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ANALYSIS OF WIND POWER INTEGRATION WITH POWER SYSTEM PLANNING

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ABSTRACT

Clusters and arrays of wind turbine generators (WTG) can be used to produce large-scale electric power which potentially presents an attractive alternative to electric utilities for meeting their load demands. This also means, substantial savings of conventional fuel and capacity. To bring about a conventional capacity displacement, wind power must itself have firm capacity. Two wind power models are developed to compute the amount of wind power from wind turbines in different configurations. The impact of placing multiple WTGs in clusters to get higher power levels are investigated. The advantages evolving out of site dispersal are also examined. In general terms, arrays of wind farm's produce some firm capacity because of the diversity of wind at the dispersed sites. Methods for determining capacity credits earned for each scenario are presented in detail using a utility reliability model. The analysis is extended to include the competition against conventional expansion plants.

1. INTRODUCTION

Wind has been a widely used source of electric power on individual farms in the Unites States during the earlier part of this century. In the past decade, wind energy has been re-examined as a viable source for electricity production for single residences and also for large systems capable of supplying electricity to a large number of customers. However the high degree of unpredictability of the wind power output and the large number of machines required to generate significant amounts of power are posing serious hurdles to the extensive use of wind turbines.

At the present stage of development, one can envisage two ways in which wind power may be used economically on a significant scale. The first is through the use of medium size machines like those having capacities between 100 KW and 200 KW. These wind machines may be used for agricultural purposes or for supplying electricity to isolated communities. The second possibility lies in the employment of large generators in the range of 1 MW to 4 MW capacity. The electric utilities constitute the largest potential market for such large wind machines. However, the value of wind energy for electric utilities is a complex issue involving an examination of daily and seasonal power demands, fuel costs, rate structures and the mix of existing equipment available for power generation. A investigation of these issues in the context of power system planning is the subject of this paper. Specific requirements for integration with system reliability and expansion model are addressed in the paper.

Analyses of the value of wind power to utilities are reported in [1], [2], [3] and [4]. The authors of these references have used capacity credit as the index of performance. This paper provides a more extensive treatment in that it examines the impact of wind power on fuel costs, reliability and utility expansion plans in addition to capacity credits.

A typical utility generation expansion planning model calculates the expected operation of each scheduled unit in the power system identifying the energy generation, the operating cost, the fuel consumption, system unserved energy and the Loss Of Load Probability (LOLP). This model also studies the long-term impact and finds the optimal generation expansion policy for the utility system.

The largest wind generators now envisioned, 1.5-3MW in rated capacity, are still very small by contemporary utility standards. New coal or nuclear-fueled generators have power ratings of about 1000MW. This fact translates into a requirement on an annual basis, of about 1500, 1.5MW units, operating at a capacity factor of about 35 per cent, to replace that coal unit. To offset the need of a large number of wind turbine generators (WTG) to gain some capacity credit, the WTGs may be placed in clusters in several areas under the jurisdiction of the utility, thus forming an array of clusters of WTGs. This technique will have the additional advantage that some firm power might be obtained through diversity of wind regimes at the widely scattered sites.

The issues of wind clusters and arrays need to be addressed before wind generated power can be absorbed into the grid.

2. ELECTRICAL POWER PRODUCTION FROM WIND

Estimation of the energy from wind has some unique problems. For example, unlike fossil fuel reserves, the amount of energy available from wind varies with the season and the time of day. Besides, there are other causes of variations (viz., gusts, turbulence), inversion layers, changing weather patterns, etc. The amount of energy which can actually be produced by a WTG depends significantly upon the assumed performance characteristics, operating height, and horizontal spacing of the WTGs.

2.1 Available Wind Energy

The power P_a available in a cross-sectional area A, perpendicular to the wind stream moving at speed v, is the kinetic energy flux (i.e., kinetic energy density x velocity x area)

$$P_a(v) = (0.5\ \rho v^2) \times (v) \times (A) = 0.5 \rho v^3 A \tag{1}$$

where ρ is the air density. For a circular cross-section, $A = \pi D^2/4$, D being the diameter. Also, for standard sea level density $\rho = 1.225\ \text{kg/m}^3$.

2.2 Extractable Wind Energy

The amount of power which can be extracted from the wind stream depends on the available wind energy and on the operating characteristics of the wind energy extraction device. Thus the output power P of a WTG is,

$$P(v) = P_a(v) \times C_P = 0.5\rho C_P A V^3 \qquad (2)$$

where, $P_a(v)$ is as in Equation (1) and C_P is the power extraction coefficient of the machine.

It can be shown from momentum theory that the maximum amount of energy that can be extracted by a wind turbine from a windstream is eight-ninths of the kinetic energy of the windstream passing through it. Under these conditions, the maximum loss in wind speed will be two-thirds of the initial velocity of the windstream, V_o. Therefore, for a system of 100% efficiency, the maximum power density that can be extracted by the turbine from the windstream in the above process will be,

$$P_{max}/A = 2/3\ V[(8/9\ (\rho V^2)/2] = 0.593\ \rho V^3/2 \qquad (3)$$

The factor, 0.593 is known as the Betz Coefficient. It is the maximum fraction of the power in a windstream that can be extracted by a turbine in the windstream.

2.3 Wind Speed Distribution

Wind speed probability distributions are important for many applications in wind energy studies. These distributions may be used to evaluate: (1) the mean wind power density, (2) the probability that the wind speed lies in certain intervals (e.g., between the cut-in and cut-out) for a particular wind turbine, (3) the energy pattern factor for a particular wind turbine, and (4) the capacity factor for a particular wind turbine.

The Weibull Distribution

The Weibull distribution has been used to represent wind speeds for quite some time and has been accepted by many wind researchers as an accurate modeling. The Weibull probability density function is represented by:

$$f(v) = (k/c)(v/c)^{k-1}\exp[-(v/c)^k] \qquad (4)$$

where c is called the scale factor, k is the shape factor and v is the wind speed. The cumulative distribution function is given by,

$$F(v) = 1 - \exp[-(v/c)^k] \qquad (5)$$

The mean of the distribution, i.e., the mean velocity V, is equal to

$$V = c\Gamma(1+1/k) \qquad (6)$$

where Γ represents the gamma function. The Weibull distribution is characterized by k and c. In most cases, the values of the shape factor k, lies between 1.5 and 3.5. For these values, c = 1.1V.

The Rayleigh Distribution

The Rayleigh distribution has also been tried in many wind energy studies with acceptable results. The Rayleigh distribution of wind speeds has an advantage over the Weibull distribution in that only one parameter is required. Thus the modeling is simplified. The Rayleigh probability distribution function may also be taken to be a special case of the Weibull distribution function. The former is given by,

$$f(v) = (v/c^2)\exp[-(v^2/2c^2)] \qquad (7)$$

where, c is the scale factor.

2.4 Capacity Factor

The Capacity factor is the ratio of the average load on a WTG for a period of time considered, to the capacity (rated power) of the WTG. The average output power can be evaluated by:

$$P = \int_0^\infty P(v)f(v)dv \qquad (8)$$

where, P(v) is the extractable power, v is the wind speed and f(v) is the wind speed probability distribution function corresponding to blade center elevation. The average is over the time interval for which the distribution P(v) is specified (e.g., monthly, seasonal, annual).

From Equation (2), with Cp replaced by $C_P\eta$, η being the efficiency
of conversion, P(v) is given by,

$$P(v) = 0.5A(C_P\eta)_v \rho v^3 \qquad (9)$$

The rated power is similarly,

$$P_R = 0.5A(C_P\eta)_R \rho V_R^3 \qquad (10)$$

Therefore, the Capacity factor is,

$$CF = P/P_R = 1/(C_P\eta)_R \bullet V_R^3 \int_0^\infty (C_P\eta)_v f(v) v^3\,dv \qquad (11)$$

If we consider a Weibull distribution for the wind speed, then f(v) is given by (4) and for Rayleigh distribution, f(v) is as in (7).

3. METHODOLOGY ANALYSIS

Three separate models are used in the analysis. These are:

- Individual windfarm model
- Dispersed wind power system model
- Utility generation expansion planning model

3.1 Individual Windfarm Model

In this model, a number of wind machines are grouped together at definite crosswind and downwind distances and arranged in a specific configuration for optimum power output. This configuration may be called a cluster. Power extraction through the use of wind turbines introduces a momentum loss in the downstream flow field which is manifested by a region of reduced mean velocity, the so-called wake region. The available energy in the wake region is smaller than in the undisturbed flow. Turbines located totally or partly in the wake region will hence deliver less power than those in the undisturbed flow field. The wake interference effect is measured by the velocity deficit at a certain point behind the upwind WTG. Using the atmospheric boundary layer theory, the reduction in the hub-height speed due to the turbulence caused by the WTGs (upwind) in a cluster can be calculated. Modified wind speeds at various rows (several rotor diameters apart) are then calculated. These wind speeds and various WTG parameters (namely cut-in, rated and furling speeds and hub-height) are then used to find the capacity factor for the WTG in each row.

The approach taken to evaluate the impact of a cluster deals with the calculation of the capacity factor from the windpower availability point of view. The evaluation of cluster effects starts with the wind speed data for a site and ends with the calculation of capacity factors for WTGs arranged in a number of rows several turbine blade diameters apart. The cluster analysis is outlined in the following steps.

Step 1: *Calculating Hourly Mean Wind Speeds*:-
Use observed wind speed data to determine the average speed at a site. The total number of observations used for each time period influences the dependability of results. The National Climatic Center maintains records of wind speed observations for several years at a number of sites around the U.S. Long term wind speed data should be used to generate hourly mean speeds for a typical day of each month of a composite year. Recognizing the cubic relationship between the wind speed and the power output, use the following equation for averaging:

$$V_i = (\sum_j v_{ij}^3/N)^{1/3} \tag{12}$$

where v_i = long term average of observed wind speed for a period i, (usually one hour) and $j = 1,2,...,N$, the no. of observations available for that period i. Note that these mean speeds should be projected to the hub-height (H_{hub}) from the anemometer height (H_{anem}) using the 1/7 power law given below:

$$v_{hub} = v_{anem} [H_{hub}/H_{anem}]^{1/7} \tag{13}$$

Step 2: *Choosing The Capacity Factor Expression*:-
Assuming the wind speed to be either Weibull or Rayleigh distributed, the capacity factor is given by Eqn. (11). It should be stated here that this is the capacity factor for WTGs placed on the first row when cross-wind effects are ignored. Capacity factors for WTGs placed downwind may be reduced due to the wake effect as explained below.

Step 3: *Calculating Hourly Velocity Deficits*:-
It is assumed that the turbulent boundary layer above a finite cluster of WTGs remains unchanged above a certain height. Below this height, the turbulence is enhanced and the wind speed downwind is reduced as an inverse function of the distance from the first row of WTGs [5]. Using the technique presented in [6], calculate the decrease in the hub-height velocity v_h due to the wake effect. A set of values for v_h should be calculated for various downwind distances from the first row.

Step 4: *Evaluating The Performance*:-
Knowing the velocity reduction at each row (behind the first row) calculate the new mean velocity seen by the downstream row (v_i) and the wind speed distribution parameter c and k for each period. These are then used in equation (4) or (7) to calculate the corresponding capacity factors.

Numerical examples of applying the cluster model to specific scenarios are presented in [6].

3.2 Dispersed Wind Power System Model

A WTG array is comprised of a set of units or windfarms which are dispersed over an area which is large enough to ensure that wind diversity will affect the array power. An analysis of the performance of arrays is very useful for economic and operational assessments of electricity generation from windpower. The array analysis consists of studying the spatial cross-correlation between the rows in the cluster and between the dispersed sites. The correlation between spatial positions in close proximity is zero, which means the spatial cross-correlation is equal to unity. It can be proved that inter-row cross-correlation is negligible compared to the inter-site cross-correlation, because of their relative spatial distances.

Considering this phenomenon, the calculation of capacity factors for the array is quite different from that of the cluster. In this analysis, the entire cluster at one site should be considered as one single unit. Assuming this and refering back to Eqns. (4) and (7), we observe that modified values for the wind speed distribution parameters (c and k) are to be found for calculating the capacity factors of an array of windfarms. The following equations [7] are used for calculating such parameters:

Mean distance between sites:-

$$r_n = (n+1)(R_{max})/(3(n-1)) \tag{14}$$

where, R_{max} = maximum distance among the n sites.

Spatial correlation factor, ρ:-

$$\rho = \exp[-r_n/520]^{0.57} \qquad \text{for } r_n > 200 \text{ km} \tag{15}$$

Mean value of standard deviation of wind speeds for all sites:-

$$\sigma_n = 1.11\sigma_o[(1+(n-1)\rho)/n]^{1/2} \tag{16}$$

$$\sigma_0 = [\sum_{i=1}^{n} \sigma_i^2/n]^{\frac{1}{2}} \tag{17}$$

Wind speed distribution parameters for the array:-

$$k_n = (\sigma_n/V_n)^{-1.086} \tag{18}$$

$$V_n = \sum_{i=1}^{n} V_i/n \tag{19}$$

V_i = mean velocity for each site

$$c_n = V_n/\Gamma(1+1/k\sigma_n) \tag{20}$$

where Γ represents the gamma function.

Using these k_n and c_n parameters in equation (4) or (7), we can calculate the capacity factors for the array of windfarms. Results of applying the array model to specific sites is presented in [8].

3.3 Utility Reliability Model

A utility planning model analyzes alternative expansion plans for a number of years in the future using available generating units. These units may again be classified into two categories: scheduled and expansion units. Scheduled units are those units which exist at the beginning of the study period and those units which are firmly scheduled for further additions. The expansion units are those candidate units for future addition that are not firmly scheduled at the beginning of the study period but that can be added to the system if selected for optimum system expansion. All possible combinations of new candidate generating units that satisfy certain criteria are evaluated. This evaluation requires simulation of the system energy production and reliability during each year, considering both the scheduled and expansion units. Subsequently, these combinations of new candidate generating units are compared, using a mathematical optimization technique (commonly, dynamic programming), for finding the optimal solution.

There are two phases in the generation expansion planning model. These are:

- Production costing, and
- Reliability analysis.

Production costs associated with a generating unit is composed of total fuel costs and the total operations and maintenance costs. Production costing is done in order to determine the total operating costs of the utility so as to maintain a certain reliability figure, measured by the index called the LOLP. The LOLP of a particular power system can be best understood by using a load duration curve (LDC). The latter is frequently used to represent the system load over an extended period of time. The area under the curve therefore, represents the total system energy requirement during the period. The abscissa of the LDC represents the number of hours during which the system load equals or exceeds the associated amount of power on the ordinate. If the abscissa is normalized, it may also be considered to represent the probability that a particular value of the system load will be equalled or exceeded.

Determining the LOLP of a Power System

Probabilistic production costing was first studied in the late 1960s. For the purpose of determining the LOLP, the ordinate and abscissa of the LDC are reversed. This form of the curve is called the inverted load duration curve (ILDC). If all units were assumed to be available 100% of the time, the amount of energy generated by each unit could be determined by plotting on the ILDC, each unit's capacity in order of increasing cost of operation.

In reality though, all generating units are subject to random outages. To consider the effect of random outages of generating units, it is more convenient to increase the load artificially rather than to decrease the total on-line capacity [9]. Therefore, if L(x) is the original load function, then the function $L_e(x) = L(x-w)$ is the augmented load function, where w is the outage capacity. The function $L_e(x)$ is called equivalent load and the resulting curve is called the equivalent load duration curve (ELDC). When, all generating unit capacities (with their respective random outages) in the system (represented by C) are plotted on the ELDC, the final curve looks like that shown in Figure 1. The figure shows that there is a finite probability P, for a part of the load to remain unserved. P is the probability of having an equivalent load equal to or greater than the system generating capacity and is called the LOLP for the generating system. The shaded area under the equivalent load curve to the right of C represents the expected energy demand that the generating system would not be able to serve and and is called the "unserved energy".

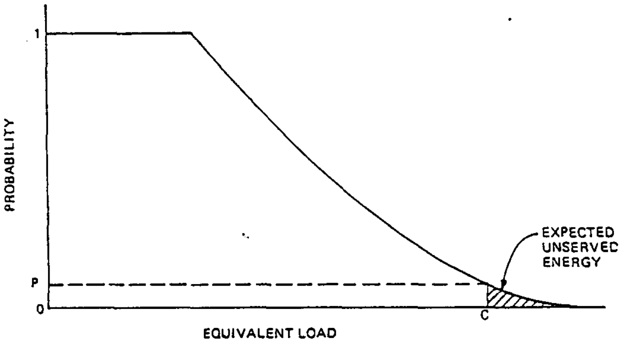

Figure 1. The Equivalent Load Duration Curve and the LOLP

4. INTEGRATION ISSUES

4.1 Utility Load Modification by the Wind Output

Before a wind power system can be added to an existing utility system, it is necessary to establish hourly wind plant operation. This hourly approach is required to reflect the uncertainty and variability associated with wind power. Wind plant operation is a function of the performance characteristics of the wind plant itself and the wind conditions at a particular hour. Once the hour by hour wind power output is determined, utility loads can be modified by treating the wind output as a negative load. The other generation units in the utility network comprising of the thermal units and any hydro or pumped storage units, are left with the task of serving the residual load. On this basis, both the magnitude and timing of the wind power output will affect the total system operation, energy disposition, and fuel costs.

4.2 Reliability Studies

The analysis has been divided into two parts - (i) reliability evaluation of the system and (ii) optimal expansion policy determination of the overall utility system.

Reliability evaluation studies are made with conventional generation first, considering both scheduled and expansion plants to determine the operating costs in millions of dollars, the total energy demand in MWH, the total generation in MWH , the minimum and the maximum reserves in MW, the unserved energy in MWH and the loss of load probability for each year of the study. Later, the process is extended to include wind power in order to meet a load modified by the wind power output. The reliability index in both cases is the LOLP.

In the optimal expansion policy determination part, potential candidates of plant types need to be identified to yield the required reliability. The above procedure gives the following information:

- The construction expenditures associated with each unit type for all years of the study period.
- Operating costs for each plant types for all years of the study period.
- The number of units from each expansion candidate that comes on line.
- The system LOLP and unserved energy.

After the base case studies have been completed, the next step is to conduct the modified case studies where wind power is included in the system in the form of an individual wind farm (Section 3.1) or a WTG array (Section 3.2). The study is divided into two more parts. The first of these two, deals with the actual capacity credit earned for the wind power system by displacing a certain amount of conventional capacity. The other part deals with the competition against conventional expansion units.

Capacity Credit Evaluation

The capacity credit of wind power W, is defined [2] as C_c, satisfying,

$$P(L > A_{co} + C_c) = P(L > A_{co} + W) \tag{21}$$

where P is the probability, L denotes the load, A_x, the amount of conventional plant with total rated power x which is actually available for generation (i.e., not on outage) and co is that value for which,

$$P(L > A_{co}) = P_o \tag{22}$$

where, P_o is the LOLP specified by the utility as its standard of reliability. Thus co is the required installed capacity in the absence of wind power.

A comparison of the two most important parameters, unserved energy and LOLP for the base case and the modified case identifies the capacity credit earned by the wind system.

Wind Power System in Competition Against Expansion Plants

In this part of the analysis, wind power systems are brought in, the same way as in the previous analyses, but this time only changes in expansion plants are studied instead of the existing plant. The cost savings in terms of expansion plant construction and operation costs are compared. Capacity that can be deferred because of the presence of wind power is also credited to the value of the wind system to the utility.

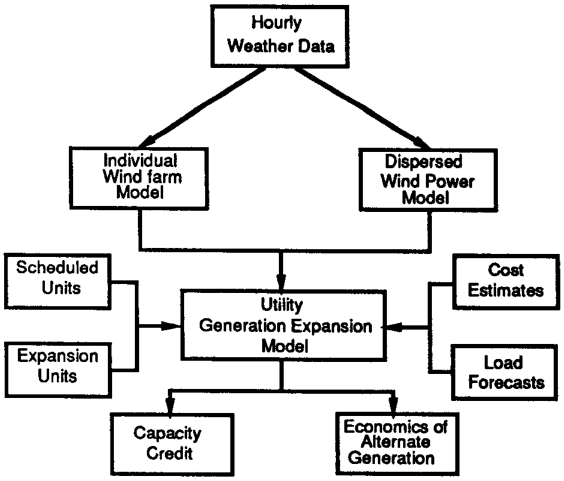

Figure 2. An Overview of the Methodology

4.3. Methodology Overview

Figure 2 shows the methodology in block format, used for determining the value of wind power to an electric utility.

5. CONCLUSION

A step-by-step methodology is presented for carrying out an investigation of the value of wind power systems on the electric utility from a system planning perspective. Before an integration can be successfully accomplished, it is imperative that that an accurate model be developed for the wind power system.

A major conclusion that can be reached from the wind integration analysis is that wind power should be seriously regarded as a potential candidate for large scale power generation by the utility expansion planners. In order to prove that wind power systems are capable of earning capacity credit and saving millions of dollars in conventional plant construction cost, one should resort to the chronological methodology presented in this paper. The effect of integrating wind energy conversion devices on system reliability should be studied before making decisions on the integration. It shoudl be pointed out here that because of the intermittent nature of the wind power output, the effect of storage should also be investigated. It is only fair to assume that storage will have a positive effect on capacity credits earned.

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