# AN AC/DC/AC INTERFACE CONTROL STRATEGY TO IMPROVE WIND ENERGY ECONOMICS

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Abstract- A control strategy for an AC/DC/AC interface to smooth or limit wind farm output is investigated. The need to follow rapid power variation from uncontrolled wind farms with expensive gas turbines limits the amount of penetration of wind energy systems in existing utilities. An AC/DC/AC interface makes it possible to limit the power variations from the wind farm. An optimal level to which the wind output should be limited is found in terms of the distribution of wind power output and the relative cost of the fast acting and base loaded units. Using the optimal cutting point for the wind output each wind farm can be included in the economic dispatch calculation. The economic advantage of limiting wind power output is demonstrated on an example system. Using a hypothetical system it is shown that wind penetrations as high as 16.75% may be economical using the optimal strategy made possible by the AC/DC/AC interface.

## INTRODUCTION

Recent research[1,2,3,4,5] has demonstrated that large wind-power variation from wind farms can cause serious operating problems for a power system. These problems occur because present control practices assume that hourly load changes are predictable and that fast cyclic load changes are small. These problems can be even more serious when a wind storm hits a wind farm because the entire farm might produce significant power loss in less than ten minutes which is the Automatic Generation Control (AGC) reaction time.

In order for the AGC to perform its function of maintaining scheduled system frequency economically and within established interchange limits, it must have the ability to adjust generation. The control function for regulating frequency and the tie-line load is the area-control error (ACE) given by

$$ACE = (T_n - T_s) - 10B(F - F_s) \qquad (1)$$

where

$T_n$ = true area net interchange, MW.

$T_s$ = scheduled area net interchange.

F = system frequency in Hz.

$F_s$ = system scheduled frequency.

B= biased setting, Megawatts per 0.1 Hz.

A detailed description of the control scheme for conventional load-frequency control (LFC) can be found in [6] with additional restrictions provided by the North American Power Systems Interconnection Committee

(NAPSIC) guidelines [7]. Without modifications to the LFC or NAPSIC guidelines, systems with large amounts of wind generation must integrate with these system performance specifications and practices.

The second component of AGC is the economic dispatch (ED) which attempts to minimize generation operating cost necessary to meet load within a short time frame (5-10 minutes) [8] assuming a fixed-generation mix is on-line. As developed in [8] , optimum production economy for a given combination of machines in service is obtained when the incremental cost of received power is the same from all the variable sources. Stated mathematically, we have

$$\frac{dF_n}{dP_n} L_n = \lambda \text{ for all } n \qquad (2)$$

where $\frac{dF_n}{dP_n}$ = incremental cost of source n in dollars per Mw-hr.

$L_n$ = penalty factor of source n.

$\lambda$ = incremental cost of received power in dollars per Mw-hr.

The penalty factor for source n is defined by

$$L_n = \frac{1}{1 - (\partial P_L/\partial P_n)} \qquad (3)$$

where $\partial P_L/\partial P_n$ = incremental transmission loss of source n.

The idea of using hydro generation to follow wind-power variations instead of expensive gas turbines has been considered [9]. A dynamic simulation of long-term power system response to changes in the load and generation patterns resulting from significant penetration of wind farms was performed. The simulation showed that the area-control error increased significantly because of wind variation and that the hydraulic units cannot follow the fast-changing wind power. There are two options:

(1) Change current operational specifications and practices.

(2) Smooth wind power output.

Because the first option requires many changes, the authors conclude that a control scheme should be developed to moderate the ramp rate of the wind farms.

Another realistic solution was proposed in [10] in terms of increasing the system load-following capacity. The load-following requirement derived by the method in [10] is enough to cover both the variations of wind and load. Unfortunately, their solution increases production cost greatly and limits wind penetration to approximately 5%. Smoothing the wind-power output seems to be the only reasonable approach to the solution of the cost problem. The following section contains a description of an AC/DC/AC interface that is capable of smoothing the wind-power output. Next a technique of operating the wind farms through the interface to minimize operating costs is developed. The time constant for wind-energy control

is discussed in terms of the spectrum of the wind and AGC requirement. Examples are given for a hypothetical system.

## AC/DC/AC INTERFACE

In order to inject substantial amounts of wind power into a utility grid, large numbers of machines will be required. Each machine will have its own individual set of control systems. As indicated in[11], however, there are substantial problems associated with simply paralleling large numbers of individually optimized machines onto a single utility bus. Figure 1 illustrates a proposed method of interfacing a high-power wind-turbine farm into a utility grid through the series DC current loop that has been discussed in previous chapters.
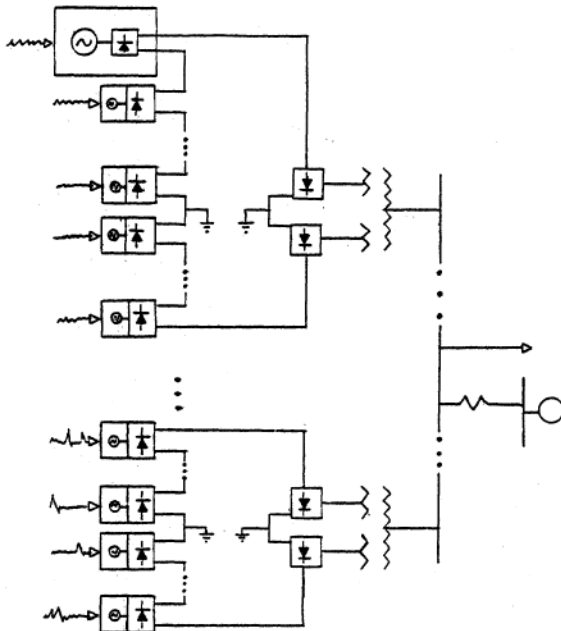


Figure 1. AC/DC/AC Interface

The primary motivation for this interface configuration is protection and coordinated control of the farm. The interface also enables variable speed generation and thereby considerably increases control flexibility. This flexibility requires that each wind-turbine generator (WTG) have a speed-control system that can adjust turbine efficiency while minimizing electrical power fluctuations, and have a generator (synchronous or induction) excitation control system to control torque production in response to speed demand. The entire collection of WTGs (i.e. the farm) must be capable of setting and controlling the DC loop current so that, for example, each generator in the string is in a feasible operating region. Individual dynamic-control system designs which can accommodate these requirements are discussed in [12,13]. For the purposes of quasi-static operation, it is assumed that at each instant in time there is a power demand requirement $P_d$ which is less than or equal to the power available from the wind. The demand $P_d$ is based on some operational requirement such as maximum extraction of power from the wind [12] , load-frequency control, economic dispatch[14], or transient stability [15]. Given an inverter voltage $V_d$, we require a loop current of

$$I_d = P_d / V_d$$

Each individual WTG is then required to adjust its terminal voltage to deliver its set-point power demand at the loop current value $I_d$. This imposes a special operational requirements on the rectifiers since it may be necessary to operate the wind generators at widely varying ac voltages. This restriction will require operation of the rectifiers at firing angles approaching 90 degrees. The inverter, on the other hand, is connected to the ac system and consequently operates at fairly constant ac voltage. Its transformer taps t and marginal angle, $\gamma$, are controllable and are adjusted to obtain a favorable power factor and/or voltage profile. Specific details of the rectifier/inverter requirements are discussed in [15]. For the purpose of this chapter we require only that there is a mechanism that allows for an adjustable power demand, a mechanism which is not present in a conventional ac interconnection. The use of the adjustable power-demand control amounts to a smoothing of the wind-farm output.

## PROPOSED OPERATION

The need to follow the fast variations in wind-power output with expensive fast-reacting units such as gas turbines, limits the penetration of wind-energy control systems (WECS) in a typical system. Figure 2 shows a typical wind-farm output over an interval of time.
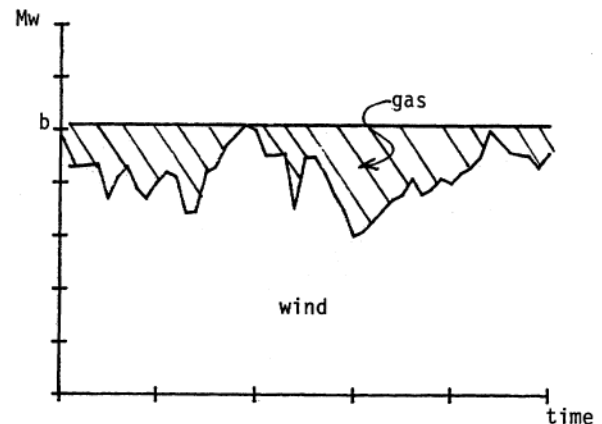


Figure 2. A Typical Wind Farm Output

The shaded area above the curve represents energy that must be supplied by, say, gas turbines that are as much as six times more expensive than coal-fired units. The effective cost of generating b Mw over the interval shown can be very high. Clearly some technique of smoothing the wind power output is needed.

The AC/DC/AC interface provides a mechanism which we will show is effective in improving WECS performance. Figure 3 shows the same wind-farm output where the AC/DC/AC interface has been used to limit the farm output to a Mw. The shaded area between a Mw and the wind output must still be supplied by gas turbines but the area between b Mw and a Mw can be supplied by less expensive, slower units such as coal-fired generators. The cost of generating b Mw in Figure 3 is clearly smaller than the cost in Figure 2. The issue is to determine if there is an optimal value of the limiting output, a Mw.

Let the wind-power output during an interval T be considered a non-negative random variable with probability distribution F(x). Let g(x) be a saturating or clipping function as shown in Figure 4.
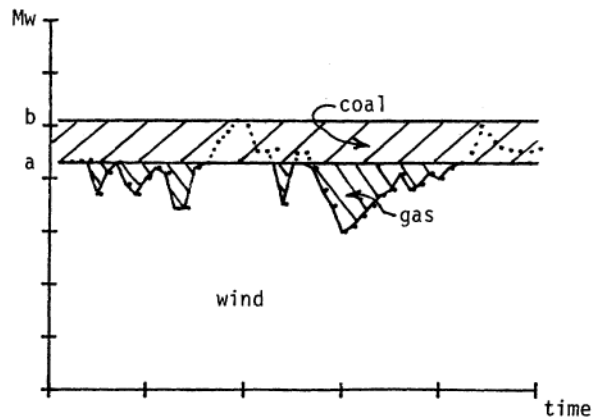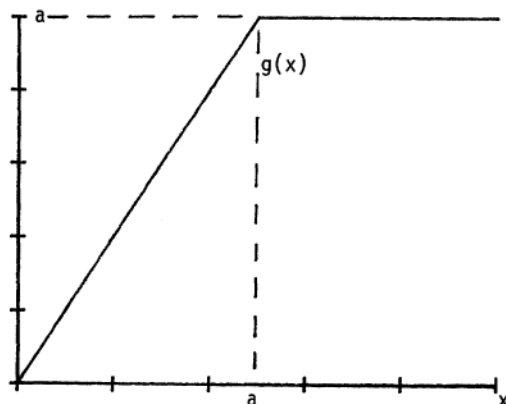
Figure 3, A Wind Farm Output with Power Cutting



Figure 4, Saturating Function g(x)

It is an exercise in elementary probability to show that

$$E\{g(x)\} = \int_0^a (1 - F(x)) \, dx \qquad (4)$$

where $E\{\,.\,\}$ denotes expectation. Equation (4) gives the expected power output of a wind farm controlled as in Figure 3. The total cost of producing b Mw of power, as in Figure 3, is then

$$C(x) = (a - g(x)) c_2 + (b - a) c_1 \qquad (5)$$

where $c_2$ is the gas-turbine cost and $c_1$ is the coal-generator cost. The first term in (5) represents the gas-turbine costs and the second the coal-generator costs. Taking expectations and using (4) gives

$$E\{C(x)\} = (b - a) c_1 + c_2 x \int_0^a F(x) \, dx \qquad (6)$$

Taking the derivative of (6) to obtain the value of a to minimize the expected cost, results in

$$F(a^*) = \frac{c_1}{c_2} \qquad (7)$$

where $a^*$ is the optimal cutting-point value (the second derivative is positive so $a^*$ is a minimum). We will consider $F(x)$ to be continuous here so that (7) has a solution. Discontinuous $F(x)$ are considered in [14]. In general, the optimum cutting point $a^*$ exists and is unique.

A typical wind-power distribution is shown in Figure 5. For ratios of $\frac{c_1}{c_2}$ of less than $\frac{1}{2}$ it can be seen that the wind-power output is being cut below the

mean to limit the expensive load-following requirement. The fact that such control minimizes operating costs will be verified by examples. The impact on annual production costs of extracting less than the available energy from the wind will be evaluated at the end of this chapter.

Deciding the Time Constant

As discussed above, a time constant must be chosen to describe the wind power output distribution $F(x)$. Without $F(x)$ defined, we are unable to determine the optimum cutting point. To choose this time constant, the present control scheme and the wind characteristics will be studied so that the choice will be a reasonable one.
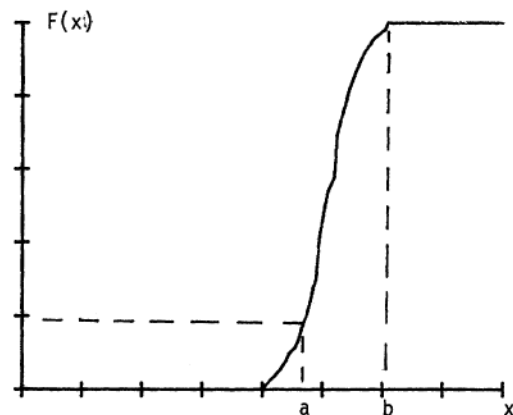


Figure 5, A Typical Wind Distribution with Cutting

(i) From the Point of View of the Spectrum of Wind Speed

In a short time period, minute-to-minute turbulence of the wind is caused by the roughness of the terrain and the heat transformation from different altitudes. The mean wind-speed flow pattern during a period of hours to days is dominated by the atmospheric pressure and the rotation of the earth. As a result of these forces, winds at altitudes above 300 m follow the lines of equal atmospheric pressure.

A method to quantify the fluctuation in wind speed is the spectral density function. It is generally accepted that there are two peaks of energy distribution at four-day and at one-minute intervals[16]. . The peak at four days comes from the large-scale atmospheric pressure. The peak at one minute is attributed to the wind turbulence or gusts around the surface. A small peak is presented at one-half day. This peak is caused by the diurnal influence. The frequency band between 20 minutes to 2 hours is called " the spectral gap " because of the absence of energy within this band.

If the time constant is chosen to be one or five minutes, the reference point or the computed cutting point will be changed rapidly because the profiles of one and five minutes still have fast ramps. The averaging time of 30 minutes not only keeps the profile of the wind speed but also has a smooth curve. Averaging times greater than 30 minutes are not good because the wind profile would be distorted too much. Thus a time constant between 15 to 30 minutes should be used to follow the wind profile and give smooth control.

(ii) From the Point of View of AGC

The AGC adjusts generation to continuously meet

the load requirement and minimize cost. The AGC consists of two processes: economic dispatch and load-frequency control. As discussed in the last section, economic dispatch is a process that tries to minimize the generation cost within a short time period (particularly 5-10 minutes).

Every three to four minutes, the computer will check every plant on line trying to find the best generation mix, then each plant will be assigned a ratio of total generation during the following five minutes. This process is important to the operation of the power system. If the time constant T is chosen to be less than five minutes, then the wind-power output will not be considered by this process. For the above reason, the time constant T should be long enough to allow the economic-dispatch program to include the wind generation. As discussed above, this time constant must be greater than five minutes.

According to the wind-speed spectrum (as discussed above), the time constant T should be between 15 and 30 minutes, which is greater than the economic-dispatch reaction time. Therefore, from both points of view of present control practices and wind characteristics, any time constant between 15 and 30 minutes is a good choice. We will use a T of 20 minutes for the rest of the examples.

### MARGINAL COST AND CONTROL SCHEME

#### (i) Defining the Marginal Cost of Wind Power

As we discussed in the last section, economic dispatch obtains the generation mix in a given time period ( 5 minutes). If the incremental cost for each plant is well defined, the solution of the generation mix will be found by Equation (2). The incremental costs of coal-fired and hydraulic units are well understood. The incremental cost of wind power may be defined from an analysis based upon calculation of the optimum cutting point.

If the wind-power output distribution during the time period T is $F(x)$, and the fuel cost, which is used to follow the variation of wind power, is a constant $c_2$ dollars per Mw-hr, then the incremental cost of wind power, $MT(a)$, cut at point $a$ is

$$MT(a) = F(a)c_2 \qquad (8)$$

Equation (8) represents the area labeled "gas turbines" in Figure 3, and is obtained by computing

$$E\{ (a - g(x) ) c2 \} = c_2 * a - c_2 \int_0^a (1-F(x))\, dx$$

$$= c_2 \int_0^a F(x)\, dx$$

Equation (8) then permits the inclusion of WECS in economic dispatch. It is clear that in practice the cost $c_2$ may depend on current operating conditions and that the distribution $F(x)$ is a function of the current mean-wind-speed at each wind farm. Each wind farm should be dispatched based on its own marginal cost.

It is important to note that the marginal cost defined by (8) is consistent with the condition for optimum production economy as in Equation (2). If the marginal cost of coal is $c_1$ then (2) implies

$$MT(a) = c_1 \qquad (9)$$

$$\text{or} \quad c_2 F(a) = c_1 \qquad (10)$$

which agrees with (7). Again, in practice both $c_1$ and $c_2$ will depend on the amount of power required and on operating conditions. The optimum cutting-point calculation can be regarded as an extension of the economic-dispatch calculation. The only real additional data set required is the distribution of wind-farm output based on the mean-wind-speed.

#### (ii) The Control Scheme

A final control scheme is suggested as follows: With wind power on the economic-dispatch time scale of five minutes, use the previous 20 minutes of data to find the mean-wind-speed. For each wind farm, compute the cutting point according to the previous experimental output distribution of this mean-wind-speed.

### EXAMPLES

The simulation in [17] shows a wind-power output with a mean of 749 Mw and a standard deviation $\sigma = 68.49$ Mw for 30 minutes. For convenience, we examine the cost under the assumption that the wind output has a Gaussian distribution with a mean of 749 Mw and $\sigma = 68.49$ Mw for a time interval of 20 minutes (the control time period we chose in the last section). Table 1 [10] shows the production costs and fixed costs of the power generation units. The column labeled CYCLE stands for combined cycle, while TURBINE stands for combustion turbines and NUC. refers to nuclear units. The coal-generation cost is 25.06 dollars/Mwh and the fuel cost of combustion turbines is 132.86 dollars/Mwh, which is five times as expensive as the coal-generation cost. For example, if we use gas turbines to follow the wind variation, according to equation (7) (the condition of the optimum operation point), then the optimum cutting point $a$ of the wind power should satisfy $F(a)= 25.06/132.86=19.411\%$.

Table 2 and Table 3 are constructed by consider-

TABLE 1, The Fixed and Production Costs for Different Power Units

| | COAL | NUC. | CYCLE | TURBINE |
|---|---|---|---|---|
| CAP. PLANT COST($/kw) | 889 | 950 | 382 | 188 |
| O&M, FIXD($/kw/yr) | 5.5 | 6.1 | 2.7 | 1.1 |
| O&M, VARIABLE(mills/kWh) | 3.57 | 1.53 | 2.82 | 4.55 |
| AVERAGE HEAT RATE(Btu/kWh) | 10400 | 10400 | 8800 | 11500 |
| PLANNED OUTAGE RATE(%) | 10 | 12.9 | 7 | 3.9 |
| FORCED OUTAGE RATE(%) | 12.4 | 8.4 | 11.7 | 5.9 |
| LEVELIZED FUEL COST($/Mwh) | 25.06 | 25.79 | 80.61 | 132.86 |
| ($/MBtu) | 2.31 | 2.40 | 9.09 | 11.48 |

ing total power (i.e. b in (5)) of 749 Mw and 908.58 Mw. The obvious reason 749 Mw (the mean wind power output) was chosen for this part of the study is because the power output has only one-percent chance of exceeding this value, which we calculate from a = 749+2.33σ (the distribution F(a)=99.0%). Thus, this case might be considered to represent the uncontrollable case. Table 2 shows the result of using oil-fired generation to follow the wind power. The procedure used to generate this table is the following:

(1) Generation with #2 oil costs 80.61 dollars/Mwh, so the optimum cutting point satisfies F(a)=25.06/80.61= 31.09%.

(2) The wind-power output is taken to be a Gaussian distribution with a mean of 749 Mw and a standard deviation of 68.49 Mw. Thus, the cutting point should be 749-(68.49x0.49)=715.44 (From the table of Gaussian distribution, the point 31.09% is m-0.49 σ).

For the case of the total power of 749 Mw:

(a) If the wind output is cut at 749 Mw, then the mean wind-power output should be $\int_0^{749} F(y)dy$ = 721.7Mw. The gap of 27.3 Mw between 749 Mw and 721.7 Mw must be filled by the generation with #2 oil, so the total cost of 749 Mw is

(749-721.7) x 80.61 x (20/60) = 733.6

dollars for twenty minutes (as shown in Table 2).

(b) If we cut the wind power at 715.44 Mw (the optimum cutting point), the real mean wind power will be $\int_0^{715.44} F(y)dy$ = 702.2Mw. Although the power extracted from the wind is 721.7 - 702.2Mw = 19.5Mw which is less then that of cutting at 749 Mw, only 715.44 - 702.2 = 13.2Mw must be filled with #2 oil generation instead of 749 - 721.7 = 27.3Mw. The difference between 749 Mw and 715.44 Mw must be filled by coal-fired generation. Thus, the total production cost for 749 Mw for this cut will be

[ (749-715.44)x25.06 + (715.44-702.2)x80.61 ]

x (20/60) = $635.36

For the case of total power at 908.58 Mw:

(c) Similar calculations to those of procedures 2(a) and 2(b) are made except that the wind output is scheduled at 908.58 Mw and 715.4 Mw instead of 749 Mw and 715.4 Mw. Results indicate that there is a substantial difference between total cost scheduled at 908.58 Mw and that scheduled at 715.4 Mw, with the total cost without control being approximately twice that when the optimum cutting point is used(4294.4 vs 1968.4 dollars, as shown in Table 2).

(d) For the load-following requirement three different cases (cutting-point = 715.4, 749, 908.58) are computed. The point at which F(a)=1% is

m - 2.33σ = 749 - 2.33*68.49 = 589.42Mw

This result means that for 99% of the time, within twenty minutes of operation, wind power will be above 589.42 Mw. In practice a 99% con-

fidence interval is reasonable. Therefore, the load-following requirements for operating at points 715.4 Mw, 749 Mw, and 908.58 Mw are 715.4 - 589.42 = 125.98 Mw, 159.6 Mw, and 319.2 Mw respectively.

Table 2. Oil-Fired Generation Load-Following Costs

| COMBINED CYCLE COST = 80.61 $/Mwh | | | | |
|---|---|---|---|---|
| THE OPTIMUM CUTTING POINT a=715.4,F(a)=31.092% | | | | |
| TOTAL POWER (Mw) | 749 | | 908.58 | |
| CUTTING POINT (Mw) | 749 | 715.4 | 908.58 | 715.4 |
| MEAN WIND POWER (Mw) | 721.7 | 702.2 | 748.76 | 702.2 |
| TOTAL COST ($/Mwh) | 733.6 | 635.4 | 4294.4 | 1968.4 |
| LOAD-FOLLOWING (Mw) | 159.6 | 126.0 | 319.2 | 126.0 |

Table 3 gives the costs of using gas turbines to compensate for the wind variations. The optimum cutting-point satisfies F(a)=18.862% at a = 690.1 Mw. The same two total power outputs (908.58 and 749) as in Table 2 were investigated and the same approach was taken in forming this table. With 908.58 Mw total power output, the total cost, with the wind-power cutting point operating at 908.58 Mw, is $7077.9, which is more than three times more costly than $2152.8, the cost with the optimum cutting point. It is obvious that the more expensive the production cost associated with the requirement, the more beneficial it is to use the optimum cutting point.

Table 3. Gas-Fired Generation Costs

| GAS COST =132.86 $/Mwh | | | | |
|---|---|---|---|---|
| THE OPTIMUM CUTTING POINT a=690.1,F(a)=18.862% | | | | |
| TOTAL POWER (Mw) | 749 | | 908.58 | |
| CUTTING POINT (Mw) | 749 | 690.1 | 908.58 | 690.1 |
| MEAN WIND POWER (Mw) | 721.7 | 682.7 | 748.76 | 682.7 |
| TOTAL COST ($/Mwh) | 1209 | 819.7 | 7077.9 | 2152.8 |
| LOAD-FOLLOWING (Mw) | 159.6 | 100.7 | 319.2 | 100.7 |

### ANNUAL PRODUCTION COST

As discussed in [10] , the optimum penetration level for WECS is considered to be 5% for a typical size power system with no control of wind power. In this section the optimum penetration level will be analyzed with moderate wind power in effect. The analysis is based on these assumptions:

(1) The capacity of the base system is 4500 MW. Each wind farm will be assumed to be composed of one hundred 2.5 Mw turbines with forced outage rates of 20%. In[18] it is shown that the expected output energy of such a farm is essentially 80% of the output of a farm with turbines having forced outage rates of 0%. The annual production cost will be computed with a number of such farms added to the base system.

(2) The base power system consists of 8% gas turbines, 15% combined- cycle turbines, 57% coal plants, and 20% nuclear plants. The must-run part of this power system is assumed to be 30% of the capacity.

(3) The yearly load distribution is shown in Figure 6.

(4) Each wind farm includes 100 WTGs. To make the calculation of the congregate distributions easier, any two farms will be separated by at least two hundred miles, so that the annual wind-power output distributions of any two farms are assumed to be independent.

(5) All the costs and forced-outage rates for the base system are taken from Table 1 and a fixed-charge rate (FCR) of 0.15 is assumed. Generally, fixed charge consists of depreciation, rate of return, taxes and insurance. For example, if the total cost of building a 1,000 MW nuclear unit is $500 million, FCR=0.15 says that the annual fixed charge of this unit is 0.15x(500)= $75 million.

In Table 1, the fixed cost of a WTG is not defined. Assuming that the construction cost for a WTG is 600 $/Kw, land costs are 184 $/Kw[19], and the converter and inverter cost is 50 $/Kw, then the construction cost of a WTG will be 834 $/Kw.

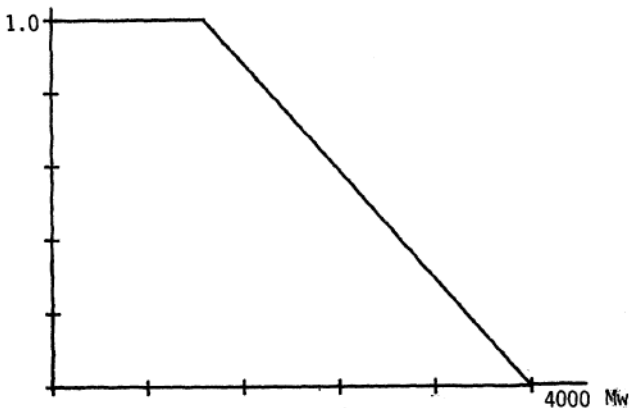(6) The wind distribution is assumed to be with Weibull parameters c and k at 7.17m/s and 2.29,



Figure 6, The Yearly Load Distribution

respectively, defining a site with the yearly mean-wind-speed of m=14 mph at 10 m. Correcting for height, the average speed at the height of the WTG hub (200 ft) is close to 20 mph (the MOD-2 designed speed).

(7) Since the optimum cutting point is employed, no increase in spinning reserve in considered necessary.

To evaluate the estimated annual production cost of a power system with WECS, the following steps are performed:

1. Choose one penetration level and find the distribution of the wind- power output for a whole year. A detailed simulation involving the Weibull distribution, the turbine characteristics, and the effect of optimal cutting is employed.

2. Obtain the effective load distribution by convolving the wind-power distribution with the original load distribution.

3. Compute the production cost of the system using the effective load distribution found in the last step and the base-system generating units.

4. Repeat steps 1 to 3 to calculate the annual total cost for different penetration levels, then compare the costs of different penetration levels to find the optimum wind-penetration level.

The final results are shown in Table 4 for a 4500 Mw base system. with the cost units given in thousands of dollars. It can be seen that the minimum annual costs are for a penetration level of 16.74%.

## CONCLUSIONS

A solution to operating problems associated with large penetrations of wind-turbine systems in utility grids has been proposed. The AC/DC/AC interface suggested for protection and coordinated control provides a means of integrating large wind farms. An optimal level to which the wind output should be limited has been computed in terms of the relative costs of fast-acting and base-loaded units. A marginal cost is obtained for wind generation that is consistent with economic dispatch. The economic advantage of limiting wind-power output to smooth wind-power variations is clearly demonstrated.

Using a hypothetical system it has been shown that wind penetrations as high as 15% may be economical with smoothing at the optimal levels. While no claims are made for any particular system, and the roughness of the number (particularly the fixed costs of wind generation) are acknowledged, it seems clear that previous results limiting wind penetration to 5% must be reconsidered in light of the optimum cutting-point results. While the optimum cutting results can not be applied to the wind output during a storm front, the AC/DC/AC interface could be used (given some warning of an approaching storm) to minimize sudden changes in wind-farm output.

The cutting point is chosen with the wind distribution defined. Before a utility can employ optimum cutting-point control, more work must be done to form F(m,x) for that particular system. The same effort applies to the various costs.

When the system contains more than one large wind farm, mean-wind-speed might be different for each farm. If the wind distribution for each farm is known and the wind speeds between farms are independent, the congregate distribution could be calculated by convolving all the individual distributions. On the other hand, if the wind speeds between farms are not independent, the computations become much more complicated.

TABLE 4, Annual Production Costs for Different Penetration Levels

| PENETRATION LEVEL | PRODUCTION COST | FIXED COST | TOTAL COST |
|---|---|---|---|
| 0% | 65,768 | 56,744 | 122,512 |
| 5.58% | 62,064 | 59,739 | 121,803 |
| 11.16% | 58,240 | 62,734 | 120,974 |
| 16.74% | 55,064 | 65,729 | 120,793 |
| 22.32% | 52,200 | 68,724 | 120,924 |

REFERENCES

1. Schlueter, R. A., Park, G. L., Modir, H., Dorsey, J., and Lotfallian, M., "Impact of Storm Fronts on Utilities with WECS Arrays," DOE Report (EG-77-S-02-4450) (Oct, 1979).

2. Schlueter, R. A., Park, G. L., and Lotfallian, M., "Operation Model for Utilities Using Wind Generator Arrays," DOE Report (DE-AC02-79ET23168) (Oct, 1980).

3. Schulueter, R. A., Park, G. L., and Bouwmeester, R., "Power System Operation with Wind Arrays," DOE Report (W-7405-eng-26) (Jan, 1983).

4. Zaininger, H.W. and Bell, D.J., "Wind Power Generation Dynamic Impact on Electric Utility Systems," (EPRI Report AP-1614), Zaininger Engineering Co. (Nov, 1980).

5. Curtice, D.H. and Reddoch, T.W., "An Assessment of Load Frequency Control Impacts Caused by Small Wind Turbines," IEEE Trans. on PAS Vol. PAS-102, no. 1 pp. 162-170 (Jan, 1983).

6. Cohn, N., Control of Generation and Power Flow on Interconneted Systems, Wiley, New York (1966). Gov't. ordering no. EPRI Report AP-1614

7. , Minimum Criteria for Operating Reliability. The North American Electric Reliability Council (NERC) (November, 1981). Gov't. ordering no. EPRI Report AP-1614

8. Kirchmayer, L.K., Economic Control of Interconnected Systems, John Wiley & Sons, New York (Oct, 1959). Gov't. ordering no. EPRI Report AP-1614

9. Simburger, E. J. and Cretcher, C. K., "Load-Following Impacts of a Large Wind Farm on an Interconnected Electric Utility System," IEEE Transactions on Power Apparatus and Systems, pp. 687-692 (March, 1983).

10. Lee, S.T. and Yamayee, Z.A., "Load-Following and Spinning-Reserve Penalties for Intermittent Generation," IEEE Transactions on PAS Vol. PAS-100, No 3(March 1981).

11. Thomas, R.J. and Thorp, J.S., "Integration Problems With Large Wind Energy Conversion Systems," Proceeding of the Eighteenth Annual Allerton Conference on Communication, Control, and Computing. (Oct, 1980).

12. Lyons, J. P. and Thomas, R. J., "Control of a Variable-Speed Wind Turbine Generator," Proceeding of the 22nd Conference on Decision & Control, (Dec, 1983).

13. Lyons, J. P. and Thomas, R. J., "Control of a Variable-Speed Wind Turbines Generator," Cornell Report EE-8311, (Sep, 1983).

14. Shi, A.J., "Optimum Penetration Levels of Wind Farms," Cornell Ph.D Thesis, (Aug, 1984).

15. Thomas, R.J., Phadke, A.J.G., and Pottle, C., "Operational Characteristics of a Large Wind-Farm/ utility-system with a controllable AC/DC/AC Interface," Submitted to the IEEE Transaction on Power Apparatus and Systems, ().

16. Van der Hoven, "A Simple Model for the Adjustment of The Velocity Spectra in Unstable Conditions Downstream of an Abrupt Change in Roughness and Heat Flux," Boundary- Layer Meteorology Vol. 21 pp. 341-356 (1981).

17. Chan, S. M., Curtice, D., and Change, S-K., "Methods for Wind Turbine Dynamic Anaysis," EPRI AP-3259 (EPRI Report AP-1614) (Oct. 1983).

18. Wang, X., Dai, H., and Thomas, R.J., "Reliability Modelling of Large Wind Farms and Associate Electric Utility Interface Systems.," IEEE Trans. on PAS, Vol PAS-103, no 3, pp. 569-573 (March, 1984).

19. Thomas, R.J., Private Communication, (June, 1984).