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Simulation of 2017 Wind Farms into Series Capacitor Sub-Synchronous Oscillation Events

R. O'KEEFE, E. REZAEI, K. ANDOV, Y. GONG
American Electric Power
USA

Y. CHENG, J. ROSE
Electric Reliability Council of Texas
USA

SUMMARY

In 2017, three separate events occurred on the AEP transmission system within ERCOT that resulted in certain wind farms becoming radially connected through series compensation. In two of the events, the wind farms tripped offline and in the third event the series capacitors were automatically bypassed. A post-event analysis of high speed fault recorder data revealed that periods of sub-synchronous oscillations (SSO) had occurred in all three instances leading to the tripping or bypassing. This was unexpected because prior to their energization, all the wind farms participating in the SSO had originally been required to conduct sub-synchronous resonance studies and to demonstrate SSO mitigation.

This paper illustrates the difficulties encountered in attempts to reproduce these events on an electromagnetic transient (EMT) simulation platform. It also highlights the further work that needs to be done to ensure both that manufacturer-provided black box EMT models accurately simulate SSO behavior and that the SSO behavior is more effectively mitigated.

KEYWORDS

Subsynchronous Oscillation, Subsynchronous Control Interaction, Event Replication, Event Analysis

rjokeefe@aep.com

Introduction

The possibility of sub-synchronous control interaction (SSCI) between wind generation projects and series compensated transmission lines has been a concern ever since a 2009 event on the AEP system in Texas awoke the industry to the possibility.[1,2] The 2009 event was the consequence of a fault and normal clearing of one section of a series compensated transmission line that reconfigured the transmission system serving certain wind generation projects such that the projects became radially connected through the series capacitor. The high sub-synchronous currents that resulted caused significant damage to the Type III wind turbines within the wind projects. The study of sub-synchronous oscillation potential and analysis of SSCI mitigation measures has been an ERCOT regional requirement of new generation projects since the 2009 event.

Three more recent SSCI events, also on the AEP system in Texas, resulted in certain other Type III wind generation projects located along a different 345 kV series compensated transmission line similarly becoming radially connected through two banks of series capacitors. The high-speed recordings available from each of these events show clear indication of sub-synchronous voltage and current content superimposed on the 60 Hz waveforms. These Type III wind generation projects had been analyzed for the possibility of SSCI prior to their energization and mitigation measures had been studied and designed, and then implemented on site. Despite these SSCI mitigation measures, the wind projects exhibited substantial magnitudes of sub-synchronous current immediately upon becoming radially connected into series capacitors following a line section outage. The events resulted in either bypass of the series capacitor banks by their own internal overcurrent protection, or else tripping of the wind projects due to main transformer current saturation and operation of transformer differential protection. In these instances, there was no damage to either the wind plants or to the series capacitors.

SSCI differs from the more well-known sub-synchronous resonance (SSR) phenomenon that is caused by resonance conditions between series compensated transmission systems and natural torsional frequencies of turbine-generator shafts. Rather, the control system responses of wind machines which act within sub-cycle time-frames can interact with the natural frequencies of a series compensated system to which they are attached.[3,4] Any resulting currents in the sub-synchronous frequency range can persist until some protective function either removes the participating wind generation project(s) or bypasses the participating series capacitor bank(s). Phasor Measurement Units (PMU) with typical 30~60 per second sampling rates are not able to adequately capture the sub-synchronous frequency oscillations. Operations personnel are thus unable to identify a SSCI event in progress. While series capacitor bypass is not a system reliability concern once in a radial configuration, the possible extreme distortion and increasing amplitude of waveforms caused by the sub-synchronous content is a system reliability risk as other non-radial equipment such as other transformers, FACTS devices, or HVDC converters may be at risk of tripping in response to the unwelcome currents.

In this paper, the aforementioned 2017 events on the AEP system are analyzed. After a few less than successful attempts to simulate each of the events on an electromagnetic transient (EMT) simulation platform, it became clear that the magnitude, damping, and frequency of SSO content are quite sensitive to the status and MW and MVAR initial conditions of the various wind plants. The adequacy of the wind plant EMT modeling also remains in question and the design and verification of more effective SSCI mitigation has been hindered as a result. The event analysis points to the need for and importance of accurate EMT modeling of wind generation resources.

2017 SSCI Event Descriptions

Referring to Figure 1, the various 2017 SSCI events are described as follows:

Event 1: August 24th, 2017

Station 4 – Station 5 line section non-fault outage and series capacitor bypass. Subsequent series capacitor manual reinsertion and trip of wind plants 3 and 4.

An inadvertent trip of the line section between stations 4 and 5 caused wind plants 3 and 4 to operate into the two series capacitor banks between stations 3 and 4. Sustained sub-synchronous content was observed and both series capacitors were bypassed by their internal overcurrent protection. Approximately 20 minutes later, with line section 4-5 still open, the series capacitors were manually re-inserted. Sub-synchronous current again appeared immediately and rapidly increased in magnitude. Wind plants 3 and 4 tripped in stages within one second of the series capacitor re-insertions.

Event 2: September 27th, 2017

Station 2 – Station 3 line section fault induced outage and trip of wind plants 1 and 2.

A phase-to-ground fault and normal clearing of the line section between stations 2 and 3 caused wind plants 1 and 2 to operate into the two series capacitor banks between stations 3 and 4. Sub-synchronous currents appeared immediately and increased rapidly. Wind plants 1 and 2 tripped on transformer differential protection within 24 cycles of the initial fault.

Event 3: October 27th, 2017

Station 4 – Station 5 line section fault induced outage and no wind plant trip.

A phase-to-ground fault and normal clearing of the line section between stations 4 and 5 caused wind plants 3 and 4 to operate into the two series capacitor banks between stations 3 and 4. Sub-synchronous current of a lower level compared to that of Event 1 was recorded and was dissipated by the time of successful manual reclose of the faulted line section about three minutes later. Wind plants 3 and 4 did not trip.

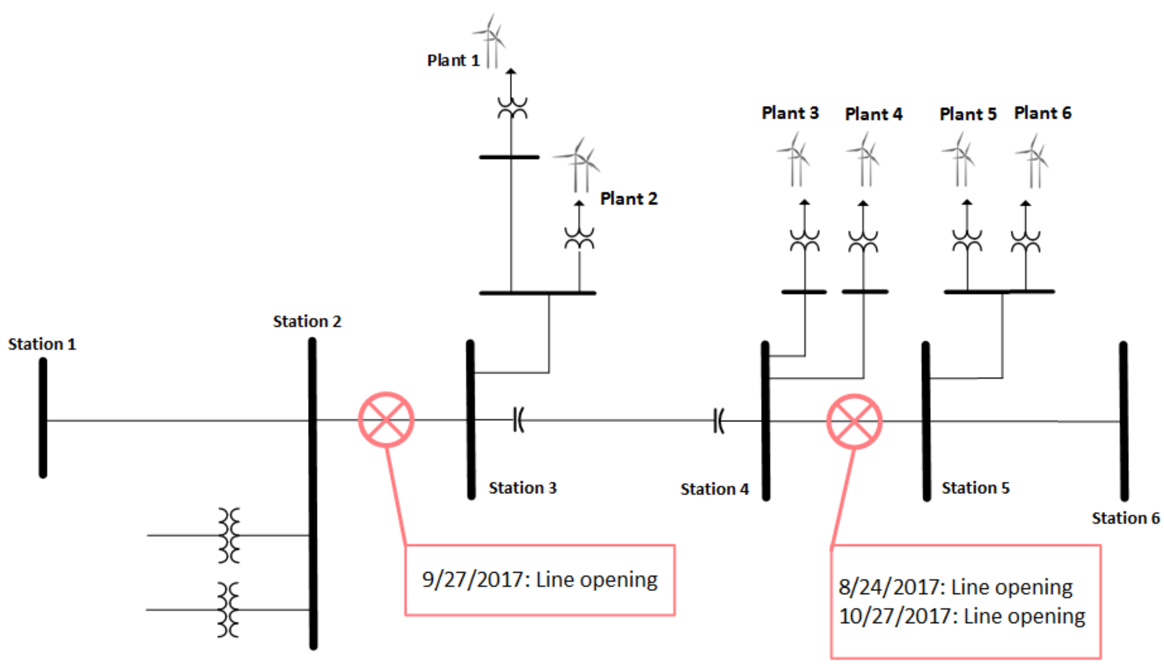

Figure 1: SSCI Events Caused by WGRs Becoming Radially Connected Through Series Capacitors

SSCI Event Data Records and Analysis

Although the SSCI events reported in this paper persisted for as long as several seconds and phasor measurement units (PMU) were nearby, they were unable to provide the event data in the sub-cycle time frame necessary for detection. These events were captured by digital relays in the area with the sampling rate of 2k samples/second or above in raw data format. The data is not filtered. Figures 2 and 3 show the recorded oscillography and FFT analyses of the sub-synchronous current contents of Event 1.

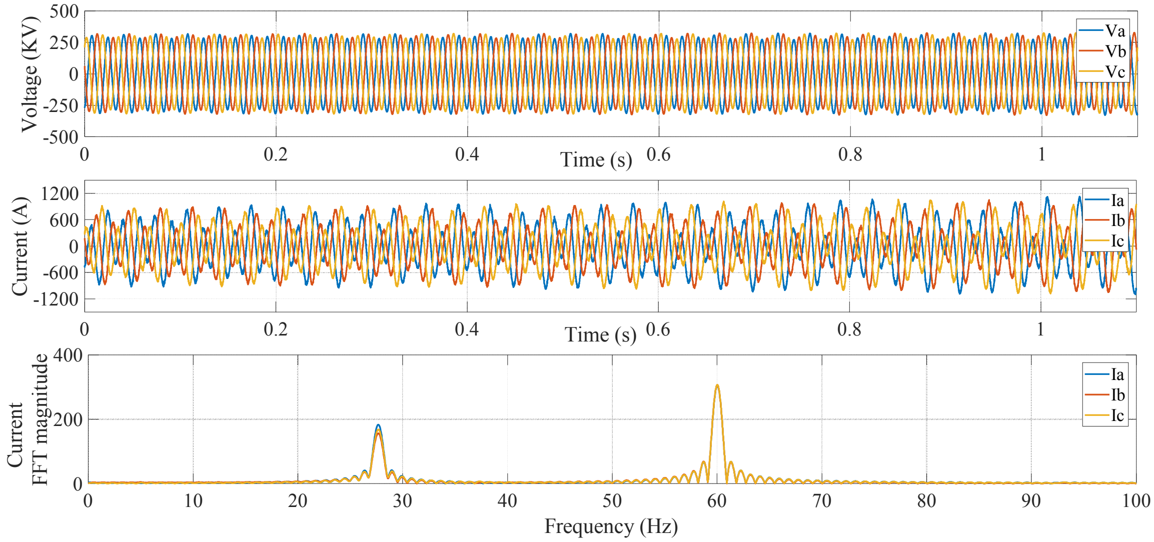

Figure 2: Event 1 three-phase instantaneous voltage and current on Station 4 – Station 3 line at Station 4 after Station 4 – Station 5 line section trip and before series capacitors auto-bypassed; FFT line current spectrum.

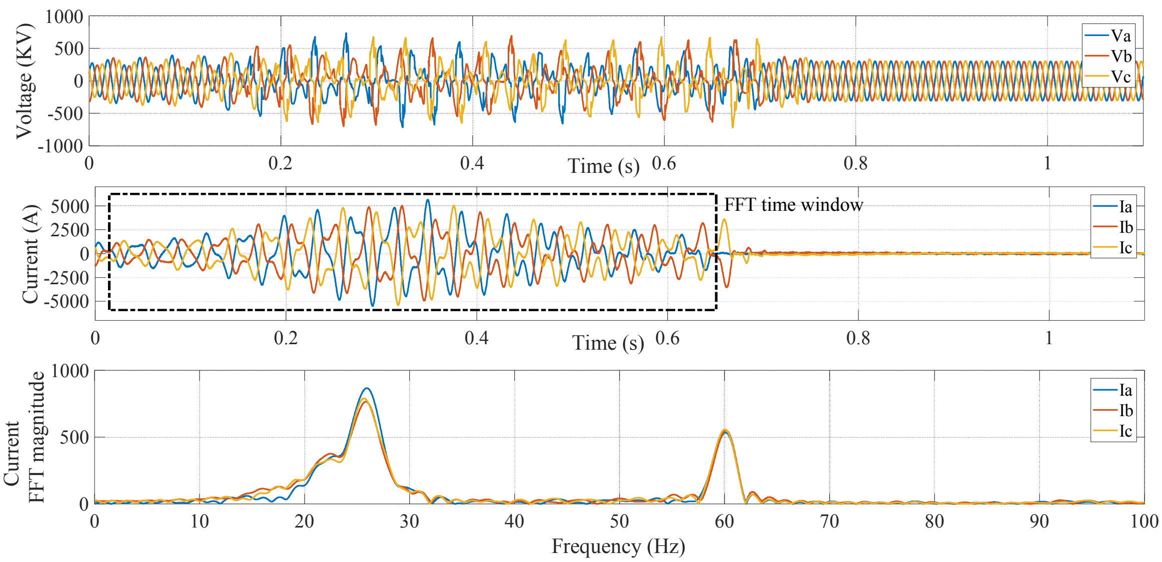

Figure 3: Event 1 three-phase instantaneous voltage and current on Station 4 – Station 3 line at Station 4 after series capacitor re-insertions also showing tripping of wind plants 3 and 4; FFT line current spectrum.

Figure 4 shows the recorded oscillography and FFT analysis of the sub-synchronous current content of Event 2.

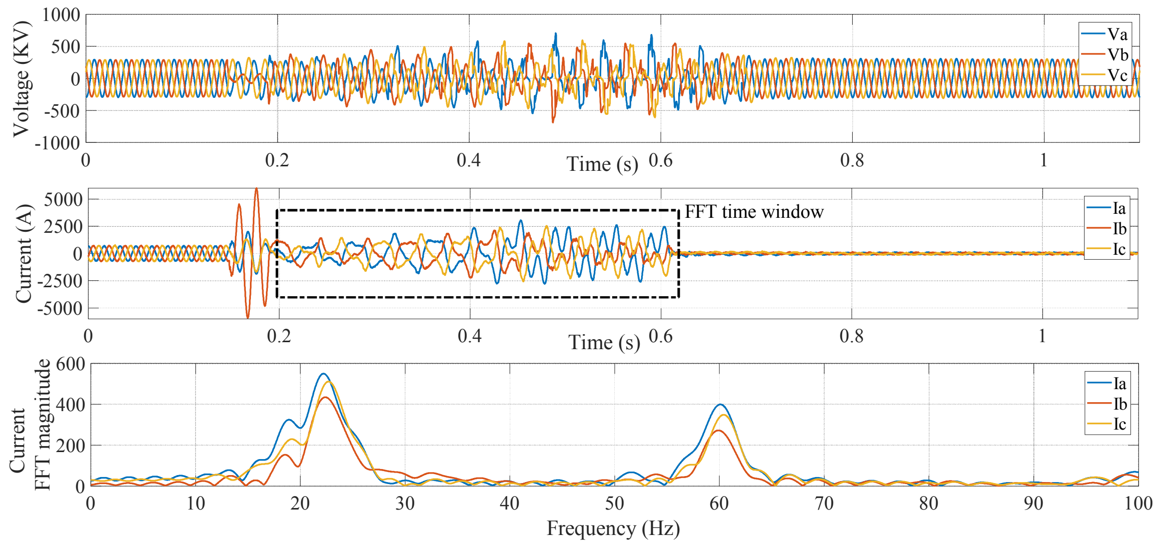

Figure 4: Event 2 three-phase instantaneous voltage and current on Station 3 – Station 4 line at Station 3 after Station 2 – Station 3 line section fault and trip also showing tripping of wind plants 1 and 2; FFT line current spectrum.

Figure 5 shows the recorded oscillography and FFT analysis of the sub-synchronous current content of Event 3.

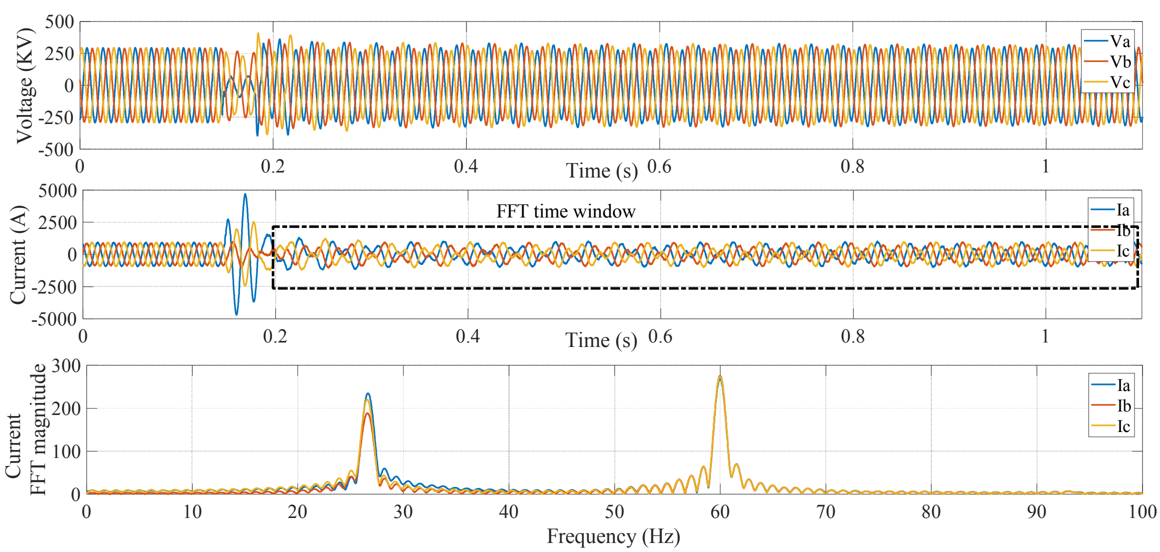

Figure 5: Event 3 three-phase instantaneous voltage and current on Station 4 – Station 3 line at Station 4 after Station 4 – Station 5 line section fault and trip; FFT line current spectrum. The SSCI in this event eventually dissipated with voltage and current traces returning to normal.

SSCI Event Simulation and Analysis

An effort to reproduce the events in EMT simulations was undertaken to better understand the causes of the SSCI mitigation failure and to verify the EMT-based wind project modeling. A 114-bus EMT power system model was formed from the ERCOT transient stability model database including and extending beyond stations 1 through 6 of Figure 1. To this were added detailed vendor supplied EMT-level models of wind plants 1 through 6. State estimator saved power flow cases at the times just prior to the events were applied to form the pre-event power system conditions necessary to perform EMT simulations of each event. The EMT platform was PSCAD Version 4.6.2. Figures 6 through 9 show the attempts to simulate the SSCI events.

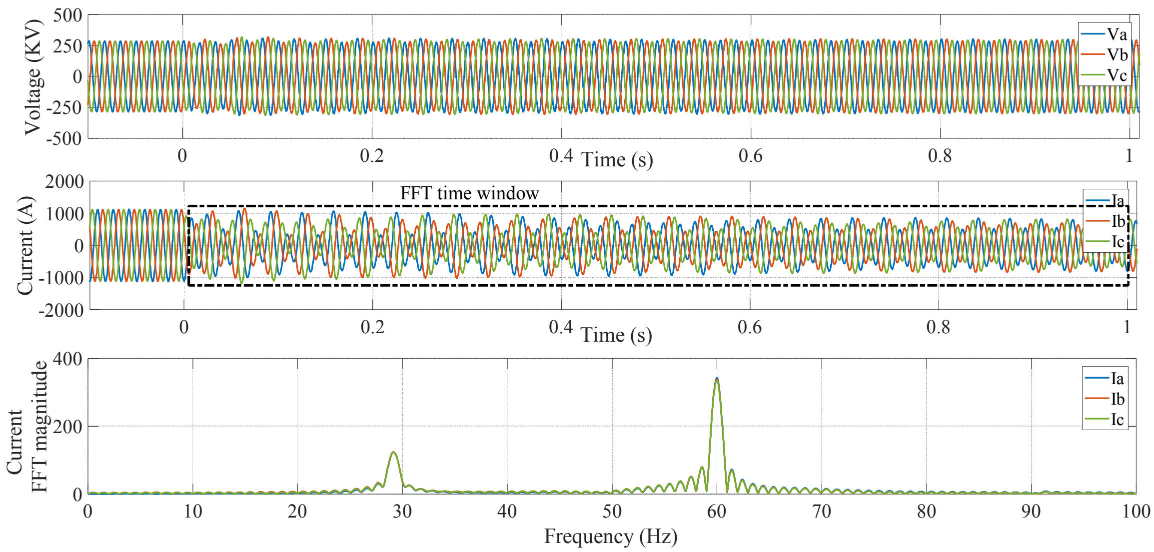

Figure 6: Event 1 simulation three-phase instantaneous voltage and current on Station 4 – Station 3 line at Station 4 after Station 4 – Station 5 trip; SSCI damping is slightly positive compared to the slightly negative damping seen in the event; FFT line current spectrum showing SSCI frequency of 29.1 Hz as compared to 27.7 Hz in Event 1 (see Figure 2).

Event and Simulation Observations

In each event, SSCI appeared immediately upon the wind plants becoming radially connected through the series capacitors. The wind plants did not trip when the SSCI was sustained but not increasing in magnitude (figures 2 and 4). Whether there is any wind plant tripping or not, SSO/SSCI events are not easily observable and may appear only as a spurious relay activation(s) if at all to operations personnel. Detection of SSO requires high resolution measurement equipment; PMUs are not suitable for detecting SSCI events. Therefore, it is possible for the distortions to persist unnoticed for some time perhaps leading to other undesired consequences.

As for the attempts at replication, it is clear that in no instance did the PSCAD simulations exactly match the SSO content of the events in sub-synchronous current magnitude and damping, and frequency of sub-synchronous current. Successful replication of the SSCI events was found to be highly sensitive to the wind plants' MW and MVAR initial outputs. In view of these sensitivities, mitigation control design would seem to require consideration of a wide range of transmission grid and wind generation project status and dispatch conditions. Inclusion of neighboring wind generation projects with similar SSCI risk in the EMT cases may further be necessary to devise SSCI mitigation. It remains unclear whether oversight of this point in the original mitigation studies is a factor in failure of the SSCI mitigation schemes. The proprietary nature of the EMT-level modeling also makes transmission planners and operators dependent on the wind machine suppliers for accurate modeling and effective SSCI mitigation.

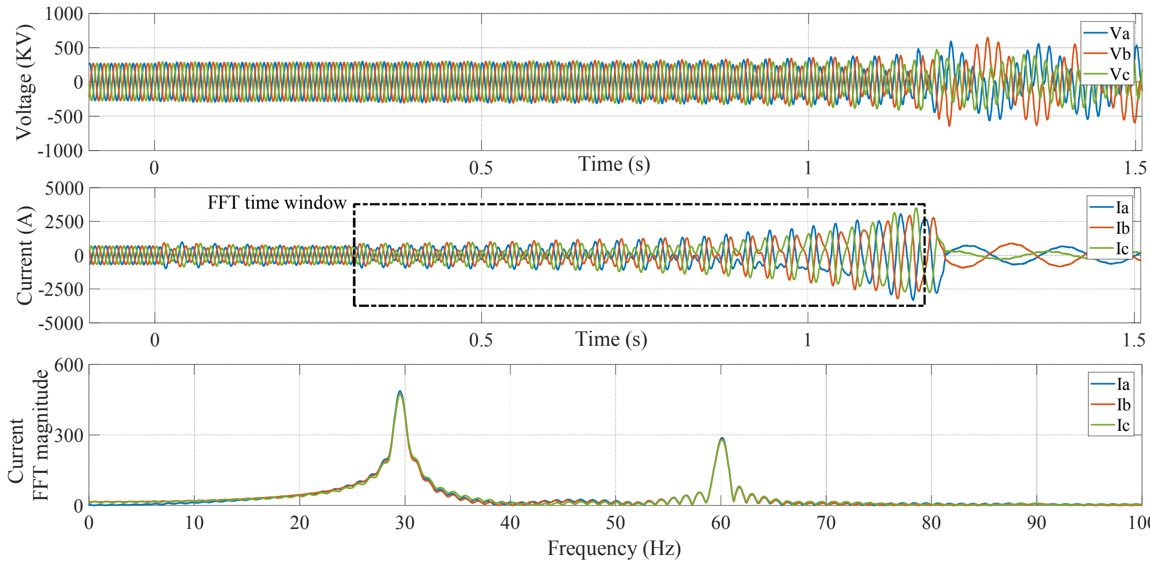

Figure 7: Event 1 simulation three-phase instantaneous voltage and current on Station 4 – Station 3 line at Station 4 after series capacitor re-insertions; SSCI distortion is close to that observed in event and wind plants 3 and 4 trip similarly in less than one second; FFT line current spectrum showing SSCI frequency of 29.5 Hz as compared to 25.6 Hz in Event 1 (see Figure 3).

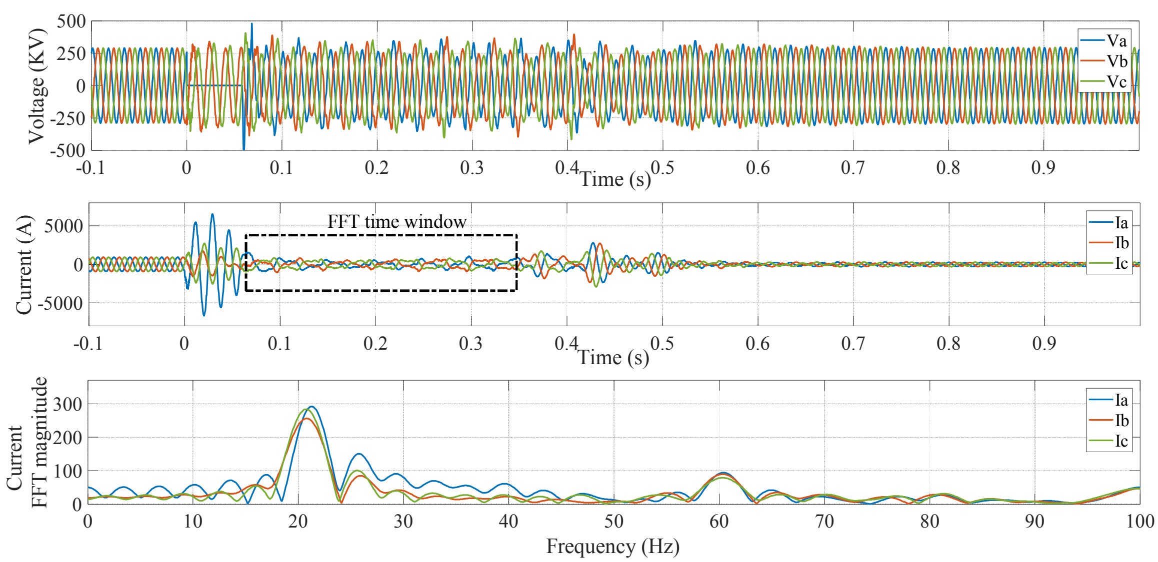

Figure 8: Event 2 simulation three-phase instantaneous voltage and current on Station 3 – Station 4 line at Station 3 showing Station 2 – Station 3 line fault and trip but successful suppression of SSCI by wind plants' 1 and 2 modeling as compared to event (Figure 4) and no tripping of wind plants 1 and 2; FFT line current spectrum showing SSCI frequency of 21.2 Hz as compared to 22.5 Hz in Event 2 (Figure 4).

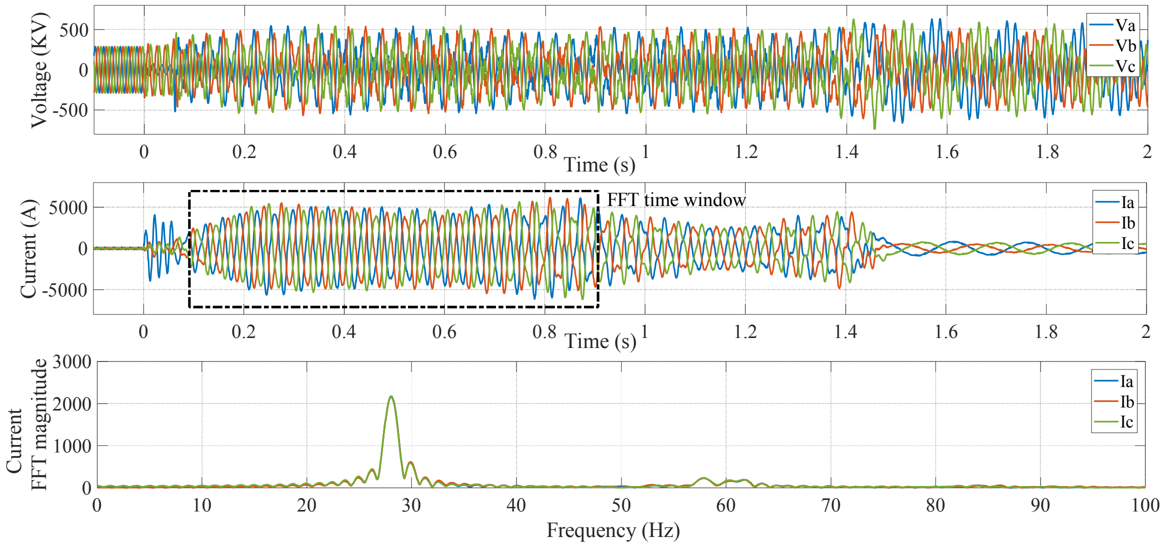

Figure 9: Event 3 simulation three-phase instantaneous voltage and current on Station 4 – Station 3 line at Station 4 after Station 4 – Station 5 line section fault and trip but greater SSCI content and unsuccessful suppression by wind plants' 3 and 4 modeling as compared to event (Figure 5) leading to their tripping; FFT line current spectrum showing SSCI frequency of 28.1 Hz as compared to 26.5 Hz seen in event (Figure 5).

Conclusions

SSCI risk was previously identified at each of the wind plants 1 through 6 of Figure 1 due to their interconnection on a series compensated transmission line and the certainty of becoming radially connected through the series capacitors during certain N-1 line section outages. In each instance, SSCI studies were completed as part of interconnection study requirements, SSCI vulnerability was identified, and mitigation was designed and implemented on site. The studies were completed and mitigation designed looking at each wind plant independently and not in concert with other adjacent wind projects. These mitigations failed to suppress SSCI as the events make clear.

As experienced in the effort to replicate the events by simulation, the SSO magnitudes, frequencies, and damping could not be replicated precisely, even after improved EMT models were made available by the wind machine manufacturers. The simulated SSO levels were also found to be sensitive to the initial wind plant MW and MVAR outputs. It is thereby understood that effective SSCI mitigation must encompass a wide range of system and wind plant conditions. It may further be necessary to consider the presence of the other nearby wind plants when analyzing SSCI behavior and designing mitigation for any one plant.

In view of the difficulties in adjusting the EMT modeling supplied by the wind turbine manufacturers to the exact pre-event MW and MVAR conditions, and the inability to match the SSO recorded frequencies, magnitudes, and damping, the EMT modeling is still believed not entirely adequate to simulate the SSCI behavior of the wind projects as recorded during the events. Work continues with the wind plant owners and manufacturers affected by these events to obtain more accurate EMT-level simulation modeling and assurance of effective SSCI mitigation.

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