Detection of Undamped Sub-Synchronous Oscillations of Wind Generators with Series Compensated Lines

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Abstract - Interaction between wind generators and a series compensated line in the Xcel Energy's 345 KV system resulted in undamped subsynchronous oscillations. This paper describes the switching event, analysis of the event and the conclusion that led to the development of a sub-synchronous frequency detection device.

Key words-Series compensated line, Wind generators, subsynchronous oscillations

1.0 Background

Minnesota Legislature in 2007 adopted a resolution to mandate all utilities to build or contract 25% of total energy from renewable energy sources by 2025. Xcel Energy which owns nuclear generation was required to build or contract additional 5%, (30%) by 2025. Since 2004, wind generation increased significantly in southern Minnesota and South Dakota regions due to production tax credits and the state resolution.

With increase in generation in Southern Minnesota and south Dakota, significant transmission system improvements were planned and implemented by Xcel Energy Inc. including the series compensation of the 54 mile 345 KV Wilmarth (WLM)–Lakefield Generating station (LFD) transmission line. The degree of series compensation was determined to be 60% through planning studies to provide load relief to constrained interfaces and to reduce the impedance of the direct path (Lakefield Junction (LAJ) -LFD -WLM –Blue Lake 345 KV) to Twin Cities load center [1].

Xcel Energy Inc. decided to install 240 MVAR, 40KV, 2000A series capacitor at the middle of the line at Fieldon substation (FDN). The installation was completed as a turn key project in October 2007.

 Figure 1 shows Xcel Energy Inc. transmission system substations connected to the series compensated line.
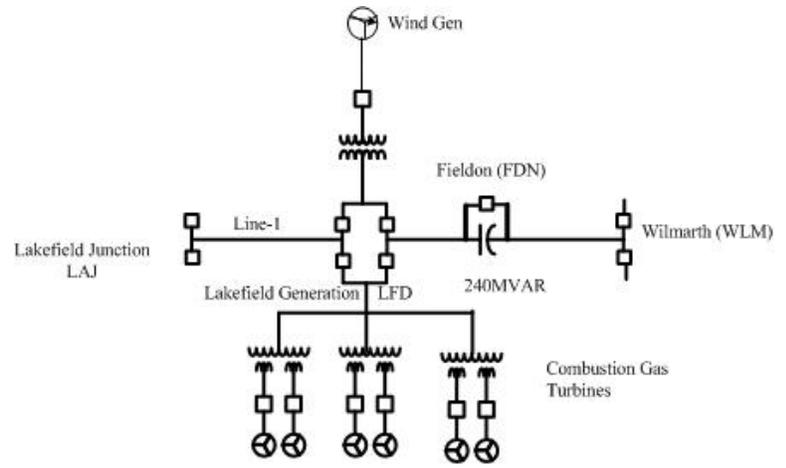

Figure 1: One-line of the 345 KV system around series compensated line

With steam, combustion turbine and wind generators connected at both ends of the series compensated line, the effect of sub synchronous oscillations due to the capacitance on mechanical resonant modes of these machines was investigated. Sub synchronous resonance (SSR) analysis was performed on all generators in the area [2]. The report did not identify any SSR issues with the combustion turbines at LFD. However, the neighboring utility, Great River Energy (GRE) which owns Combustion turbine generators at LFD decided to install SSR relays.

The report identified the induction generation effect in case of a radial connection of wind generation to Wilmarth substation and suggested bypass of series capacitor on loss of LAJ -LFD line.
Special protection scheme was designed to bypass the series capacitor at Fieldon for any configuration at Lakefield substation (LAJ) or at Lakefield Generation (LFD) that resulted in a radial connection of any LFD generation to Wilmarth via series capacitor. Transfer trip (bypass) scheme, based on open breaker status, was installed only at LFD prior to energizing the series capacitor at Fieldon.

The series capacitor platform was energized on Thursday, October 4, 2007 and capacitor was placed in service by opening the bypass breaker on October

5, 2007 without the bypass scheme installation completed at LAJ end.

2.0 Switching Event

Transfer trip bypass scheme implementation at Lakefield Junction (LAJ) for open breaker status, was scheduled for Monday October 8, 2007. The system conditions were as shown in Figure 2
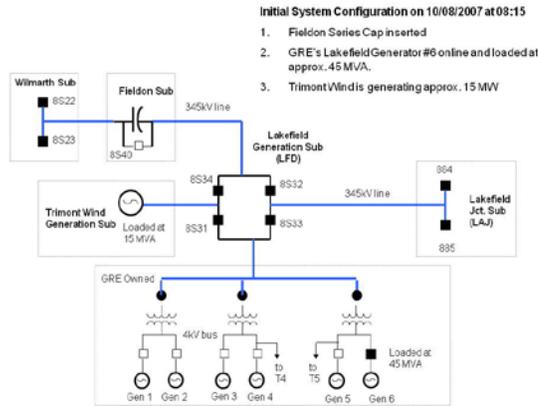
Legend: ■ - Breaker Closed; □ - Breaker Open
Figure 2: System configuration prior to switching. The switching request to outage the LFD-LAJ line started with the opening of breakers 884 and 885 as shown in Figure 3.
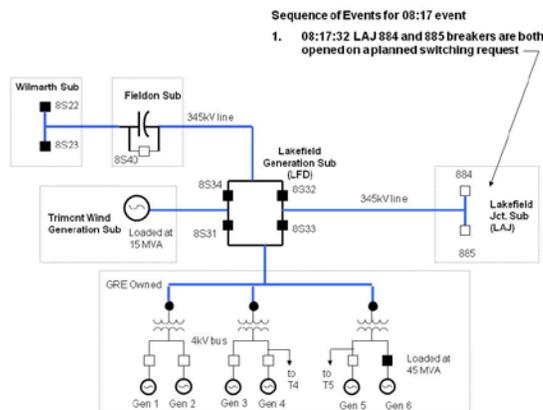

Figure 3: System configuration with LAJ breakers 884 and 885 open.

After approximately 6 seconds protection schemes on LFD generators operated and opened generator 6 breaker, 8S31 and 8S33 breakers. The configuration was as shown in Figure 4. The 345 KV bus voltage

jumped up from 1.03 PU to 1.08 PU prior to the opening of breakers 8S31 and 8S33. Wind generators were still connected to the system.
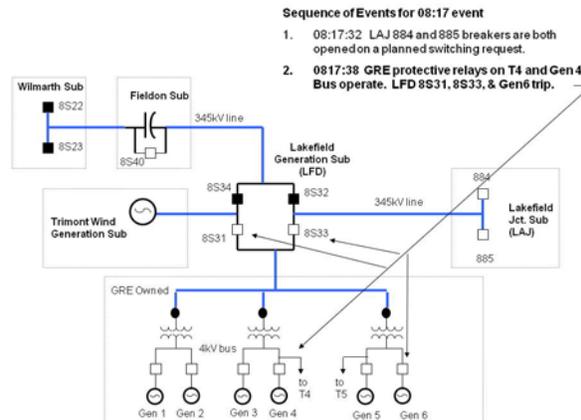

Figure 4: System configuration after generator trip

The system operator opened 8S32 breaker that resulted in bypassing the series capacitor as designed at LFD substation. The final configuration was as shown in Figure 5.
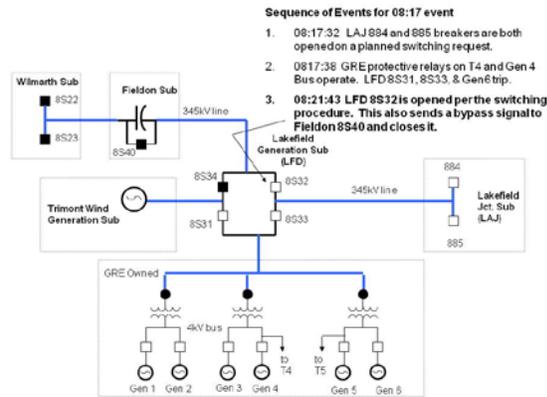

Figure 5: Final configuration after opening the LAJ line breaker at LFD substation

After nearly two hours, to restore the power to the plant, the faulted generator transformer (T2) section was isolated and 8S31 breaker was closed to energize other GSUs as shown in Figure 6.
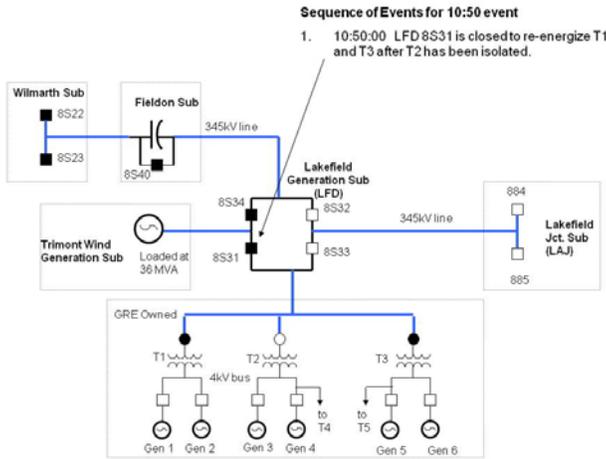
Figure 6: Reenergization of the Generator Transformers T1 and T3

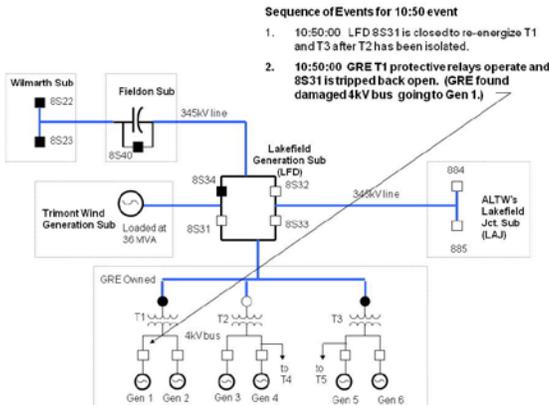Transformer Differential relay on T1 operated to trip open 8S31 breaker as shown in Figure 7

Figure 7: Final configuration after the second event

3.0 Analysis of the event

Waveforms captured by the fault recorder at LFD substation during the switching event as described in figures 3 and 4 , indicated the presence of several frequencies in addition to 60 HZ. The CT generator current waveform is as shown in Figure 8.
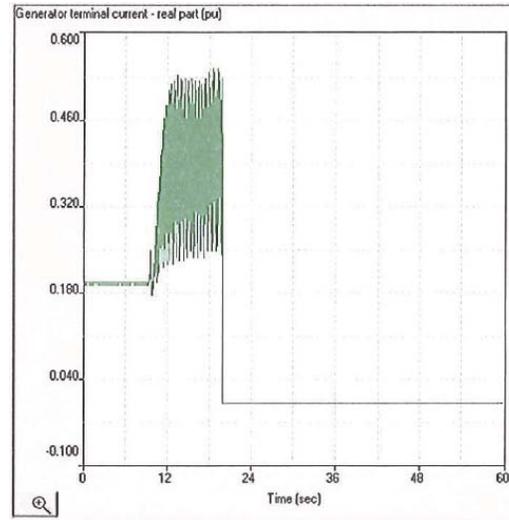The current waveform on the wind generators had similar shape and characteristics.

Figure 8: CT Generator current waveform

The shape of the waveform indicated the presence of DC and several harmonics. Prony analysis was used to determine the harmonic content.

The Prony analysis, developed in 1795, uses equally spaced data points to determine the frequency, magnitude, phase angle and damping factor. It is a methodology that extends Fourier analysis by directly estimating the frequency, damping, strength, and relative phase of the modal components present in any signal.

The method decomposes the signal into its dominant modes of oscillation. The signal is represented as
$$f(t) = \sum A_i e^{-\sigma_i t} COS(2\pi f_i t + \varphi_i) \qquad (1)$$
where, A_i is the amplitude, σ_i is the damping coefficient, f_i is the frequency and φ_i is the phase angle.

For better understanding, the results of Prony analysis are given as frequency, amplitude and the relative damping ratio for each oscillatory mode where the damping ratio, ξ, expressed as a percentage number is given by

$$\xi = 100*\sigma_i/(\sqrt{(\sigma_i{}^2 + \omega^2)}) \qquad (2)$$

Damping ratios number has been used as a key indicator of system dynamic stability [3]
The minimum acceptable level of damping is not clearly known. A damping ratio less than 3% seems to be accepted with caution. Damping is considered

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adequate if all electromechanical modes have a predicted damping ratio of at least 5%.

The dominant frequencies in the current waveform of Figure 6 with damping ratios are as shown in the table-1.

Total current is 0.19 PU

Frequency (HZ)	Magnitude (PU)	Damping (%)
10.95 HZ	0.14	3.23
11.58 HZ	0.15	3.477
12.41 HZ	0.09	3.776
15.78 HZ	0.06	2.123

Table-1: Frequencies with damping ratio

The modal frequencies of LFD Turbine generators were measured by the manufacturer to be at 14.7 HZ and 42.6 HZ. The records did not indicate the excitation of modal frequencies (60- 14.7=46.3 HZ or 60-42.6=16.4 HZ).

Since most of the protective relays were designed to operate around power frequency of 60HZ, Xcel Energy decided to work with Relay and disturbance recorder manufacturer to develop a relay to detect frequencies in the range of 5 HZ to 25 HZ to provide back up Protection to SSR relays and the special protection schemes installed around the series compensated line.

Wind generator currents and the Generator transformer currents are as shown in Figure
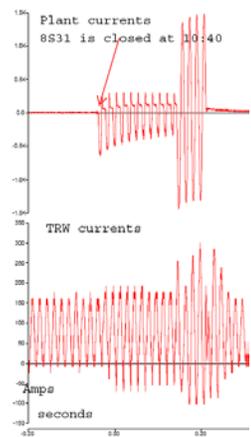

Figure 9: Wind Generator currents and Combustion Turbine Generator transformer energization currents.

Analysis of wind generation currents prior to transformer energization indicated the presence of 9-12 HZ components. This could be the sustained subsynchronous current or could be generated by the wind machines operating at super synchronous speeds.

4.0 Relay Specifications:

The following requirements were specified for the subharmonic relay
- Frequency detection in the range of 5-25 HZ settable in 1 HZ steps.
- Settable percentage of harmonics to fundamental ratio
- Settable percentage ratio total subharmonic distortion to fundamental ratio
- Ability to set independent channel multi-level alarm and trip set points with time delay.
- Ability to measure harmonic components from voltages and currents channel.
- Ability to record events.

5.0 Relay setting, testing and commissioning:
The event record from the second switching event as shown in Figures 6 and 7was used to determine the settings on the relay. Manufacturer's spreadsheet tool was used to identify the individual subharmonic contents of currents and voltages. The following table-2 shows the frequency components from the event file.

	DC	9	10	11	12	13	14	15	16	17	18	19	60
GB VA	0.3	0.9	0.9	0.8	0.7	0.9	1.3	1.8	2.2	2.5	2.4	2.1	12
GB IA	0.1	0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0001
LAJ IA	0	0	0	0	0	0	0	0	0	0	0	0	0.1
WLM/LAJ.Va.345KV PT	0.3	2.1	4.5	4.9	4.6	2.6	1.6	1.8	3.1	1.6	1.5	0.9	67
TRW.Ia.TRW A PH.	0.2	0.2	0.4	0.3	0.1	0	0	0	0	0	0	0	0.4
WLM.Ia.345KV CT.	0	0.2	0.3	0.4	0.4	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.4
individual subharmonic to fundamental ratio													
GB VA	8%	8%	7%	6%	9%	11%	15%	18%	21%	20%	18%		1
GB IA	0%	infinite	infinite	infinite	infinite	infinite	infinite	infinite	infinite	infinite	infinite		1
LAJ IA	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%		1
WLM/LAJ.Va.345KV PT.	3%	7%	7%	7%	4%	2%	3%	5%	2%	2%	1%		1
TRW.Ia.TRW A PH.	50%	100%	75%	25%	0%	0%	0%	0%	0%	0%	0%		1
WLM.Ia.345KV CT.	50%	75%	100%	100%	50%	25%	25%	25%	25%	25%	25%		1
total subharmonic distortion to fundamental ratio													
GB VA	0.81	0.81	0.64	0.49	0.81	1.69	3.24	4.84	6.25	5.76	4.41	5.45	45%
GB IA	0	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.32	infinite
LAJ IA	0	0	0	0	0	0	0	0	0	0	0	0.00	0%
WLM/LAJ.Va.345KV PT.	4.41	20.25	24.01	21.16	6.76	2.56	3.24	9.61	2.56	2.25	0.81	9.88	15%
TRW.Ia.TRW A PH.	0.04	0.16	0.09	0.01	0	0	0	0	0	0	0	0.55	137%
WLM.Ia.345KV CT.	0.04	0.09	0.16	0.16	0.04	0.01	0.01	0.01	0.01	0.01	0.01	0.74	105%

Table-2: Analysis of the waveforms using manufacturer's spreadsheet

An example of settings selected on the wind generation currents is as shown in figure 8;

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Figure 10: Setting examples.

The relay was tested and commissioned by replaying the COMTRADE files from the event and also files created with waveforms containing several frequencies.

6.0 Conclusions:
The switching event around the series compensated line connected to wind and combustion turbine generation resulted in sustained subsynchronous oscillations. . The wind generator currents after the initial event indicate the presence of sustained 9-12 HZ components in wind generator currents. The event analysis was used to develop a protection scheme to detect the presence of subsynchronous frequencies.

7.0 Acknowledgement:
Authors would like to thank Dr. Krish Narendra of ERLPhase Technologies in providing support to determine the frequencies using Prony analysis and developing a protection device

8.0 References:
[1]   Xcel Energy Inc. internal report, "Wilmarth-Lakefield 345 kV Series Compensation:
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[3]   Ray, Cody, Huang, Zhenyu, "Power Grid Dynamics: Enhancing Power System operation
 through Prony Analysis", Journal of undergraduate research, office of Science, US Department of Energy, Volume VII, 2007

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