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Analyses of Wind Energy Impact on WFEC System Operations

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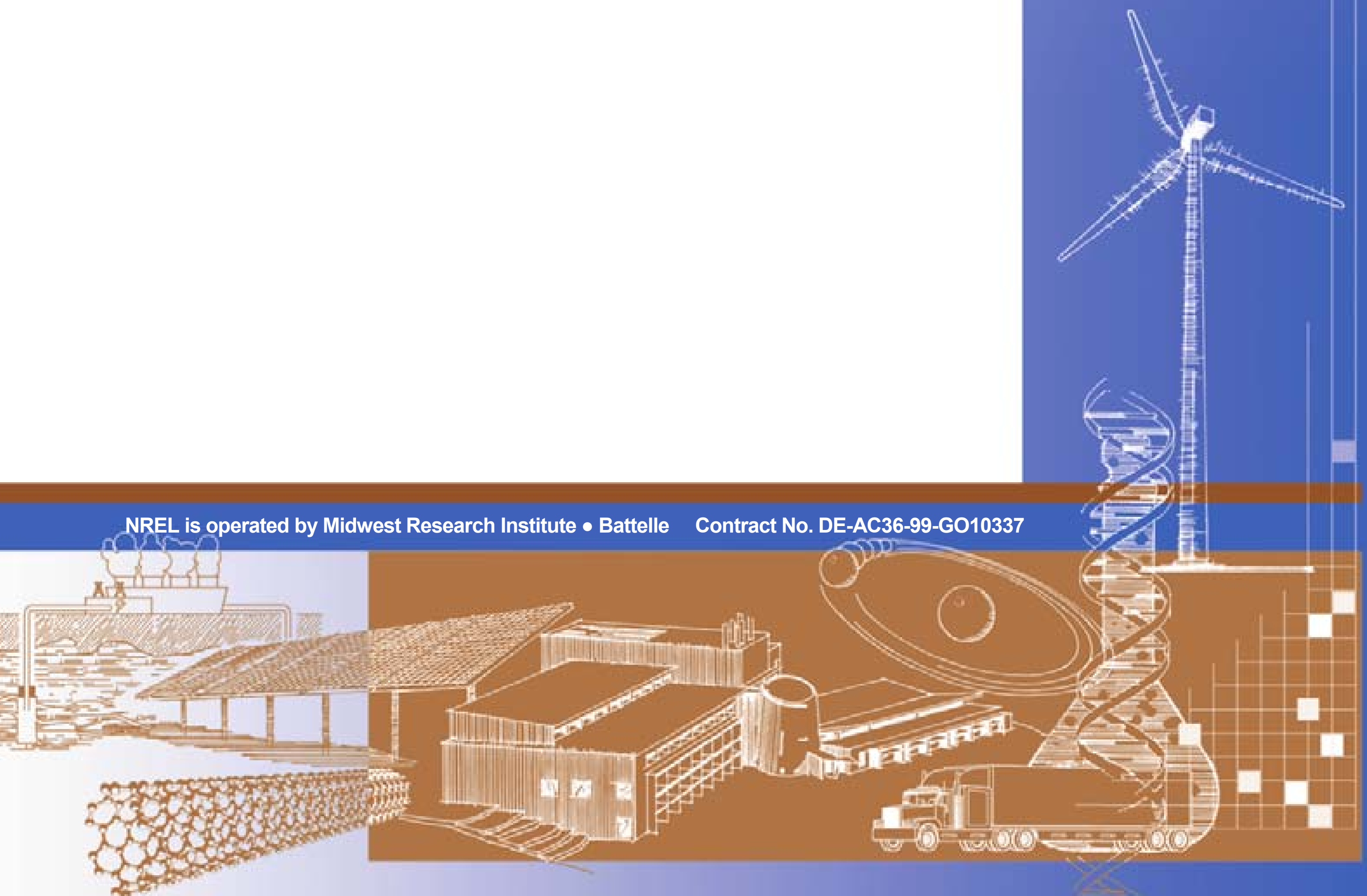

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Summary

Western Farmers Electric Cooperative (WFEC) is a generation and transmission Cooperative in Oklahoma. At the end of 2003, it added 74 megawatts (MW) of wind power to its energy portfolio by purchasing the output of the Blue Canyon Wind Power Project located north of Lawton, Oklahoma. The wind plant has the potential to provide about 6% of WFEC's peak summer demand. During periods of high winds and low loads, wind power may reach 16% of the control area load. The National Renewable Energy Laboratory (NREL) worked with WFEC to analyze the impact of wind power on WFEC system operations through the 1-minute system data stream (load, total generation, scheduled interchange, actual interchange, frequency, and ACE) collected from the energy management system (EMS). The results show that, at such a penetration level, wind power has a very small effect on system operations. The fluctuations of wind power caused only a slight increase in the variability of the system apparent load (system load minus wind power). After the addition of wind power, WFEC continues to meet the control performance standard 1 and 2 (CPS1 and CPS2) requirements for area control error (ACE) with some adjustments in operating procedures and reserve margin. Actual data show that there was virtually no correlation between system ACE and the fluctuations of wind power, and no significant changes in the ACE that could be attributed to changes of wind power. System regulation needs are still dominated by short-term, random load changes.

Abstract

Western Farmers Electric Cooperative (WFEC) is a generation and transmission Cooperative in Oklahoma. At the end of 2003, it added 74 megawatts (MW) of wind energy to its energy portfolio by purchasing the output of the Blue Canyon Wind Power Project located north of Lawton, Oklahoma. This report analyzes system and wind energy data recorded by the WFEC control area energy management system (EMS) and evaluates the effects of wind energy on system operations. The results show that, at low penetration levels, wind energy has a very small effect on system operations. After the addition of wind power, WFEC continues to meet the control performance standard 1 and 2 (CPS1 and CPS2) requirements for area control error (ACE) with some adjustments in operating procedures and reserve margin. There were no significant changes in the ACE that can be attributed to wind energy. The fluctuation of wind energy caused only a slight increase in the variability of the overall system load. The data showed that on average the standard deviation of the 1-minute system apparent load (system load minus wind power) is about 8% higher than that of the system load alone. System regulation needs are still dominated by short-term, random load changes.

I. Introduction

To analyze the effects of wind energy on its system operations, WFEC collected 1-minute data from the EMS. Table 1 below is a sample of the 1-minute EMS data stream that includes (1) time stamp, (2) wind power, (3) 1-minute sliding average area control error (ACE), (4) frequency, (5) system load, (6) actual interchange, (7) scheduled interchange, and (8) total on-line generation (wind power and other generation combined). A negative interchange value means power was imported into the control area. The example below shows the system scheduled to import 239 MW (column 7) at 19:46 central standard time (CST), and the actual import was 243.16 MW.

Table 1. Sample Data Stream from WFEC EMS

(1) Time	(2) Wind Power	(3) ACE	(4) Freq.	(5) Load	(6) Actual Interchange	(7) Scheduled Interchange	(8) Total Gen.
19:46:00	53.23	2.82	60.01	796.71	-243.16	-239.00	553.56
19:47:00	53.14	1.99	60.01	795.54	-244.14	-239.00	551.39
19:48:00	52.57	-2.95	60.01	797.34	-248.00	-239.00	549.33
19:49:00	54.56	1.82	60.01	794.91	-243.29	-239.00	551.63
19:50:00	55.73	5.22	60.01	792.83	-240.18	-239.00	552.65
19:51:00	54.82	2.96	60.02	793.22	-243.32	-239.00	549.90
19:52:00	56.21	1.16	60.01	793.55	-244.91	-239.00	548.64
19:53:00	56.95	0.88	60.02	793.73	-245.92	-239.00	547.81
19:54:00	55.64	2.19	60.03	793.09	-245.80	-239.00	547.28
19:55:00	57.86	1.73	60.01	791.19	-244.48	-239.00	546.71

In addition to 1-minute data stream from the EMS, 10-minute average wind power data series are also available. The 10-minute data series are from wind plant supervisory control and data acquisition (SCADA) system.

II. Short-Term Wind Power Fluctuations

Short-term wind power fluctuations are stochastic in nature. To gauge the variability of Blue Canyon wind power, statistics and distribution of output single step changes (the step changes are differences between two consecutive values of wind power in a time series) are calculated from the 10-minute wind power data series and hourly average power data series (derived from the 10-minute data series).

Table 2 compares the monthly standard deviation values of 10-minute wind power series from the Blue Canyon Project, two Midwest wind power plants (Lake Benton in Minnesota and Storm Lake in Iowa), and four Texas wind power plants (Indian Mesa, King Mountain, Trent Mesa, and Texas Wind Power Project [TWPP]). The average values of the monthly step changes (positive and negative) are nearly zero for all cases, and therefore, are not shown. Numbers in the lower portion of the table are the normalized standard deviation values obtained by dividing the standard deviation values with the nameplate rating of respective wind power plants. It can be seen that the 10-minute fluctuations of Blue Canyon wind power plant are similar to that of the other wind power plants. When more data are included in the calculation, the standard deviation values of step changes of all large wind power plants expressed in terms of nameplate rating are remarkably close [1].

Table 2. Statistics of 10-minute Wind Power Step Changes

	Blue Canyon	Lake Benton	Storm Lake	Indian Mesa	King Mtn	Trent Mesa	TWPP
	Stdev (MW)	Stdev (MW)	Stdev (MW)	Stdev (MW)	Stdev (MW)	Stdev (MW)	Stdev (MW)
June	5.0	3.8	3.4	3.9	3.4	7.8	1.6
July	4.4	3.3	3.1	2.6	1.9	5.7	1.3
August	3.8	3.8	3.3	2.6	1.8	5.1	1.0
September	3.9	4.5	3.6	2.3	2.6	4.3	0.8
October	4.4	4.7	3.4	3.2	3.1	6.1	0.9
November	3.4	3.2	3.0	3.1	3.1	5.5	1.4
6 months	4.1	3.9	3.3	3.0	2.8	5.9	1.2
				Normalized Standard Deviation			
June	7%	4%	3%	5%	4%	5%	5%
July	6%	3%	3%	3%	2%	4%	4%
August	5%	4%	3%	3%	2%	3%	3%
September	5%	4%	3%	3%	3%	3%	2%
October	6%	5%	3%	4%	4%	4%	3%
November	5%	3%	3%	4%	4%	4%	4%
6 months	6%	4%	3%	4%	4%	4%	3%

Figure 1 shows the distribution of Blue Canyon wind power 10-minute step changes. Eighty-four percent of all step changes are within ±1σ (±4 MW or ±5% of nameplate rating). Ninety-nine percent of all 10-minute step changes are within ±3σ (±12 MW or ±16% of nameplate rating). Table 3 shows the hourly wind power changes. Again numbers in the lower half of the table are the standard deviation values in terms of plant rating. Wind power level variations are larger in longer time frames. The standard deviation of hourly wind power changes at Blue Canyon ranges from 6.2 MW to 8.6 MW (8% to 12% of the nameplate rating). Again there is little difference in the hourly step change statistics between Blue Canyon and other large wind power plants. Figure 2 shows the hourly wind power step changes at Blue Canyon are scattered over a wider range. However 98% of all hourly step changes are still within ±3σ (±22.5 MW or ±30% of nameplate rating).

III. Short-Term Load Variations

The utility system load has a well-defined, predictable daily pattern that corresponds to daylight and routine human activities. Figure 3 plots the 1-minute average load (green trace) and wind power (blue trace) for a day. The general trend

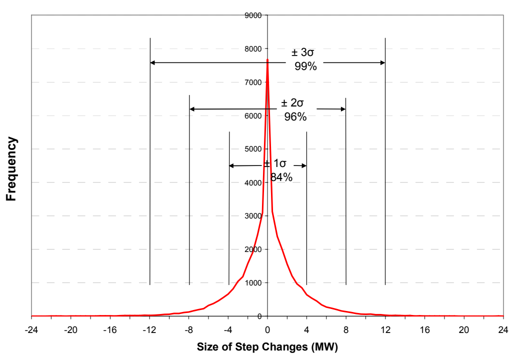

Figure 1. Frequency distribution of 10-minute wind power step changes

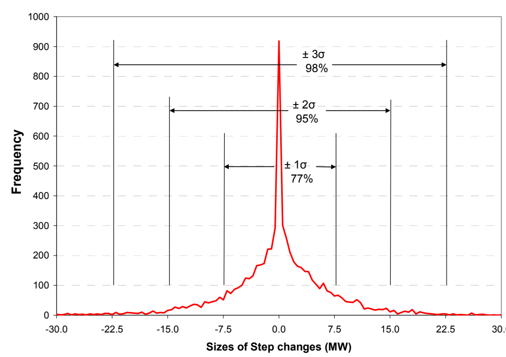

Figure 2. Distribution of hourly wind power step changes

of the system load—morning load pick-up, late evening peak and nightly load drop-off—is clear. A utility can usually predict these trends fairly accurately based on experience, weather forecast, and knowledge about load within its service territory. The plot shows that the system load also contains a rapid-changing component (the zigzags in the load profile trace) that is similar to the short-term wind power fluctuations. These short-term fluctuations are stochastic in nature. To show the rapid fluctuations of load and wind power in detail, Fig. 4 plots the 1-minute average load and wind power for a four-hour period. The system load and wind power short-term changes are very similar.

Table 3. Statistics of Hourly Wind Power Step Changes

	Blue Canyon	Lake Benton	Storm Lake	Indian Mesa	King Mtn	Trent Mesa	TWPP
	Stdev (MW)	Stdev (MW)	Stdev (MW)	Stdev (MW)	Stdev (MW)	Stdev (MW)	Stdev (MW)
June	8.6	9.2	9.5	9.1	7.2	18.7	4.1
July	7.7	7.9	6.7	5.7	3.6	16.2	2.7
August	6.2	9.5	9.1	5.5	3.5	12.6	2.4
September	6.4	9.9	8.7	6.5	5.4	12.2	2.0
October	8.0	8.7	9.2	8.1	6.6	15.1	2.0
November	7.2	8.9	8.8	7.8	7.0	13.4	3.4
6 months	7.4	9.1	8.7	7.2	5.9	15.1	2.9
	Normalized Standard Deviation						
June	12%	9%	8%	11%	9%	13%	12%
July	10%	8%	6%	7%	5%	10%	8%
August	8%	9%	8%	7%	4%	8%	7%
September	9%	10%	8%	8%	7%	8%	6%
October	11%	8%	8%	10%	8%	10%	6%
November	10%	9%	8%	9%	9%	9%	10%
6 months	10%	9%	8%	9%	7%	10%	8%

During the 24-hour period, wind power step changes are within the range of 3.7 MW and –3.9 MW. It has an average value of 0.0 MW and a standard deviation value of 0.8 MW. The system load exhibits a higher volatility than the wind power. During the same period, the system load step changes vary between 6.4 MW and –7.2 MW. The system load step changes have an average value of 0.0 MW and a standard deviation value of 1.9 MW.

While the data show there is positive but weak correlation between the short-term fluctuations of system load and wind power, they are practically two independent events. The daily correlation coefficients between 1-minute step changes of load and wind power ranges from –0.02 to 0.22. This suggests that wind power tends to move in the same direction as the system load. From a system operations point of view, this is a desirable situation. However, this specific phenomena could be associated with the limited available data. There is no reason for the short-term fluctuations of wind power and system load to be related. More short-term data should provide a clearer picture.

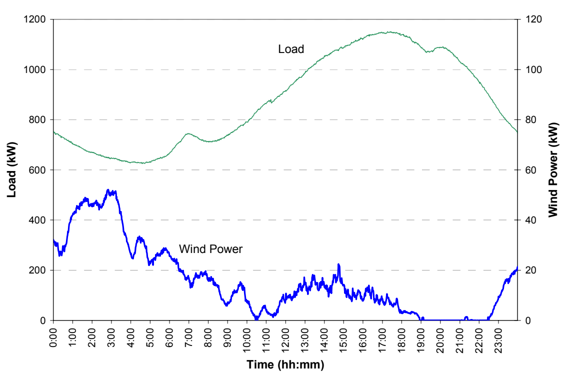

Figure 3. Profiles of 1-minute average wind power and system load

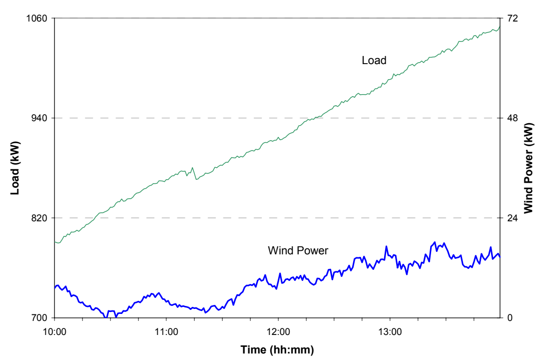

Figure 4. Wind power and system load fluctuations details

IV. Variability of System Load and Wind Power

The electric system responds to the short-term load fluctuations by adjusting the outputs of designated online generating units that can change its output quickly and are under automatic generation control (AGC). This function, called regulation, helps a control area maintain its interchange schedule, support the system frequency, and balance its generation and load under normal operations.

When wind power is added to a utility system control area, the system must respond to fluctuations of both system load and wind power. One way to gauge the effect of wind power on system regulation requirement is to examine the variability of wind power, system load, and the apparent load (i.e., load minus wind power). The wind power is treated as a negative load in this analysis because WFEC does not regulate the Blue Canyon output. Whenever wind power is available, the rest of the control area generating units will see a reduced load. The fluctuations of the apparent load are the combination of load and wind power fluctuations, and they represent the regulation requirements to the system after wind power is added. Table 4 lists the monthly standard deviation values of wind power (σ_W), system load (σ_L), and apparent load step changes (σ_A) and their extreme values from the 1-minute data series. The average values are not listed because they are very small or zeros.

Table 4. Standard Deviations of 1-Minute Wind, Load, and Apparent Load Step Changes

	Standard Deviation (MW)				Maximum (+) Step Change (MW)			Maximum (-) Step Change (MW)		
	Wind Step σ_W	Load Step σ_L	Apparent Load Step σ_A	% change	Wind Step	Load Step	Apparent Load Step	Wind Step	Load Step	Apparent Load Step
June	1.5	2.2	2.6	18%	20.5	64.8	64.8	-19.0	-111.2	-112.7
July	1.2	2.3	2.6	13%	25.7	144.4	144.7	-19.5	-52.1	-55.5
August	1.1	3.2	3.3	3%	21.4	77.7	77.4	-44.8	-81.6	-81.8
September	1.0	2.7	2.8	4%	15.7	71.3	70.9	-12.9	-68.9	-68.8
October	1.1	1.5	1.7	13%	7.2	9.9	10.6	-7.3	-13.0	-13.0
November	1.1	1.8	2.1	17%	7.5	33.2	34.2	-7.3	-20.0	-20.5
6-month	1.1	2.6	2.8	8%	25.7	144.4	144.7	-44.8	-111.2	-112.7

Table 4 shows that the apparent load has a higher variability than the system load. The apparent load is smaller in magnitude than the system load, but its step changes generally have larger standard deviation values. Although this indicates that wind power causes the variability of the apparent load to increase, which in turn increases the system regulation requirement, the increases are relatively moderate. Compared to the step changes of the system load alone, the step changes of the apparent load have a standard deviation value that is 3% to 18% larger. The average increase is about 8%. The small changes in both maximum positive and negative step change values also suggest that relatively little additional regulation is required by wind power. As shown in the table, the addition of wind power only slightly increases the extreme values of apparent load step changes.

Table 5 lists the hourly step change statistics for wind power, system load, and apparent load. It shows that the addition of wind power causes only a slight increase in the hourly variability of the apparent load (about 3%). The differences in apparent load step change extreme values are also relatively small.

Table 5. Hourly Variability with Wind Power

	Wind Step Changes (MW)	Load Step Changes (MW)	Apparent Load Step Changes (MW)	% Change
Standard Deviation	6.8	45.0	46.3	3%
Max (+) Step	56.3	97.5	109.6	12%
Max (–) Step	-41.8	-116.8	-143.8	23%

V. Wind Power Impact on System Operations

To see how system operations are affected by the fluctuations of wind power, the correlation between the wind power step changes and various other system parameters are computed and examined. Table 6 lists the correlation coefficients calculated from 6-month, 1-minute data series.

Column (1) shows the correlation coefficients between wind power step changes and actual interchange step changes. Column (2) shows the correlation coefficients between wind power step changes and control area net online generation (i.e., total generation minus wind power). Column (3) shows the correlation coefficients between system load step changes and actual interchange step changes. Column (4) shows the correlation coefficients between system load step changes and net online generation. Column (5) shows the correlation coefficients between changes in apparent load and actual interchange. Column (6) shows the correlation coefficients between changes in apparent load and net online generation, and (7) shows the correlation coefficients between wind power step changes and ACE. Column (8) shows the correlation coefficients between system load step changes and ACE, and column (9) the differences between scheduled and actual interchanges and the ACE. It should be noted that the numbers in Table 6 are numerical results of mechanic computations performed on random series (such as wind power step changes and system load step changes) of limited length. The absolute values of these numbers are therefore less important than their relative relations and the underlining pattern they display. Nevertheless, the correlation coefficient values in Table 6 confirm the expected interactions between wind power and system operations under normal conditions.

Table 6. Correlation Coefficients from 1-Minute Data Series

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Wind Power Changes	Wind Power Changes	Load Changes	Load Changes	Apparent Load Changes	Apparent Load Changes	Wind Power Changes	Load Changes	Actual & Schedule Interchange Differences
	Actual Interchange Changes	Net Gen Changes	Actual Interchange Changes	Net Gen Changes	Actual Interchange Changes	Net Gen Changes	ACE	ACE	ACE
Overall	-0.22	-0.03	0.59	0.08	0.60	0.08	0.08	-0.15	0.97
				Range of daily values					
Max.	0.14	0.33	0.91	0.24	0.92	0.23	0.36	0.05	1.00*
Min.	-0.64	-0.20	0.21	-0.11	0.25	-0.14	-0.06	-0.37	0.80

*Due to rounding

As shown, there is a negative correlation between wind power step changes and actual interchange step changes. The daily correlation coefficients range from 0.14 to –0.64 and the overall correlation coefficient for the entire period is –0.22 (column 1). The wind power and actual interchange move in opposite directions. The correlation between wind power changes and net online generation is also negative, but small (the overall correlation coefficient is only –0.03). When wind power increases, the actual interchange tends to decrease (i.e., less power into the control area) as does the outputs from other online generators. This is an expected outcome because when more power becomes available within the control area (i.e., an increase in wind power), both online generation and power flow into the control area will decrease to maintain the balance between load and generation. The correlation between wind power changes and net online generation is weaker than the correlation between wind power changes and actual interchange. It shows that the frequency response of the entire grid is faster than that of a single control area. In this case, it appears that wind power fluctuations are mostly taken up by the grid in the form of higher interchange variability.

Changes in actual interchange are strongly related to changes of system load. The overall correlation coefficient is 0.59 (column 3) with daily values varying between 0.21 and 0.91. The correlation between changes in load and changes in net online generation is also positive, but much weaker; its overall correlation coefficient is only 0.08 (column 4) with its daily values ranging from –0.11 to 0.24. These results show that when load increases, both online generation and the amount of power imported increase to meet the additional demand, but the control area's interchange tracks the short-term fluctuations of system load within the control area more closely than does the control area's net online generation. This is similar to responses of the online generation and actual interchange to the changes in wind power discussed above.

It is clear that load fluctuations cause more variability in the interchange than do the wind power fluctuations. Load fluctuations also have more influence on control area net online generation than do the wind power fluctuations. The strong correlation between the changes in apparent load and actual interchange (column 5) and the weak correlation between changes in apparent load and control area net online generation (column 6) reinforces this idea.

VI. Wind Power Impacts to ACE

The efficiency of the system regulation function is measured by ACE statistics. The available data show that wind power fluctuations have minimal influence on ACE for the WFEC control area. The correlation between system load changes and ACE (overall correlation coefficient of –0.15; column 8) is stronger than the correlation between wind power changes and ACE (overall correlation coefficients of 0.08; column 7). This result again shows that load fluctuations have a greater impact on system operations than do wind power fluctuations. The negative correlation coefficients between system load changes and ACE mean an increase in system load (a positive step value) tends to associate with negative ACE values (power flows into the control area) and vise versa.[1] The positive correlation coefficients between wind power step changes and ACE are just the opposite—increases in wind power tend to associate with positive ACE values.

[1] According to industry convention, positive ACE indicates power going out and the negative ACE indicates power flowing into the control area.

The differences between actual and scheduled interchanges are the major driver of a control area's ACE [1]. Correlation coefficients calculated from the WFEC 1-minute data series confirms this relationship. The correlation coefficients between ACE and differences of actual and scheduled interchanges range from 0.80 to 1.00 with an overall value of 0.97 (Column 9 in Table 5). However, further examination of the data revealed that the majority of the large ACE values (positive and negative) have no relation to either system load changes or wind power changes. Large ACE values occurred during periods when there were large inter-hour interchange schedule changes. The available data have not shown that small short-term wind power fluctuations have any noticeable effect on ACE.

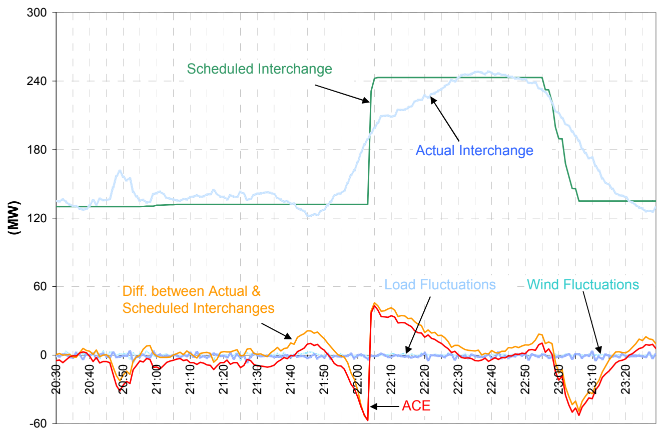

Figure 5. Correlation between ACE and interchanges

Figure 5 is an example of such an event. It plots 1-minute actual and scheduled interchanges and their differences, 1-minute ACE values, and 1-minute step change values of wind power and system load. The figure clearly shows that the ACE has no correlation with either load or wind fluctuations. The ACE tracks the differences between actual interchange and scheduled interchange and becomes very large during periods when the interchange schedule takes a large step change and the generators within the control area have not had time to bring the actual interchange to the new designated level. The situation shown in Fig. 5 is not a special case. In fact the intra-hour interchange schedule changes are the major cause of large ACE values. The consequence is that large ACE values occur during the period 10 minutes before and 10 minutes after the hour. Figure 6 plots the frequency of large ACE values (in this case an ACE magnitude of 29 MW or larger) against the time of such occurrence during a 6-month period. The concentration of large ACE values around the start of the hour is clear. In fact the available data show that only one of the more than 6,600 occurrences of large ACE values was directly caused by wind power change.

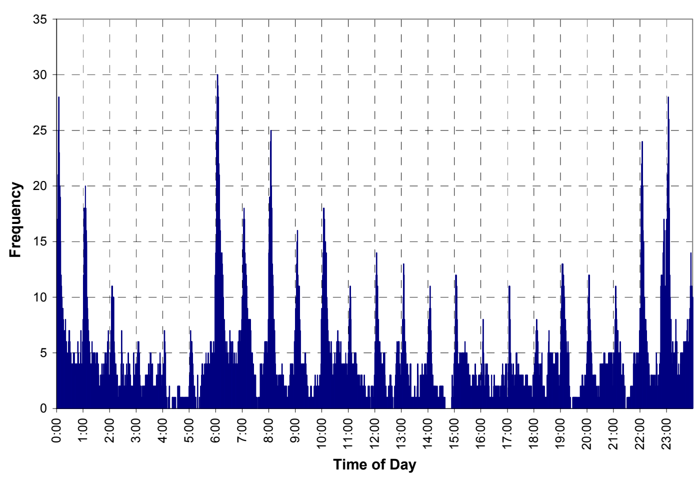

Figure 6. Frequency and time of occurrence of large ACE values

All the control areas are required to meet the Control Performance Standard CPS1 and CPS2 requirements [1]. CPS1 measures the long-term impact of ACE on the health of the interconnection in terms of frequency. CPS2 measures the short-term excursions (10 minute average) of ACE against a predefined limit for each control area.[2] The CPS1 and CPS2 graphs for 2003 and 2004 for the WFEC control area are shown in Figs 7 and 8. Although the graphs show that a downward trend of CPS1 before the Blue Canyon wind power plant came on-line in December 2003, it is evident that the CPS1 deterioration accelerated in early 2004 after wind power was included into the control area. Uncertainty of wind power availability affected the unit commitment decisions made by the system operators and worsened CPS1. With more experiences, WFEC system operators began to take corrective actions[3] in March of 2004 and the CPS1 eventually returned to the level before wind power was added. There is very little difference on CPS2 before and after wind power.

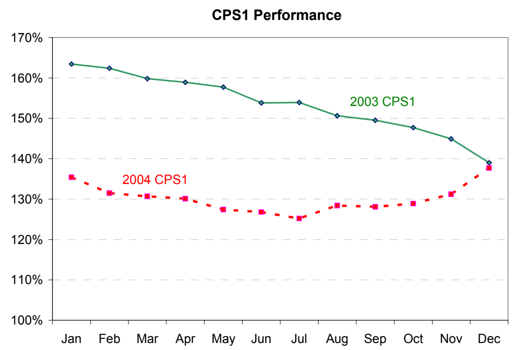

Figure 7. CPS1 for 2003 and 2004

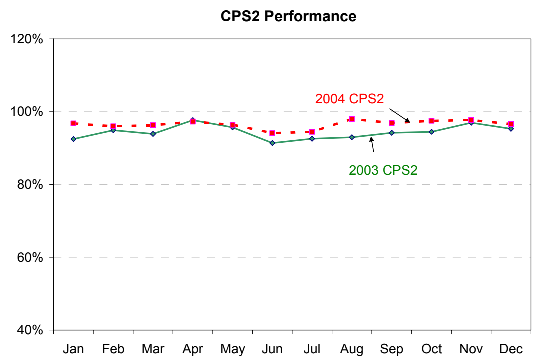

Figure 8. CPS2 for 2003 and 2004

VII. Conclusions

The generating rating of the Blue Canyon Wind Power Project is about 6% of WFEC's peak load, and during light load periods it may approach 14% of the load. At such levels, the data show that on average the fluctuations of wind power only increase the short-time frame variability of system apparent load by 8%. For a longer-time frame, the increase in system apparent load variability is even less. The available data show that wind generation has less impact on system regulation requirements than system load. At low penetration, the impact of wind power on system operations is small. The magnitudes of short-term changes in system load are greater than that of wind power, and consequently changes in system load dominate the control area operations. Changes in wind power only had small influence on actual interchange and online generation. The correlation between the ACE and changes of system load is stronger than the correlation between the ACE and wind power changes. Furthermore, the data show that almost all high ACE values are caused by big changes in interchange schedule.

WFEC CPS1 and CPS2 statistics before and after wind power was added to the control area confirm that the wind power impacts on system operations are small and manageable. Although compliance with CPS1 showed an initial deterioration (but still within minimum performance standard), it recovered to its pre-wind level after operators gained more experience and made some adjustment in operation procedures. There was very little change in CPS2 compliance.

Short term wind power fluctuations can be accommodated by additional spinning reserve and regulation margin. The uncertainty of wind power availability complicates the day-ahead resources scheduling and hour-ahead adjustment processes, which determine the available spinning reserve and regulation margin. Longer term wind power variation may also affect control area load following operations. Better wind power forecasting can help improve the system performance. WFEC is working with Blue Canyon Wind Plant operators to improve wind power forecasting. Actually, two issues need to be addressed. One is to improve the accuracy of wind power forecasting, and the other is how system operators will incorporate the information into scheduling and operating decision processes. The effect of wind power forecasting on operations will be analyzed in future studies. Researchers are also conducting additional research to determine optimal operating reserve under the uncertainty of wind power forecasting.

[2] The minimum performance standard is 100% for CPS1 and 90% for CPS2.

[3] Including paying closer attention to ACE movement and developing new empirical formula for generator control.

It is clear that at low penetration levels, wind variations have much less impact on system regulation requirements than that of load variations. System operators may still consider wind generation harder to manage because it is easier for operators to predict system load than wind power. The operators are more experienced with load forecasting than wind power forecasting and they feel comfortable using load forecasting information in system operations. However, as demonstrated by WFEC CPS1 statistics, operators learn to manage the variability of wind and can maintain satisfactory system performance. Good wind power forecasting is obviously of high value to system operators. Equally import are specific operating procedures on how to use wind power forecasting in control area operations.

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The National Renewable Energy Laboratory (NREL) worked with the Western Farmers Electric Cooperative (WFEC), a generation and transmission Cooperative in Oklahoma, to analyze the impact of wind power from the Blue Canyon Wind Power Project located north of Lawton, Oklahoma, on WFEC system operations. The analysis showed that, at such a penetration level, wind power has a very small effect on system operations. The fluctuations of wind power caused only a slight increase in the variability of the system apparent load (system load minus wind power).

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