Gamma(1+\frac{1}{\beta})} - 1\right] \qquad (2.6)$$

where μ and σ are mean and standard deviation respectively; Γ denotes the gamma function.

Standard methods have been established in literature for this estimation, such as Analytical (or Empirical) by Justus in 1978, Empirical by Lysen in 1983 and Graphical (log-log plot) [14]. Fig. 2.3 and 2.4 show Weibull density and distribution functions for different values of scale and shape parameters respectively.

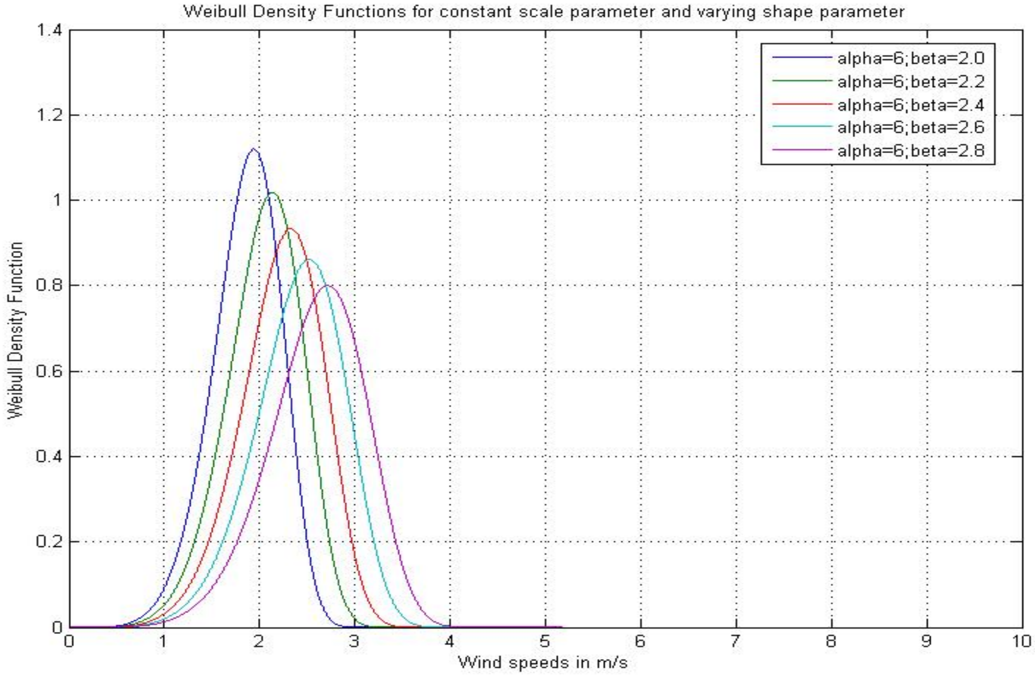


Figure 2.3: Weibull density function for a constant scale parameter (6 m/s) and varying shape parameter

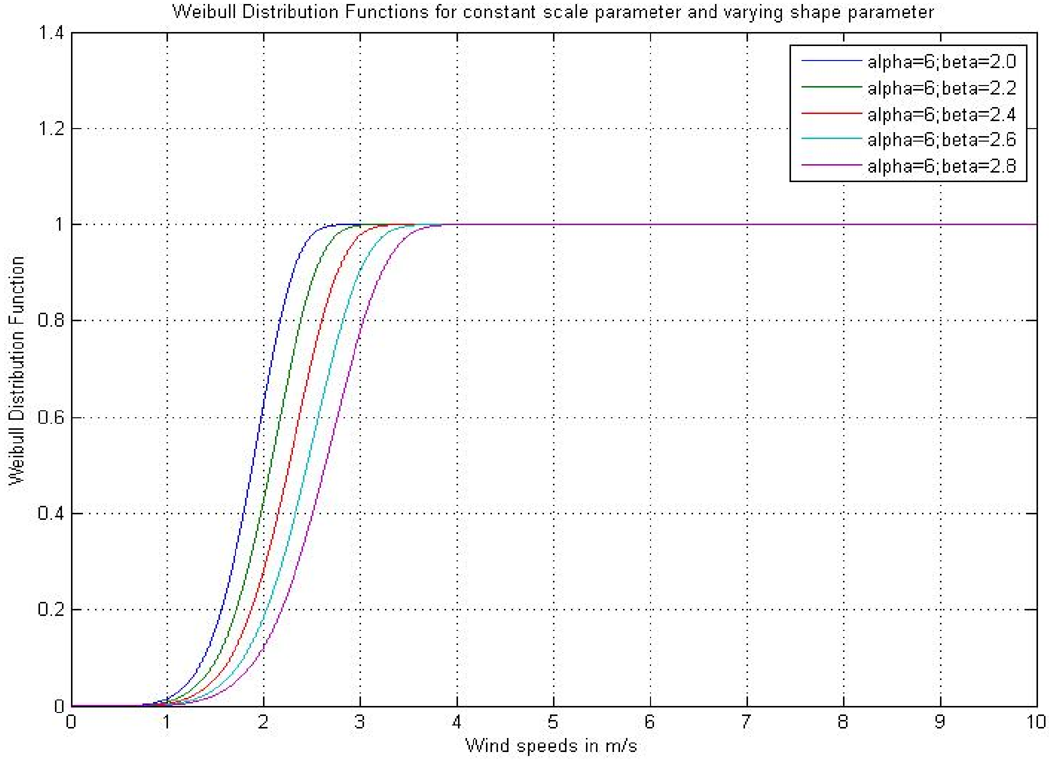


Figure 2.4: Weibull distribution function for a constant scale parameter (6 m/s) and varying shape parameter

2.5 Performance Assessment Techniques for WECS

Electrical energy generated from WECS is influenced by both wind variability, mode of operation of WECS and electrical characteristics of the generator. Thus performance assessment of WECS is not as straightforward and simple as that of conventional generation plants. Wind farms can very well be termed as energy reserves, while conventional resources as capacity reserves. Conventional power plant generates as per the requirement of the grid and so is termed as capacity reserve. Capacity reserves are classified into two major categories, namely spinning reserves and non-spinning reserves. Spinning reserves are the extra generation capacity available in already online generating plants, whereas non spinning reserves can be brought online within a short interval of time to meet the load demand. All these terminologies only indicate the flexibility and energy "on demand" feature of conventional generation.

Wind Electric Conversion Systems (WECS) can be used in two main configurations to supply load - namely standalone configuration and grid connected configuration. Standalone configuration is suitable for remote areas without transmission networks, and is simpler to analyze. They supply electrical loads directly. Wind farms with multiple WECS are connected to grid via suitable tie lines and are relatively complicated to analyze. From the grid perspective, it has interplay of conventional generation (fixed and scheduled), renewable generation (variable and unscheduled) and varying electrical load demand. Two techniques to assess performances of generation resources - chronological method and probabilistic method - are well established. It has been documented that, chronological methods are more suitable for system operators whereas probabilistic methods for system planners. Thus in no way they are alternative methods, but they serve different objectives and are in fact complementary [19].

As discussed in section 2.3, wind speed variations are observed on time scales ranging from seconds to minutes. As such chronological information on the changes of wind speeds, corresponding output of WECS, and the load will lead to a well-defined relation. The relation so obtained can be used to quantify reliability measures to assess the performance of wind farms. Availability of data and extensive data processing are the two disadvantages associated with the chronological performance analysis of WECS. The study presented here is based on probabilistic methods and treats the problem from system planning perspective. It is also computationally easier to execute and involves application of basic probability and stochastic theories. The next chapter deals with probabilistic assessment of WECS in a grid connected configuration supplying a varying electric load.

CHAPTER III

MODEL DEVELOPMENT

This chapter discusses the development of modeling power output of WECS in probabilistic context. This model will be flexible enough for numerous system planning studies.

3.1 Power Output Characteristics of WECS

3.1.1 Power in Wind: Power available in wind at a speed v through an area A is given as:

$$P = \frac{1}{2} \times \rho A v^3 \qquad (3.1)$$

where, P = power available in wind in W; ρ = air density in kg/m^3; v = wind speed in m/s; and A = area of wind mass m^2.

Theoretically, this is the maximum possible power available in wind for energy conversion. If it is fully extracted, there would be no air mass motion after energy extraction, as kinetic energy of wind would become zero. Practically, this proposition is not feasible with any designs of wind electric conversion systems (WECS). Any design of WECS can extract a fixed fraction of the kinetic energy of wind depending on the design of blades. The maximum value of this fraction is 59.3% and is well known as the Betz limit or Power Coefficient (C_p). Albert Betz, a German physicist was the first to estimate the value of this fraction in the year 1926 [20].

3.1.2 Output Characteristics of WECS: Output characteristic of WECS is a plot of output power versus the incident wind speed at the hub height. The power output of WECS is influenced by a number of factors such as the wind speed, generator characteristics, control mechanism, and mode of operation. These characteristics account for the overall efficiency of the aerodynamic (wind and blade interaction), mechanical (gear box and other transmission system if present) and electrical (generator and the power conditioning unit) systems involved in the energy conversion process. Output power is a direct function of the wind speed, which in turn is a function of atmospheric parameters such as temperature (K), humidity, and altitude above the sea level (m). Control mechanisms are inbuilt in WECS so as to execute desired energy conversion process via appropriate mode of operation. Commonly employed controls strategies are pitch control (passive type), stall control (active type), active stall control and yaw control [21]. At any instant, a specific control scheme is functional depending upon the desired output determined by the prevailing wind conditions. A general equation for power output-wind speed characteristic of a WECS is as follows [22]:

$$p = \begin{cases} \mathrm{Pr} \times \frac{(v^n - Vc^n)}{(Vr^n - Vc^n)} & V_c \leq v \leq V_r \\ P_r & V_r \leq v \leq V_f \\ 0 & \text{Otherwise} \end{cases} \tag{3.2}$$

where p is power output of WECS in kW as a function of wind speed v; P_r is the rated power output of WECS in kW; V_c,V_r and V_f are cut-in wind speed, rated wind speed and furling wind speed in m/s respectively. The values of V_c,V_r and V_f are a part of the design constraint of WECS and are influenced by existing wind regime. The exponent ‘n’ has integer values dependent on the aerodynamic design of the blades and its interaction with the wind flow. Figure 3.1 shows the power output characteristic for an exponent value of n=1, i.e. a linear relation between output power and wind speed within the range V_c and V_r.

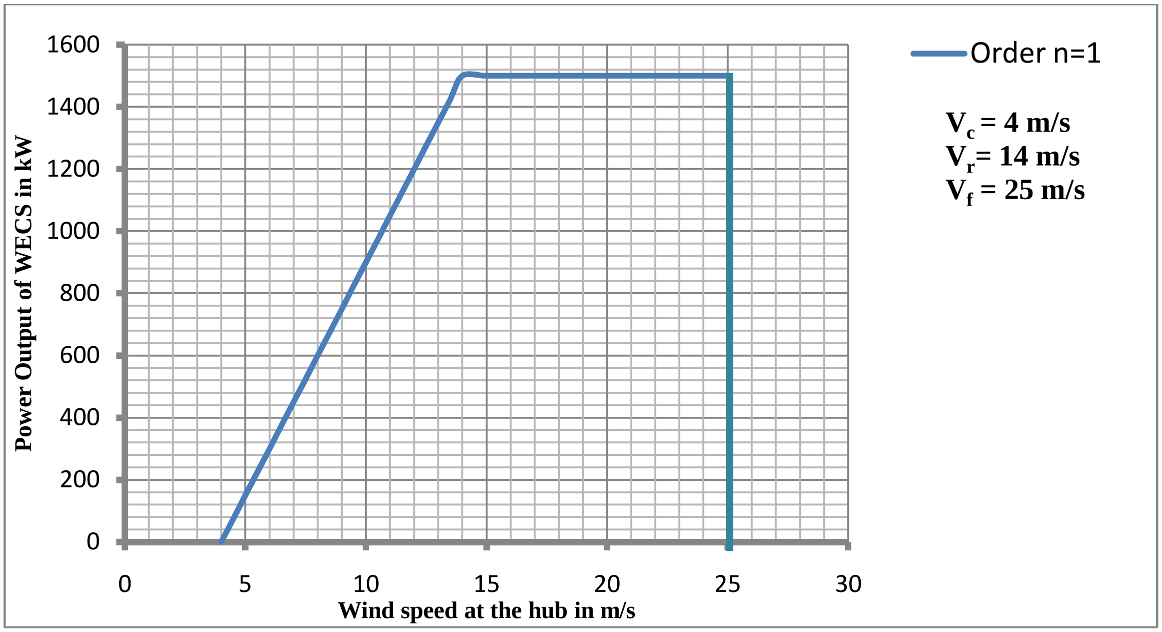


Figure 3.1: Power output characteristic of WECS with an exponent value of n=1

The characteristic has two distinct regions namely, maximum power output region and power regulation region. The maximum power output region is the linear region between cut-in wind speed (V_c) and rated wind speed (V_r) and power regulation region is the flat region between the rated wind speed (V_r) and the furling wind speed (V_f). The maximum power output region is also referred to as variable output region as the relation between power generated and wind speed can be linear, squared, etc. depending on the design of WECS. WECS operates in the maximum power output mode and power regulation mode during the respective regions. In the maximum power output mode the WECS strives to extract maximum possible energy from the wind. While operating in the power regulation mode excessive energy is spilled and only the rated power output (P_r) is generated. As the wind speed exceeds the furling wind speed value (V_f) WECS is turned away from the wind direction to avoid excessive mechanical turbulences, vibrations and stresses.

3.1.3 Wind Speed and Weibull Distribution: Wind speeds measured on an annual scale follow Weibull distribution, as mentioned in section 2.4. The Weibull density and distribution functions are given in equations 3.3 and 3.4 respectively:

$$f(v) = \left(\frac{\beta}{\alpha\hat{}\beta}\right) \times v^{\beta-1} e^{\left[-\left(\frac{v}{\alpha}\right)^{\beta}\right]} \tag{3.3}$$

$$F(v) = 1 - e^{\left[-\left(\frac{v}{\alpha}\right)^{\beta}\right]} \tag{3.4}$$

where α and β are the scale and shape parameters respectively and v is the instantaneous wind speed at hub height in m/s. A higher value of shape parameter β i.e. in the range of 2.5 to 3 indicates a lower variation of wind speeds about the mean whereas a lower value of β i.e. in the range of 1.2 to 1.5 indicates a larger variation of instantaneous wind speeds about the mean value. Value of α is directly proportional to the mean wind speed. Thus, larger values of both α and β are desirable and would be advantageous from system planning point of view.

3.2 Probability Function Modeling

The wind speed in the power output characteristic given in equation 3.2 follows a Weibull distribution. Thus, the power output of WECS can also be treated as a random variable as it is a function of wind speed. The probabilistic approach of performance assessment requires treating variables including the power output of WECS as random variables. So, the probability density function of the power output of WECS is obtained by combining the equations for the power output characteristics and Weibull density function on the basis of the transformation theorem [23]. The resulting probability density function for the power output of a single WECS is given by equation 3.5:

$$f(p) = \begin{cases} [q_{ow}+p_{ow}(1-F_1)]\delta(p) & \text{for } p=0 \\ p_{ow}\times\left(\frac{1}{\left|\frac{dp}{dv}\right|}\right)\times\left(\frac{\beta}{\alpha^{\beta}}\right)\times(v)^{(\beta-1)}\times e\hat{}[-\left(\frac{v}{\alpha}\right)^{\beta}] & \text{for } 0<p<Pr \\ p_{ow}F_2\delta(p-Pr) & \text{for } p=Pr \\ 0 & \text{Otherwise} \end{cases} \tag{3.5}$$

where p_{ow} and q_{ow} are availability and unavailability of WECS hardware respectively; F_1=F(V_f)-F(V_c); F_2=F(V_f)-F(V_r); v=[V_c^n+(V_r^n - V_c^n)×(p/P_r)]^($\frac{1}{n}$); $\left|\frac{dp}{dv}\right|$ is the derivative of instantaneous power w.r.t. wind speed v; P_r is the rated power output of WECS; F_1 and F_2 are the probabilities of wind speed lying inside the range of cut-in and furling wind speeds and rated and furling wind speeds respectively.

The probability density function for power output of WECS has two impulses located at zero power output and rated power output of WECS. The strengths of these impulses are proportional to the probabilities $1-F_1$ and F_2 respectively. The impulse at zero power output can be justified from the characteristics by the probability of wind speeds outside the range of cut-in and furling wind speeds during which no power will be generated. The impulse at the rated power output can be justified from the characteristics by the probability of wind speeds in the range of rated and furling wind speeds during which constant rated output will be generated. The density function has both discrete as well as continuous region. Thus, power output of WECS is a mixed random variable. The variable region or the maximum power output region of the characteristics correspond to the continuous part of the density function whereas the regulated power output region and zero generation regions of the characteristics correspond to the discrete part of the density function. A typical probability density function for the power output of WECS is shown in figure 3.2:

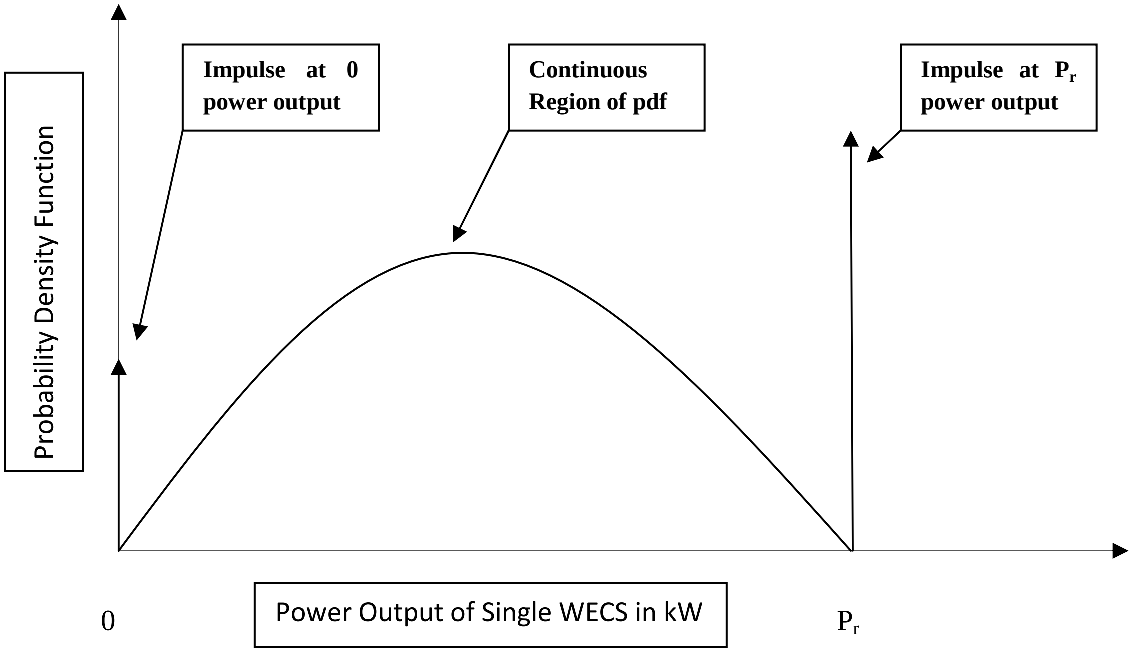


Figure 3.2: General probability density function for power output of WECS

The operational difference between conventional power plants and wind farms is that they operate as per schedules which are predetermined via forecasting and power flow models. Probability density function of power output of a conventional power plant will be discrete in nature with impulses at 0 and P_r only, and no continuous region. If compared with the general density function of power output of WECS the strength of impulse at rated value (P_r) for conventional power plants will be significantly higher. The strength of impulse at zero power output for conventional power plants will be smaller as compared to the impulse strength at zero output of the WECS [24].

3.3 Combined Power Output Density Function of Multiple WECS

For grid connected configuration, as per the availability of land and planning studies multiple WECS are installed. The power outputs of these generators are combined in a suitable manner to feed into the grid. Power output of each WECS will follow the density function as given by the equation 3.5. In order to represent the power output of the wind farm as a single random variable, the individual density functions for power output of WECS need to be aggregated. The convolution principle is employed to obtain combined power output density functions for multiple WECS [23].

The concept presented in this section can have various applications in system planning, probabilistic power flow, optimal power flow studies, and interconnection planning studies. A straightforward application is provided in the next section for a grid-connected large scale wind farm and its load supplying capability.

CHAPTER IV

APPLICATION TO GRID-CONNECTED WIND FARM

The probability density function model for power output of WECS is applied in a performance assessment framework of a wind farm. It involves extension of the model to combined power output of multiple WECS.

4.1 Specifications and Assumptions: Specifications of the WECS and wind regimes are listed in the section 4.1.1 and assumptions for the probabilistic models and analysis are discussed in the section 4.1.2.

4.1.1 Specifications: The parameters of WECS used throughout the study correspond to the GE 1.5 s unit which is a widely used machine for commercial purposes. Following are its parameters [25]:

1. Cut-in wind speed (V_c) = 4 m/s;
2. Rated wind speed (V_r) = 14 m/s;
3. Furling wind speed (V_f) = 25 m/s;
4. Rated power (P_r) = 1500 kW; and
5. Hub height (h) = 65 m.

Selection of a suitable wind regime is a very critical step in system planning studies and in the success of wind farms. Normally, anemometers at potential wind regime sites are erected at standard heights such as 10 m. Measurements thus obtained are treated by the "Power Law for Wind Speeds" in order to obtain the wind speeds at desirable heights. Wind speed measurements at hub height are the most desirable, however often expensive. Two wind regimes have been selected here for analysis from Taiwan. They are Heng Cheun (site-I) and Jang Bin (site-II). Wind speeds at these regimes are measured at 65 m height which is the hub height of WECS. The scale and shape parameters of the Weibull distribution for these regimes are [26]:

	α	β
Distribution-I	10.66 m/s	1.92
Distribution-II	11.91 m/s	1.77

4.1.2 Assumptions: The assumptions to simplify the analytical treatment of the probability functions obtained from the model and also those modeled further are listed below:

1. The specifications of GE 1.5 s and values of scale and shape parameters of site-I and II are the same throughout the analysis.

2. Numerical convolutions are performed for obtaining combined probability functions for multiple WECS.

3. Impulses are converted to rectangles of width 20 kW and height is calculated using the impulse strength and width (i.e. 20 kW) so that the random variable can be treated as continuous.

4. Density functions are uniformly sampled at widths of 20 kW to avoid any loss of information during convolution.

5. Load demand is assumed to follow normal distribution over an annual range and it is also sampled uniformly at intervals of 20 kW.

6. The exponent 'n' for the variable region of the characteristics of WECS has values 1 through 5 and are represented in all figures unless specified.

7. For combined power output density function estimations, each WECS is assumed to be subjected to the same wind speed distribution ignoring wake and shadow effects experienced in case of large wind farms.

8. Transmission, distribution and other electrical losses are ignored for the sake of simplicity.

4.2 Probability Density Functions for Single WECS Output

The specifications and assumptions from section 4.1 and equation 3.5 are used to plot the density functions for the power output of a single WECS. Figures 4.1 and 4.2 are the plots of probability density functions of power output for a single WECS located in wind regime-I and II respectively.

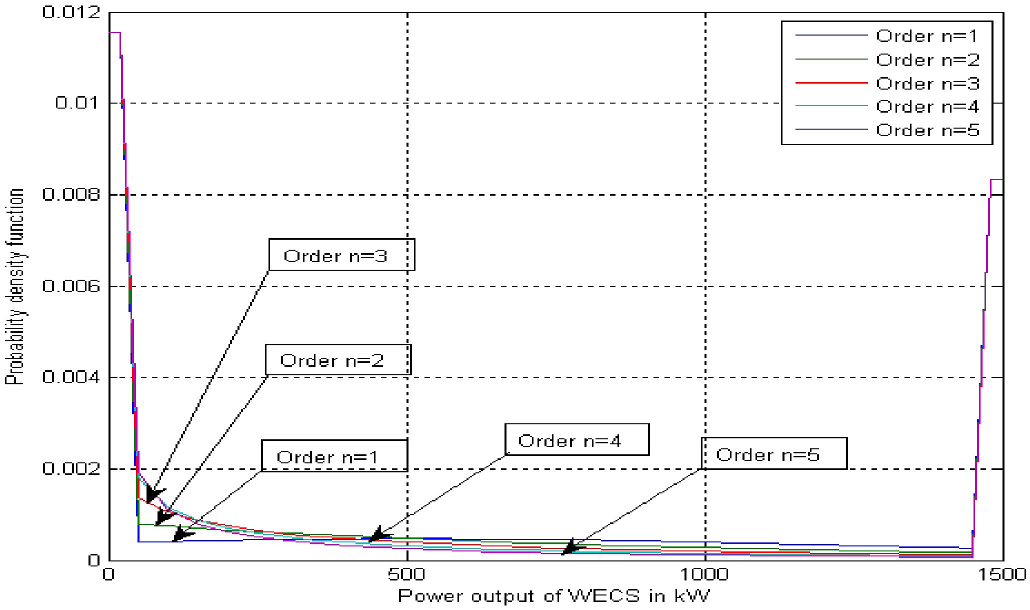


Figure 4.1: Probability density function plots for the power output of single WECS operating in wind regime-I for exponent values n=1 through 5

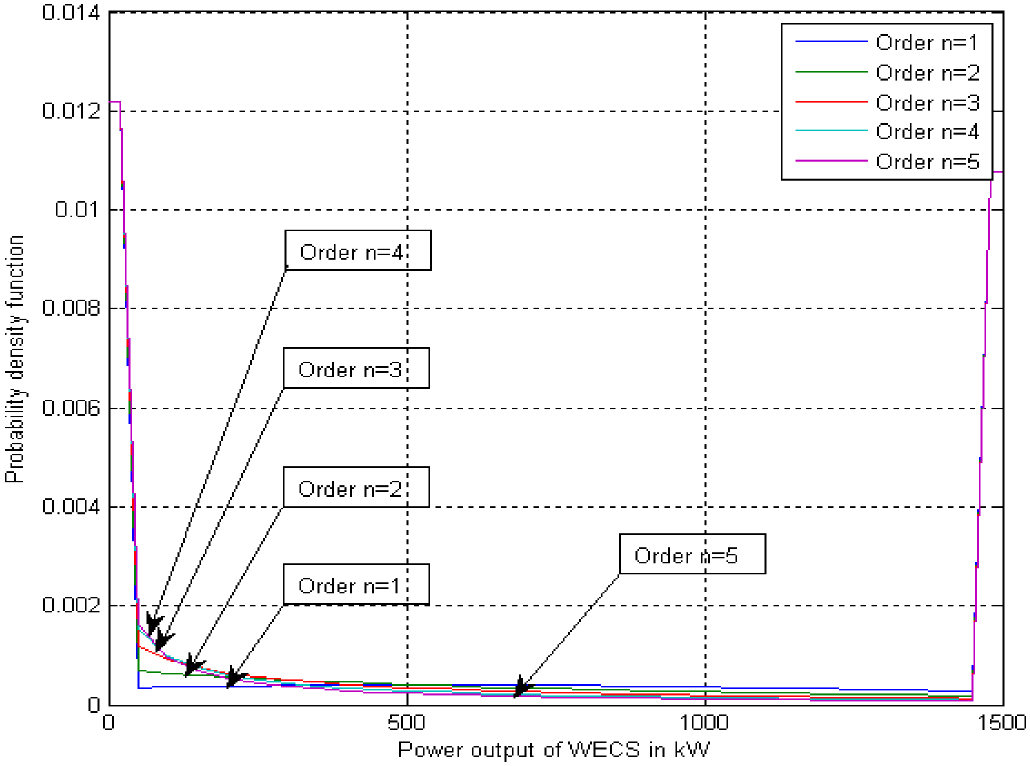


Figure 4.2: Probability density function plots for the power output of single WECS operating in wind regime-II for exponent values n=1 through 5

Explanation of Assumption 3: For the probability density function of a single WECS in wind regime-I, the impulse strength at zero power output is 0.23. In order to treat the function as continuous, this impulse is approximated as a rectangle with width of 20 kW. Maintaining the area the same and equal to the strength of the impulse, the height of this rectangle will be 0.0115. Similarly, all the impulses have been approximated and thus the density function for power output of individual WECS can be treated as continuous. It is also ensured that the total area under the density functions under all circumstances remains unity.

4.2.1 Impacts of Exponent 'n':

The probability density function for power output of individual WECS in wind regimes I and II as shown in figures 4.1 and 4.2 respectively, have two distinct regions labeled as 1) approximate impulse region and 2) area redistribution region.

1) **<u>Approximate Impulse Region:</u>** The area of approximation of the impulses at the 0 kW and 1500 kW power output are termed as approximate impulse regions. Both these rectangular regions have widths of 20 kW and areas equal to the respective impulse strengths. The heights of these approximate impulse regions are determined by the probability of occurrences of wind speeds outside the generation range and within regulated operation range of WECS respectively. There is no impact of the exponent on the dimension of these approximate impulse regions.

2) **<u>Area Redistribution Region:</u>** The non-approximated part of the function lying in between the two approximate impulses is termed as the area redistribution region. Five distinct curves in both sets of probability density functions are observed and they correspond to the different exponent values ‘n’. The plots rise in the region closer to the approximate zero impulse whereas they dip down over the rest of the plot as the exponent increases in value. This leads to a slight redistribution of probabilities of output in this region. The amount of redistribution is uniform in the sense that unity area condition is adhered to for all the exponent values.

4.2.2 Redistribution Regions for Exponents 1 and 2: This section compares in details the redistribution occurring due to the increase in exponent value from 1 to 2. Near the zero power output approximate impulse region it is observed that the curve for exponent n=2 has a larger area, which is termed as “redistribution area gain” over the curve for exponent n=1. Close observation of the plots in the latter half reveals that the curve for exponent n=2 has a lesser area, and is termed as “redistribution area loss” over the curve with exponent n=1. Figures 4.3 and 4.4 show the redistribution area gain and loss for the curve with exponent n=2 over the curve with exponent n=1 for WECS located in wind regime-I respectively. Additionally, the magnitudes of redistribution area gain and redistribution area loss are of equal magnitude leading to unit area under the plots.

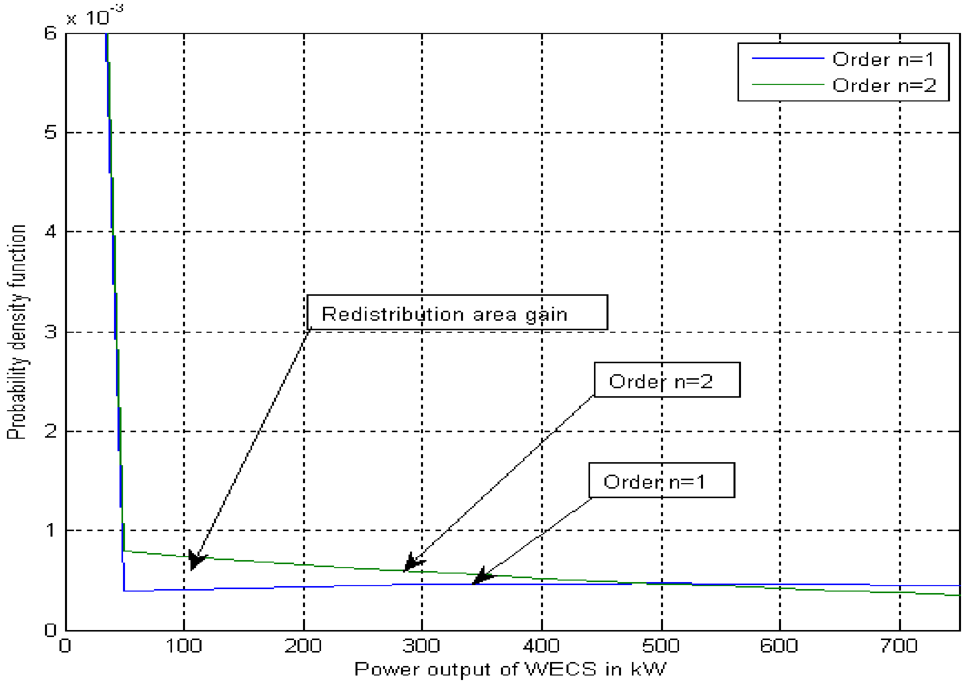


Figure. 4.3: Redistribution area gain near approximate impulse region at zero power output for exponent n=2 over n=1 for single WECS in wind regime-I

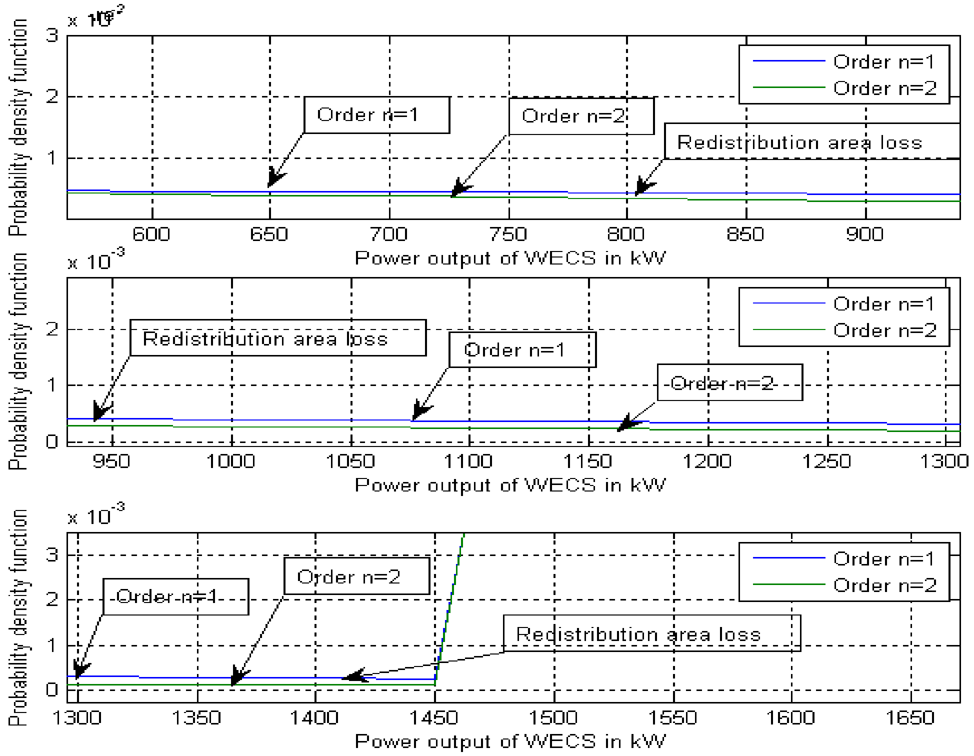


Figure. 4.4: Redistribution area loss near approximate impulse region at 1500 kW power output for exponent n=2 over n=1 for single WECS in wind regime-I

4.2.3 Redistribution Regions for Exponents 1 and 3: Similarly, if the curves corresponding to exponents n=1 and n=3 are compared, the same trend in the redistribution area gain and loss for the higher order exponent is observed. A significantly larger magnitude of area is redistributed in this case and similar trend for other higher values of exponents is noted. Figures 4.5 and 4.6 show the redistribution area gain and loss for curve with exponent n=3 over curve with exponent n=1 for single WECS located in wind regime-I respectively.

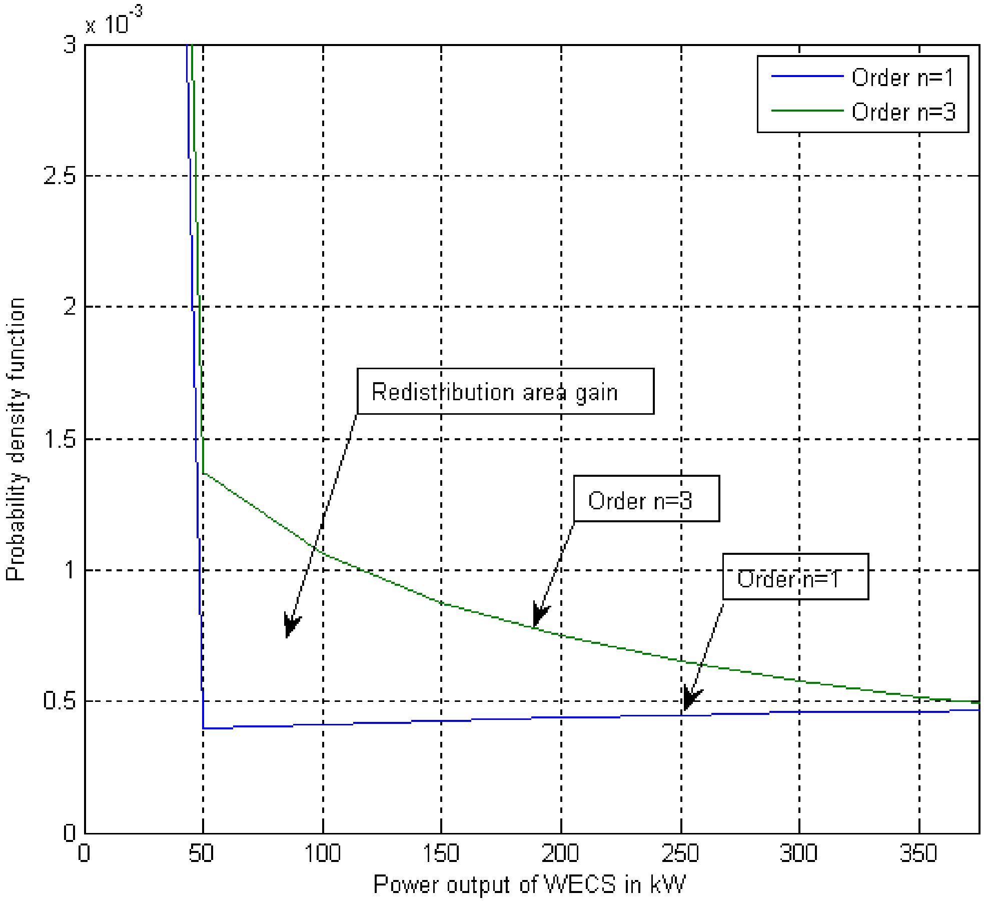


Figure. 4.5: Redistribution area gain near approximate impulse region at zero power output for exponent n=3 over n=1 for single WECS in wind regime-I

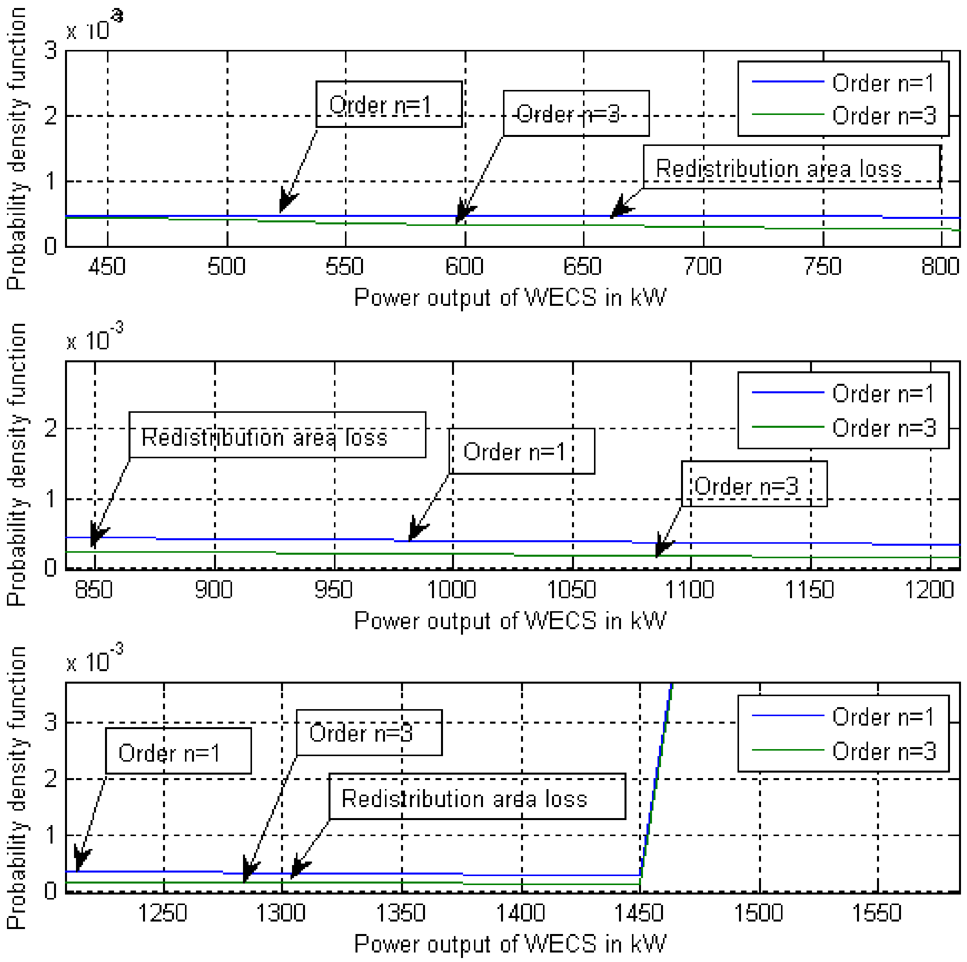


Figure. 4.6: Redistribution area loss near approximate impulse region at 1500 kW power output for exponent n=3 over n=1 for single WECS in wind regime-I

4.3 Combined Probability Density Function for Outputs of Multiple WECS Output

The method to obtain combined probability density function for multiple WECS is based on the convolution theorem. The probability density functions (assumed continuous) are sampled at regular intervals of 20 kW for the numerical convolution. Proper scaling is also done after the convolutions to obtain the desired density functions for combined power output of WECS. Joint density functions for the power output of two, four and eight WECS are presented and discussed in the following subsections. Three cases under each subsection are considered; e.g. for combined power output density function of four WECS, the three cases will be four WECS in wind regime-I, wind regime-II and two each in wind regime-I and II.

4.3.1 Probability Density Functions for Power Output of Two WECS: Power outputs of the two WECS are treated as independent and identically distributed random variables. The combined power output density function of two WECS is computed by numerically convolving density functions of power outputs of individual WECS. The three cases illustrated are:

a) Two identical WECS in wind regime-I;

b) Two identical WECS in wind regime-II;

c) One WECS each in wind regime-I and II.

Figures 4.7, 4.8, and 4.9 show the plots for the three cases a, b and c respectively.

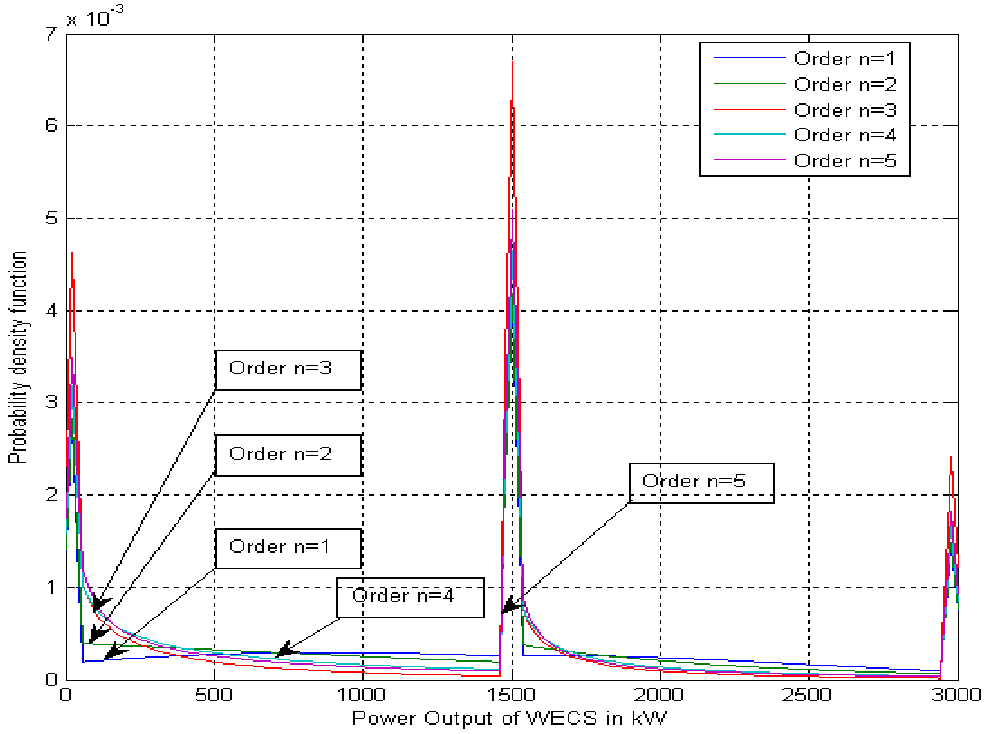


Figure 4.7: Combined power output density function plots of two WECS operating in wind regime-I

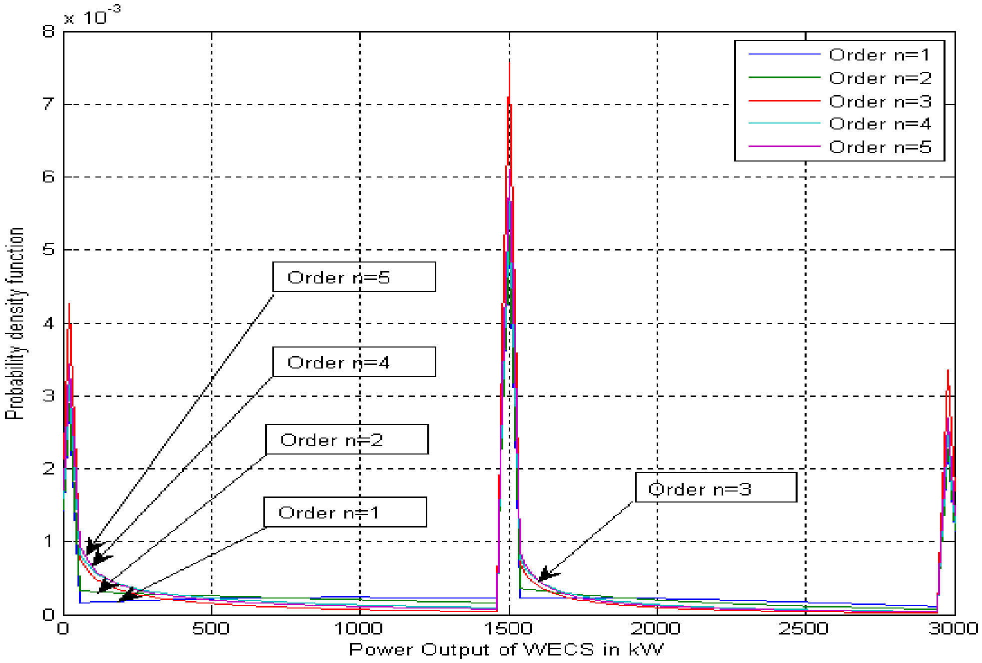


Figure 4.8: Combined power output density function plots of two WECS operating in wind regime-II

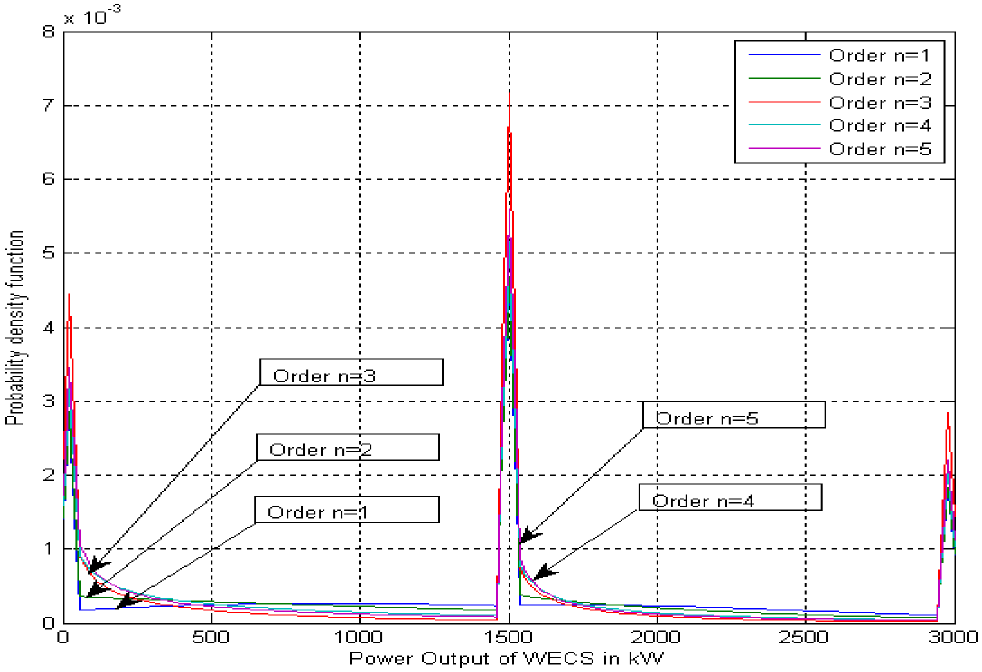


Figure 4.9: Combined power output density function plots of two WECS operating each in wind regime-I and II

Discussion: All the three cases show an occurrence of three approximate impulses - at 0 kW, 1500 kW and 3000 kW power outputs. The power output of 1500 kW is the most probable, while 0 kW and 3000 kW are the next probable outputs. Redistribution of areas occur in the regions between the three approximate impulses for different exponent values with a trend similar to that explained in sections 4.2.2 and 4.2.3. The magnitude of redistribution is low and can be regarded as insignificant. Thus, the impact of exponent on the combined density functions of two WECS is “minor”. The area under the density functions for each exponent is unity for all three cases.

4.3.2 Probability Density Functions for Power Output of Four WECS: The combined probability density function for power output of four WECS is obtained by numerically convolving the combined density functions of power output of two WECS, treating them as identical and independent. Three cases analyzed in this section are:

a) Four WECS operating in wind regime-I;

b) Four WECS operating in wind regime-II;

c) Two WECS operating each in wind regime-I and II.

Figures 4.10, 4.11, and 4.12 are the plots for the three cases a, b and c respectively.

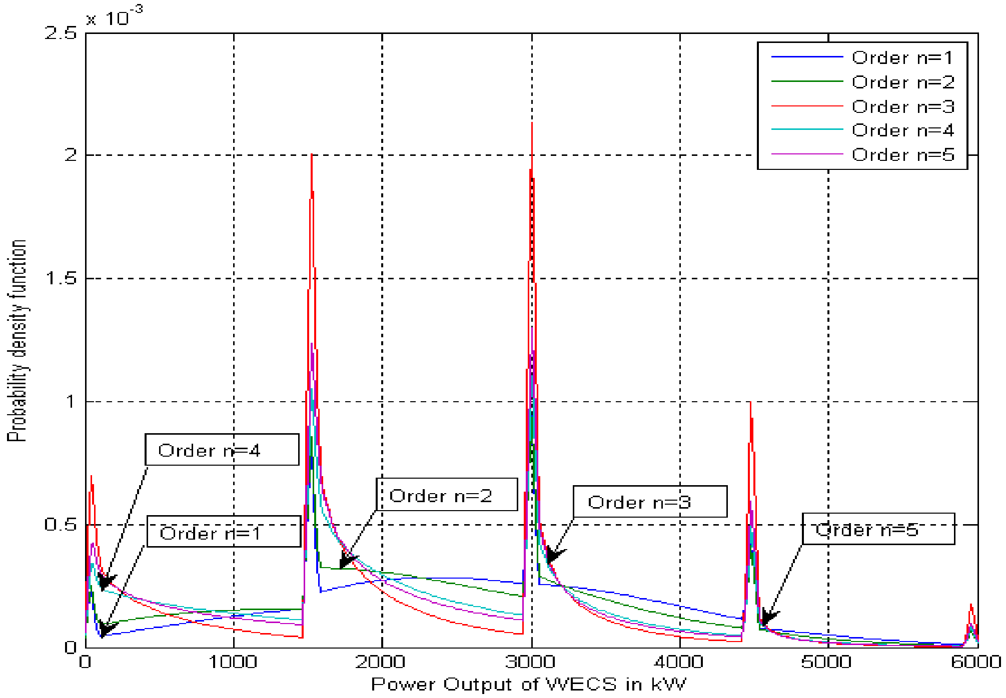


Figure 4.10: Combined power output density function plots of four WECS operating in wind regime-I

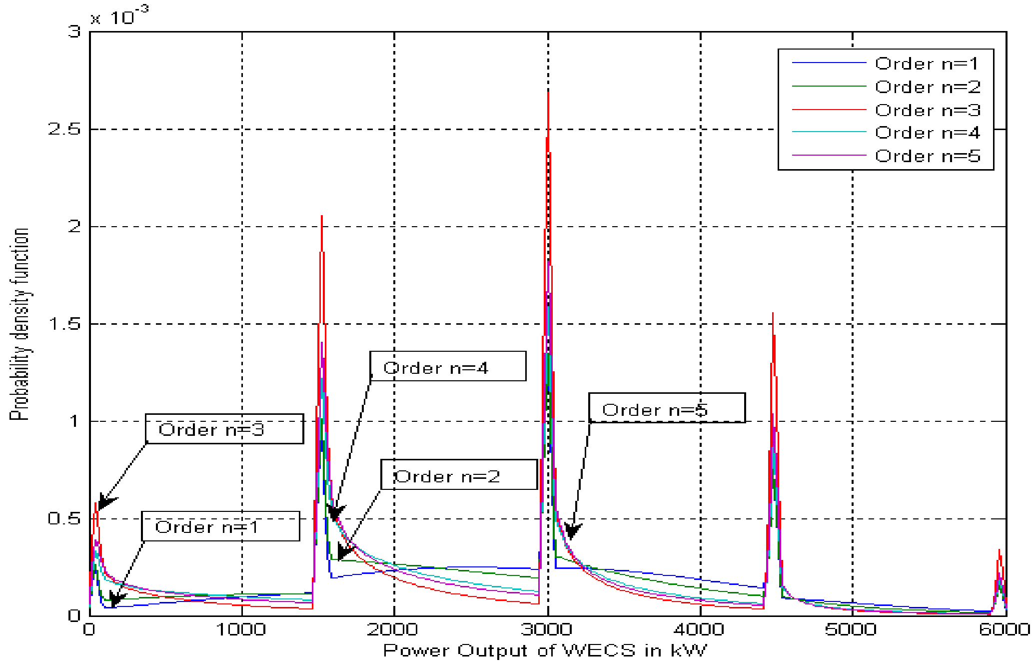


Figure 4.11: Combined power output density function plots of four WECS operating in wind regime-II

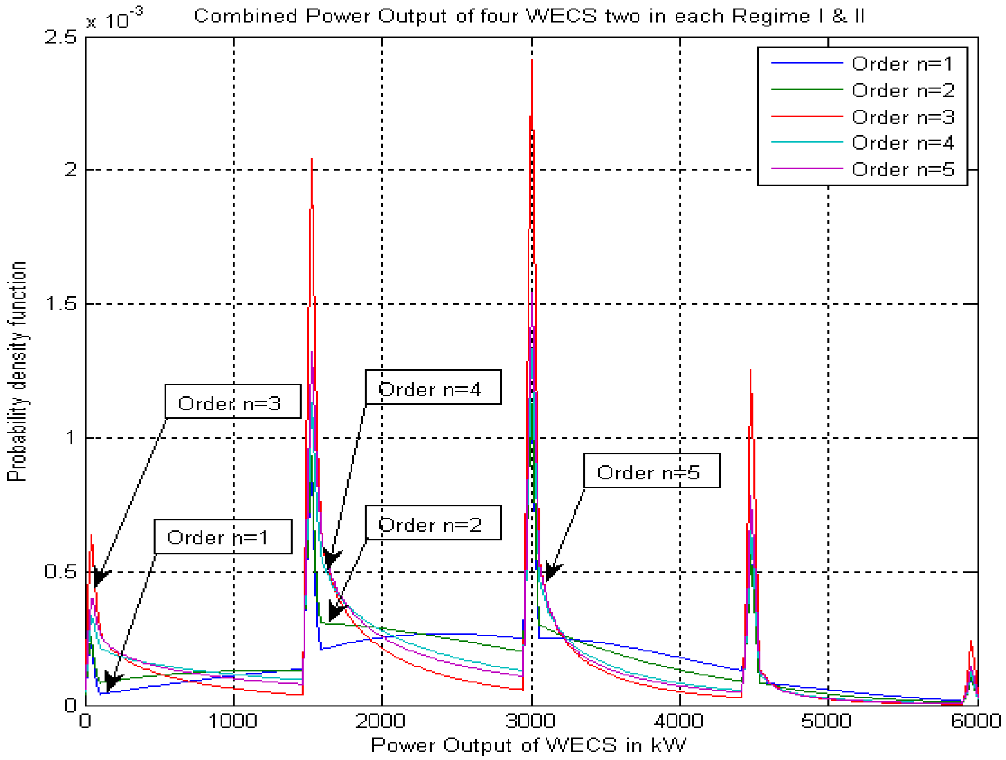


Figure 4.12: Combined power output density function plots of four WECS operating two each in wind regime-I and II

<u>Discussion:</u> All the three cases exhibit five approximate impulse regions located at 0 kW, 1500 kW, 3000 kW, 4500 kW, and 6000 kW power output. The strength of the impulses is a collective function of corresponding wind speeds lying outside the generation mode and within the regulation mode of operation for each WECS. In all the three cases, the probability of power output being 3000 kW is the maximum. The redistribution region is present in between the five impulse regions for different exponent values. However, the impact of redistribution is insignificant and can be regarded as “minor”. The area under all the density functions is confirmed as unity.

4.3.3 **Probability Density Functions for Power Output of Eight WECS:** Similar approach leads to combined probability density functions of power output of eight WECS. Figures 4.13, 4.14 and 4.15 show the density functions for the three cases with eight WECS in wind regime-I, wind regime-II and four each in wind regimes-I and II.

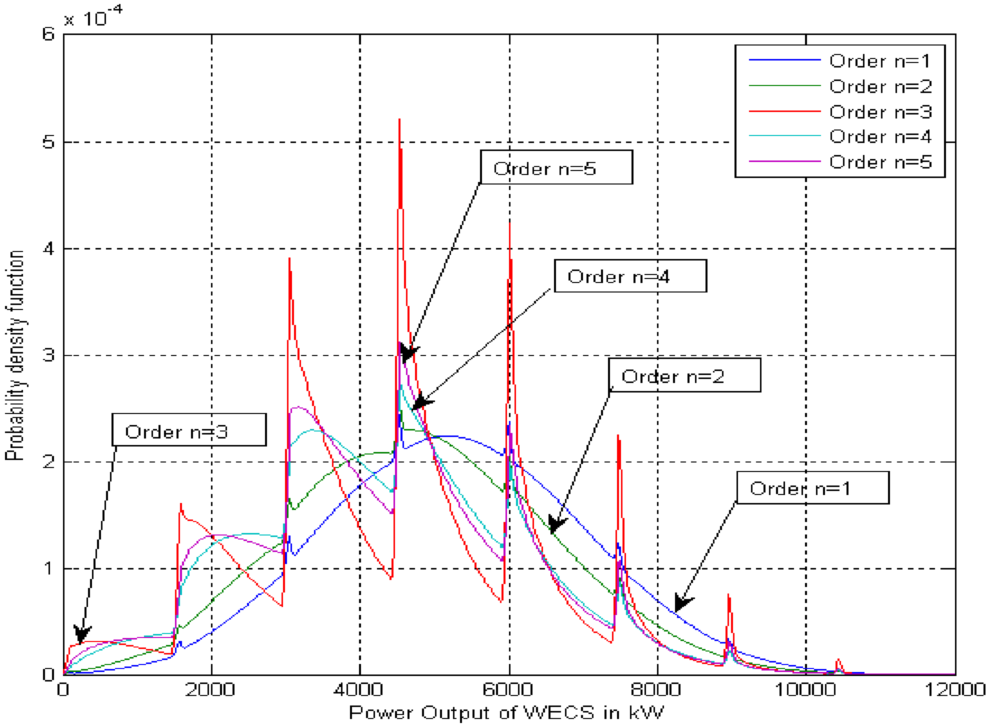


Figure 4.13: Combined power output density function plots of eight WECS operating in wind regime-I

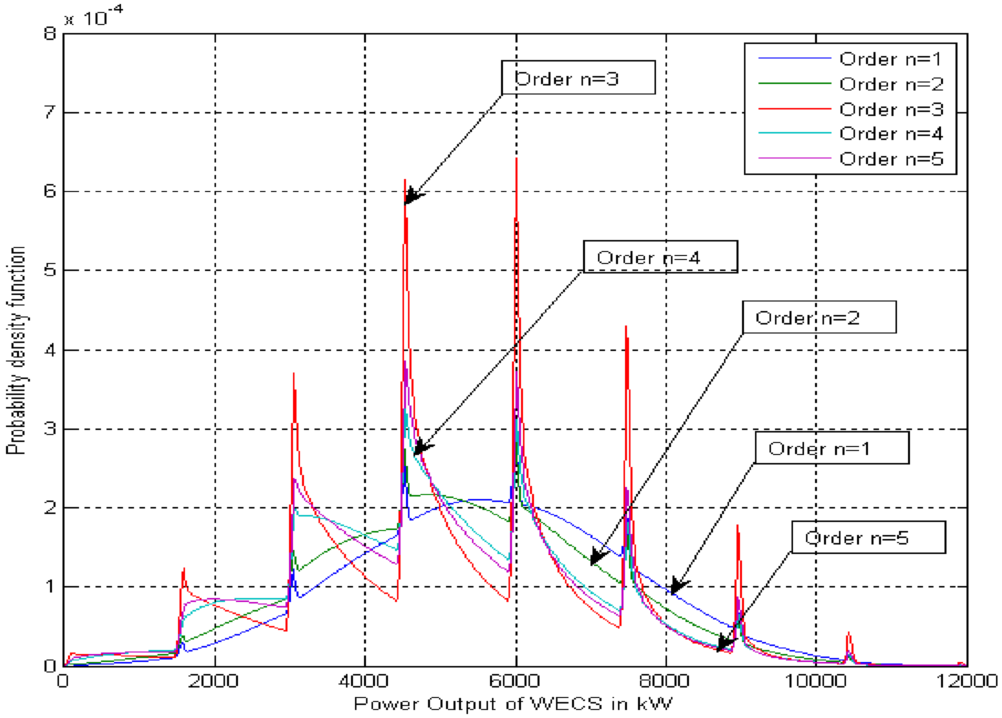


Figure 4.14: Combined power output density function plots of eight WECS operating in wind regime-II

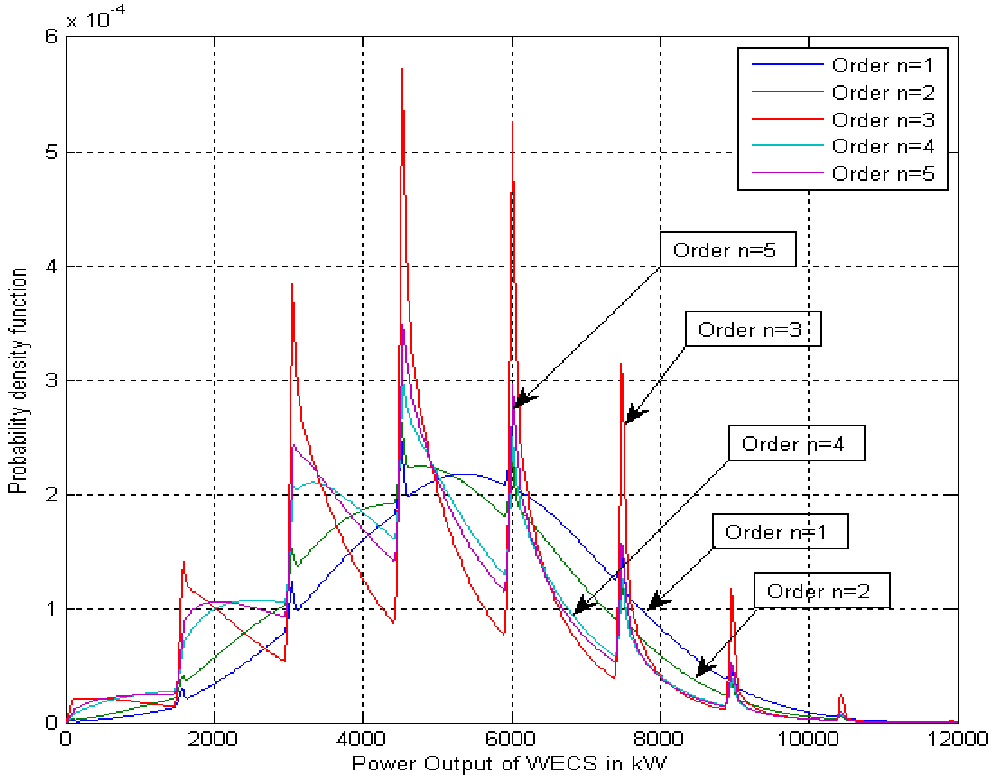


Figure 4.15: Combined power output density function plots of eight WECS operating four each in wind regime-I and II

Discussion: As observed in previous combined density function plots, approximate impulses occur at integral multiples of 1500 kW (i.e. the rating of individual WECS). The critical observation in these density functions is that the redistribution region has become significant and hence the impact of exponent cannot be treated as minor. From the density function plots the maximum probable power outputs for different exponents are easily identifiable. The impulses for different exponents 'n' are distinctly apart and this is also an impact of variability.

4.3.4 Wind Farm-Grid-Load Interfacing

The case presented here is based on a very unique subset of the modern electric grid system. A large wind farm with 2048 WECS (i.e. installed capacity = 3072 MW) is connected to the grid and electrical load via a suitable electrical interface. This electrical interface enables bidirectional flow of energy within this subset under two special conditions. These two conditions for generation-load levels practically realizable are wind farm generation greater than the load and wind farm generation less than the load. In the former case, excess energy is injected into the electric grid and in the latter case deficient energy is drawn for the electric grid. The possibility of both levels being equal has been ignored. Figure 4.16 shows the diagrammatic representation of this type of interface. The objective of this analysis is to fit the model in probabilistic assessment framework to determine energy exchange within the network.

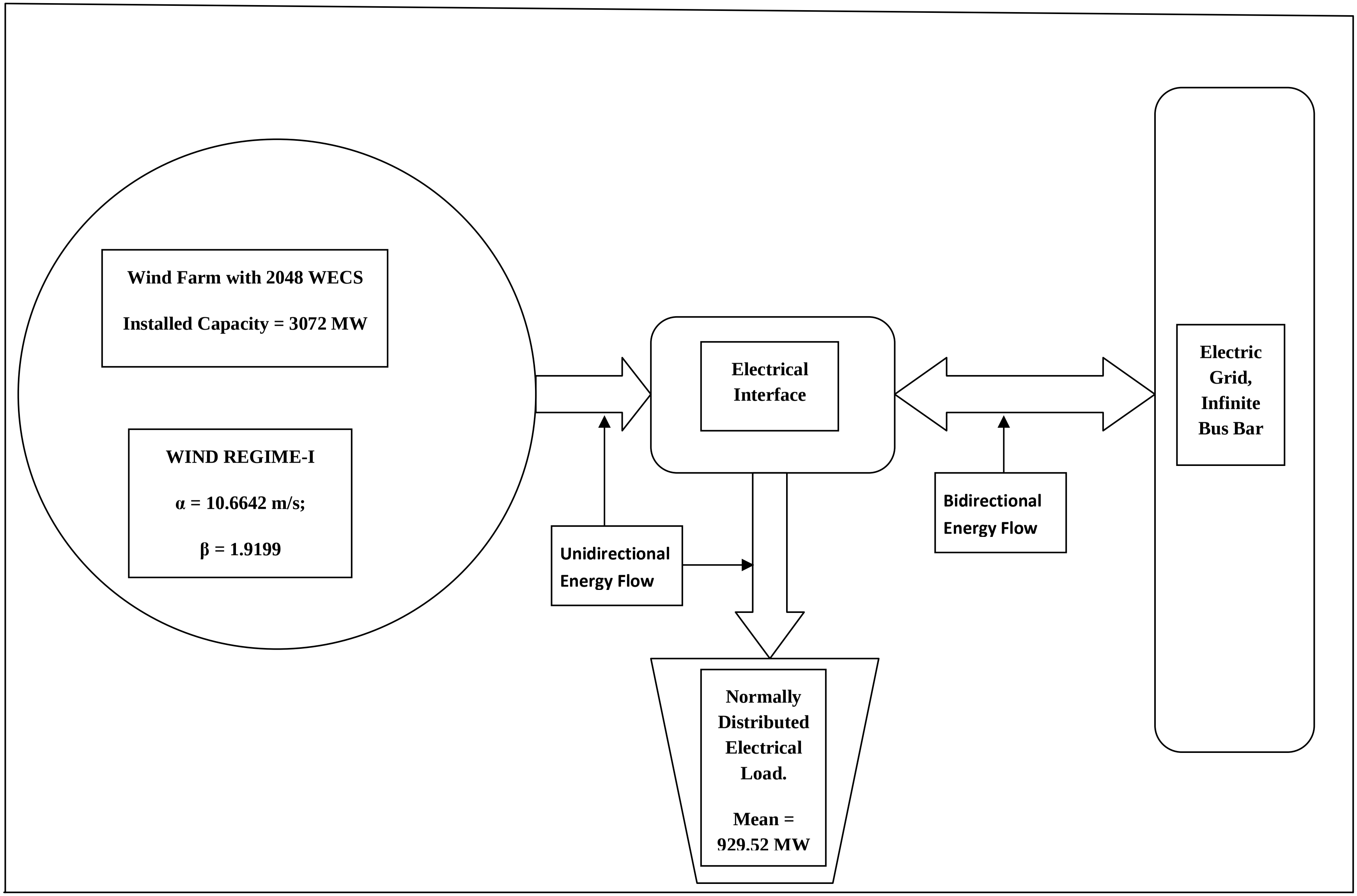


Figure 4.16: Diagrammatic Representation of the interfacing of Large Wind Farm, Electric Grid and Load

4.3.5 **Application of Central Limit Theorem to Model Wind Farm Output:** Central limit theorem deals with approach to normality of a sum of several random variables. The central limit theorem can be stated as: “Let X_1, X_2,. . . be independent random variables, each having mean μ and standard deviation $\sigma > 0$. Let $S_n = X_1 + X_2 + \ldots + X_n$. Then the sum S_n approaches a normal distribution with mean $n\mu$ and variance $n\sigma^2$.” The random variables involved can be continuous, discrete or mixed in nature [27].

For a large scale wind farm, if power output of each WECS is treated as an independent, identically distributed random variable, then central limit theorem will be applicable for the convolution of the individual power output density functions. For the wind farm shown in figure 4.16, there would be 2048 identical and independently operating WECS. Then the combined power output of 2048 WECS i.e. the whole wind farm power output can be treated as a single random variable, which is the resultant of convolution of all power output density functions of individual WECS. As per the central limit theorem and law of large numbers, this density function will be Gaussian in nature; as the number of random variables is large. Corresponding probability density function and probability distribution function plots for exponents n = 1 through 5 for power output of wind farm are shown in figures 4.17 and 4.18 respectively. The distribution function confirms the areas under the density functions are unity and hence they are valid.

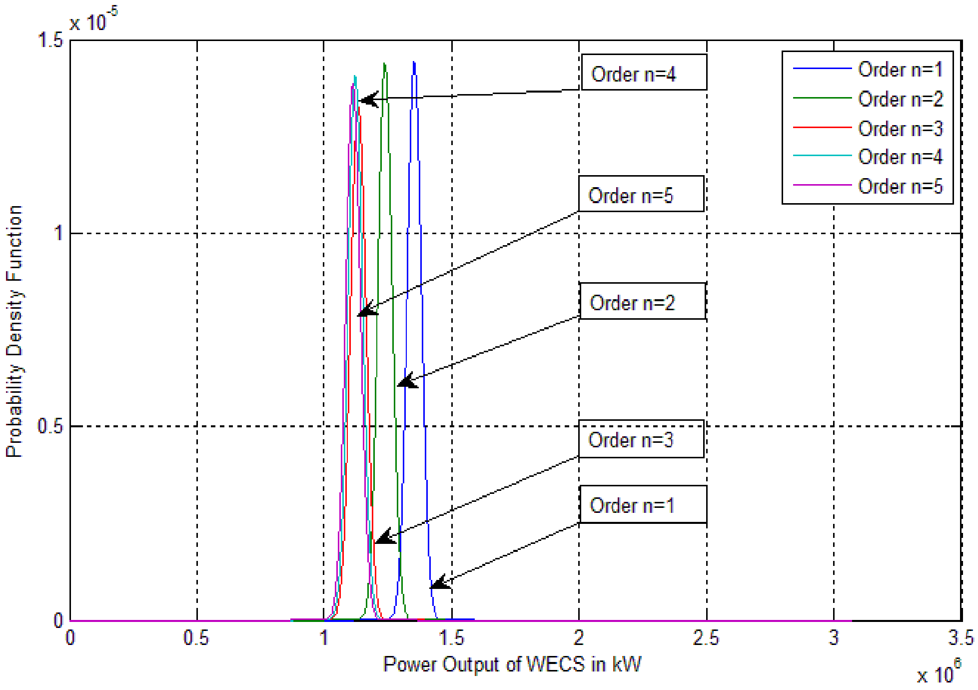


Figure 4.17: Combined power output density function plots of 2048 WECS operating in wind regime-I

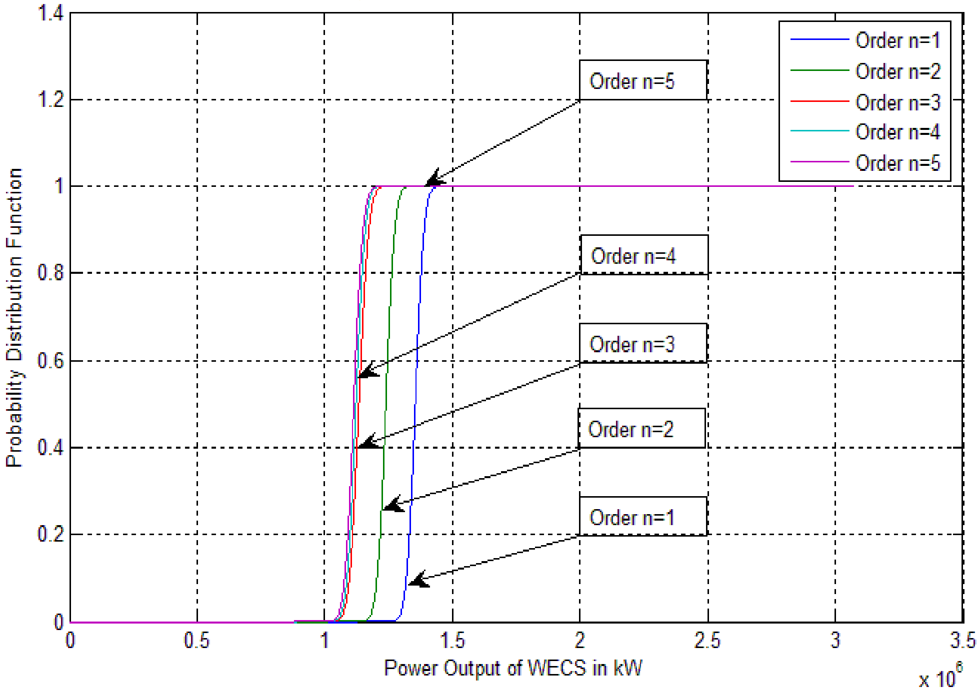


Figure 4.18: Combined power output probability distribution function plots of 2048 WECS operating in wind regime-I

4.4 Load Modeling

Electrical load demands can be modeled in several different ways to suit the type of analysis to be performed. For probabilistic analysis, load demand of a geographical zone or at a strategic node can be treated as a random variable. The distribution for electric load demand is obtained from 10 minute load demand values. From a histogram plot of these readings a suitable smooth curve fitting is performed. It is an established fact that electric load demands follow Gaussian distribution on an annual time scale [28-29]. Load measurements for the year 2008 were obtained from ERCOT database for “North Zone” over a 10 minute scale and were used to obtain the distribution [30]. The histogram plot for these readings with bin width of 20 kW and an ideal, approximated Gaussian density function are shown in figures 4.19 and 4.20 respectively.

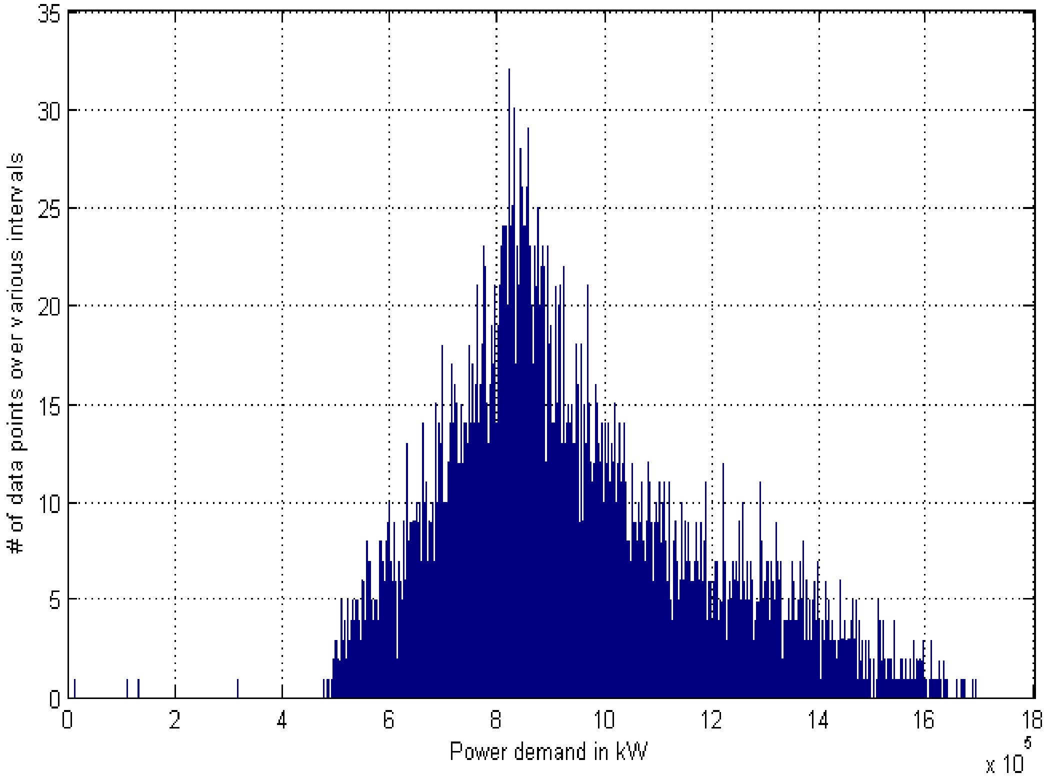


Figure 4.19 Histogram plot for load demand of Northern zone in ERCOT with 20 kW bins

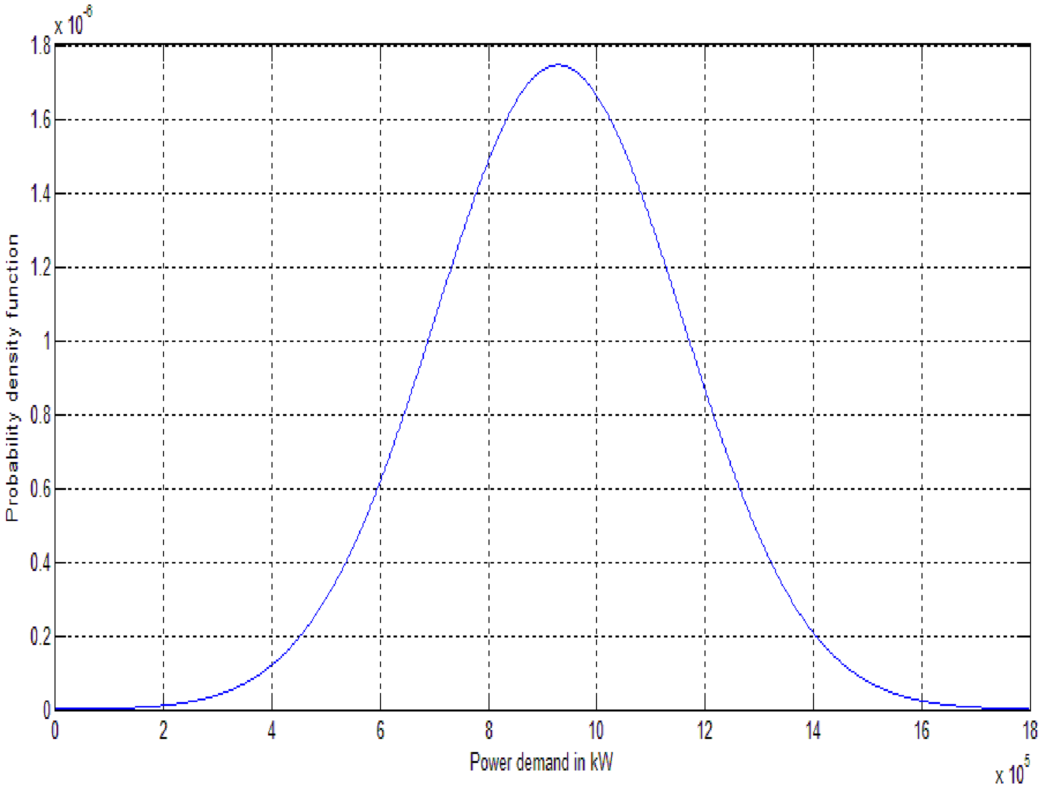


Figure 4.20: Idealized Gaussian load density function plot of load demand of Northern zone in ERCOT

4.5 Resultant Probability Functions for the Grid

The power drawn from or injected into the grid will be a function of the interaction of the wind farm output and electric load. The random variable representing the electric load is subtracted from the random variable representing the combined power output of wind farm by using the convolution theorem to obtain the grid power random variable. Figure 4.21 represents the density and distribution functions of power input to the grid for all 5 exponents.

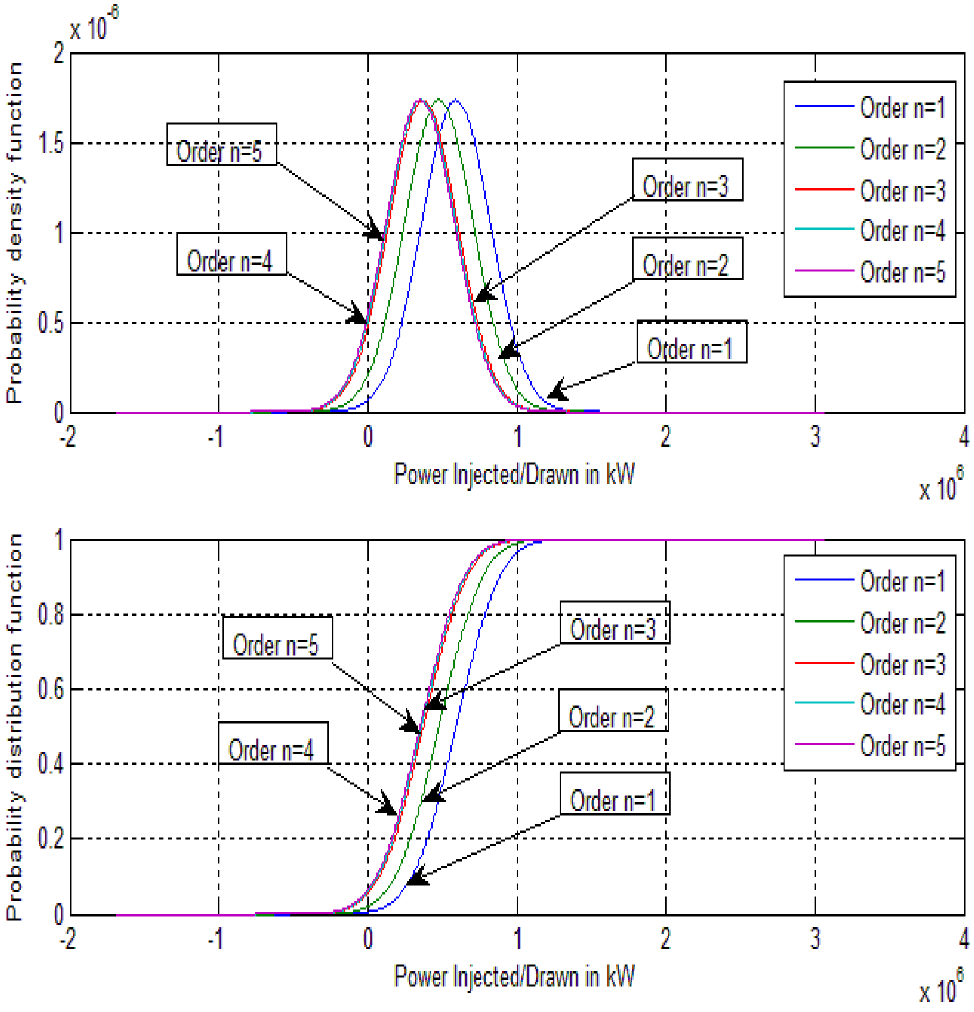


Figure 4.21: Probability density and distribution functions of power associated with the grid in the interaction

The distribution functions for the power associated with the grid are employed to calculate the energy exchanges i.e. energy injected or drawn from the grid to supply the assumed load for the five exponent values. It is worthwhile to note that all the three density functions utilized within the interfacing are modeled over an annual time scale. Also, the load duration curves get modified from the grid perspective as the wind farm supplies a majority of the demand. The power duration curve is a plot of power associated with the grid S(t) and $[1-F_s(S)]T$, where T is the study period. The upper and lower limits for the power duration curve will be $(2048*P_r - L_{min})$ and $- L_{max}$ respectively. The limit $(2048*P_r - L_{min})$ corresponds to the condition of wind farm operating at its rated power and load is minimum, hence it will be the upper limit for power duration curve. The limit $-L_{max}$ corresponds to the condition of wind farm generating zero output and load is maximum, hence it will be the lower limit for power duration curve. The area under the curve within the interval $(2048*P_r - L_{min})$ and 0 will be the energy injected into the grid after supplying the load over the study period. The area enclosed by the curve within the limit $-L_{max}$ and 0 will be the energy drawn from the grid to supply the load over the study period. Typical power duration curve is shown in figure 4.22 indicating energy exchanges E_1 and E_2 which imply energy injected in the grid by the wind farm and energy drawn from the grid to supply the load respectively [31].

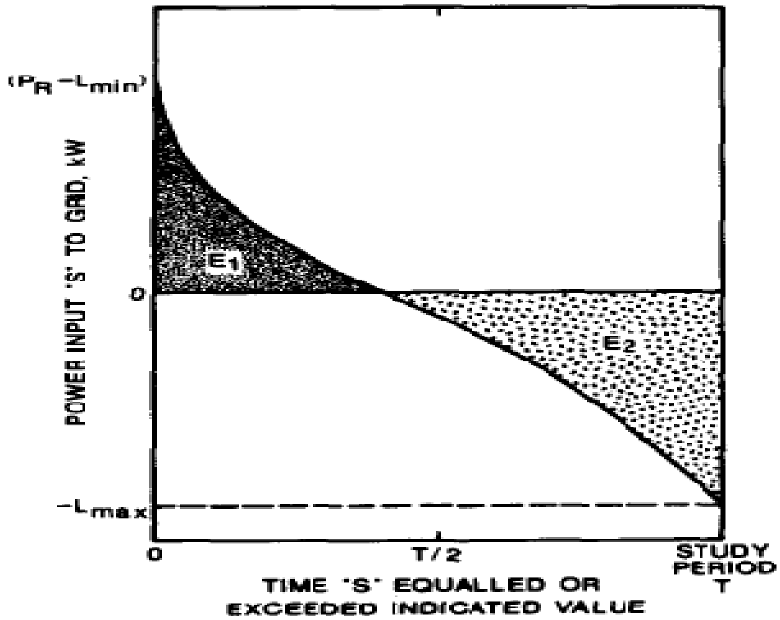


Figure 4.22: Typical power duration curve for the random variable 'power input to the grid' [31]

The values of E_1 and E_2 can be numerically found out by using the equations 4.1 and 4.2 [31]:

$$E_1 = (2048*P_r - L_{min})*T - T*(\int_0^{2048*Pr-Lmin} Fs(S)ds) \tag{4.1}$$

$$E_2 = T*(\int_{-Lmax}^{0} Fs(S)ds) \tag{4.2}$$

where E_1 and E_2 are energy injected into and extracted from the grid respectively in kWh; P_r is the power rating of WECS in kW; L_{min} and L_{max} are the minimum and maximum values of load demand from the data in kW; $F_s(s)$ is the probability distribution function of power associated to the grid; T is the study period in hours.

The power duration curves for the study case for exponents 1 through 5 are shown in figure 4.23.

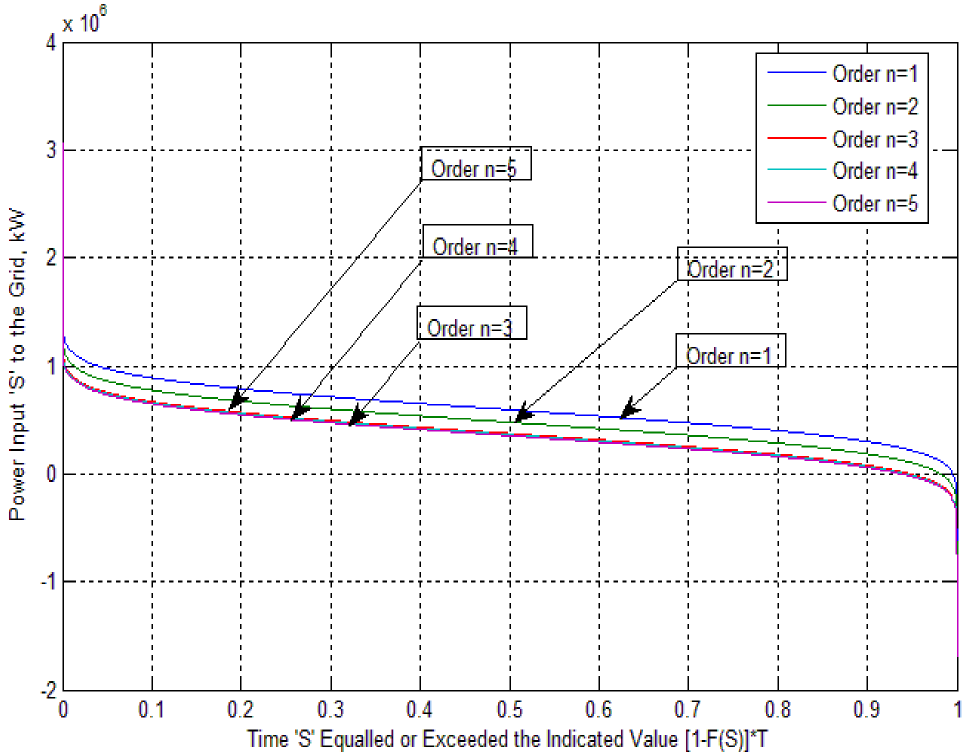


Figure 4.23: Power duration curve for the random variable power input to the grid for the study case

The values of energy injected into the grid by wind farm and drawn from the grid to supply load with the assumed configurations of wind farm and load for different exponents is as given in the table 4.1:

Exponent *'n'* from variable part of output characteristic	**Energy Injected into the Grid (E_1) (kWh)**	**Energy Drawn from the Grid (E_2) (kWh)**
1	4.6631*(10)^9	2.8101*(10)^6
2	3.7720*(10)^9	1.2457*(10)^7
3	2.9735*(10)^9	4.0442*(10)^7
4	2.8779*(10)^9	4.5406*(10)^7
5	2.8121*(10)^9	4.9697*(10)^7

Table: 4.1: Energy exchanges between wind farm and grid to supply load

The significance and trends of the values obtained above will be discussed in the discussions section of Chapter VI.

CHAPTER V

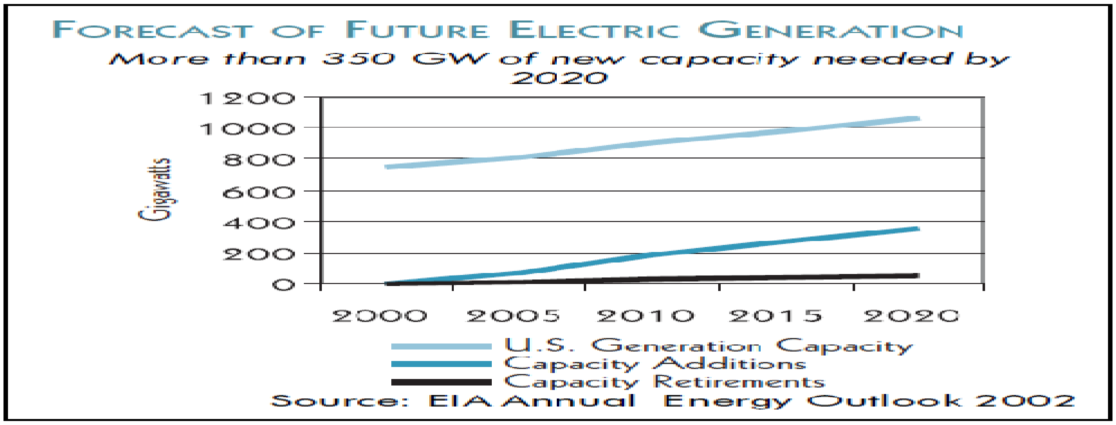
SMART GRID – THE MODERNIZED GRID

5.1 Electric Grid-Past and Present

The birth of electric grid is marked by the first ever dc network with centralized generation, transmission lines and lighting loads in the year 1882 by Thomas Edison in New York City. Edison was a staunch proponent of dc electric networks; whereas Westinghouse promoted the advantages of ac over dc. He set up an ac system network with generation station at Niagara Falls and distribution in nearby cities. The effectiveness of ac networks became obvious and hence dominated the future of electric power grids. History of electricity and its establishment in the U.S. can be marked by the following eras [32]:

a) 1880 – Birth of Electric Power Industry
b) 1901 to 1932 – The Era of Private Utilities
c) 1933 to 1950 – The Emergence of Federal Power
d) 1951 to 1970 – Utility Prosperity
e) 1971 to 1984 – Years of Challenge
f) 1985 to 1990s – “Non-Utility” Growth
g) Present – An Overlooked Network System
h) Future – Modernized and Efficient Energy Network

Electricity sector has played a major role in the economic prosperity of the U.S. as it supported business, commerce and trade, manufacturing houses and even transportation. The economics of this sector indicates astronomical investments in all 3 sectors of generation, transmission and distribution. Gross asset value well exceeds the mark of $800 billion with a split of 60% in generation sector, 30% in distribution sector and 10% in transmission sector. The annual federal electric revenues are approximately $247 billion. More than 10,000 conventional power plants are operated all over the U.S. in the generation sector with additions of 5,600 distributed energy facilities by 2001. The backbone of transmission sector operates at 230 kV with a 157,000 miles long network acting as energy corridors. The national electric network is divided into three sections - Eastern Interconnection, Western Interconnection and Texas Interconnection. Weak dc ties are located at strategic points to connect these systems for energy exchanges. The distribution sector is the most complicated of all, due to the presence of numerous residential and industrial consumers with continuously varying demands. It comprises of the network from substations to consumer meters. The tariff for electricity is a very complex function of numerous network and economic variables; however the average value is 7 around cents per kilowatt-hour [33]. Figure 5.1 shows an extrapolation plot forecasting of future electric generation:



Source: EIA Annual Energy Outlook 2002

Figure 5.1: Forecast of future electric generation for the U.S. electricity sector [33]

Major causes of the era “1971 to 1984 – Years of Challenges” were the Northeast Blackout in 1965, Clean Air Act of 1970, Arab Oil Embargo in 1973-74, Three Mile Island accident in 1979 and rising inflation. This led to the development of seemingly effective regulatory and federal policies to reform the electricity sector. From the technical perspective, ensuring a higher reliability, acceptable power quality and reducing blackouts and hence the associated economic losses, an increase in generation capacity was the guiding principle for system planning and development. This is complemented by the fact that only 60% of the asset valuation belongs to the generation sector. Investment trends in generation and distribution sectors have been rising due to such policies whereas transmission investment stood still. Regular congestions and bottlenecks at the corridors are reported leading to higher costs of average electricity and losses scaling to as high as $180 billion dollars annually [33]. Thus infrastructure and investment wise the transmission sector remained a largely unimproved and underdeveloped sector.

5.2 Smart Grid

The term “Smart Grid” has been a buzz word in the power industry for about a decade now. It is perceived as a solution to the numerous problems faced by consumers, system operators, and utilities while dealing with electricity consumption and trading. In a technical context, it has numerous definitions in regards to its configuration, implementation and operation. Configuration of Smart Grid is one of the most crucial aspects of the system and it is still largely under development.

Definition: A Smart Grid is defined as a broad range of solutions that optimize the energy value chain [34].

Current electric grid system performs some of these to a large extent and satisfies demands under manual supervision. This indicates the current grid is smart but not selfgoverning. In our context the term smart grid actually refers to a modernized, self-sufficient and an evolved smarter grid.

5.2.1 Technical Perspective: Researchers and academicians are involved actively to define smart grid, its configurations and operational methodologies. It is a wide philosophy rather than a specific algorithm of dealing with power systems. The realization of a complete smart grid is a very long term process and involves a unique blend of technologies such as communications, measurements and sensing, advanced control systems, storage systems, artificial intelligence, and cyber security. Such a myriad of technologies have to be interactive amongst each other and with the electric grid to function as a single network. The subsections that follow discuss such technologies and their roles in the future and modernized electric grid. As mentioned earlier, all these technologies have been intuitively chosen and are experimentally tried on micro networks (often referred as micro-grids) so as to obtain a perfect configuration. Two subsections are devoted smart grid's technical perspective - 1) Smart Transmission Systems and 2) Smart Distribution Systems. Descriptions of their infrastructure and operational characteristics are provided in sections 5.2.2 and 5.2.3 respectively.

5.2.2 Smart Transmission Systems: Transmission system acts as the backbone of any electric grid by facilitating electricity transfer from generation stations to the end users. They operate under high voltage and low current levels so as to maintain low transmission losses. Losses occurring during congestion periods leading to bottlenecks in the system are the most critical. It is estimated that the average load factor in the U.S. is about 55%; it implies an overall utilization of approximately half of the system's resources [33]. Another inference drawn from patterns of congestion and bottlenecks is that they occur during specific times of the day at specific points influenced by large commercial and industrial load demands. Except for these overloading patterns of lines and power equipments, the rest of the operational cycle is fairly acceptable. In addition to the electrical losses congestion also accelerates the ageing of transmission lines, high voltage insulators and equipments. Instead of transmission expansion planning the existing transmission requires modernization in terms of sensors, measurements, rapid communication, instant decision making and a stronger tie up amongst the bulk interconnections. Various ways of transforming the transmission lines have been put forth in the literature under the scope of “Smart Transmission Systems” to empower it to function at higher efficiencies [35-36]. The configuration is also alternatively named as Controllable Energy Flow (CEF) which enables the operating authorities to exercise greater control over the energy flow in the system. With greater renewable energy penetrations, transmission systems should be robust to handle the variability introduced and maintain transmission standards. The concept of CEF will be a combined result of usage of specific power flows and FACTS (Flexible AC Transmissions System) devices [35]. Specific power flows imply using lightly loaded lines for renewable energy transmission rather than others and successfully accommodating the renewable portfolio mandates in Smart Transmission Systems. A detailed study of the necessary set of variables of the transmission system and the necessary data processors is provided in [36]. It emphasizes the importance of phasor measurements and information provided by them. Data exchanges between substations and far off data centers create latency as communication period and decision time have large magnitudes. The paper proposes an efficient way of treating these measurements by introducing Phasor Data Concentrators (PDC) at strategic locations. Also, selectively communicating to the central data center variables measured at the substation units by a high speed network such as fiber optics will be highly helpful. Restricting less critical measurements to a Local Area Network (LAN) and local decision making will be beneficial due to overwhelming volumes of data generation at substations. Most of the configurations proposed as of now are either in simulation or minor experimental stages and hence are yet to be established for practical implementation.

5.2.3 Smart Distribution Systems: Distribution systems are networks formed by residential, industrial and commercial consumers acting as load sinks. The voltage levels at which they are served varies widely. Normally, industrial and commercial consumers are supplied through sub-transmission networks. Overall grid resource usage is about half as the average load factor of the grid is 55% in the U.S. However, large transmission losses, hence economic losses, due to transmission congestion and bottlenecks result over transmission corridors. These facts certainly appear to be contradictory, but in fact they are not. Observation of load demand curves reveal that during specific times of the day demands are very high; while during the rest of the hours they are relatively low. The high load demands during peak load hours cause transmission congestion and bottlenecks, whereas low load demands during off-peak hours reduce the average load factor.

Industrial loads have a very peculiar load demand pattern and are mostly uniform on a daily or even weekly time scale. Implementations of energy conservation and saving strategies in industries have been reinforced since long; leaving less scope to alter their load duration curves. However, for domestic and commercial consumers a wide array of measures can be implemented to modify their load demands and still manage to satisfy their needs. Suitable load management schemes, if executed at distribution level, will lead to significant peak demand shifts in the system. Proper hardware controls and communication networks need to be integrated to the already existing electric circuits in homes and also operate in sync with the supply side. A generalized view of a future smart home is shown in figure 5.2:

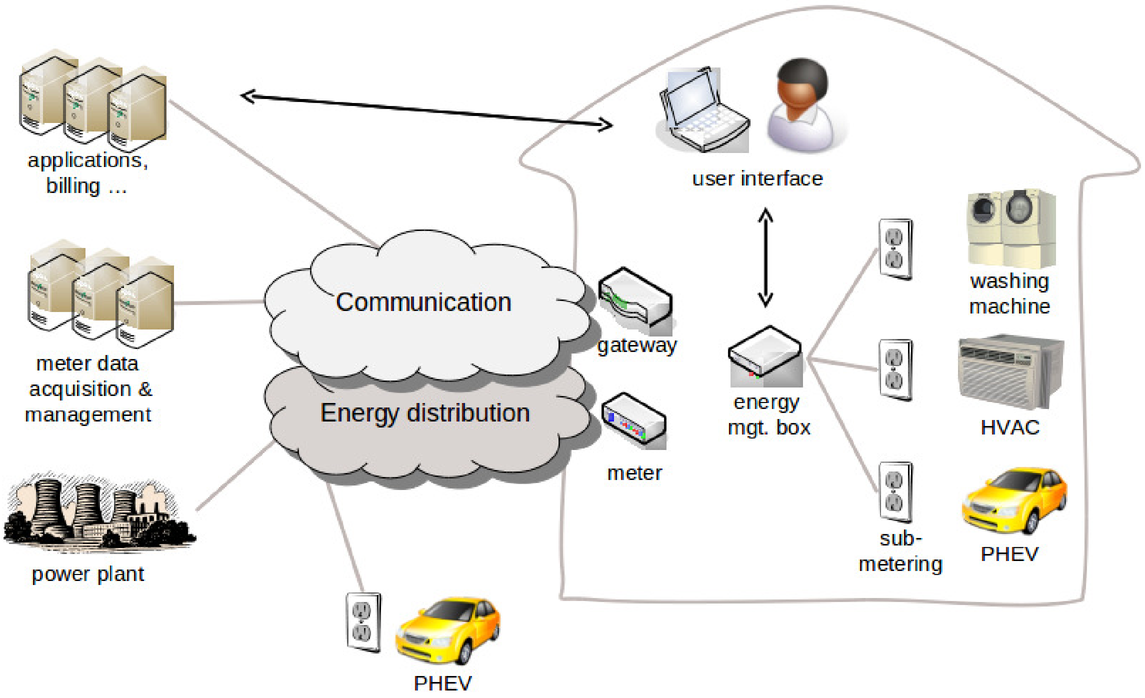


Figure 5.2: General home network architecture and components involved within the network [37].

The key to successful execution of these ideas on a residential level will be flexibility of management. Increasing levels of penetration of distributed resources is expected due to ever increasing photovoltaic installations over roofs, small wind turbines and plug in hybrid electric vehicles (PHEV). They will require two way communication and intelligent controller to moderate successful inter-operability. Another requirement will be a communication network for the appliances within the home and a different communication network between the home and the distribution substation or local data center. Smart home appliances have already been introduced in the market to work in congruence and wisely in such an energy conscious environment. Finally, the most critical player is the user interface, which should provide easy access to data such as energy units consumed, current rates and its projections, and ability to control the scheduling of home appliances. Advanced level of technologies such as artificial intelligence, control systems, and communications will come to the aid to create a smarter home in the real sense.

5.3 Ultimate Objectives

The modernized and energy optimized electric grid, the smart grid or a smarter grid, will clearly be a fairly complicated system. The volume of data generated is itself a great challenge with regards to acquisition, storage, decision making and even discarding. Another major challenge presented is the latency in transporting data and in the decision making process. Internet will play the most important role for data transfer within the system and also for customer oriented interfacing. In general, a set of ideas and well defined objectives if fulfilled by the upgraded network can be termed smart grid. This set of well-defined objectives for the modernized grid is as enumerated below [38]:

1. Intelligent: The modernized grid should be able to sense overloading conditions a-priori to avoid potential black outs. Additionally, it should be able to execute regular and emergency maneuvers as per the existing and expected conditions with minimal or even no human intervention.
2. Efficient: Researchers have expressed opinions that existing energy infrastructure and resources are sufficient to supply the current and near future demands. However, this will require utilizing the available infrastructure and resources in an efficient and optimum manner. Additional infrastructure to modernize will be required to increase efficiency, and integrate renewable generation.
3. Flexible: The grid must be flexible enough to absorb energy from potential Distributed Energy Resources (DER) of any magnitude such as wind farms, solar power plants and hydroelectric power plants. With residential installations, energy might be injected at the distribution level and hence appropriate credits should be allocated. Key players at the distribution level will be small wind turbines, roof top solar (PV) panels, and plug in hybrid vehicles (PHEV).

4. Motivating: Consumers should be provided with real time information on price, their consumption levels, monthly consumption, and scope for saving. The biggest motivating factor of scope of saving will lead to control of their energy consumption. This will create a favorable environment for the utilities and regulators to effectively implement smart grid policies.
5. Opportunistic: It should provide a greater scope for consumers to interact with the grid easily, often termed as “plug and play”. A PHEV is an example of this feature. Consumers charge their PHEVs during night time at low loads (and hence low tariffs) and discharge into the grid during day time for economic benefits. It assists the utilities in increasing loads during off-peak periods and supplying the loads during peak periods. PHEVs are environmental friendly as well.
6. Quality Oriented: With a multitude of objectives and options, the grid should provide consumers electric power according to national standards. Power electronics will play a major role in avoiding ripples, voltage sags and flicker and maintain desired power quality in a complex smart grid environment with DERs.
7. Resilient: An over friendly grid needs to be protected at all levels of operation against natural disasters as well as willful human attacks. Data security and ultra-secured communication lines are absolutely essential to accomplish this objective.
8. Truly Green: Reduction of environmental impacts and harmful gas footprints is also an important objective of the smart grid. Flexibility will provide a greater platform for the green technologies to generate electricity and make it available for consumption.

5.4 Demand Side Management

“Demand Side Management (DSM) refers to any activity adopted by an electric utility that ultimately changes the utility system’s load curve” [39]. It alters the shape, time pattern and magnitude of the load curves for the system. Desirable load duration curves can be obtained by implementing proper DSM strategies to operate the grid in an optimum manner. Examples of such strategies are: peak clipping, load shifting, valley filling, energy conservation, flexible load shape and additional energy sales [40]. A pictorial representation of these alterations is shown in figure 5.3:

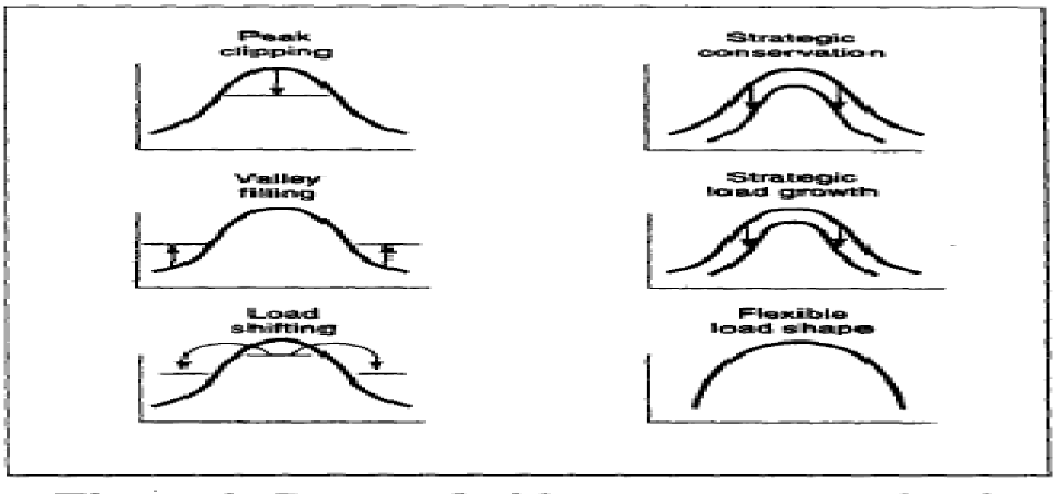


Figure 5.3: Illustrations for Demand Side Management load shape curves [41].

Till recent times, DSM objectives were implemented only on a very minor scale. With the dawn of the smart grid era it will gain greater interest and will be effective in altering the overall load duration curves leading to an optimum operating scenario. With adequate energy storage, demand response, and PHEVs the ideal net load profile could be perfectly flat. The grid operation range will be close to the peak loading conditions and will also scale up over time. This needs to be backed up with other essential infrastructure and coordinated operation within smart grid to avoid endangering reliability standards. However, ample planning and construction period will be available to counter such issues of near peak operation projected for the future [42].

5.5 Analytical Treatment for Modified Power Duration Curves

As discussed in section 5.4, the ideal load duration curve will be flat for a smart grid with the incorporation of elements such as adequate energy storage, demand response and PHEVs. A practical modified load demand curve will be an outcome of stringent DSM techniques reinforced with other smart grid functionalities. The load model explained in section 4.4 was assumed to follow normal distribution with a large standard deviation value. The modified load demand is assumed to follow a uniform distribution with upper and lower limits equal to 110% and 90% of the mean of the idealized Gaussian distribution. Appropriate DSM techniques are easily identifiable to effect such a change in the load demand. The modified uniform load density function plot is shown in figure 5.4. Analytical treatment similar to that in section 4.5 is performed for a flattened load density function. Figure 5.5 shows the power duration curve for the grid power random variable for wind farm supplying load with uniform distribution. Table 5.1 shows the energy injected and drawn from the smart grid as the modified load is being supplied. The most important observation here is area $E_2 = 0$ which implies that no energy is drawn from the grid to supply the load.

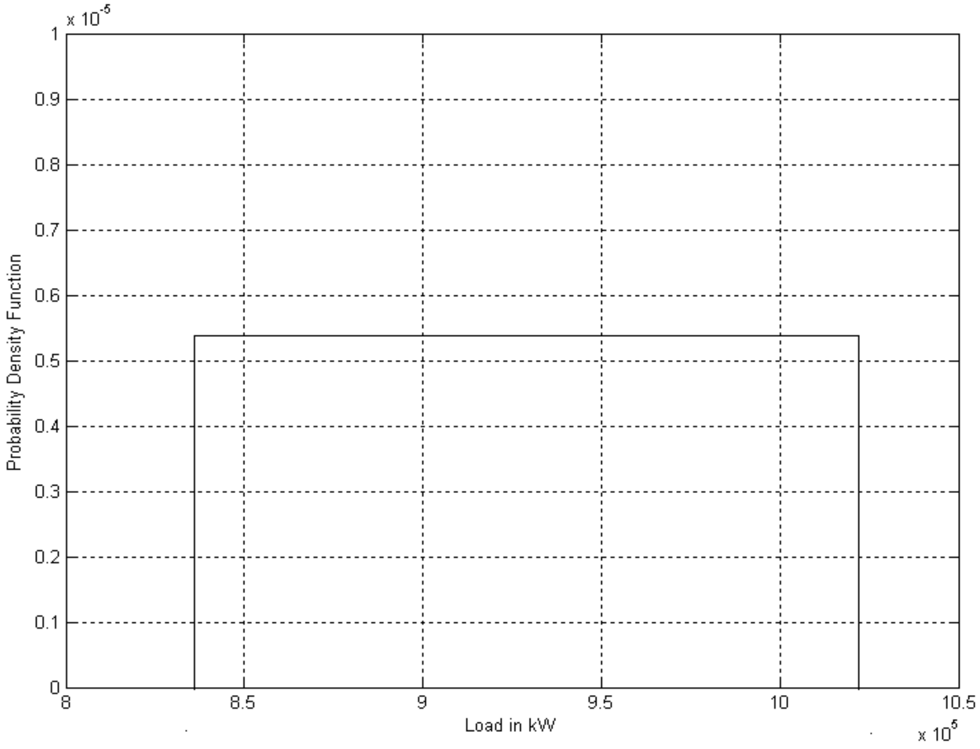


Figure 5.4: Uniform load density function for load demand in smart grid under DSM

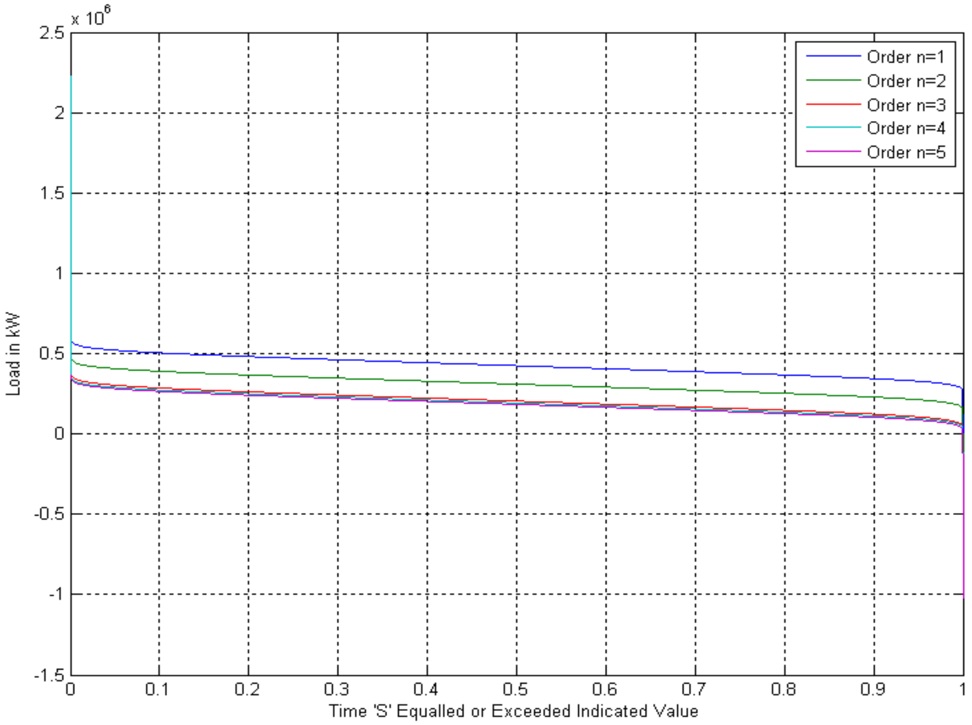


Figure 5.5: Modified power duration curves for the power input to the smart grid

Exponent '*n*' from variable part of output characteristic	**Energy Injected in the Smart Grid (E_1) (kWh)**	**Energy Drawn from the Smart Grid (E_2) (kWh)**
1	3.3348*(10)^9	0
2	2.4334*(10)^9	0
3	1.6068*(10)^9	0
4	1.5147*(10)^9	0
5	1.4447*(10)^9	0

Table 5.1: Energy exchanges between wind farm and grid to supply uniformly distributed load

Further details on power duration curves and energy injected into and drawn from the smart grid are discussed in the next chapter.

CHAPTER VI

DISCUSSION OF RESULTS

Four important results from the study are discussed in this chapter. They are primarily concerned with the impact of the exponent ‘n’ on the interfacing and energy exchanges for large wind penetrations. Results for both Gaussian and Uniformly distributed loads are discussed.

6.1 Overall impact of the exponent ‘n’ in the WECS power output pdf

The impact of the exponent ‘n’ on the combined probability density function plots for power output of WECS varies with the number of WECS involved. From the plots and discussion provided in sections 4.2 and 4.3, the impact of exponent can be treated as “minor” for the combined power output pdf of a small number of WECS. The impact begins to be significant as the number of WECS being added increases such that it leads to five distinct Gaussian pdfs for the five exponents. The combined pdf of 2048 WECS for the five exponents are five distinct Gaussian density functions shown in figure 4.17. The standard deviation for all the five Gaussian pdfs is constant whereas the mean decreases steadily as the exponent value increases from 1 through 5. The mean values lie in the range of 1354 MW and 1113.5 MW. This clearly signifies the impact of the exponent value on the combined pdf for power output of WECS in large wind farms. The exponent n=1 has the largest value of mean for the source Gaussian density function and hence appears to be most beneficial over other values.

6.2 Power Duration Curves and Wind Energy Penetration

Power duration plot for the power associated with the grid is basically an alternate way of presenting the information provided by its distribution function. This plot easily helps identify and even gauge the energy exchange between the interfacing elements with the grid. Power duration curves are observed to follow an interesting pattern with both the load distribution models. As wind penetration increases in the grid the power duration curve flattens. Power duration curves for wind penetration values of 128 MW, 256 MW, 512 MW, and 1024 MW are shown in figures 6.1 through 6.5 respectively for both load models and all five exponent values.

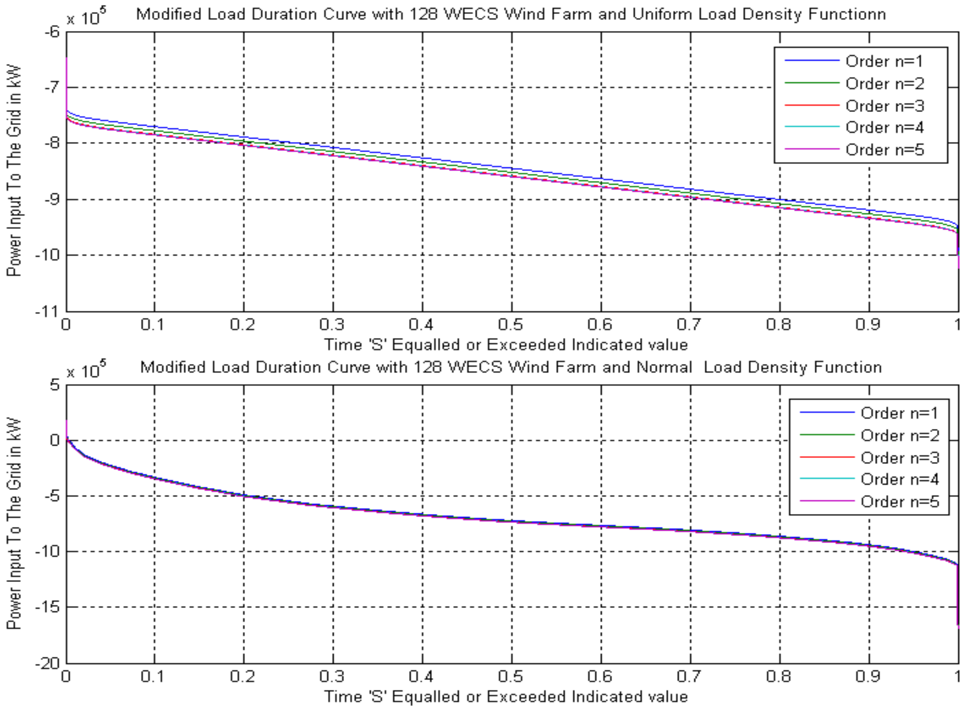


Figure 6.1: Load flattening concept for power duration curves with a wind farm comprising of 128 WECS

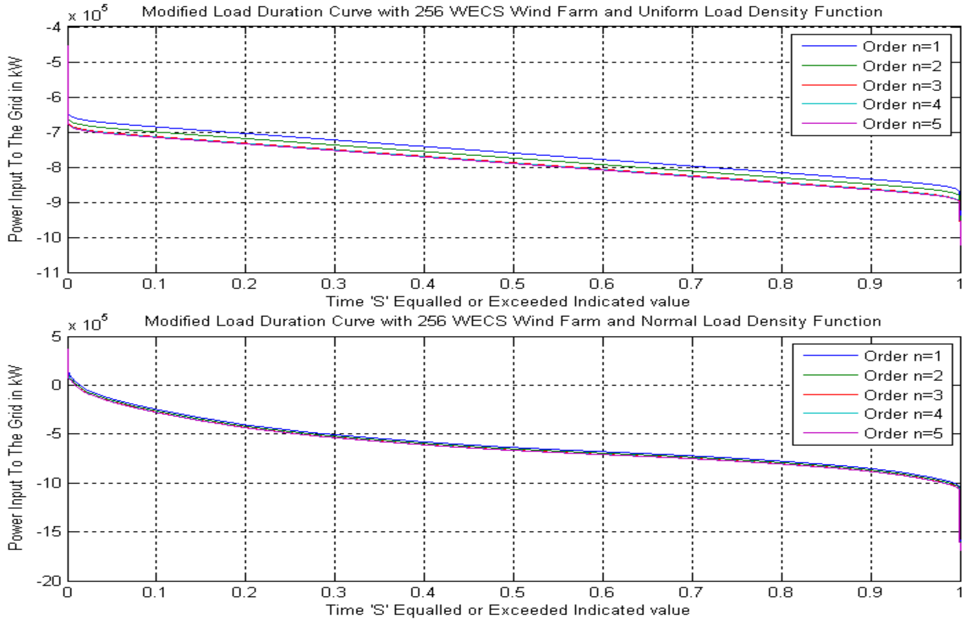


Figure 6.2: Load flattening concept for power duration curves with a wind farm comprising of 256 WECS

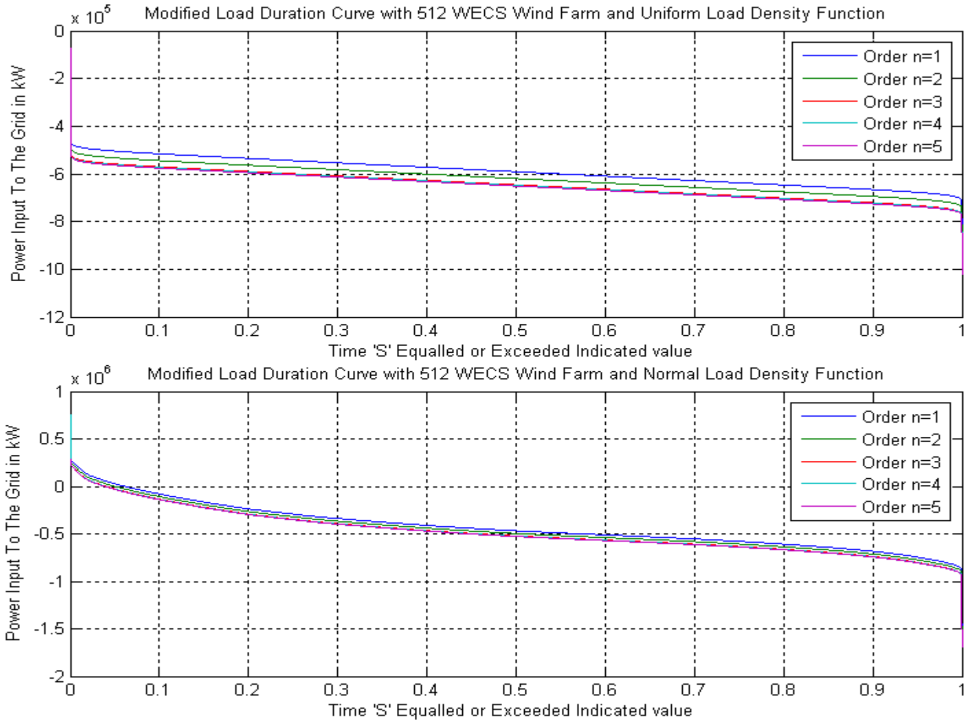


Figure 6.3: Load flattening concept for power duration curves with a wind farm comprising of 512 WECS

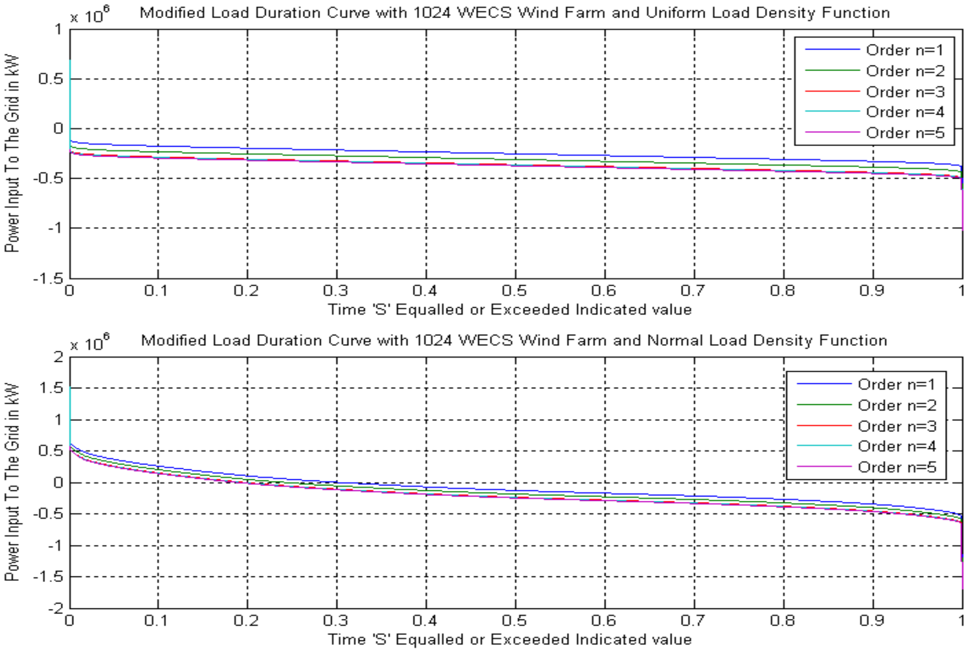


Figure 6.4: Load flattening concept for power duration curves with a wind farm comprising of 1024 WECS

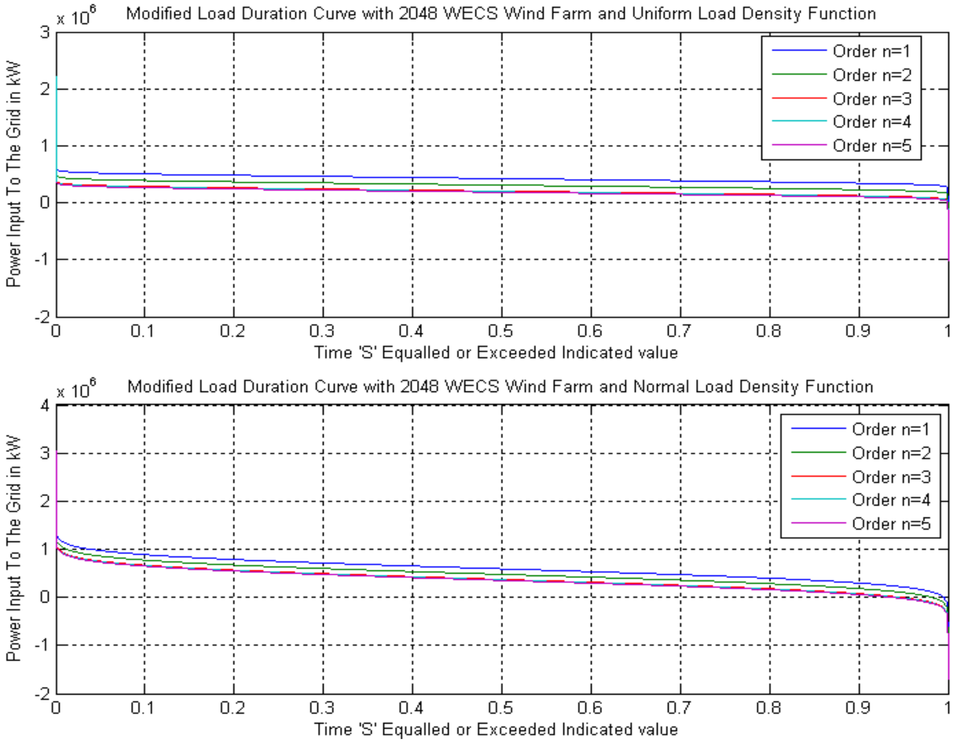


Figure 6.5: Load flattening concept for power duration curves with a wind farm comprising of 2048 WECS

Another important observation is that for any given configuration of the wind farm, the resultant load duration curve while supplying load with a uniform density function is flatter as compared to the one while supplying load with a Gaussian density function. Flattening of power duration curves is a one of the objectives of the future electric grids to facilitate system planning and optimum operation. In a way, if DSM techniques are complemented with other smart grid functionalities, successful assimilation of large scale wind energy penetration will be more flexible.

6.3 Energy Exchange Trends for Current Grid

This section discusses the trends observed for the energy injected into and energy drawn from the grid to supply a Gaussian load connected to the wind farm with an installed capacity of 3072 MW. The supply and demand functions both are Gaussian, and hence the resultant grid power will also be Gaussian. The resultant grid power pdf is calculated using the convolution theorem. Figures 6.6 and 6.7 illustrate the trends of energy injected into and drawn from the grid for supplying a Gaussian load respectively:

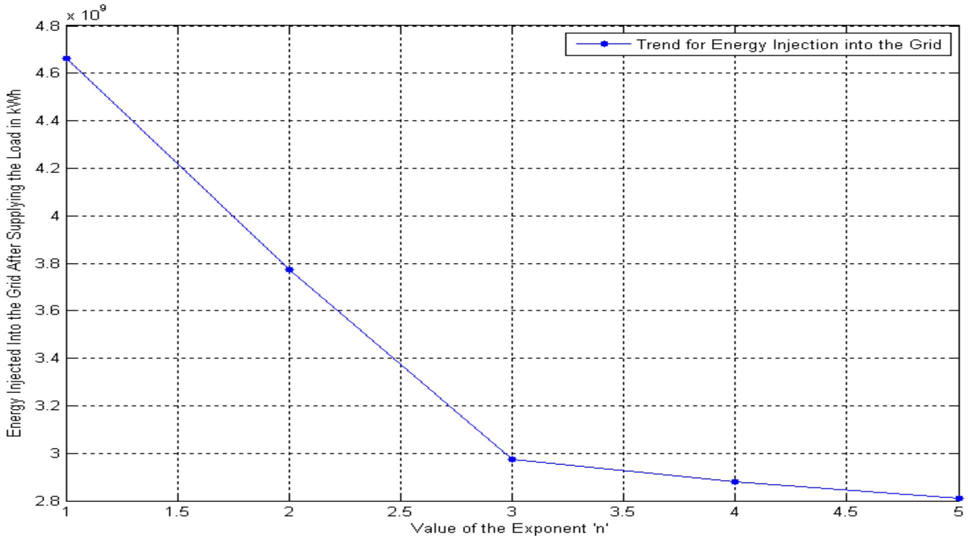


Figure 6.6: Trend for energy injected into the grid by the wind farm after supplying the Gaussian load

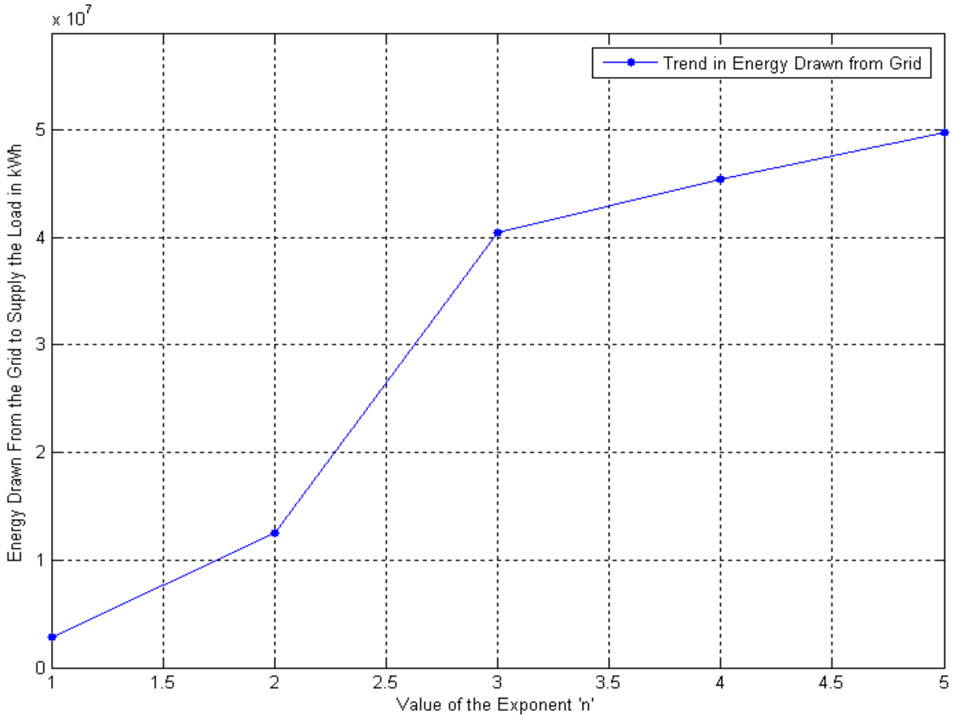


Figure 6.7: Trend for energy drawn from the grid by the wind farm to supply the Gaussian load

A constant reduction in the energy injected into the grid is observed in figure 6.6 as the exponent value increases from 1 to 5. This is obtained from the areas ‘E_1’ depicting energy injections in figure 4.23; which has a larger value for the plot with exponent n=1 and then reduces with an increase in the value of the exponent. Similarly, the areas ‘E_2’ depicting energy drawn from the grid to supply the load has lower value for the plot with exponent n=1 and then increases with an increase in the value of the exponent. It can be inferred that a significant part of the Gaussian load is being supplied by the grid as well and a lower value of exponent ‘n’ is preferable over others.

6.4 Energy Exchange Trends for a Smarter Grid

A smart grid environment that modifies the load towards uniform distribution supplied by the wind farm leads to a near peak operation. Though it raises reliability concerns due to near peak operation, the current behavior and future expansion are accurately predictable. This provides ample time for system expansion in terms of generation resource addition as well as transmission expansion. The source pdf for the power output of the wind farm is Gaussian and the load demand is uniformly distributed over a fixed range. Resultant grid power is a quasi-uniform distribution with smeared out edges as shown in figure 6.8. From figure 5.5 it is observed that energy is only injected into the grid and no energy is drawn from it to supply the load. This is certainly an advantage over the energy drawn for supplying Gaussian load that has non-zero energy drawn from the grid. Energy injected follows a similar trend as discussed in section 6.3 with maximum energy injected by the curve with exponent n=1 which reduces with an increase in exponent value. The trend is plotted in figure 6.9:

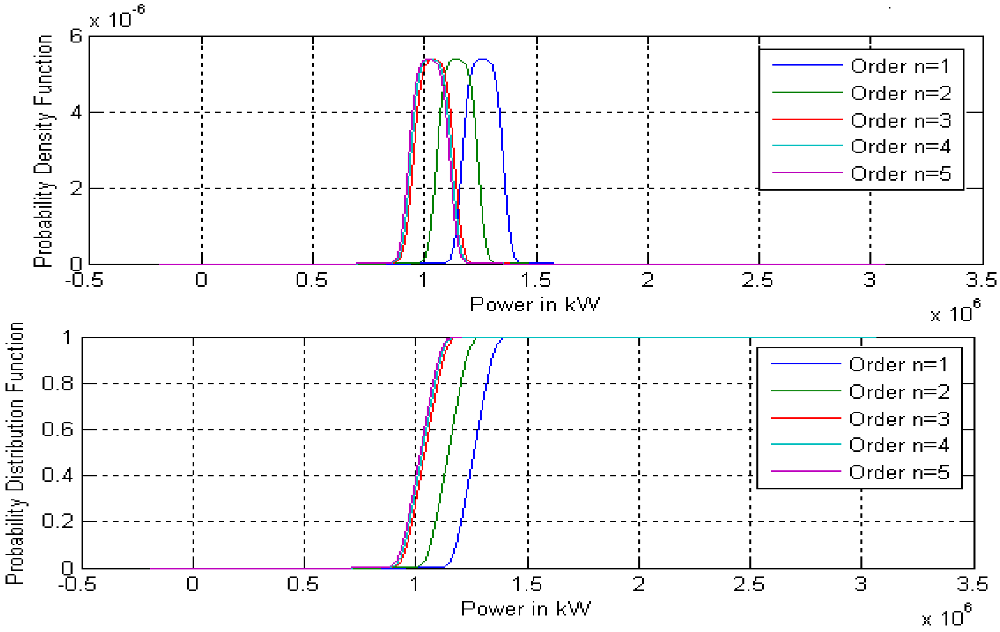


Figure 6.8: Quasi-Uniform density and distribution with smeared edges for the grid power in smart grid environment

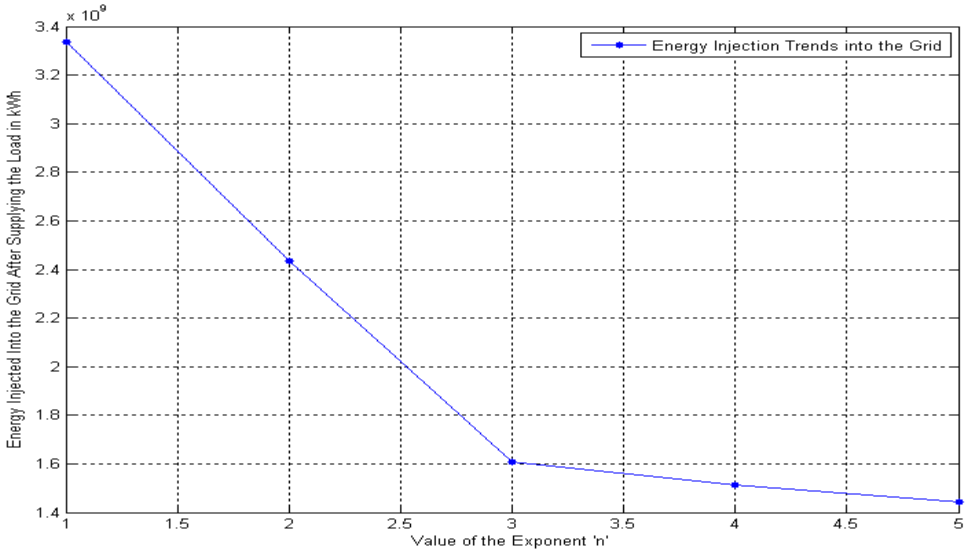


Figure 6.9: Trend for energy injected into the grid by the wind farm after supplying the uniformly distributed load

The uniform distribution has lower and upper limits as 90% and 110% respectively of the mean value of the original Gaussian distribution of the load to demonstrate the effectiveness of DSM to accommodate larger wind penetrations and their load supplying ability. It is worthwhile to note that the magnitudes of energy injected into the grid under uniformly distributed load conditions by all the exponent values are lower as compared to the energy injections under Gaussian distributed load by the corresponding exponents values.

This concludes the discussion of the impact of the exponent ‘n’ on the interfacing of large scale wind farm with the load under current and smarter grid environment.

CHAPTER VII

CONCLUDING REMARKS AND SCOPE FOR FUTURE WORK

7.1 Summary and Concluding Remarks

Wind is inherently variable and is a classic example of random behavior. This inherent variability has an impact on the power output of WECS. The output power of WECS is also treated as a random variable due to its direct relation to the incident wind speed. Probability functions can be effectively used to model wind speed and hence the output of WECS. A general expression for the probability density function for the power output of a WECS has been derived, plotted and studied in details. It has also been extended to study the combined power output of multiple WECS operating in grid-connected configuration. The variable region of the characteristics of WECS has been modeled with five exponents ‘n’ values, 1 through 5. It was observed that for individual and combined power output density functions of a small number of WECS its impact can be regarded as “minor”. The impact becomes significant on the density functions as more and more WECS outputs are added cumulatively. A large scale wind farm study has been studied to which demonstrate this impact in great detail. The power output of a large wind farm follows a Gaussian distribution. As far as exponent values are concerned, Gaussian distributions with different mean but the same standard deviation are obtained. Interfacing of a large scale wind farm supplying a Gaussian distributed load is considered and the corresponding power duration curves have been derived and studied. Flattening of power duration curves occurs with increased wind penetration. Smaller the exponent value larger the energy injected into the grid and smaller the energy drawn to supply the load as per the existing conditions and vice versa.

Smart grid objectives and Demand Side Management techniques can very well complement the goal of effective optimization of electric grid operation. An electric load distributed uniformly as an outcome of DSM and smart grid functionalities is treated in a similar manner as the first case. Power duration curves obtained are flatter as compared to those obtained with Gaussian distributed loads. Additionally, drastic reduction in energy drawn from the grid to supply the load is observed. Thus, large scale wind penetration can be assisted by the implementation of smart grid functionalities and DSM techniques.

7.2 Scope for Future Work

Probabilistic modeling for active and reactive powers associated with WECS and hence a wind farm is a viable extension for this study. It can assist in establishing a more realistic model for the power output of WECS in a probabilistic framework. Addition of models for photovoltaic power plants, cumulative impact of plug in hybrid vehicles and other DER strategies can provide a mix of expected generation sources in a modernized grid. System planning in a more complete sense will then be possible which will provide more accurate results. Estimation of transmission network expansion, construction of dc ties for interconnections, and capacity and spinning reserve requirements are some of the expected outcomes from this assessment framework. Wind regime and resource assessment is also an additional application of this model.

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VITA

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Scope and Method of Study: Purpose of the study is to model the power output of Wind Electric Conversion System (WECS) as a random variable given that wind speeds incident on them is random. The model is extended to model probability functions for combined power outputs of multiple WECS located in a wind regime. The impact of variable region in the power characteristic on the probability functions for power output of individual and multiple WECS is investigated. This model is employed in performance assessment of wind farms within probabilistic framework to obtain its load supplying capability. Smart grid functionalities and Demand Side Management (DSM) are identified to have complementary behavior beneficial for optimal operation of electric grid. This is demonstrated using the obtained model for wind farms and a possible modification of load demand distribution function.

Findings and Conclusions: The power output of WECS is a mixed random variable. Impact of exponent ‘n’ on the probability density function (pdf) for power output of multiple WECS is “minor” for a low number of WECS. For a large number of WECS, there occurs a major redistribution of probabilities of power outputs leading to distinct pdf plots for different exponents. Increasing wind penetration leads to flatter power duration curves. Smart grid functionalities and DSM techniques if complemented in a suitable manner will assist in greater assimilation of wind energy into the grid.

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