2

Integration of Wind Energy into the Electrical Utility System: An Overview of the Issues

Bonneville
POWER ADMINISTRATION

September 1989

DOE/BP/63406--11

DE90 009468

OREGON STATE UNIVERSITY
DEPARTMENT OF MECHANICAL ENGINEERING
ENERGY RESOURCES RESEARCH LABORATORY

REPORT NO. BPA 89-32 SEPTEMBER 1989

INTEGRATION OF WIND ENERGY INTO THE ELECTRICAL UTILITY SYSTEM: AN OVERVIEW OF THE ISSUES

FINAL REPORT

prepared for

Bonneville Power Administration
Division of Resource Management
Portland, OR 97208

by

Energy Resources Research Laboratory

Principal Authors

John E. Wade, Stel N. Walker, and Robert W. Baker

OREGON STATE UNIVERSITY
DEPARTMENT OF MECHANICAL ENGINEERING
ENERGY RESOURCES RESEARCH LABORATORY

REPORT NO. BPA 89-32 SEPTEMBER 1989

INTEGRATION OF WIND ENERGY INTO THE ELECTRICAL UTILITY SYSTEM: AN OVERVIEW OF THE ISSUES

FINAL REPORT

prepared for

Bonneville Power Administration
Division of Resource Management
Portland, OR 97208

by

Energy Resources Research Laboratory

Principal Authors

John E. Wade, Stel N. Walker, and Robert W. Baker

SUMMARY

This report examines the issues related to integration of wind energy into the utility system grid. In California alone there are nearly 17,000 wind turbines with ratings over 17.5 kW. The changing nature of the wind and reactive power demands of the predominantly induction wind generators will present a number of integration challenges for utilities.

The Pacific Northwest is endowed with substantial wind energy resources. Integrating this resource into our utility systems will require planning to resolve the technical problems that affect safety, economics, system stability and overall system reliability. Integration problems in this report will be examined from the point of view of the quantity of energy available, its value to a utility and the quality of energy delivered.

Much experience has been gained on wind energy integration in California, Hawaii, and in Denmark. Here in the northwest, experience with wind turbines is more limited. Integration experience in this region and around the world will be described. The major conclusions are noted below.

The amount of penetration of wind energy into the system is an important factor determining the integration problems that will be encountered. As long as wind's contribution to the total energy resources of a utility is less than 10%, integration problems are of minor concern. In two of the U.S. Department of Energy wind energy demonstration studies wind contributed more than 20% of energy for the local utility and some power quality problems were encountered.

When large arrays of turbines are employed at widely spaced locations the problem of fluctuations in the wind is reduced considerably. Even within an array of wind turbines some averaging of wind fluctuations may occur.

The value of wind energy is dependent on displaced energy and capacity credit. As the ability to predict wind energy availability improves, so will its value. Also, if a means to store wind energy is developed, its value will increase.

In addition to the problem of dispatching a variable source of energy, is the concern of line voltage fluctuations. Isolated wind turbines on the grid can present safety problems. If a wind turbine is supplying power to a portion of the system disconnected from the main grid, injury, death, or material damage may occur.

The high reactive power demands of induction wind generators is another issue that has given rise to needs for better reactive power compensation. In some cases the reactive demands of wind turbines may exceed the real power produced. Utilities often require developers to provide their own reactive power requirements in the way of capacitor banks.

Bonneville Power Administration has supported "state-of-the-art" research on new techniques for compensating for the reactive power demands of dispersed sources of energy such as wind turbines. In addition to such power electronics technology, advances in variable wind speed generators will enhance utility system compatibility.

In specifying the type and configuration of wind turbine generation plants these integration issues described above will need to be considered. If a large quantity of energy is needed, a dispersed network of large wind turbines will be required. For small systems where wind energy penetration will exceed 10% of the utility generation load, power quality problems will need priority attention. For systems requiring displaced base load, such as here in the northwest, a means of storage of energy generated will be a prime concern. For systems requiring peaking, load matching studies will determine the ability of wind to match peaking needs.

ACKNOWLEDGEMENTS

This research was funded under Bonneville Power Administration contract DEAI79-86BP63406. We would like to acknowledge the substantial contributions of Nicholas Butler, electrical engineer and Contract Officer from BPA's Division of Resource Management. We would also like to thank those authors listed in the references and bibliography section who sent copies of papers and reports. Particularly appreciated were the contributions of Carel Dewinkle, Wisconsin Energy Group; Dr. David Lindley, Wind Electricity Generating Board; Clyde Nagata, Hawaii Electric; M. Poul Nielsen, Danish Electricity System; D.I. Page, Energy Technology Support Unit; and David Smith, Coos Curry Electric. We are also indebted to Laurie Dockendorf for her word processing support and Linda Hubbard, who provided the administrative support.

TABLE OF CONTENTS

		Page
1.0	INTRODUCTION	1
2.0	QUANTITY	3
	2.1 Energy Output and Utility Experience	3
	2.2 Penetration	5
	2.3 Connection	7
3.0	VALUE	9
	3.1 Storage	9
	3.2 Load Matching	11
	3.3 Capacity Credit	12
	3.4 Loss of Load Probability	13
	3.5 Diversity	13
4.0	QUALITY	15
	4.1 Dispatching	15
	4.2 Transients, Faults and Voltage Fluctuations	17
	4.3 Isolation or Islanding	21
	4.4 Reactive Power and Power Factor Control	22
5.0	REFERENCES AND BIBLIOGRAPHY	29

LIST OF FIGURES

Figure Page

1 Relation Between Apparent, Active and Reactive Power 23

1.0 INTRODUCTION

This report will examine: a) the part played by wind turbines as a source of power in a network of mixed energy systems, and b) the experience of utilities in integrating wind into their systems. Although change is an inherent characteristic of utility operation, integrating wind into the utility system will present a new challenge of matching changing demand with non-coincident changing supply. This report summarizes some of the important findings on the problems, experience, and some new solutions to the problem of integrating wind into utility grids. The issue of integration of wind energy into the utility system will be examined from three perspectives: the quantity of energy, its value, and its quality.

Integration is a particularly important issue now. Less often are power planners looking at 1,000 megawatt plus central station capacity additions. In the future, supplementary sources of electrical energy are expected to be from plants of less than 100 megawatts, and at more dispersed locations. Integrating these small dispersed energy sources into the utility electrical grid system will require resolving several technical problems that affect safety, economics, and system stability and reliability. In the past utility planning and power systems were oriented more to using power from large central power plants. New control strategies and revised operational procedures will be required for adequate integration of wind energy and other dispersed sources of generation (DSGs) such as solar and low-head hydro.

The Pacific Northwest is endowed with substantial resources of both hydro and wind energy for electrical power generation. The combination of these energy sources into an integrated and optimized system has the potential for supplying a major portion of the future energy and peak power requirements of the region (see Baker et al. 1978). Wind energy is particularly attractive as an energy source that can be brought on line within a year in small increments as loads increase.

2.0 QUANTITY

The quantity of energy from dispersed sources of generation (DSGs) that a utility can handle varies depending on the size of the system. Contributions (penetrations) of less than 10% of total system capacity presents fewer problems than penetrations of greater than 10%. In this section we will examine some of the experience of utilities when integrating wind into their systems. The experience of utilities with wind power plants ranges from contributions of less than 1% to more than 50% of total system generation.

2.1 Energy Output and Utility Experience

There are over 20,000 wind turbines operating in the United States. In California alone there are about 16,800 generators with a rating of 17.5 kW or greater. The California Energy Commission reports that at the end of 1987 the cumulative wind energy generating capacity was about 1,600 MW with a capital investment of 2.5 billion dollars. Much of this report is based on experiences in California. The following paragraphs will summarize integration expereince outside California.

The U.S. Department of Energy, in the late 1970s, conducted several well documented studies of individual large (100 kW) turbine's integration problems. Over 38,000 hours of operation experience were logged by four MOD OA machines (Shaltens and Birchenough, 1983). The wind turbines were primarily fuel savers. A Clayton, New Mexico wind turbine produced 2.5% of the town's total energy and up to 20% of the total energy at certain times during the early morning hours. The town had seven diesel systems. The wind turbine did not experience any problems in maintaining synchronism with the Clayton system which has a relatively wide range of acceptable frequency (60 Hz ± 23 Hz). Hawaiian Electric Company operated one MOD OA at Kahuku on Oahu. The turbine operated for 25 months. Average output was 169 kW (rated was 200 kW).

Another state, besides California, with considerable integration experience is the state of Hawaii. In Hawaii, the annual wind energy potential is 10 to 20 times the present demand in the state. On the big island (Hawaii) the available energy is 100 times the demand. Wind energy at the present time provides less than 1% of energy, most of the enery generation is from combustion of oil.

Hawaiian Electric Company has set up a program to characterize all generating plants including renewables (Zaninger 1986). Details included: number; type; power rating; control strategy; characterization of power output; peak power output; and ramping ratios. They also characterized the transmission and substation system. This characterization included: line impedance; line losses; power quality; transformer characteristics; voltage; and current. Plans included an analysis of ten years of wind data and load histories. The information was intended to provide base line interface data for a future wind integration study. The Hawaiian utility is also studying the value of battery storage wind generated electricity. BPA should continue to follow developments in Hawaii, because the information is pertinent to the remote parts of the BPA system.

Wind energy is also in use in several European countries. As of January 1, 1987, there were about 1200 turbines in Denmark with an output capacity of 73 MW (Nielsen, 1987). The total amount of wind generated electricity in Denmark in 1986 was 120 GWh. An agreement between Association of Danish Electrical Utilities and the Danish Windpower Association (wind turbine owners) provides for the utilities to buy electricity at specified rates. Surplus production from wind turbines is purchased by the utilities at a rate of 70 to 85% of the utility's net selling price to ordinary domestic consumers.

Here in the Pacific Northwest experience includes a demonstration of a 500 kW Alcoa vertical axis turbine located at Newport, Oregon, in 1981. The project was jointly sponsored by Alcoa Aluminum Company and a consortium of Oregon consumer-owned utilities. In 1982, Pacific Power and Light Company installed a 200 kW WTG machine at its Whiskey Run site on the southern Oregon coast. Three types of wind turbines were installed at the Livingston Bench Site near Livingston, Montana in 1981. The Livingston demonstration units in Montana were plagued by cold climate problems. One unit remains in operation.

Elsewhere in Montana, a small commercial development consisting of five 20 kW Enertechs installed at Ulm (near Great Falls) is now out-of-service.

Three 2.5 MW Boeing MOD-2 turbines were installed at Goodnoe Hills in south central Washington in 1980. The prime sponsor was the U.S. Department of Energy (USDOE), with participation by the Bonneville Power Administration, the Boeing Company, the National Aeronautics and Space Administration, and Electric Power Research Institute and others. The purposes of the project included field testing of the MOD-2 machine, assessment of wake interactions among large-scale machines, assessment of turbine and blade materials and design, and noise assessments. In 1986 the experiments ended after termination of USDOE funding. The MOD-2 units have been dismantled. BPA also sponsored installation of five small-scale (1.5 to 10 kW) wind turbines at nearby private homes in Klickitat County, Washington.

In this region there are also many individually owned turbines. A 1982 Oregon survey by the Oregon Department of Energy inventoried 42 turbines of 1 to 10 kW capacity. A 1984 Washington survey by the Washington State Energy Office, documented 36 small-scale wind turbine generators, besides the small-scale machines of the USDOE/BPA Goodnoe Hills project.

The last commercial wind project in this region was at Whisky Run, on the southern Oregon coast. The development began in 1983 and originally consisted of 25 ESI-54 turbines with a total plant capacity rating of 1.25 megawatts. Pacific Power and Light Company purchased the power. The project has been afflicted with low capacity factors and corrosion-related machine failures. The wind project ceased operation in May of 1989.

2.2 Penetration

Wind energy generators may be adapted within an electrical-energy producing system without storage facilities, on a fuel savings basis, but only up to limits determined by the available surplus generating capacity and operating and transmission grid stability margins of the system. According to Sorenson (1976) this leads to a maximum penetration of a few percent to around 10%. Industry surveys show small amounts of DSG have been used without problems in system operation, but integrating higher percentages of DSG into the system will require more experience than is available to date (Chan et al., 1987). Utilities would prefer to limit wind to 2 to 5% of the spinning reserve. This restriction would reduce the integration problems, but would seriously limit wind energy potential.

Most utility applications of wind power generation have been in clusters of machines rated at 50 to 200 kW connected to utility transmission network and operated in tandem with the total utility generation mix. Since wind fluctuations result in minute to minute turbine output variations, large penetrations of wind on the system (> 10%) are expected to cause dynamic impacts, such as severe system swings, excessive frequency excursions, or system instability (Zaininger and Bell, 1980). Potential dynamic impacts may limit potential wind turbine penetration and/or cause significant system operation restrictions.

The penetration limitation is more likely to be more severe for small isolated utility systems than for large interconnected systems. However, even for large interconnected systems there may be other concerns that may limit penetration. Wind plants in the Tehachapi Mountains of California, because of limitations in the transmission line capacity, have been forced to shut down. Forced shut-downs could significantly lower annual energy production. Southern California Edison pays for non-generation in forced outages.

In Hawaii, utilities are concerned about the consequences of the load from an intermittent energy source, such as wind, exceeding 10% penetration levels. Four of five major islands have loads under 100 MW. Nighttime demand on the big island, Hawaii, is 50 MW; present wind energy capacity is around 15 MW.

Past experience at Clayton, NM, where wind power penetration reached 20%, resulted in no significant interface difficulties (because of wider range of acceptable frequencies). At Block Island, penetration reached 60 to 70%, some significant integration problems with fluctuating line voltages were encountered. These machines were synchronous generators. A synchronous generator operates at constant rpm. the machine produces power synchronized directly with the power produced by utility's other power sources. An induction generator, on the other hand, operates at nearly constant rpm. The disadvantage of an induction generator is that it operates at a low power factor due to the magnetization requirements. However, induction generators are often less expensive because they require less sophisticated speed control mechanisms. While a synchronous generator may supply better quality power, it draws power while motoring and has a greater tendency to fall out of synchronism during gusts.

2.3 Connection

Wind energy can be directly connected to the utility grid. However, the grid network is complex, consisting of transmission lines of different sizes and capacities. Tieing in new generation facilities with different characteristics presents additional problems. Often, proximity to tie in points and load centers may be a barrier to wind energy development (Tawa, 1980).

Wisconsin Power and Light's procedure for interconnecting parallel generators contains a detailed outline of the responsibilities of the various departments to: 1) prepare the contract with the customer, 2) determine what construction, if any, must be done, and 3) determine minimum requirements to accept the parallel generator (protection schemes, sectionalizing requirements, interconnections/metering). When the customer and Company come to an agreement, the contract will be signed, operations will record the location, and the telephone and cable television companies will be notified that a parallel generation facility is being installed.

Smith, 1988, a Coos-Curry electric cooperative executive, reports that the normal cost to the utility to wheel the output energy over the distribution system is one to three cents per kWh at 50% load factor. The costs are peak demand rather than energy related. A 5% output factor (such as typically experienced at Whisky Run) would have ten times the cost of a 50% load factor. Mr. Smith felt that while 1 to 3¢ per kWh may seem high, it is probably an understatement of the cost.

INTEGRATION OF WIND ENERGY INTO THE ELECTRICAL UTILITY SYSTEM: AN OVERVIEW OF THE ISSUES

3.0 VALUE

The deferred cost of displaced energy, capacity of conventional power plants, transmission and distribution deferrals, and transmission and distribution loss savings determine the value of wind energy. Cost consists of capital and operation and maintenance of the wind plants (Kaupang, 1983). The value of distributed wind power generation was found to be generation energy and capacity value dominated rather than by transmission and distribution system concerns. A wind power and storage combination appeared to have a higher value than wind alone, but the value cost ratio was poorer for the former because of the additional cost of the storage plant.

The BPA report "Wind Energy in the Pacific Northwest: Part II The Economics of a Commercial Wind Energy Project at Cape Blanco, OR," discusses the value of wind energy (see text box on following page). The report suggests that the value of wind may vary depending on the needs of the utility. The report also notes that the value of wind will increase as the industry matures and our understanding of wind forecasting improves.

According to Marsh (1978) the last criteria for comparing wind energy costs are total utility system costs. The energy value of wind is greatest in utilities having both favorable winds and substantial oil fired generation. Both the capacity and energy value of wind depends strongly on the wind characteristics and load characteristics of the utility systems to which they are applied. The costs of conventional generation and the relative times of daily load and wind power peaks are particularly important. As wind plant penetration increases, incremental value decreases. The energy displacement shifts to conventional units of lower energy costs and capacity displacement diminishes.

3.1 Storage

Wind energy must be used, stored, curtailed, or dumped. This may place special demands on a utility system to provide storage for energy generated, but not needed at the moment. Such storage may be in the form of other, higher cost fuel not expended but left for later use. In California, the principal means of integrating wind into California's utility systems is by displacing more costly oil and gas consumption. The Pacific Northwest has

"Up to now wind generation costs have been discussed in terms of energy only, that is, kWh. In a more perfect world, cost and "value" would be identical. In the world we inhabit they are not. There is no simple means of weighing costs and benefits of competing resources and identifying a clear winner. System needs vary from time to time, depending on the utility system assessed. For some considerations (the risk of over- or under-building to satisfy demand or address environmental costs and benefits) it may be impossible to set a dollar value by consensus. These values are no less real for being difficult to isolate. They must be addressed to weigh properly the value of wind energy.

In addition, the study assumed no space would be available on the Pacific Northwest-Pacific Southwest Intertie for delivering excess power to California during spring runoff. While this may be the case in an average or better water year, increased Intertie capacity and a transformation from regional energy surplus to shortage would alter system assumptions dramatically. Other system issues of diurnal and seasonal peak deliveries of wind power may also adjust assumptions regarding storage needs and costs.

Consider, first, day-to-day operations planning. This initially involves "pre-dispatch" scheduling of available resources to meet the next day's forecasted loads. As more data are gathered on the weather patterns that influence winds, the ability to plan accurately for the availability of wind energy on a seasonal and daily basis will improve commensurately. Already the patterns of temperature and pressure variation that produce the winds in California's interior passes are predicted dependably. The ability to predict the frequency and intensity of storms is also improving. To the extent that these patterns predictably coincide with diurnal and seasonal peak demands, allowing daily scheduling of wind facilities, wind generated energy may be assigned partial capacity value. "Real-time operations," which require the ability to dispatch a resource instantaneously, present a more difficult hurdle. Yet, techniques have been devised that may allow commitment of wind "units" to a system in a fashion that reduces to manageable levels potential mismatches between total generation and load. Wind projects that are dispersed geographically and subject to different meteorological influences may deliver both system-planning and operations-capacity value where any single, isolated site might not.

Finally, there are advanced battery and other energy storage techniques and mechanisms being explored today that may significantly change the future value of utility system of zero fuel-cost resources such as wind and hydro. All the complementary resource/storage technology combinations require careful evaluation from a cost and system integration basis."

Source: Wind Energy in the Northwest, Part III: The Economics of a Wind Energy Project at Cape Blanco, OR, 1988, Bonneville Power Administration, Portland, OR.

little high-fuel-cost generation. Storage here is more likely to be in the form of water held behind dams, displaced while wind kilowatt-hours enter the system (see BPA, 1988).

With ample storage, wind works to the advantage of the system here in the Northwest, adding flexibility and, therefore, value. When storage space is reduced, as it is in the region's spring runoff, excess wind energy may have to be dumped. One BPA study estimated that, for the worst case, as much as 40% of the total production from a 3,000 mW wind resource might have to be dumped in a year ("Wind Energy Integration Study," BPA, August 1980). Such a conclusion would have serious implications for the cost-effectiveness of wind energy in the region. "However, no sophisticated modeling or demonstration project testing of this proposition has taken place. In particular, such potential losses need to be weighed together with system benefits of wind during low-water, ample storage years, and with other potentially synergistic relationships (of wind with solar photovoltaics or pumped storage facilities, for example). Testing would need to address a range of system costs and benefits, not solely the question of storage" (BPA, 1988).

An example simulation of a storage system was conducted by Quinlan and Scheffler (1987). The system included 400% relative power capacity, 80% conversion efficiency, and 40% relative converter capacity representing 1000 MW of wind park capacity and 4000 MWh of battery storage, 80% throughput efficiency and 1600 MW AC-DC, DC-AC energy converter. This system resulted in a 65% improvement in the value of energy delivered to Southern California Edison. The maximum efficiency systems delivered energy at 111% of the value of unassisted wind energy systems.

3.2 Load Matching

Utilities often regard wind generated electricity as non-firm energy, with little or no capacity, or "on-call" peaking value as opposed to thermal plants which can deliver power when needed. However, Southern California Edison (SEC) has found that the summer wind season generally coincides well with the peak summer demand for power. Wind's ability to displace the addition of conventional peaking combustion turbines to utility systems has been recognized by the California PUC as offering utilities measurable--and compensable--value (see BPA, 1988).

A study by Argonne (see Van Kuiken et al., 1980) suggest that wind can contribute to reliability, but the contribution decreases with increasing penetration. The study also noted a nearly linear percentage reduction in fuel use with increasing penetration.

The availability of wind at times of high demand is another measure of its ability to reduce the load. Wade et al., (1988) found the monthly match of available wind energy at the Whisky Run wind generation facility to the requirements of the local utility is good on a seasonal basis. However, on a day to day or hourly basis, it is poor, with wind energy often not available during peak demand.

Wind turbine generation from a wind regime that produces a high percentage of energy during the power system's on-peak-hours is ideal for integrating with a hydro system. Combining the wind turbine generating duration curve with a load duration curve separated by off-peak- and on-peak-hours is a good method of determining compatibility and optimum amount of wind energy. Eldeen and Moneth (1986) found the most favorable mode of operation was, when wind energy is added to cancel load. The mix of conventional equipment can be reoptimized to satisfy the remaining load. They suggest this mode is more efficient than adding wind to the ideal mix of equipment selected to satisfy the original load.

3.3 Capacity Credit

Determining the capacity value for wind in system-wide planning is complex and subject to debate over the best means of calculating the real-time ability to dispatch energy. The question is also complicated by the differences between utilities in their generation mix. The capacity credit for wind may vary from one utility to the next depending on the utilities' requirements and generation mix. It is not dependent solely on wind characteristics (see Davitian, 1978). The value of capacity varies also with its abundance or scarcity in a utility's system. The Pacific Northwest has an abundance of capacity in its hydro system. Future resource additions are likely to be baseload plants as opposed to peaking units. Wind facilities in this region will thus target offsetting new baseload resource needs and the associated capital costs.

Utilities should take into account, in capacity credit assumptions the complementary relationships that yield capacity and energy at lower total system costs. A combination of wind/photovoltaic might produce power both on sunny, calm days and on cloudy, stormy days. Wind together with increased storage in U.S. and Canadian storage reservoirs could reduce the need for additional firm capacity.

3.4 Loss of Load Probability

It is important to utilities that wind farm output fit their needs. Wind is particularly valuable when it reduces the loss of load probability (LOLP). The LOLP is the statistical chance that, due to high load or failure of supply, the utility would not be able to meet the need for energy. PG&E examined the effect of loss of load probability (LOLP) during the month of June, 1986 (Steely et al., 1987). The addition of wind turbines in the generation mix reduced loss of load probability by 19%. During hours of peak load, wind energy in the PG&E system reduces LOLP by about 25%.

3.5 Diversity

Wind can sometimes gain value, despite its variable nature, if turbines are placed at widely spaced locations to gain from the diversity of the wind. Low winds at one location may be complemented by strong winds at another location. The decrease in random power fluctuations for a wind energy at dispersed locations was first suggested by Molly (1977).

An investigation was conducted here in the northwest of the monthly zero output time for a hypothetical network of six widely spaced locations. For individual sites zero output varied from 0.1-7.4%. The longest continuous network outage was only 8 hours; the average zero output from the network was 2.5 hours (see Baker et al., 1977).

Diversity improvements in reliability were noticed even within an array of wind turbines in one facility in Hawaii because of the averaging effects of a number of wind turbines. Power output fluctuations of roughly 15% around the mean over a period of a minute for an individual turbine were reduced to only 3% for the array of turbines (Mutone and Milnes, 1987). A wind farm with a large number of turbines may improve the quality of output by smoothing fluctuations.

4.0 QUALITY

Change is an inherent characteristic of electric utility operation. Changes in load respond to changes in the mix of customers during the day and patterns of use. With "run of the river" hydroelectric power there may be changes in the supply of energy attributed to variations in the water supply. The same is true for wind energy, only to a greater degree. The fluctuations in the supply of wind energy provide added burden to the power dispatcher who already has to be concerned with fluctuations in the demand for energy.

4.1 Dispatching

An intermittent generation source is one over which a utility dispatch has minimal control over the amount of power available at any instant. The power may fluctuate freely over the range from zero to maximum. For a utility planner, this form of resource presents problems in the determination of reliability and worth. To account completely for wind turbine variation, wind prediction is required and that is not an easy task (see Wade et al., 1989).

Most utilities use some type of program that raises and lowers generation to match the load. If there are several types of generators, they also may have a program that adjusts generation to equalize the marginal cost of all the generators to produce least cost energy. Some types of turbines have specialized roles. For instance, a utility may have generators on line that "follow the load" (increase and decrease output to meet demand). They also have spinning reserve generators are immediately available which take on additional load and non-spinning reserve units that can be quickly brought on line to meet load.

When wind energy is increasing or decreasing with the load, in a sense it is acting as load following, except the dispatcher has no control over it. If it is increasing when load is decreasing or vice versa, the dispatcher faces a bigger problem than with no wind energy on line. This is only true if wind makes up more than 2 to 5% of the spinning reserve.

Bosse and Anderson (1983) note that if wind turbines are controlled by utilities they should be treated as "must run" facilities because their fuel cost is zero. If the power is being purchased by the utility from an independent power producer and the utility has no control over the generation, the wind energy should be viewed as negative load. However, if the utility has control over the wind energy being delivered by the independent power producer, the generation should be scheduled together with other available generation.

Park and Bowmeeter (1983) suggest a modified unit commitment generation control program combined with a 15-minute and one hour speed prediction program. These programs would allow start up or shut down if hydro or gas generators that can be brought on line with 15-minute notice to complement the wind energy. This generation control strategy would mean that coordinated blade tip control could be used to limit all wind power variations above the predicted trend of hourly wind power output. This would eliminate unloadable generation.

A program developed by Chan et al. (1987) determines hourly system operating requirements and dispersed device control program formulates DSG usage strategy, taking into account hourly operating requirements and an augmented economic dispatch program adjusts generator output based on available DSG. Another method of integrating DSGs including wind was developed by Fegan and Percival (1979). Their model integrates dispersed energy resources into a utility production cost model. The model provides improved approximations in production costs and the loss of load calculations.

The Danish Electricity System is 90% dependent on coal-fired power stations. There is a large amount of combined heat and power production which will presumably increase over the next 5-10 years. The composition and structure of the Danish electricity supply system suggests a substantial surplus production of wind energy could occur with a considerable penetration by wind energy. The Danish utilities initiated a study of the economic value of surplus wind energy. A model was developed which simulated hour-by-hour and day-by-day planning of operation for all available generation units. The model is designed to calculate optimal load dispatch. Because wind has only limited predictability, the unit commitment procedure in the Danish model is carried out ***before*** the wind power production is subtracted from the predicted load. The load dispatching is carried out after the subtraction. This insures sufficient power capacity in operation to meet expected demand. Since the Danish system is dominated by coal units, there was uncertainty that the thermal units would be able to respond quickly enough to match wind power variations. Since wind was assumed to be unpredictable, the control action cannot be anticipated further complicating operational decisions. Real world experience with load dispatching strategies that include wind are needed.

4.2 Transients, Faults and Voltage Fluctuations

Unlike conventional generating plants which are characterized by constant speed prime movers, a wind generating plant exhibits unsteady input behavior. There was early concern by utilities about the effect of transients. Transients are short-term voltage or power fluctuations resulting from wind gusts and turbulence and transient swings from network disturbances (i.e., faults or line switching operations) (see Chan et al., 1983).

The extent that wind gusts will present a transient problem depends on the number of turbines and spatial size of the wind plant. Severe transient and electrical stresses can be induced for certain system configurations. Best results were obtained by interposing rate or damped compliant couplings between the wind turbine and a synchronous generator (see Johnson and Smith, 1976). Induction generators do not require such damping. Blade pitch control limits output above the rated wind velocities.

Wind gusts may not be a big problem if the wind power plant is large enough such that the effect of individual transient gusts would be averaged over an array of multiple wind turbines. For large interconnected utility systems transient stability will not be endangered by the addition of wind turbines (Zaininger and Bell,1980). This is because operational practice is based on other criteria, such as area control error. Restriction of allowable ramping rates of conventional generation during a sudden wind change occurs simultaneously within seconds of a large change in system demand under light loading conditions. The combined effect requires steep ramping up or down in conventional generation mix. The effect of these operational practices may limit wind turbine penetration to avoid steep ramping.

Isolated wind turbines on the utility grid may present a problem for utilities and their customers. Utilities are likely to be held liable if a wind turbine continues to operate isolated, thus causing damage due to frequency and/or voltage excursions outside the normal range (Curtice and Patton, 1981). Curtice and Patton (1981) suggested relays which automatically sense abnormal frequency and voltage for automatically disconnecting isolated WTGs. They found that radial feeder over-current protection was not significantly affected by small WTGs. However, WTGs may increase the number of voltage regulator operations, thus increasing equipment maintenance costs. They developed a method to analyze possible utility load frequency control problems. For large wind turbines in arrays voltage fluctuations were not expected to cause significant problems and were well understood. However, there was some earlier concern that oscillatory interactions between and among wind turbine generators would be a problem (see Glasgow and Robbins, 1979).

At Block Island, where penetrations exceeded 60%, the effects of transient frequency variations were significant. Although frequency varied by ± 1/2 Hz , the variations were roughly the same magnitude as those caused by the major load demands during diesel operation alone (see Shaltens et al., 1983). Shaltens et al. (1983) concluded "wind turbine generation even when producing a large portion of the power required by an isolated utility, can be a practical option resulting in system disturbances no greater than those found in conventional diesel systems."

According to Mutone and Milnes (1987) experience in Hawaii with the Westinghouse wind farm produced the following conclusions:

- Power and reactive power were controlled at the local level to produce the desired effect at the electrical substation. Power, kvar, voltage, and power factor output requirements were satisfied.
- No instability was observed in any of the various modes of operation. These modes included voltage control of transients, power factor control, reactive power control, above rated operation, below rated operation, and operation during a farm wide wind gust.

- A wind farm with a large number of turbines can, therefore, operate with a remarkable quality level in its total electrical output.

The integration of a potential wind farm at Cape Blanco into BPA's electrical grid was investigated using several power flow computer simulations. The electrical system near Cape Blanco has a 230 kv line that interconnects the Fairview and Rogue substations. The wind plant would tap in south of the 115-kv Bandon substation. Two integration scenarios were considered for the 80 MOD-2 wind turbines. The MOD-2 would have a 2.5 MW synchronous generator. To maintain a nominal voltage of 4.16 kV at the MOD-2 generators, the generators must produce or consume little reactive power. If the MOD-2 units were not able to regulate voltage within acceptable levels, BPA could change transformer taps on the system and would have to coordinate to maintain an adequate voltage profile. The Flow Wind scenario included an 80 MW farm of 160 kW Flow Wind vertical axis machines with induction generators. These machines do not have voltage control. Reactive power demands have to be met by shunt capacitors and/or surrounding electrical grid. Interconnection to BPA grid at the 230 kv level as opposed to the 115 kv level was suggested to reduce voltage flicker problems and prevent problems with thermal loading limits of the smaller line.

Pacific Gas and Electric's (see Hillesland et al., 1984) experience with the Solano MOD-2 wind turbine showed that some unstable power oscillations near the above rated wind speeds occur. Several changes in the pitch control system were made to achieve power stability.

Kaupang (1983) discussed the problem of voltage fluctuations on distribution feeders from wind turbines due to wind gusts in Hawaii. In most realistic applications, the voltage fluctuations would not be a limiting criterion for a practical wind turbine penetration level. Reactive power compensation was assumed. In actual experience, Hawaiian Electric Light Company found voltage fluctuations of 130-140 volts well above PUC allowances for the over 200 turbines installed and feeding power to their system. HELCO had concerns about KVAR problems as the penetration by wind turbines expanded. Clyde Nagata (1988) of Hawaii Electric Light Company reported that HELCO's system is 116 MW at evening peak with no reserve generation on the island of Hawaii. They have 11 MW of interconnected wind energy capacity. They have experienced poor power factor from wind farms which has caused voltage problems. Also power fluctuations due to wind gusts have resulted in voltage swings. They have attempted to reduce the problem by intermittently reducing the output of the wind farms to avoid disconnecting the wind systems from the grid.

In Denmark, Møller (1983) reported that when wind turbines are installed it is often necessary to reinforce the distribution network (line size) in order to avoid unacceptable reductions in the quality of voltage. The voltage is influenced by fluctuations in wind power production and on/off cycles of the wind turbines. The cut-in of turbines requires special attention because it causes high in-rush currents and correspondingly deep voltage dips. In cases where the in-rush current is limited by thyristors, a short circuit level at the point of connection of at least 20 to 30 times the maximum power output of the turbine is required. One Danish utility company demands a short circuit level 80 times the maximum instantaneous output if in-rush current is not limited. Some preliminary investigations have shown that 20 to 30 times the machine maximum output should be sufficient.

In 1976, the Association of Danish Electric Utilities (DEF) published a set of general guidelines for the connection of small-scale wind turbines to the utility grid system. The main conditions were as follows:

- Connection of private power-generating equipment must be reported to the local electric utility by the electrical contractor.
- A person must be assigned as responsible for the operation of the equipment. An agreement between this operator and the local electric utility must establish rules for the operation of the grid interface equipment.
- Permission to connect a wind turbine to the power grid is granted under the condition of no disturbances in the voltage to the power grid.
- The equipment must be designed so that the wind turbine is automatically disconnected from the grid in cases of malfunctions, either on the utility grid or in the equipment itself.
- Technical staff of the local electric utility may disconnect the power-generating equipment from the utility grid at any

time. For instance, when maintenance or repair work on the grid is being carried out.

The Danish also found that power lines must have sufficient capacity to avoid over voltages caused by connected wind turbines. If a large array of wind turbines, connected to the same 10 kV feeder line or directly to the 10 kV bus bar in the 60/10 kV substation may also cause a varying voltage drop. This may occur through the 60/10 kV transformer, because of the effect of gusty winds on wind turbines. The automatic voltage control system in the substation is designed to maintain constant voltage on the 10 kV bus bar. They also expected that gusty winds would introduce many control actions by the voltage control system and would have been damaging to the system. Their recent measurements carried out in windfarms have shown that the problem is less serious than was first assumed. This is because the power output from the individual wind turbines are to a high degree equalized when all contributions are added together. For this reason, they expect only in special cases will it be necessary to choose a larger or even a separate 60/10 kV transformer.

Wisconsin Power and Light requires customers to operate the generator so that voltage surges, harmonics, and other service impairing disturbances are not propagated into the Company's electrical system. The customer is responsible for correcting such conditions at the customer's expense. WP&L maintains the right to discontinue service if operation of the generator impairs service to other electrical customers.

4.3 Isolation or Islanding

Islanding occurs when a wind turbine supplies power to a portion of the system which is disconnected from the main system. This could lead to both death or injury of personnel and material damage. Isolated wind turbines on the utility grid may present liability problem for utilities and their customers. Isolated wind systems are often small wind turbines at a customer's home and may not have adequate reactive power compensation.

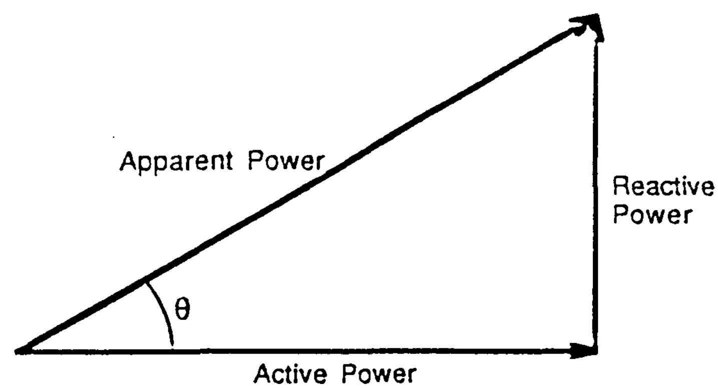
Wisconsin Power and Light's Standards for parallel generators are based on the rules adopted by the Public Service Commission. Items pertinent to isolation include:

> The customer shall provide an isolating device to automatically disconnect the customer's generator from the Company's electrical system in the event of a Company power outage. The isolating device shall not reclose until after power is permanently restored to the Company's electrical system. The isolating device shall be a circuit breaker, relay contacts, switch, or equivalent equipment. The above isolating device shall be activated by reliable sensors which detect loss of power system AC voltage, low or high frequency, generator overload, or other suitable input. WP&L suggests installation of a capacitor battery in each wind turbine and to design and operate it in such a way that islanding situations would be of short duration and not accompanied by over voltages.

To avoid any risk of islanding, in Denmark frequency detection relay (50 ± 3 Hz) are recommended as a safety precaution. An over-voltage detection relay (242 V for more than 10 seconds) is also recommended as a wind turbine may cause the voltage to rise to an intolerably high level. (This applies to individual turbines. Specific regulations have been set up for windfarms with capacitive compensation.) As a general rule, automatic reclosing is normally allowed on distribution systems with a high percentage of temporary faults. Danish protection equipment is designed in such a way that an automatic reclosing event automatically disconnects adjacent wind turbines from the grid. Until recently, a manual reset action was needed to restart the turbines.

4.4 Reactive Power and Power Factor Control

Rotating machines, such as wind turbines, require reactive power. The ratio of active or real power to apparent power is called the power factor (Smith, 1988). Total apparent power demanded by a load is the product of the current through the load times the voltage across the load terminals. This power is called apparent power because not all of it will produce work. The portion that produces effective work is defined as the real or active power and portion that produces no work is called reactive power (see Figure 1). The reactive power is used to magnetize the iron or steel in transmission lines, transformers, generators, and motors.



$$\text{Power Factor} = \frac{\text{Active Power}}{\text{Apparent Power}} = \cos\theta$$

$$\text{Reactive Power Factor} = \frac{\text{Reactive Power}}{\text{Apparent Power}} = \sin\theta$$

Figure 1. Relation Between Apparent, Active and Reactive Power (from Smith and Herrara, 1988).

Because of the reactive power demands of wind generators, they are prime prospects for future applications of power electronics equipment according to Goodman (1988). Advances in power electronics are expected to improve power conditions for wind power stations. Recent studies show that wind power technology can be significantly enhanced and made more attractive to the utility industry by a proper application of power electronics" (EPRI, 1988).

The principal areas of power electronics application to wind power are: static VAR compensators and variable-speed wind turbines. Because a wind power station consists of many small generating units and a large power collection network, power electronics equipment will most likely be applied to station control and protection requirements. Induction machines are increasingly used in wind farm applications because of their ruggedness and simplicity. Because the induction machine requires external excitation, it draws lagging reactive power from the utility system. Adverse reactive power flows are particularly of concern when inductive loads are concentrated in one area such as several large arrays of wind farms in California and Hawaii. Utilities often require windfarm operators to provide their own reactive power or charge the operators for utility supplied reactive power. If the utility charges for reactive power, the reduction of reactive wind farms can reduce utility charges by providing their own reactive requirements in the form of a capacitor bank. High reactive power flows also results in inefficient use of electrical equipment within a wind power station and in the adjacent utility system (EPRI, 1988).

Reactive power problems of induction wind generators has provided a requirement for new types of static VAR compensators. Wind induction generators present special reactive power compensation challenges. This is because the reactive power is subject to continuous random fluctuations in response to wind variations. Reactive compensation also needs to be modular or scalable to allow a flexible range of rating levels among wind turbines.

According to Smith and Herrara (1988) attention at the design stage to reactive power management can avert operating problems when the wind farm begins operation. There are many important considerations when considering the reactive power problem. The following material describes important considerations in reactive power compensation, recent research on compensation techniques (power factor controllers) and recent utility experience.

Reactive power concerns become more critical as the size of the wind farm becomes a larger fraction of the short circuit capacity of the utility system. Experience in Hawaii with the Westinghouse wind farm showed that power and reactive power can be controlled at the local level to produce the desired effect (power, kvar and power factor output requirements were satisfied) at the electrical substation (see Mutone and Milnes, 1987).

Strong wind conditions can result in the turbines' output exceeding the rated output. Power station design should allow for wind's unique operating characteristics or else power collection networks will experience overloads and faults (Zaninger, 1987). Zaninger (1987) describes one station where crude power factor correction resulted in self excitation of the induction generators. Assmussen (1981) notes that reactive power often exceeds the real power. For a wind power plant on the southern Oregon Coast, Wade et al. (1988) found that reactive power requirements or KVARs seem to increase with decreasing wind farm output at the Whisky Run wind plant on the southern Oregon coast.

Adverse reactive power flows, in the past, were often partially compensated by using fixed, mechanically switched capacitors or static VAR compensators. The wind farm operator has several options for locating capacitors. Capacitors can be placed on the low or high voltage side of generator transformer; low or high side of substation transformer; or on the connecting feeder. Capacitors placed at low voltage bus installation are more expensive, but provide better voltage support than at the high voltage bus. Smith and Herrera (1988) site a number of design alternatives available to accommodate reactive power requirements including:

- individual machine compensation
- total farm compensation
- a combination of individual turbine and total farm

According to Venkata et al. (1986) there are six classes of reactive power compensations:

- noncapacitor phase control
- switched inverter
- thyristor-controlled reactor and fixed capacitor
- thyristor-controlled reactor
- mechanically switched capacitor
- thyristor switched capacitor

Venkata and Boardman (1982) found the real power output with respect to speed and power showed no difference between forward and reverse rotation. Generator efficiency improved by 5 to 6 percentage points when driven the reverse direction for clockwise or counter clockwise reference. This finding proved that the auxiliary winding and the running capacitor caused a direction-dependent efficiency effect.

One type of reactive power control device - the adaptive power factor controller (APFC), senses reactive current drawn by the machine and provide the needed power to improve the power factor to close to unity. The adaptive power factor controller, because it is an electronic device, can rapidly and adaptively switch to adapt to wind turbine rapid fluctuations in reactive power drawn without introducing harmonics or transients to the system. It can achieve close to unity power factor at the point of installation and avoids over-voltage. It can be also be applied to unbalanced, three-phase systems, is modular to fit various size compensation, and is simple and cost effective. The APFC is a modular harmonic free device creating no line transients. The design eliminates self excitation problems associated with power factor controls on induction generators (El Sharkawi et al., 1984).

A newly designed CL-APFC or Closed Loop Adaptive Power Factor Controller is an effective device to compensate the reactive power of rapidly varying loads (see El-Sharkawi et al., 1987). The accuracy of the compensation is not affected by the fluctuation in line voltage and the effect of line voltage harmonics on the switching current components is minimized. Although effective and reliable, the device is simple and easy to build.

An investigation by BPA (see Venkata and El-Sharkawi, 1988) of viable schemes to improve steady-state performance of commercially available induction generators found that the efficiency of induction generators could be improved by combining the following four factors in several possible ways:

- the direction of rotation
- the supply voltage phase sequence
- the insertion of series capacitor in each auxiliary winding, and
- the incorporation of a proper phase shift between the main and auxiliary winding on the same phase belt.

This research showed that the alternate schemes tested provide better performance than the conventional mode of operation of the generator. The advantages included:

- Performance was increased
- Power factors increased substantially because of insertion of a fixed capacitor.

Natarajan (1987) examined the economic payback of adaptive power factor controls and found a payback period of 6.7 to 7.4 years reducing to 3 to 3.5 years accounting for tax credits.

Power factor correction capacitors have several benefits. Reddoch and Herrera (1986) note that incorporating controlled variable-speed wind turbine generation in wind turbine design could greatly enhance utility system compatibility of wind turbines. This is not cost effective now, but has the following benefits.

- Enhanced utility system compatibility by substantially improving the ability to regulate power and reactive power.
- Easier tailoring to site specific wind characteristics through control parameter adjustments.
- Improved dynamics (torsional damping and structural load alleviation) to enable reduced component wear and/or weight reduction.
- More flexible and efficient operating abilities. (Energy capture improved.)

According to EPRI (1988), most wind turbines operate at constant or nearly constant rpm to comply with the constant electrical frequency established by the utility system. Using the right electronics circuitry, it is feasible to decouple the wind turbine's rotor speed from the utility system's operating frequency to allow the wind turbine to operate at variable rpm. Variable-speed wind turbines offer improvements in torsional dynamics and energy capture compared with constant-speed systems. The improved torsional dynamics reduce structural loads and thus reduce weight, increase component service life, or both. These advantages would improve the economics of wind turbines. The power electronics circuitry might also aid in power factor control. According to EPRI the research challenge "is to develop a suitable power electronics package that provides an optimal blend of the above benefits and to integrate that package into a wind turbine system, while maintaining a total system cost-to-benefit ratio less than unity." To this end EPRI and

U.S. Windpower are jointly funding research on the role of power electronics in wind power.

5.0 REFERENCES AND BIBLIOGRAPHY

J. Asmussen, Jr., G.L. Park, O. Krauss, and D. Linvill, 1978: *Application Study of Wind Power Technology to the City of Hart, Michigan, 1977*, Final Report, U.S. Department of Energy, ERDA Contract #E(11-1)-2992, NTIS number COO/2992-78/1. UC-60. 244 PP. Summarized in *Proceedings, Third Wind Energy Workshop*, Vol. 1, Washington, DC, May 1978. Conf-770921/1 UC-60, pp. 285-281.

Asmussen, J. Jr., D. Manner, and G.L. Park, 1978: "An Analytical Expression for the Specific Output of Wind Turbine Generators," *Proc. IEEE*, Vol. 66, No. 10, October 1978, pp. 1295-1298.

Asmussen, J. Jr., R. Wong, J. Clark, W. Hawroth, J. Matilla, R. Nabozny, and H. Flaishe, 1979: *Solar Manufacturing Technology Assessment*, Reports X1-9-8001-1, X1-9-8021-1 by Central Solar Energy Research Corp. (CSERC), Detroit, MI, June 1979.

Assmussen, J.J., 1981: "Wind Power, Its Promises and Problems," *Energy Communications*, Vol. 7, 495-580.

Asmussen, J. Jr., T. Anuskiewicz, and O. Frankenfield, 1981: "Analyzing the Requirements for Mass Production of Small Wind Turbine Generators," *Proceedings of the Small Wind Turbine Systems Workshop*, May 1981, SERI/CP-635-1212, pp. 107-121. (See also CSERC report *Producibility of 15 kW WTG*," September 1981.)

Asmussen, J. Jr., 1980: "Wind Power, Its Promises & Problems," papers in the series *Energy Sources, The Promises & Problems*, L.H. Klotz, editor, Center for Industrial and Institutional Development, University of New Hampshire, Durham, NH, February 1980. Also printed in *Energy Communications*, Vol. 7, 1982, pp. 495-580.

Baker, R.W., E.W. Hewson, N.G. Butler, and E.J. Warchol, 1978: "Wind Power Potential in the Pacific Northwest," *Jour. Applied Meteor.*, 17, pp. 1814-1826.

Baker, R.W., 1979: "Wind Power Potential of the Pacific Northwest Region," *Power Engineering*, pp. 64-67.

Bose, A. and P.M. Anderson, 1983: "Impact of New Technologies on Generation Scheduling," presented in *International Electrical Energy Engineering/Power Engineering Section/Proceedings*.

Bouwmeester, R.J.B., R.A. Schlueter, and G.L. Park, 1985, "Simulation and Assessment of Power Variations from Wind Arrays During Local Storms," *Jnl. Wind Engr & Ind. Aerodyn.*, Vol. 21, pp. 207-221.

BPA, 1988: "Wind Energy in the Pacific Northwest: Part II The Economics of a Commercial Wind Energy Project at Cape Blanco, OR," *Wind Energy Report*, 10, pp. 37-49.

Chan, S., D. Curtice, and S. Chang, 1983: *Methods for Wind Turbine Dynamic Analysis*, EPRI Report AP-3259, Electrical Power Research Institute, Palo Alto, CA.

Chan, S., S. Cheng and D. Curtice, 1987: *Integrating Dispersed Storage and Generation into Power System Control*, EPRI Report EL-4957, Electrical Power Research Institute, Palo Alto, CA.

Curtice D. and J. Patton, 1981: "Operation of Small Wind Turbines on a Distribution System," Systems Control Inc., Palo Alto, CA.

Davitian, H., 1978: "Wind Power and Electric Utilities: A Review of the Problems and Prospects," *Wind Engineering*, 2, pp. 234-255.

Eldeen, E.L. Sharif and P.M. Moneth, 1986: "Probabilistic Modeling of WECS/Utility Systems," presented in *Proceedings of the 6th ASME Conference*, Dallas, TX.

El-Sharkawi, M.A., S.S. VenKata, T.J. Williams, and N.G. Butler, 1984: "An Adaptive Power Factor Controller for Three-Phase Induction Generators," presented in the *IEEE Power Engineering Proceedings*, July, Seattle, WA.

El-Sharkawi, M.A., et al., 1987: "Development and Field Testing of a Closed-Loop Adaptive Power Factor Controller," IEEE Power Engineering Summer Meeting, San Francisco, CA.

EPRI Journal, 1988: "Power Electronics Advances," *Electrical Power Research Institute Journal*, January/February, 1988.

Fegan, G.R. and C.D. Percival, 1979: "Integration of Intermittent Sources Into Balleriaux-Booth Production Cost Models," *Proceedings of IEEE Winter Power Meeting*, New York, NY.

Glasgow, J.C. and W.H. Robbins, 1979: "Utility Operational Experience on the NASA/DOE MOD-OA 200 kW Wind Turbine," *Proceedings of the Workshop on Economic and Operational Requirements and Status of Large Scale Wind Systems*, July 1979, Monterey, CA.

Goodman, F., 1988: "Power Electronics for Renewables," *EPRI Journal*, February 1988. Electric Power Research Institute, Palo Alto, CA, pp. 44-47.

Hillesland, T., et al., 1984: *Solano County MOD-2 Wind Turbine Field Experience*, EPRI Report AP-3896, Electrical Power Research Institute, Palo Alto, CA.

Johnson, C. and R.T. Smith, 1976: "Dynamics of Wind Generators on Electrical Utility Networks, *A Transactions Aerospace and Electronic Systems*, AES 12, pp. 483-493.

Kaupang, B.M., 1983: *Assessment of Distributed Power Systems*, EPRI Report AP-2882, Electric Power Research Institute, Palo Alto, CA.

Lindley,D., 1988: 29 February 1988 letter.

Marsh, W.D., 1978: "Wind Power Plants in Electric Utility Systems," presented in *American Wind Energy Association Conference Proceedings*, Hyannis, MA.

Molly, J.P., 1977: "Balancing Power Supply form Wind Energy Conversion Systems," *Wind Engineering*, 1, pp. 57-66.

Mφller, J., 1983: "Wind Power in the Danish Electricity Supply System," presented at the IEA-Expert Meeting, Palo Alto, CA.

Mutone, G.A. and R.D. Milnes, 1987: "Utility Interaction Dynamics with the Makani Mao'e Wind Farm," Sixth ASME Wind Energy Symposium, February 1987, Dallas, TX.

Natarajan, R., S.S. Venkata, M.A. El-Sharkawi, and N.G. Butler, 1987: "Economic Feasibility Analysis of Intermediate-Size Wind Electric Energy Conversion Systems Employing Induction Generators," *International Journal of Energy Systems*, 7, 2, pp. 90-94.

Neill, D.R., 1983: "Utility Interface Concerns and Related Programs in Hawaii," *American Wind Energy Conference Proceedings*, October, San Francisco, CA.

Nielsen, P., 1987: "Wind Energy Activities in Denmark," *Wind Power 87 Proceedings*, October, San Francisco, CA.

Park, G.L., O. Krauss, and J. Miller, 1982: *"Testing Interconnected SWECS*, Final Report by Michigan State University Division of Engineering Research, March 1982, 94 pp. 300 copies distributed.

Park, G.L., O. Krauss, and J. Miller, 1984: "Performance Testing of Small Interconnected Wind Systems," *ASME Jnl. Solar Energy*, Vol 106, No. 2, May 1984, pp. 212-217.

Park, G.L., O. Krauss, J. Miller, and B. Weinberg, 1983: "Measuring SWECS Performance at the Owner's Site," *Proceedings Sixth Biennial Wind Energy Conference and Workshop*, American Solar Energy Society, Minneapolis, MN, June 1983, pp. 653-661.

Park, G.L., O. Krauss, B. Weinberg, and S. Tedeschi, 1984: *Windmill Performance in Michigan*, Final Report by Michigan State University Division of Engineering Research, November 1984, 83 pp. 400 copies distributed.

Park, G.L., P. McCleer, B. Hanson, B. Weinberg, and O. Krauss, 1985: *AC Motor and Generator Requirements for Isolated SWECS*, Final Report DOE/NASA/0530-1, submitted NASA/DOE, October 1985, 79 pp.

Park, G.L. and O.W. Zastrow, 1982: "Interconnection Issues Concerning Consumer-Owned Wind Electric Generators," *IEEE Trans. Pwr. App. Sys.*, Vol. PAS-101, No. 7, July 1982, pp. 2375-2382.

Park, G.L. and R.W. Stafford, 1982: "Technical Problems of WECS Interconnection," *Proceedings Rural Wind Energy Workshop*, June 1-3, 1982, SERI/CP-254-1689, pp. 191-216. Available NTIS.

Park, G.L., 1983: "Small Consumer-Owned Wind Machines and Associated Interface Problems," *Proceedings 10th Energy Technology Conference*, Washington, DC, February 28-March 3, 1983, Gov't Institutes, Inc.

Park, G.L. and J. Miller, 1984: "Measured Interconnected Behavior of Wind Turbine Inverters," *IEEE Trans. Pwr. App. Sys.*, Vol. 103, No. 10, October 1984, pp. 3074-3079.

Park, G.L. and R.A. Schlueter, "Interfacing Fluctuating Energy Sources to Utility Networks," in *Trends in Electric Utility Research*, edited by C.W. Bullard and P.J. Womeldorff, Pergamon Press, April 1984, pp. 67-78.

Park, G.L., "Wind and Turbine Characteristics Needed for Integration of Wind Turbine Arrays into a Utility System," DOE/NASA Large Horizontal-Axis Wind Turbine Workshop, July 28, 1981, Cleveland, OH. SERI/CP-635-1273, pp. 331-336.

Park, G.L., O. Krauss, J. Lawler, and J. Asmussen, Jr., 1979: *Planning Manual for Utility Application of WECS*, U.S. Department of Energy, Washington, DC, Contract No. EG-77-S-02-4450, June 1979. Available NTIS, 243 pp.

Park, G.L. and R.A. Schlueter, 1981: "Effect of Wind Generator Arrays on Utility System Operations, *Proceedings (Vol. II) Wind Workshop V*, Washington, DC, October 1981, SERI/CP-635-1340, pp. 393-406.

Park, G.L. and O. Krauss, 1980: *Is Wind a Viable Energy Source for Me?*, October 1980. 500 copies of booklet given to Michigan citizens interested in wind power.

Portland General Electric, 1986: *Cape Blanco Wind Farm Feasibility Study: Technical Report No. 4*, Electrical Engineering, Bonneville Power Administration Report DOE/BP-11191-4.

Price, W.W. and S.L. Macklis, 1979: "Wind Energy Conversion Systems Transient Performance Analysis".

Quinlan, P.J. and R.L. Scheffler, 1987: "Parametric Modeling of the Effectiveness of Energy Storage Applied Regional Wind Park Energy Production," in *Windpower "87" Proceedings*, October 5-8, 1987, San Francisco, p. 142-147.

Reddoch, T.W. and J.E. Herrera, 1986: *Testing Requirements for Variable-Speed Generating Technology for Wind Turbine Applications*, EPRI Report AP-4590, Electrical Power Research Institute, Palo Alto, CA.

Rose, W.T., J. Asmussen, Jr., and B.A. Stout, 1981: "A Comparison of Six Methods for Calculating the Annual Energy Output of Wind Turbines," paper presented at Wind Energy Technology Conference, Kansas City, MO, March 1981. Printed in *Conference Proceedings*, pp. 197-205.

Rose, W.T. , J. Asmussen, Jr., and B.A. Stout, 1981: "Performing Life-Cycle Cost Economic Analyses for Small Wind Energy Conversion Systems with a Programmable Calculator," paper presented at Wind Energy Technology Conference, Kansas City, MO, March 1981. Printed in *Conference Proceedings*, pp. 1-7.

Schlueter, R.A., G.L. Park, H. Modir, J. Dorsey, and M. Lotfalian, 1979: *Impact of Storm Fronts on Utilities with WECS Arrays*, Final Report, U.S. Department of Energy, Washington, DC, Contract No. EG-77-S-02-4450, October 1979. UC-60, 147 pp.

Schlueter, R.A., G.L. Park, H. Modir, J. Dorsey, and M. Lotfalian, M., 1983: "Analysis and Simulation of Storm-Induced WECS Generation Changes on System Operation," *IEEE Trans. Power App. & Sys.*, Vol. PAS 102, No. 1, January 1983, pp. 142-152.

Schlueter, R.A., G.L. Park, M. Lotfalian, H. Shayanfar, and J. Dorsey, 1983: "Modification of Power System Operation for Significant Wind Generation Penetration," *IEEE Trans. Power App. & Sys.*, Vol. PAS 102, No. 1, January 1983, pp. 153-161.

Schlueter, R.A., G.L. Park, J. Dorsey, and M. Lotfalian, 1981: *Operations Model for Utilities Using Wind Generator Arrays*, Final Report, U.S. Department of Energy, Contract No. DE-AC02-79ET23168-80/1, October 30, 1981. Available NTIS, 187 pp.

Schlueter, R.A., G.L. Park, M. Lotfalian, and H. Shayanfar, 1981: "Effect of Wind Turbine Generator Model and Siting on Wind Power Changes Out of Large WECS Arrays," Second DOE/NASA Wind Turbine Dynamics Workshop, Cleveland State University, Cleveland, OH, February 24-26, 1981. In *NASA Conference Publication 2185*. SERI/CP-635-1238, pp. 343-352.

Schlueter, R.A., G.L. Park, M. Lotfalian, J. Dorsey, and H. Shayanfar, 1983: "Methods of Reducing Wind-Power Changes from Large Wind Turbine Arrays," *IEEE Trans. Pwr. App. & Sys.*, Vol. PAS-102, No. 6, June 1983, pp. 1643-1650.

Schlueter, R.A., G.L. Park, M. Lotfalian, A. Shayanfar, and P. Rastgoufard, 1984: "Simulation and Assessment of Wind Array Power Variation Based on Simultaneous Wind Speed Measurements," *IEEE Trans. Power App. & Sys.*, Vol. PAS-103, No. 5, May 1984, pp. 1008-10106.

Schlueter, R.A., G.L. Park, T.W. Reddoch, P.R. Barnes, and J.S. Lawler, 1985: "A Modified Unit Commitment and Generation Control for Utilities with Large Wind Generation Penetrations," *IEEE Trans. Power App. & Sys.*, Vol. PAS-104, No. 7, July 1985, pp. 1630-1636.

Schlueter, R.A., G.L. Park, and R. Bouwmeester,19__: *Power System Operation with Wind Arrays*, Final Report, USDOE Contract W-7405-ENG 26, ORO-7405-1 UC 60. Available NTIS, 252 pp.

Schlueter, R.A., G.L. Park, G. Sigari, and T. Costi, 1984: *Improved Models for Increasing Wind Penetration, Economics and Operating Reliability*, Final Report, USDOE/NASA Contract NAG 3-399, DOE/NBM-1077 UC 60, April 1984. Available NTIS, 187 pp.

Schlueter, R.A., G. Sigari, and T. Costi, 1985: *Effect of Accuracy on Wind Power Prediction on Power System Operations*, Final Report, USDO/NASA Contract NAG 3-399. MSU-ENGR-85-026 (NASA). June 1985, 185 pp.

Shaltens, R.K. and A.G. Birchenough, 1983: "Operational Results for the Experimental DOE/NASA MOD OA Wind Turbine Project," presented at the ASES/Wind Workshop VI, June 1983, Minneapolis.

Smith, J.C., 1988: "Windfarm reactive power compensation considerations for power factor correction capacitor applications," presented 88 Proceedings of the American Wind Energy Association.

Sorenson, B., 1976: "Dependability of Wind Energy Generators with Short-Term Energy Storage," *Science*, 194, pp. 935-937.

Steely, W.J., M.A. Ilyan, and D.R. Smith, 1987: "Summary of Wind Energy Activities at Pacific Gas and Electric's Department of Engineering and Research," in *Proceedings of the Sixth ASME Wind Energy Symposium*, Dallas, TX.

Surbrook, T.C., 1978: *Wind Power*, Extension Bulletin, Cooperative Extension Service, Michigan State University, File No. 18.82, Bulletin No. E-1112, November 1978.

Otawa, T., 1980: "Wind Energy Planning: Development and Application of a Site Selection Method for Wind Energy Conversion Systems," *Energy Research*, 4, pp. 283-306.

Thomas, P.H., 1945: *Electric Power from the Wind*, Federal Power Commission Washington, DC.

VanKuiken, J.C.,W.A. Buehring, C.C. Huber and K. A. Huber, 1980: *Reliability, Energy, and Cost Effects of Wind-Powered Generation Integrated with a Conventional Generating System*, Argonne National Labs. ANL/AA-17, Argonne IL.

Venkata, S.S. and E.C. Boardman, 1982: *Investigation of Small Wind Turbine Induction Generators*, BPA Report DOE/BP 137, Bonneville Power Administration, Portland, OR.

Venkata, S.S. and M.A. El-Sharkawi, 1988: *Wind Energy Generator Induction Program*, BPA Research Draft Report, Bonneville Power Administration, Portland, OR.

Venkata, S.S., M.A. El Sharkawi, and C.C. Liu, 1987: *Reactive Power Management*, EPRI Report AP-5210, Electric Power Research Institute, Palo, Alto, CA.

Wade, J.E., S.N. Walker, and R.W. Baker, 1988: *Forecasting and Integration of Wind Energy Generating Systems*, PPL Report PWE 88-1017, Pacific Power and Light Company, Portland, OR.

Watts, A.W., 1980: *Wind/Hydro Generation Assessment*, U.S. Bureau of Reclamation White Paper, Denver, CO.

Weinberg, B., O. Krauss, and G.L. Park, 1985: *Detailed Measurement of Wind Speed*, Final Report Battelle PNL Contract B-M2766-A-3, December 1985, 16 pp.

Wind Power Costs, Agricultural Engineering Department Information Series, Michigan State University, East Lansing, MI 48824, File No. 18.8, AIS No. 369, 1981.

Zaininger, H.W., 1986: *Wind Penetration Study*, Hawaiian Electric Company Report.

Zaininger, H.W. and D.J. Bell, 1980: *Wind Power Generation Dynamic Impacts on Electrical Utility Systems*, EPRI Report AP-1614, Electrical Power Research Institute, Palo Alto, CA.

Zaininger, H.W., 1987: *Electrical Behavior of Wind Power Stations*, Electrical Power Research Institute Report, AP 5220, Palo Alto, CA.