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Short-Term Power Fluctuations of Large Wind Power Plants

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SHORT-TERM POWER FLUCTUATIONS OF LARGE WIND POWER PLANTS

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ABSTRACT

With electric utilities and other power providers showing increased interest in wind power and with growing penetration of wind capacity into the market, questions about how wind power fluctuations affect power system operations and about wind power's ancillary services requirements are receiving lots of attention. To evaluate short-term wind power fluctuations and the range of ancillary service of wind power plants, the National Renewable Energy Laboratory (NREL), in cooperation with Enron Wind, has started a project to record output power from several large commercial wind power plants at the 1-Hertz rate. The project's purpose is to acquire actual, long-term wind power output data for analyzing wind power fluctuations, frequency distribution of the changes, the effects of spatial diversity, and wind power ancillary services. This paper presents statistic properties of the data collected so far and discusses the results of data analysis. Although the efforts to monitor wind power plants are ongoing, we can already conclude from the available data that despite the stochastic nature of wind power fluctuations, the magnitudes and rates of wind power changes caused by wind speed variations are seldom extreme, nor are they totally random. Their values are bounded in narrow ranges. Power output data also show significant spatial diversities within a large wind power plant.

INTRODUCTION

In the past 20 years, total installed capacity of wind power has increased continuously in the United States. With the aid of various state and federal policies and the emerging green power market, more large-scale wind power plants will be built. The effects of wind power fluctuations on power system operations and requirements of ancillary services for wind power have increasingly become concerns for many electric utilities and wind power developers. Involved parties need to understand wind power fluctuations and to be able to analyze operational and ancillary service issues with real wind power output data. Despite these concerns and the need to use long-term, high-frequency, real wind-power plant output data to analyze these impacts, no U.S. programs to date have systematically collected such data.

The National Renewable Energy Laboratory (NREL), in collaboration with Enron Wind Corporation, has undertaken a project to record long-term, high-frequency (1-Hertz [Hz]) wind power output data from large wind power plants located in the Midwest. The project started in 2000. The objective is to systematically collect high-resolution wind power data so that wind power fluctuations, their frequency distribution, the effects of spatial diversity, and the ancillary services requirements of large commercial wind power plants can be analyzed with actual wind power data.

Under NREL's wind power plant monitoring project, wind power data are being collected at three locations. The first is the Lake Benton II wind power plant near Ruthton, Minnesota, which comprises 138 Zond Z50 turbines, each rated at 750 kilowatts (kW) for a total installed capacity of 103.5 megawatts (MW). Four 34.5-killivolt (kV) lines collect the power and feed it into the local utility's nearby 115-kV transmission network through a substation. Data recording equipment is installed at these four 34.5-kV interconnection points (designated as Delta, Echo, Foxtrot, and Golf) to collect real power, reactive power, phase voltages, and wind speed. All data are recorded at a rate of 1 Hz. The data collection from this wind power plant began in February 2000.

The second place is a large wind power plant located in northwestern Iowa near Storm Lake. It has 262 Zond Z50 turbines with a total installed wind power capacity of 196.5 MW. The output from 151 turbines (113.25 MW) is collected for the wind power plant monitoring project. In addition to real and reactive power and three phase voltages at 1 Hz, wind speed and wind direction data at the Storm Lake site are recorded every 30 seconds. Data from Storm Lake have been available since January 2001.

The third location is a substation called Buffalo Ridge, located in southwestern Minnesota near Lake Benton. Several wind power plants of varying size in this area (including the Lake Benton II wind power plant) all connect to this substation. An output of approximately 220 MW of wind generating capacity is recorded at the Buffalo Ridge substation. Most of the wind turbines in this area are Zond Z50 turbines, but there are also a few Micon 750-kW and Vestas 660-kW turbines. Data from this site became available in mid-February 2001. Figure 1 shows the locations of Lake Benton and Storm Lake in Minnesota and Iowa. The distance between the two sites is about 200 km (125 miles).

Figure 1. Monitored Wind Power Plant Sites

Large amounts of data have been collected. The raw data consist of power and voltage readings taken every second. From the second-by-second data, 1-minute average, 10-minute average, 1-hour average, or data at any other desired time interval average can be derived for analysis.

POWER FLUCTUATIONS

The first thing to consider from the data set is how wind power fluctuates as a result of natural wind speed changes. Simple statistics and distribution of single step changes (the difference in power levels between consecutive time steps) and ramping rates (either up or down) over specific time intervals are used to examine power fluctuations at the monitored wind power plants.

Step Changes

Step changes indicate wind power persistence. To quantify the behavior of the wind power, the maximum step changes in both positive and negative directions and their means and standard deviations, for three time steps (1-second, 1-minute, and 1-hour; see Table 1) are calculated for Lake Benton II. To focus only on the maximum power changes caused by decreasing or increasing wind speed, the recorded data stream is screened to eliminate power changes caused by forced or controlled outages and startups.

Table 1. Statistics of Step Changes at Lake Benton II

Month	1-second power (kW)			
	Max. Inc.*	Max. Dec.†	Avg.§	Std. Dev.**
Feb. 2000	1,950	-1,980	0	194
March 2000	1,870	-2,627	0	194
April 2000	3,663	-4,837	0	212
May 2000	2,296	-5,241	0	191
June 2000	4,430	-7,590	0	155
July 2000	2,908	-7,138	0	88
Aug. 2000	1,609	-4,560	0	92
Sept. 2000	1,810	-5,440	0	158
Oct. 2000	2,271	-1,260	0	139
Nov. 2000	1,900	-4,900	0	161
Dec. 2000	2,200	-6,217	0	168
Jan. 2001	2,420	-2,810	0	207
12 months			0	168
	1-minute average power (kW)			
Feb. 2000	4,969	-5,492	-1	1,091
March 2000	7,266	-7,957	-2	1,711
April 2000	11,541	-13,852	0	1,776
May 2000	9,661	-7,846	0	1,298
June 2000	10,078	-14,304	1	1,116
July 2000	7,545	-8,490	0	691
Aug. 2000	9,706	-7,232	-1	709
Sept. 2000	7,907	-14,448	-1	1,073
Oct. 2000	9,818	-8,487	2	860
Nov. 2000	5,750	-4,251	0	816
Dec. 2000	6,669	-8,217	-1	677
Jan. 2001	8,711	-5,075	1	685
12 months			0	1,103
	1-hour average power (kW)			
Feb. 2000	42,024	-50,395	-177	11,245
March 2000	53,587	-39,605	-149	11,007
April 2000	49,919	-51,653	-98	11,478
May 2000	44,420	-38,712	-69	10,080
June 2000	61,949	-38,378	73	9,955
July 2000	42,110	-45,712	-131	7,573
Aug. 2000	47,425	-42,012	29	9,757
Sept. 2000	65,410	-35,646	27	10,097
Oct. 2000	50,448	-36,868	24	9,231
Nov. 2000	61,159	-34,480	-141	10,069
Dec. 2000	53,367	-48,510	-91	10,956
Jan. 2000	61,033	-43,496	21	10,801
12 months			-56	10,220

*Maximum increase †Maximum decrease
§Average **Standard deviation

It is clear that, for short periods, the step changes are very small. The maximum increase in power is 4,430 kW, or 4.3% of the nameplate capacity (in 1-second increments), during this 12-month period. For 1-minute increments, the maximum increase in power is 11,541 kW, or 11% of the nameplate capacity, which is equivalent to a sustained ramping-up rate of 192 kW per second, or 0.2% of the rated power per second. The maximum 1-second step drop is 7,590 kW, or 7.3% of the nameplate capacity. For the same period, the maximum 1-minute step drop is 14,448 kW, or 14.0% of the nameplate capacity. This is equivalent to a sustained ramping-down rate of 241 kW/s, which is much smaller than the maximum 1-second step change value.

Because wind speed can change substantially during an hour, hourly wind power changes can be very large. The maximum 1-hour power increase during the 12-month period is 65.4 MW (63% of total capacity), and the maximum 1-hour power decrease is 51.7 MW (50% of total capacity). In terms of kW per minute, this is equivalent to a positive 1,090 kW/min and a negative 860 kW/min, respectively; both are much less than the maximum 1-minute changes. Those big changes are relatively infrequent events, as can be seen in the distribution plot in Figure 2.

The averages of all step change values are nearly zero for all cases. The standard deviation for 1-second step changes is 168 kW, less than 0.2% of total capacity. For 1-minute step changes, the standard deviation is 1,103 kW, or 1% of total capacity. For hourly step changes, it is 10,220 kW, or about 9.9% of total capacity. These relatively small standard deviation values suggest that step change distributions are tightly centered around their means, which is confirmed by plots of step change distributions for different time step sizes (Figure 2).

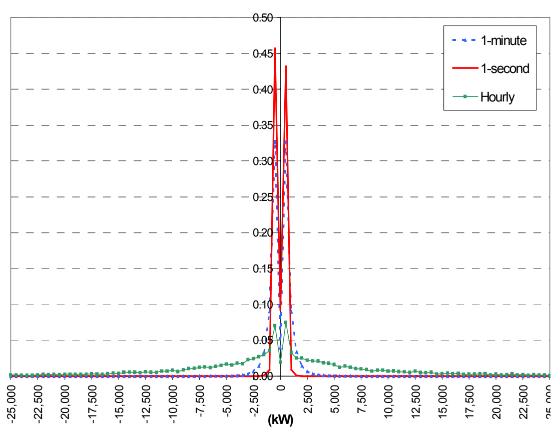

Figure 2. Distribution of step changes

The curves in Figure 2 do not resemble the familiar bell-shaped normal distribution because of a deep notch at the zero value. The low probability of zero step change values confirms the observation that wind speed and wind power plant output are not static. The low probability in the plot is largely the result of zero output values in the data stream (caused by planned and forced outages). Without these zero output values in the data stream, the probability of zero step changes would be almost zero. These plots confirm that most step changes have small values and that the short-term power fluctuations are confined to a very narrow range. Large step changes rarely occur.

From the hourly step change distribution curve, we calculated that 78.7% of all step changes are confined within the range of ±10,500 kW (roughly ±1σ), which is about 10% of total capacity. Further, 93.6% of the possible step change values are within ±20,500 kW (approximately ±2σ), or only about 20% of total capacity. For 1-minute data, the concentration is more prominent: 87.5% of all step changes are within ±1,000 kW (±0.9σ) and 94.5% are within ±1,500 kW (±1.4σ), a range of only 2.8% of the total wind power plant installed capacity. Second-by-second power level changes are even smaller. For 1-second step changes, 98% of the values are within ±500 kW (±3 σ), or less than 0.5% of total capacity. The wind power production shows distinctive seasonal patterns, but these values remain relatively constant throughout the year, as shown in Table 1.

Table 2 lists the statistics of step changes for Lake Benton II, Storm Lake, and the combined output of the two for the first 3 months of 2001[1]. Step changes at Storm Lake are very similar to those observed at Lake Benton II. This behavior is expected because both wind power plants have the same types of turbines. The maximum step changes of the combined load can be either larger or smaller than extreme step change values of individual wind power plants because they should be given the random nature of these two step change values. Expressed as a percentage of total capacity (i.e., the quantities are normalized to remove the size bias), the standard deviations of the combined load step changes are always smaller than the standard deviations of step change values (also expressed in percentages of its respective installed capacity) of either wind power plant. This result indirectly demonstrates the benefit of aggregating wind turbines—reduced variations of wind power. More on this point will be discussed later in the paper.

[1] March 2001 includes only data taken from March 1 to March 24.

Table 2. Step Change Statistics of Combined Load of Lake Benton II and Storm Lake

	Lake Benton II				Storm Lake				Combined Load			
Month	1-second power (kW)											
	Max. Inc.	Max. Dec.	Avg.	Std. Dev.	Max. Inc.	Max. Dec.	Avg.	Std. Dev.	Max. Inc.	Max. Dec.	Avg.	Std. Dev.
Jan.	2,420	-2,810	0	207	1,625	-1,655	0	93	2,231	-2,880	0	227
Feb.	1,570	-2,370	0	169	3,165	-2,591	0	134	3,115	-2,234	0	216
March	1,410	-1,460	0	130	3,473	-3,349	0	107	3,623	-3,434	0	168
	1-minute average power (kW)											
Jan.	8,711	-5,075	1	685	7,083	-4,372	0	557	8,679	-5,774	1	885
Feb.	8,189	-5,384	1	954	9,446	-4,791	1	912	9,403	-5,072	2	1,322
March	6,711	-7,291	-2	758	4,851	-5,541	-1	624	6,235	-7,908	-4	916
	1-hour average power (kW)											
Jan.	61,033	-43,496	36	10,867	29,283	-41,143	13	7,894	55,676	-57,087	48	13,734
Feb.	47,873	-42,419	88	11,061	34,514	-42,695	83	8,693	50,812	-55,343	171	14,868
March	53,620	-42,960	-102	9,979	45,330	-35,023	-82	8,876	68,450	-42,344	-214	13,621

Ramping Rates

Step change analysis shows all the single extreme values (instant changes) that the wind power plant can experience; however, those maximum values in either direction occur only infrequently. To investigate sustained power changes, ramping rates of wind power plants in either direction for various periods are calculated. The ramping rates discussed here are slopes of a straight line used to fit the wind power data points. Table 3 lists the 10-second ramping rates in kilowatts per second calculated with 1-second power data and 10-minute ramping rates in kilowatts per minute calculated with 1-minute average power. Sudden power drops and rapid power increases caused by forced or maintenance outages and manual startups are excluded from the lists of the maximum (+) and minimum (-) ramping rates in Tables 3 and 4. However, when calculating average and standard deviation values of ramping rates, unaltered data streams are used for the sake of computation expediency and to avoid the problems of data stream discontinuity.

Compared to the values of step changes, maximum up and down ramping rates are lower than single step change values, indicating the changing nature of the wind speed. For 10-second intervals, the maximum ramping-up rate is about 2,778 kW/s, or 2.7% of total capacity per second. The maximum ramping-down rate is -2,543 kW/s, or 2.5% of total capacity per second. The average values for both ramping-up and ramping-down rates are much smaller—less than 0.04% of total capacity per second. Ramping rates are higher when computed at shorter time intervals. For example, the average 10-second ramping-up rate for the 12-month period is 28 kW/s, but the average 10-minute ramping-up rate is only 4.4 kW/s (264 kW/min ÷ 60 s/min).

Table 3. Ramping Rates at Lake Benton II

10-second interval (kW/s)						
Month	**Max. (+) Ramp**	**Avg.**	**Std. Dev.**	**Max. (-) Ramp**	**Avg.**	**Std. Dev.**
Feb. 2000	946	31	36	-517	-31	70
March 2000	855	27	38	-1,070	-28	109
April 2000	2,778	32	46	-1,443	-32	106
May 2000	1,236	27	37	-1,257	-30	74
June 2000	2,626	32	39	-2,157	-33	60
July 2000	1,699	22	31	-1,513	-23	36
Aug. 2000	525	28	34	-1,020	-28	37
Sept. 2000	2,090	37	44	-1,090	-37	56
Oct. 2000	1,232	31	42	-2,543	-34	49
Nov. 2000	464	29	35	-646	-32	43
Dec. 2000	733	26	32	-636	-31	37
Jan. 2001	575	24	31	-2,086	-30	40
12-month		28	37		-41	65
10-minute interval (kW/min)						
Feb. 2000	2,896	312	470	-3,651	-315	555
March 2000	3,780	299	570	-2,785	-295	809
April 2000	4,823	337	610	-6,492	-335	763
May 2000	4,985	287	500	-6,617	-295	590
June 2000	5,429	312	450	-5,627	-310	515
July 2000	5,238	191	304	-5,562	-194	322
Aug. 2000	4,577	238	318	-4,970	-244	344
Sept. 2000	3,257	292	43	-3,911	-286	447
Oct. 2000	6,918	240	343	-6,145	-255	356
Nov. 2000	3,531	255	345	-2,789	-275	365
Dec. 2000	4,933	230	328	-3,848	-270	330
Jan. 2001	4,625	233	346	-3,864	-271	342
12-month		264	426		-278	509

The small standard deviation values of ramping rates indicate that, similar to the distribution of step change values, short-term ramping rates are also confined within a narrow range. Figure 3 plots the distribution of

10-second ramping rates, and Figure 4 plots the distribution of 10-minute ramping rates.

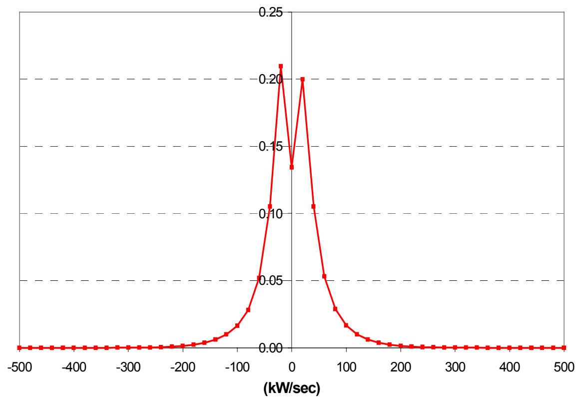

Figure 3. Distribution of 10-s ramping rates

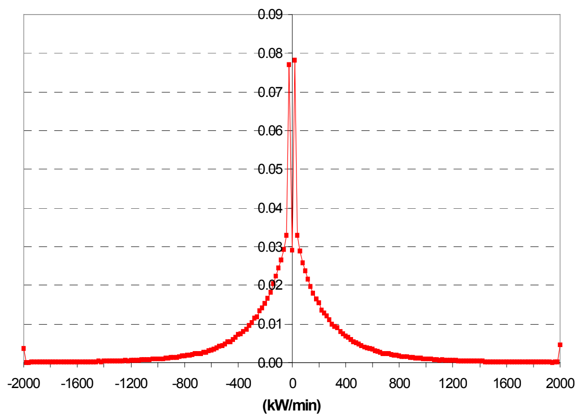

Figure 4. Distribution of 10-min ramping rates

The shapes of the curves are almost identical to those of step changes. From the distribution curves, we can calculate that for 10-second intervals, 94.9% of apparent ramping rates are within ±100 kW/s. For longer times, the ranges are even narrower. For 10-minute intervals, 90% of apparent ramping rates are within ±640 kW/min (or about 11 kW/s).

These results suggest that if another power plant were to be dedicated to regulate the output of Lake Benton II, the duty requirement for the dedicated power plant would be ±220 kW/s (or about 0.2% of the total installed capacity per second). This range would cover 99% of all apparent ramping rates for Lake Benton II. It should be noted that this analogy is not load-following, as is normally applied to electric power systems. To do load following, target power levels and generators are controlled to match the changing load level. How fast the target power level can change in any given time interval will determine the duty requirements (ramping rates) of generators that are used to follow it. Here, the rates of change in wind power plant output are used directly as the duty requirements of generators, as if these generators will be running in opposite directions of the wind power plant to cancel those changes.

EFFECT OF TURBINE AGGREGATION

Operations of the many individual turbines in a wind power plant are not synchronized, and their outputs do not rise and fall at the same time. When a wind gust sweeps through the site, it reaches some turbines sooner than others. Part of the wind power plant may experience decreasing power output while the other part may just begin an upswing in power production. As a result, the entire wind power plant should see fewer relative power variations than a single wind turbine or a small cluster of wind turbines.

One way to examine the variability of wind power at different aggregation levels is to look at the coefficient of variation (COV) of output power. COV is defined as the ratio of the standard deviation of a group of data to the mean value of the same data. COV of wind speed is used as an indicator of wind turbulence intensity. A higher COV indicates more turbulent wind and consequently more fluctuations of wind power. However, a wind power plant with many turbines will attenuate the resulting output power fluctuations.

Available power in the wind is proportional to the cube of wind speed. If the COV is calculated with the wind speed cubed and the results are compared to the calculated COV of measured power from the wind plant, a pattern of reduced variability emerges. Table 4 shows the COV values of wind speed cubed and power output at the Echo interconnection point and at the entire Lake Benton II wind power plant. A reduction in power variability between outputs from a single interconnection point at Echo and from the entire Lake Benton II wind power plant is clear. On average, variability of power output is only about half the variability of wind speed cubed.

The effect becomes more prominent when calculations are extended to the combined output of Storm Lake and Lake Benton II. Table 5 lists COVs of output power from Lake Benton II and Storm Lake, along with combined Storm Lake and Lake Benton II output for the first 3 months of 2001. The numbers in Tables 4 and 5 are calculated with 1-second power data. Obviously, the output power smoothing effect is more prominent with an increasing number of turbines and greater distance between the turbines. In the case of aggregating Storm Lake and Lake Benton II output, the result is a further 5% to 20% reduction in power level variability.

Table 4. COV of Wind Speed Cubed, Echo Output, and Lake Benton II Output

	1-second power		
Month	$(m/s)^3$	Echo kW	LB II kW
Feb. 2000	1.44	0.777	0.773
March 2000	1.86	0.989	0.978
April 2000	1.87	0.823	0.815
May 2000	1.75	1.008	0.922
June 2000	1.72	0.838	0.845
July 2000	1.78	1.228	1.172
Aug. 2000	1.44	0.918	0.899
Sept. 2000	1.64	0.894	0.868
Oct. 2000	1.29	0.936	0.911
Nov. 2000	1.31	0.774	0.771
Dec. 2000	1.44	0.807	0.803
Jan. 2001	1.64	0.756	0.750
12-month	1.91	0.912	0.896

Table 5. COVs of Separate and Combined Wind Power

	1-second power		
	LB II kW	Storm Lake kW	Combined kW
Jan. 2001	0.750	0.832	0.705
Feb. 2001	0.723	0.849	0.687
March 2001	0.870	0.916	0.800
3-month	0.782	0.852	0.715

CORRELATION BETWEEN WIND POWER PLANTS

The 138 turbines at Lake Benton II are spread out over an area of about 11.3 km (7 miles) by 14.5 km (9 miles). The four grid interconnection points are arranged along a northwest-southeast diagonal line across the wind power plant site in alphabetical order beginning at Delta and ending at Golf. Therefore, turbines connected to Delta are closer to turbines connected to Echo than turbines connected to Foxtrot and Golf. Outputs from turbines that are closer together should have more similar profiles than outputs from turbines that are further away. Mathematically, this output similarity can be expressed in terms of correlation coefficient. Table 6 gives the correlation coefficients among output power from the four grid interconnection points at Lake Benton II for the period from January to march of 2001.

Table 6. Output Power Correlation Coefficients

	Echo	Foxtrot	Golf
Delta	0.932	0.922	0.915
Echo		0.969	0.968
Foxtrot			0.975

As expected, output power from grid interconnection points that are closer together have higher correlation coefficients (i.e., their outputs are more in sync). The fact that all correlation coefficients are of very high positive values suggests that the outputs from these four interconnection points are following similar patterns because of their close proximity. The distance between Storm Lake and Lake Benton II wind power plants is about 200 km. Correlation coefficients between power data streams from these two sites are calculated for the first 3 months of 2001 to gauge the relationship between the power outputs of the two wind power plants. Table 7 lists the monthly correlation coefficients and the ranges of their daily values.

Table 7. Correlation Coefficients of Storm Lake and Lake Benton II

	Month	Range of Daily Values
Jan. 2001	0.527	-0.528 ~ 0.780
Feb. 2001	0.568	-0.297 ~ 0.969
March 2001	0.572	-0.103 ~ 0.901

Overall power outputs from these two sites are weakly related as indicated by a small positive value. The ranges of daily correlation coefficients, however, exhibit large variations. They vary from 0.969 (strong positive correlation; i.e., their outputs are synchronized) to -0.297 (negative correlation; i.e., their outputs move almost in opposite directions), suggesting a more complex relation.

Figure 5 is a plot of the profiles of 10-minute average power output for Lake Benton II and Storm Lake for the first 7 days of 2001 (from January 1 to January 7, 2001). The correlation coefficient of 0.612 during this period does not indicate a strong correlation between these two output streams, but the plot shows that these two output streams are strongly related with a time delay. A closer look at the figure reveals that the output pattern from Storm Lake is actually similar to that of

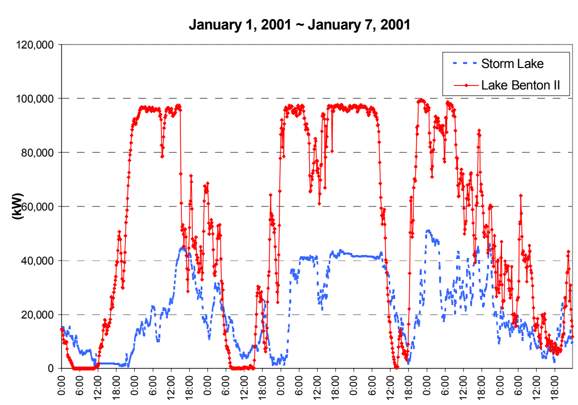

Figure 5. Output profiles of Lake Benton and Storm Lake

Lake Benton II, with a shift to the right. One of the prominent features in the figure is a plateau in the middle, representing a period of high output at Lake Benton II from around 7:00 p.m. on January 3 to around 2:00 p.m. on January 5. An almost identical plateau (of lower height because of less generating capacity are monitored at the time) from Storm Lake shows up about 6 hours later (beginning 1:00 a.m. on January 4). A calculated correlation coefficient of 0.877 for these two plateaus during this 40-hour period confirms the observation, suggesting that the same weather event that drives the wind regimes of both sites arrives at Storm Lake about 6 hours later. There is also an output power rise at Storm Lake (from about 9:50 p.m. on January 1 to around 9:40 p.m. on January 2) that corresponds to the first prominent plateau from Lake Benton II shown in Figure 5 (from about 11:50 a.m. on January 1 to around 11:40 a.m. on January 2). The calculated correlation coefficient of 0.786 during this 24-hour period confirms that these patterns are very similar except that Storm Lake has a time delay of 10 hours. The time delay is obviously determined by wind speed and direction at the time. During the winter, the winds in this region are mostly driven by northerly to northwesterly weather fronts; this explains the time delay observed at Storm Lake.

Similar behaviors were seen throughout the first 3 months of 2001. These observations supply encouraging hints about the feasibility of accurate wind power plant output forecasting. They suggest that with proper wind power plant models and strategically located wind sensors, forecasting wind power plant output with high resolution is quite feasible. Because Storm Lake and Lake Benton II have similar layouts, the same models of wind turbines, and are subject to the same Midwest plain wind regime, we can expect almost identical behaviors from the two when the same weather front causes wind sweeps through the plants.

CONCLUSIONS

Large amounts of data have been collected to analyze the short-term behavior of wind power plant output. The wind power plant monitoring is ongoing, and more data from different wind power plants will become available. However, the available data have already enabled us to draw some preliminary but important conclusions about the short-term fluctuations of wind power and output power smoothing effect of aggregating a large number of wind turbines.

Actual wind power plant output data show that although wind power fluctuations are stochastic in nature, the magnitudes and rates of power level changes caused by wind speed variations are seldom extreme, nor are they totally random. Their values are bounded in narrow ranges. For example, 94.5% of minute-by-minute power level changes are within ±1,500 kW, a range of only 2.8% of the total installed capacity. Second-by-second power level changes are even smaller (98% are within ±500 kW). The rates of sustained power changes are also relatively small, with 99% of all apparent ramping rates of a 100+ MW wind power plant within ±220 kW/s. The wind power production shows distinctive seasonal patterns, but these values remain relatively constant throughout the year.

The wind power plant output data show clearly the effect of aggregating many wind turbines. The variability of wind power decreases as the number of wind turbines in a wind power plant increases and the distances between turbines increase.

To the utility system, large wind power plants are not really random burdens. The narrow range of power level step changes provides a lot of information with which system operators can make short-term predictions of wind power. Large swings of wind power do occur, but those infrequent large changes (caused by wind speed changes) are always related to well-defined weather events, most of which can be accurately predicted in advance.

The data also offer encouraging evidence that accurate wind power forecasting is feasible. They clearly show that when one power production pattern appears at one wind power plant, an almost identical pattern can later reappear at another wind power plant, even hundreds of kilometers away. The time delay corresponds to the wind speed and direction. Correlation analysis of two power data streams confirms the observed time-delayed pattern repetition.

Future analysis of the wind power plant data will focus on output correlation among different wind power plants, as well as on ways to use available information from one wind power plant to gauge the performance of another.

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With electric utilities and other power providers showing increased interest in wind power and with growing penetration of wind capacity into the market, questions about how wind power fluctuations affect power system operations and about wind power's ancillary services requirements are receiving lots of attention. The project's purpose is to acquire actual, long-term wind power output data for analyzing wind power fluctuations, frequency distribution of the changes, the effects of spatial diversity, and wind power ancillary services.

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