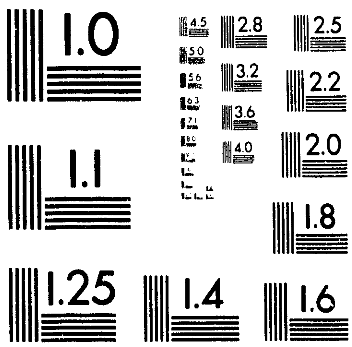
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ANALYSIS OF SUPERCONDUCTING MAGNETIC ENERGY STORAGE APPLICATIONS AT A PROPOSED WIND FARM SITE NEAR BROWNING MONTANA

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Abstract

A computer program was developed to analyze the viability of integrating superconducting magnetic energy storage (SMES) with proposed wind farm scenarios at a site near Browning, Montana. The program simulated an hour-by-hour account of the charge/discharge history of a SMES unit for a representative wind-speed year. Effects of power output, storage capacity, and power conditioning capability on SMES performance characteristics were analyzed on a seasonal, diurnal, and hourly basis. The SMES unit was assumed to be charged during periods when power output of the wind resource exceeded its average value. Energy was discharged from the SMES unit into the grid during periods of low wind speed to compensate for below-average output of the wind resource. The option of using SMES to provide power continuity for a wind farm supplemented by combustion turbines was also investigated.

Levelizing the annual output of large wind energy systems operating in the Blackfeet area of Montana was found to require a storage capacity too large to be economically viable. However, it appears that intermediate-sized SMES economically levelize the wind energy output on a seasonal basis.

Introduction

Based on wind speed measurements taken at Browning, peak output of proposed wind energy systems in the Blackfeet area would be approximately three times the magnitude of their average rating. This output characteristic could be levelized year-round by integrating an energy storage system, such as a SMES facility, adjacent to the proposed wind energy complex. The SMES unit would be charged during times when power output of the wind resource exceeds its average value. Energy would be discharged from the SMES unit into the grid during periods of low wind speed to compensate for below-average output of the wind resource. Levelizing the output in this manner would enable the necessary transmission additions to be sized for the average rating of the wind farm rather than for its peak output. Transmission construction savings of $20 million for a wind farm with an output of 165 average megawatts (MWa) and $300 million for a 1000 MWa farm would be realized in this way.

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The ideal result of levelizing the output of a wind energy system with storage is to create the equivalent of a base-load generating plant. The following sections describe an assessment of the potential for achieving this result using SMES.

Methodology

A computer model was developed to simulate the hour-by-hour charge and discharge history of SMES systems associated with the two wind resource scenarios studied by the Pacific Northwest Utilities Conference Committee (PNUCC) [Watkins et al. 1991]. Oregon State University, working in cooperation with Bonneville Power Administration (BPA), supplied computerized files consisting of hourly wind speed, temperature, and pressure measurements taken at Browning, Montana for the period between November 1985 and October 1991. The wind speed data were complete only for the years 1986, 1987, and 1990; pressure and temperature information was complete only for 1990. All data were measured at a height of 80 feet above ground level at the Browning Depot location.

Acquisition of the above information enabled the development of three computerized algorithms to simulate the operation of SMES in conjunction with the two wind resource scenarios. Several variables common to all of the algorithms include: the power generated by the wind turbine array, the rating of the power conditioning system (PCS) that interfaces the SMES unit with the grid, SMES capacity, and the levelized output power of the integrated system. Several assumptions were made to simplify and expedite development of the programs, as indicated below:

- The rating of the PCS is the difference between the peak power of the wind resource and the desired levelized output value (e.g., a 2000-MW PCS rating would be sufficient for a 1000-MWa wind energy complex having a 3000-MW peak output).

- The minimum SMES capacity considered can provide the design average power output for one hour.

The initial program was developed to determine the effectiveness of using SMES to levelize the wind energy power duration curve. The program generates an annual power duration curve for the wind farm with and without an associated SMES unit. Each of these characteristics is accumulated on an hourly basis to simulate real-time operation of a given system. The results of using this program motivated the development of an additional program, which analyzes season levelization. This program generates power duration curves for unconditioned wind power and SMES-conditioned power for the three distinguishable wind seasons (winter, summer and spring/fall). While their purposes differ, the methodology of the two programs is essentially the same.

The following variables are input by the user: maximum farm generating capacity, maximum SMES storage capacity, maximum power conditioning capability, and levelized power output. The programs use this information, together with site-specific data to simulate the power generated by the wind resource, power dispatched to the grid, and energy exchanged with the SMES unit on an hourly basis.

The wind farm power output was calculated solely as a function of the wind speed with reference to characteristics of a representative wind turbine. The power output for a single wind turbine was estimated as a function of wind speed using the AOC 15/50 power output performance curve. Two equations, extrapolated from this curve using a least squares method, are used to calculate the power.

At velocities less than 21 mph Equation (1) is used to calculate the power output for a single machine.

$$P = 17.67-4.62V+.35V^2-.004V^3 \qquad (1)$$

At wind velocities between 21 and 35 mph the power is estimated from

$$P = -249.41+26.54V-.78V^2+.007V^3 \qquad (2)$$

The wind mill reaches its peak power at a wind speed of 35 mph. This maximum power output for a single machine (66 kW) is assumed to be constant up to a wind speed of 50 mph. Zero output is assumed above 50 mph.

After the generated power has been determined, the algorithms model the processing of energy in the system according to the magnitude of power output from the wind resource. In a given hour, if the generated wind power is less than the system average or other desired level, the SMES is dispatched to make-up the difference between the required and available power. If there is not enough energy stored for this purpose, all of the generated energy is stored by the SMES unit. While this results in an immediate period of zero output, storing the power for later dispatch was found to increase the overall number of hours in a year that power is provided at the levelized value. At times when the power generated is equal to system demand, the wind resource is dispatched directly into the grid and has no interaction with the SMES unit. Finally, if the wind power generated is greater than that required by the system, the levelized value is output to the system and excess energy is stored in the SMES unit. If there is not enough SMES capacity for this purpose, the excess power is modelled as if it is dispatched into the system.

The algorithms were used for a variety of studies to determine both the characteristics of the wind and the operating profile of candidate SMES systems.

Analysis

Wind Power Duration

A series of power duration curves was generated to demonstrate that year-to-year wind characteristics are similar. Browning wind data were examined for seasonal and daily patterns that could influence the operation of the plant.

Monthly patterns were examined by calculating the average hourly power output produced by the wind turbines for each month and by examining power plots that tracked the power output over the entire month. Table 1 shows the percentage average hourly power output for a machine located at the Browning site at a height of 80 feet. Months for which insufficient data exist are left blank. From this information three wind seasons, each consisting of 4 months, were defined. Winter (identified as November, December, January, and February) is characterized by relatively steady high winds with occasional strong gusts. The summer season (May, June, July, and August) is much calmer with long lulls and overall mild conditions. Spring/Fall (consisting of March, April, September, and October) has varying conditions that oscillate between those of Winter and Summer but never achieve the intensity of either.

Table 1. PERCENT AVERAGE HOURLY POWER OUTPUT (CAPACITY FACTOR)

Month	1985	1986	1987	1988	1989	1990	1991
Jan	-	61.8	63.5	48.4	53.8	53.0	-
Feb	-	27.5	39.9	44.3	-	58.0	40.6
Mar	-	40.9	28.9	42.2	-	33.8	37.2
Apr	-	30.9	33.0	-	-	19.8	27.6
May	-	20.9	27.0	-	-	22.1	24.2
Jun	-	17.6	25.0	17.6	-	26.6	27.6
Jul	-	23.5	17.4	-	-	14.7	16.0
Aug	-	13.5	16.3	19.3	-	16.5	16.0
Sep	-	19.2	23.1	29.1	-	17.9	18.8
Oct	-	30.3	32.5	28.8	-	41.5	-
Nov	29.7	53.1	47.7	49.9	53.9	49.7	-
Dec	56.9	55.6	48.8	52.1	51.7	57.5	-

The models were also used in an attempt to identify daily wind patterns that might favor the application of smaller SMES units. No such favorable wind speed patterns were evident on a diurnal basis.

SMES Power Levelization

The simulation models were used to develop power duration curves for two wind resource scenarios associated with SMES capacity of 2000 MWh and higher. The effectiveness of SMES in levelizing output of the wind energy system was examined as a function of SMES capacity.

Figures 1 and 2 summarize the effectiveness of SMES in levelizing the power duration curves of the PNUCC 3000-MW and 500-MW (peak) wind resource scenarios, respectively. Complete levelization was estimated to require a SMES capacity of 2,000,000 MWh in the former case and 300,000 MWh for the smaller scenario. SMES capacity of these sizes is judged to be technically and economically impractical. SMES capacities on the order of 15,000 MWh are currently the maximum practical size that might be considered for applications of this type. A detailed examination of SMES benefits and costs is given by De Steese et al. (1992).

The large energy storage requirements appear to be driven by the particular seasonality of wind intensity in the Blackfeet area. As previously mentioned, the winter months are characterized by an average hourly power output approximately twice the desired 33% control level. Such high wind speeds sustained over a period of several days provides little opportunity or need to dispatch energy stored in the SMES unit and requires large storage capacity if dispatched power is to remain at one-third capacity. SMES is generally not an economic energy storage option for longer than diurnal charge/discharge cycles. As a result, the Blackfeet wind energy application forces SMES into a domain of operation for which it is ill-suited.

SMES units having more practical capacities are also shown in Figures 1 and 2. SMES capacities between 2000 MWh and 8000 MWh are fairly effective during the non-winter months, characterized by lower wind speeds. A 2000 MWh unit provides approximately 3700 hours and 4200 hours of levelized output for the 1000-MWa and 165-MWa case, respectively. The corresponding levelized output durations achievable with 8000 MWh of SMES are 4900 hours and 5400 hours, respectively.

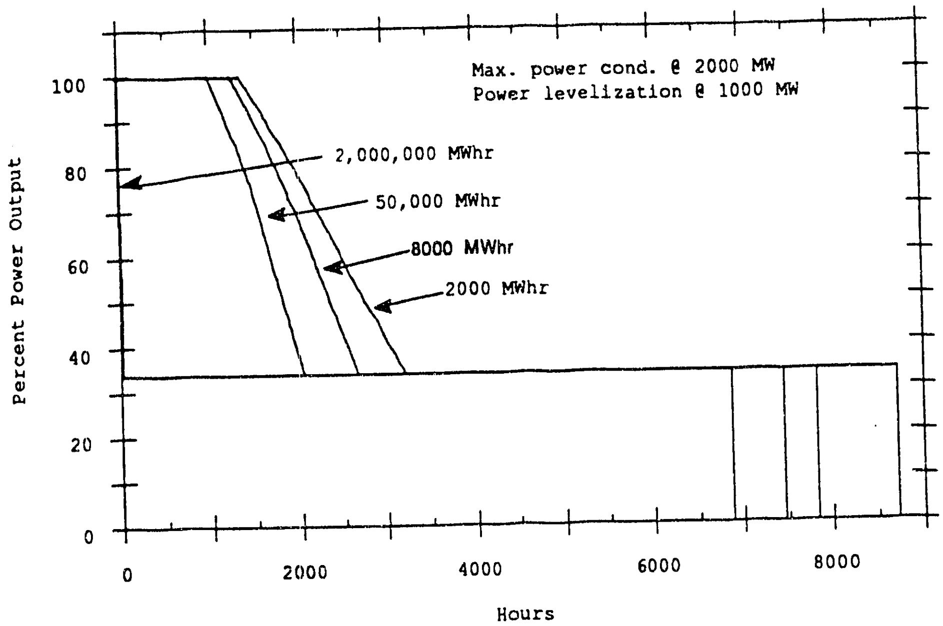

Figure 1. POWER DURATION CURVES FOR A 3000-MW (PEAK) WIND FARM.

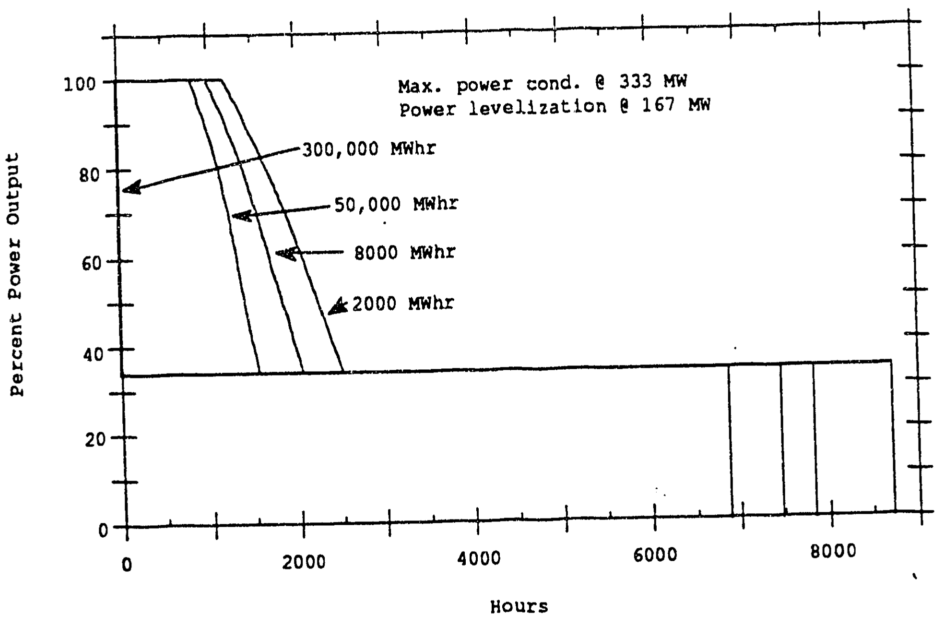

Figure 2. POWER DURATION CURVES FOR A 500-MW (PEAK) WIND FARM.

An alternative SMES scenario was considered involving the use of intermediate-scale SMES units to provide power continuity for a wind farm supplemented by combustion turbines. A third program was developed for this scenario, which performed no calculations, but counted the number of times SMES would be used to carry the load during the combustion turbine ramp-up periods following a decline in wind power. In this scenario, any time the power drops below the protected level, combustion turbines are used to augment the wind energy system. It is assumed that the SMES unit is recharged by the combustion turbines and not with energy supplied by the wind farm.

Input to the program includes the year of the data and the power level to be protected. In addition to determining the number of times SMES is accessed on a monthly basis, the program also calculates the average power delivered by the SMES unit when it is dispatched. Each time the SMES unit is dispatched, it is assumed to provide the power deficit of the system for up to 20 minutes. This approximation is based on the value of 0.3 hr being assumed as the characteristic time from minimum power to synchronization for combustion turbines. For example, if the protected plant output were 1000 MW and wind power fell to 800 MW, SMES would deliver 200 MW for 20 minutes, until combustion turbines pick-up the load. Results of exercising this program are discussed below.

Operation of the combustion turbines occurs if wind power falls below a given set-point. Two set-points were considered at the average (one-third of peak) and peak (name plate) rating of the wind resource. The program was run to estimate the frequency of SMES use in these cases and the average SMES power required as a percentage of the controlled power level. Table 2 shows the range of SMES energy and power indicated by these results. The ranges shown represent the minimum and maximum monthly average energy and power, respectively, based on analysis of 1990 wind speed data.

For year-round carryover during combustion turbine ramp-up, the SMES unit would be sized to provide the maximum energy and power indicated in each case. The SMES energy requirements shown in Table 2 indicate that SMES capacity and power of 60 MWh and 180 MW, respectively, would provide carryover protection for all of the wind resource/combustion turbine combinations except the largest (3000 MWa controlled at its peak output level).

Table 2. RANGE OF SMES CAPACITY AND POWER FOR WIND RESOURCE CARRYOVER CASES

Wind Scenario, MWa/MW Peak	Control Set-Point, MW	SMES Energy Requirement, MWh Minimum	SMES Energy Requirement, MWh Maximum	SMES Power, MW Minimum	SMES Power, MW Maximum
165/500	165	6	8	15	25
165/500	500	10	52	30	155
1000/3000	1000	30	50	90	150
1000/3000	3000	60	310	180	930

Conclusions

Because extended periods of unusually high velocity winds occur during the winter months in the Browning Montana area, the SMES capacity needed to levelize output of the proposed wind resource scenarios on an annual basis was found to be too large to be practical or economically viable. However, these seasonal high winds are peculiar to this site. Therefore, the results of this study do not preclude the beneficial use of SMES for output levelization at other wind energy sites. The use of SMES as a means of maintaining wind farm power continuity during transition from the wind resource to combustion turbines required relatively modest storage capacity and justifies further assessment of this option.

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