Detection of subsynchronous control interaction oscillations near renewable generation and HVDC

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Abstract - With the rapid addition of the power electronics in variable forms to the power system, the probability of the oscillations in the system is increasing. This includes various types of the renewable generation, HVDC interconnections to AC system, Static Vars Compensators (SVCs), FACTS, series-compensation and others. Undetected and poorly damped oscillations lead to degradation of the power quality, probability of losing the system stability, separation and islanding, blackouts and equipment damage. Several severe system disturbances caused by the sub-synchronous control interaction (SSCI) oscillations were reported lately.

When many renewable generations plants are present in the area, it’s important to identify the plant causing oscillation and if oscillation magnitude continue increasing, then the action needs to be taken to save remaining energy resources to avoid undesirable events mentioned above. Problem is that all plants in the area start responding to the disturbance by adjusting controls, which can cause “machine-to-machine hunting” aggravating situation.

This paper is focusing on the detection of the sub-synchronous control interaction oscillations. Several field events including wind and solar renewable and HVDC as well are presented to illustrate these oscillations and detection methods based on the IED direct measurements. Also concept of ‘positive’ or ‘negative’ contributor to the oscillations is presented. This paper educates protection engineers about issues associated with the SSCI oscillations and methods to detect and mitigate the effect of oscillations.

I. Introduction

A. Australia system peculiarities with large and different IBRs scattered wide

Australia is in the midst of an energy transformation. The energy landscape is changing from largely synchronous fossil fueled generation to variable renewable energy (wind and solar) and storage solutions. The Australian Government has made a firm commitment and incentivized the transition to net zero greenhouse gas emissions by 2050. The rapid uptake and widespread integration of inverter-based resources throughout the National Electricity Market (incorporating 40,000 km of transmission lines and cables, making it one of the world’s longest interconnected power systems) has resulted in ongoing system strength and inertia level challenges. Left unmanaged, these challenges pose technical transition barriers to new renewable energy projects wishing to connect or existing renewable generators having their output constrained. The Australian Energy Market Operator (AEMO) is tasked with monitoring the power system and ensuring its security and stability.

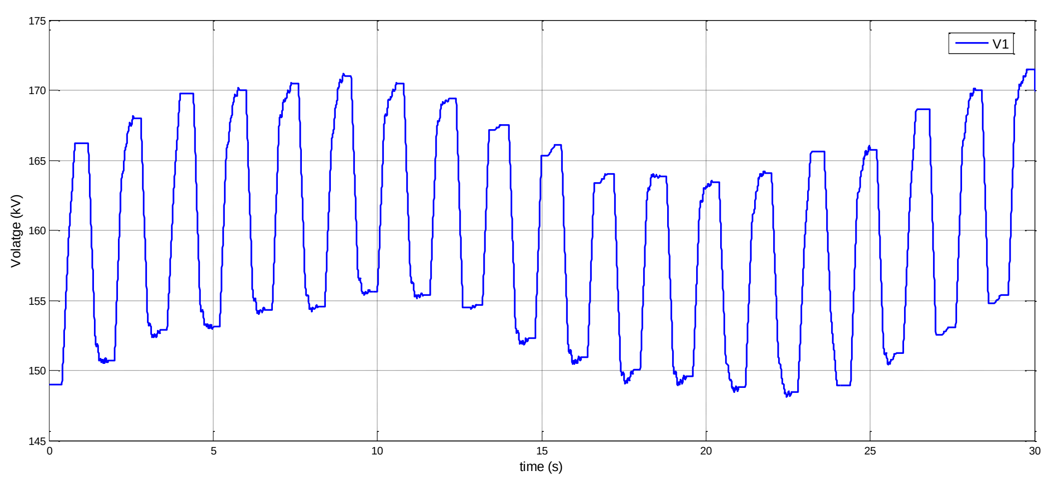
AEMO has identified and captured data of numerous intermittent and unstable power system oscillations. Some, such as the West Murray Zone (WMZ), have exposed the prevalence of oscillations in areas with low system strength and high penetration of inverter-based resources [16]. The cause of the oscillations is not always known and may not be associated with any power system disturbances. AEMO is working closely with network service providers and market participants (e.g. generators) at defining the technical requirements of a protection system for stability protection of asynchronous generation systems. The protection system implementation shall be able to detect and characterize the type of oscillation. Ideally, it should also have a mechanism for measuring the contribution of the monitored generating unit. Due to complex interactions of generating units in an area experiencing unstable oscillations, the ability to identify contribution avoids the unnecessary disconnection (or curtailment) of plant that may be assisting in alleviating instability of other generating units [17].

B. Overview of types of oscillations and danger to the system

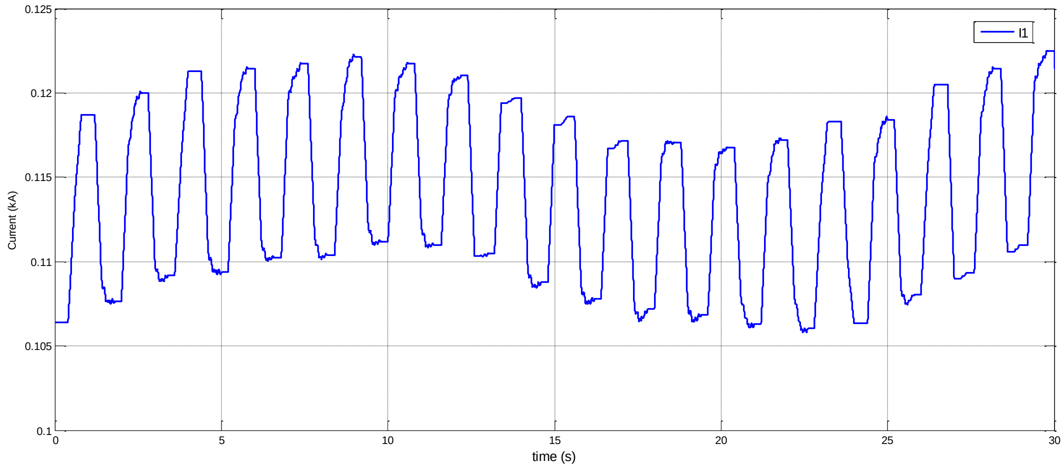
IEC defines power system stability as “The capability of a power system to regain a steady state, characterized by the synchronous operation of the generators after a disturbance due, for example, to variation of power or impedance”. Stability is the most important aspect of the power system management, where various measures are provisioned to achieve this, including system studies, real-time system state estimation, detection and isolation of the faulty element, controls to regain the new equilibrium after disturbance, synchronism restoration.

Power system oscillations are dangerous for the reliable power system operation and have to be addressed. If not addressed, it can lead to many undesirable effects on the power system operations, such as degraded power delivery quality, separation of the parts of the power system, blackouts and damage to the equipment. It can also create short- or long-term instability in the system voltage, frequency, rotor angle, converters and others.

With a rapid change in the power system related to the renewable generation, the power system stability is now one of the major concerns for the reliable operation of the power system. A lot of attention is paid to the impact of the renewable generation interfacing system via power electronics (converters) on the power system reliability. The concern is how multiple and different types of the renewable generation can interact with each other and with remaining synchronous generation to maintain system stable operation with and without disturbances. Figure 1 below depicts oscillations in positive-sequence currents and voltages phasors magnitudes recorded on the 160kV line connecting large wind farm with a system. Although oscillations are shown for the 30 seconds only for the visualization purposes, there was recorded over 300 seconds of the oscillations during this event. It can be observed that two dominant oscillation frequencies with two envelopes are present in this event, one at 6.5Hz and another at 0.5Hz.



(a)



(b)

Figure 1. Positive-sequence voltage (a), Positive-sequence current (b) oscillations on the large wind farm

System oscillations at frequencies below system synchronous frequency are referred as subsynchronous oscillations. Depending on the type of oscillations, the frequency range, how fast they evolve and long they are present in the system may be different. General description of the system subsynchronous oscillations is provided here:

- Inter-area electromechanical oscillation: slow electromechanical phenomenon of synchronous machines between different parts of system with a characteristic frequency of 0.1-2Hz.
- Forced (or control) oscillations: these oscillations can be caused by the malfunctioning control systems, incorrect stabilizer or governor control settings, incorrect DC converter settings with a characteristic frequency range of 1-20Hz.
- Subsynchronous resonance oscillations: these oscillations may occur due to interaction of the series capacitors with a type III wind power plant or due to generator torsional mode oscillations or control interactions between synchronous generators with power electronics devices (HVDC, SVC, TCSC, type IV renewable generation, with a characteristic frequency range of 10-55Hz (at 60Hz systems)

Today's power system is hosting a high penetration of inverter-based resources (IBRs) with different topologies and control strategies. From solar photovoltaics to wind turbines and beyond, these inverter-based technologies have emerged as the cornerstone of a cleaner, greener, and more sustainable future. The worldwide addition of renewable resources in the recent years has been multiple times the addition from conventional sources. For example, in 2020, the global addition of renewables has been fourfold the addition of other sources [5]. This rapid integration of the large-scale renewable resources has majorly impacted the power system dynamics, including the sub-synchronous oscillation (SSO) in power systems. SSO is not a new phenomenon. The first sub-synchronous oscillation occurred in 1970 at the Mohave generating station in South Nevada due to the interaction of a coal power plant with the capacitors of series compensated transmission lines [5]. Another subsynchronous oscillation due to the interaction of HVDC controls with a turbine generator occurred in Square Butte in North Dakota in 1977 [5].

II. Cause of oscillations with high penetration of IBRs

There are various roots of oscillations in the systems with high penetration of IBRs. The frequency of oscillations caused by IBRs varies over a wide range of a few Hz to more than 30 Hz. For example, Texas observes 4 Hz oscillations and the west region in China observes oscillations at 30 Hz [6]. The latter caused torsional interactions with a remote synchronous generator and led to shutdown of the power plant [6]. As will be shown later, this wide range of oscillation frequencies in IBRs rises from the different control loops implemented in an IBR. A typical control system of an IBR includes various control loops such as: phase locked loop (PLL), current control, voltage control, and power control. These control loops trigger various oscillation modes following a disturbance in the grid. In addition to the different control loops, the frequency of oscillations depends on the parameters and design of each control loop as well [6]. These issues will be explained later in more details. Based on the causes of oscillation, the oscillations occurring in systems with high penetration of IBRs can be divided into three major categories explained below.

1. Induction generator effect (IGE): Following a disturbance in a series compensated network, the subsynchronous currents in the stator of a rotating machine will create a rotating magnetic field at the same frequency. Since the rotor of the machine is rotating at or near the synchronous speed, the effect of the rotating magnetic field on the rotor's circuit will be similar to an induction machine in a generator mode with negative slip which results in the rotor's resistance, as seen from the armature terminals, to become negative [7]. If this negative resistance exceeds the sum of the armature and network currents, the total resistance will be negative. This results in a self-excitation effect which is termed as the IGE [5]. Inverter-based resources with rotating machines, such as the type IV wind turbines, when connected to series compensated transmission lines, may result in the IGE.

2. Subsynchronous torsional interaction (SSTI): SSTI involves electrical and mechanical dynamics of the system. Following a disturbance in the power system, the turbine generator shaft oscillates at its torsional natural frequencies, and therefore, induces armature voltage components [5]. The Torsional frequencies of the shaft are generally known and can be obtained from the manufacturer sheet of the generator [8]. On the other hand, the electrical network containing series-compensated transmission lines has its own natural frequency of oscillation. The natural frequency at which the network oscillates depends on various factors, such as the network configuration at a particular time and the level of series compensation in the transmission lines [8]. When the subsynchronous voltage components induced on the armature have a frequency close to the natural frequency of the electrical network, a rotor torque will be produced [5]. If the produced subsynchronous torque component is equal to or exceeds the inherent damping of the system, a self-excitation can occur. This is termed as SSTI.

3. Control System Interactions (CSI): The performance of IBRs is dominated by their control system and the strategy used to interface the IBR's energy source to the electric grid [9]. The control system of an IBR is composed of various control loops, e.g., current control, voltage control, power control, and phase-locked loop (PLL). To better understand the effect of the IBRs' control loops on the subsynchronous oscillations, this section briefly introduces the typical control structure of an IBR and how its different control loops interact with each other.

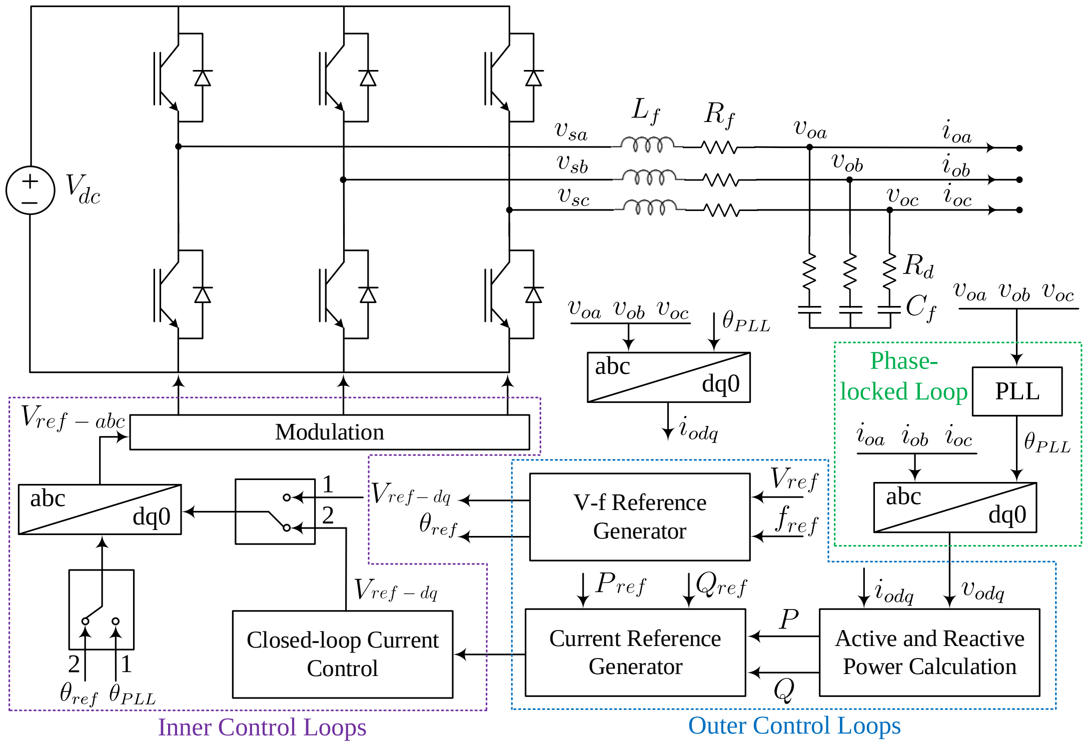


Figure 2. Typical IBR control system

Figure 2 illustrates the typical circuit of an IBR with its control system [9]. This structure is composed of two main parts, i.e., a power part and a control part. The power part includes the dc bus, the power electronic switches, and the inverter's LC filter which is then connected to the grid. The control part is composed of three components, i.e., Phase-locked loop (PLL), outer control loops, and inner control loops. PLL is the synchronization unit of an IBR which detects the angle of the grid's voltage and calculates the proper phase shift of the inverter's current, so that the reference active and reactive currents are generated. Furthermore, it provides the transformation angle for the transformation of the three-phase signals to their corresponding synchronous reference frame counterparts. PLL is currently the most dominant synchronization scheme used in the IBRs in practice [9]. Another part of the control system in a typical IBR is the outer control loops. This part includes the control functions such as active power control, voltage/reactive power control, and ride-through functions [9]. The outer control loops provide the reference currents for the inner current control loops. Typically, the outer control loops are much slower than the high-bandwidth inner control loops. The inner current control loops control the active and reactive currents generated by an IBR so that the inverter tracks the reference currents generated by the outer control loops. The close-loop current control is the fastest control loop of an inverter.

A small-signal analysis of the inverter's control system, performed by [6], shows that there are two oscillation modes regarding the control system of an IBR. One has a frequency lower than 10 Hz, termed as the low-frequency oscillation, and another has a frequency higher than 20 Hz, termed as the subsynchronous-frequency mode. It has been shown in [6] that the inverter's control parameters determine the frequency of oscillation and which of the low-frequency oscillation or the subsynchronous-frequency modes are dominant. For instance, different PLL parameters result in different oscillation frequencies for the IBR. When the PLL bandwidth is low, the low-frequency oscillation mode is dominant while for a high-bandwidth PLL, the subsynchronous-frequency mode dominates the IBR's oscillation [6]. Furthermore, the analysis in has shown that the subsynchronous mode is related to the dc-link dynamics and the PLL, while the low-frequency oscillation mode is related to the PLL and the ac voltage control. In summary, an IBR's control system may impose two oscillation frequencies, i.e., low-frequency and subsynchronous frequency modes. Furthermore, an IBR's dominant oscillation mode and the frequency of that oscillation depends on the inverter's control parameters [6]. These findings are in-line with the oscillations observed in the real-world instances of systems with high penetration of IBRs. For example, as stated earlier, the frequency of oscillations in Texas and west region in China are 4 Hz and 30 Hz, respectively [6].

IBR Technology	**Type 3**	**Type 4**	**Solar PV**	**Frequency of oscillation**
SSR	✓	✓	✓	10 Hz to 55 Hz
IGE	✓	X	X	10 Hz to 55 Hz
SSTI	✓	X	X	1 Hz to 4 Hz [10]
CSI	✓	✓	✓	Two modes: <10 Hz and >20 Hz [6]

Table 1. Correlation between renewables sources and oscillation types.

The existing dominant technologies installed for renewable resources can be divided into solar photovoltaics (PVs), type III, and type IV wind turbines. Among these three categories, type III wind turbines, also known as doubly fed induction generators (DFIGs) employ rotating induction machines. The other two technologies have no rotating part and both use full-scale voltage source converters (VSC) [6]. Therefore, among the oscillations discussed above, the IGE and SSTI do not occur for type IV and solar PVs. Table 1 summarizes the types of oscillations that can occur in each IBR technology.

Conventional generators have an inherent damping torque which is mainly affected by the machine design parameters and generator loading. Damping torque of the synchronous generators is provided by the rotor windings, i.e., the damper windings and the field winding of the rotating masses. This inherent feature of these conventional sources dissipates the energy of the system oscillations and therefore positively contributes to damp the oscillations. In addition to the rotor's damper windings, the application of power system stabilizers (PSS) can significantly enhance the damping of the synchronous generators [1].

The SSO damping mechanisms of IBRs are naturally different than those of the synchronous generators. IBRs' damping mechanisms are based on implementing a specific controller in the inverter's control system. For instance, [18] designed an auxiliary SSR damping controller based on the classical lead-lag compensators as a supplementary controller to the active power control loop of the energy storage systems. During normal conditions, the controller is deactivated, while during oscillations, the controller compensates the frequency deviations of the generator rotor speed. In this damping mechanism, wide area measurement system (WAMS) were used to collect the information from the synchronous generator. As another example, a control-based damping mechanism to deal with the SSR oscillations in a series-compensated DFIG-based wind farm was introduced in [19]. In this method, a proportional SSR damping controller is designed so that the SSR mode becomes stable while the other system modes are not decreased or destabilized.

III. Detection of the oscillations, damping and contributors

A. Bands of different oscillation types

With the integration of renewable energy sources and a variety of power electronics in recent years, the dynamics of power systems have become more complex, which brings new challenges to power system operations. Among them, subsynchronous oscillations caused by the interaction between renewable energy sources and various components of the power grid stand out as a significant concern. The frequency of the subsynchronous oscillation can vary in a wide range depending on the causes as well as the network configuration at the time, therefore it is important that the oscillation detection functions can be applied over a wide frequency spectrum, potentially with multiple oscillation frequencies. This is particularly vital to ensure that the detection function can be easily configured, where engineers would then only be required to choose a frequency range, rather than having to precisely define the expected oscillation frequency.

The Multi-range Signal Oscillation Detection (MSOD) function [4][11] consists of 4 distinct frequency bands (Band I: 0.01-0.1Hz, Band II: 0.1-1Hz, Band III: 1.0-10Hz, and Band IV: 10-55Hz), and uses a set of digital filters to extract the oscillating signal from the input quantity, which can be easily configured and used to detect oscillation phenomena triggered by various causes, including geomagnetically induced currents (GIC), inter-area or local plant oscillations, forced oscillations, subsynchronous oscillations, etc. The block diagram in Figure 3 below shows the overview of the MSOD algorithm, where voltage, current RMS magnitudes (phase or symmetrical components), 3 phase real-power or reactive power are used as the input signals for Band I-III detectors to detect lower order frequency (up to 10Hz) oscillations; voltage and current instantaneous samples are used as the input signals for Band IV detector to detect higher-order frequency (10-55Hz) oscillations.

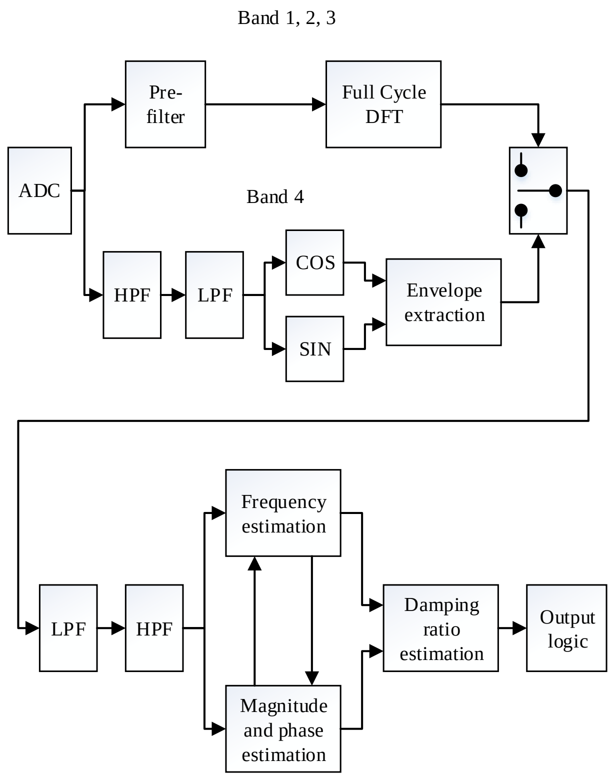


Figure 3. Block diagram of the MSOD algorithm

As shown in Figure 3, for Band I-III, the input signals are pre-filtered magnitude of V/I/P/Q signals, where elements beyond the designated frequency range—such as high and low frequency noises, especially the DC component—are eliminated, so that the final signal to be used for oscillation detection only contains the "ac" part with the frequency band of interest. For Band IV, since the input signals are instantaneous samples, additional operations are performed to extract the oscillation envelope first.

B. Oscillation and damping detection

The MSOD algorithm removes the fundamental frequency component from the operating quantity. The remaining oscillating signal is processed using zero crossing method to estimate the oscillation frequency which is then used in a feedback loop to allow the calculation of the oscillation signal magnitude. Both the frequency and the magnitude of the oscillation is used to calculate the damping ratio of the signals using the approach described below.

The oscillation signal can be expressed as a sinusoidal signal with a modulated magnitude:

$$y(t) = \sqrt{2}A(1 + m \cdot e^{\sigma(t-t_0)} \cdot sin\ (\omega_m(t - t_0)) \cdot u(t_0)) \cdot sin\ (2\pi f_1 t) \quad (1)$$

Where A is the magnitude of the signal, f_1 is the system frequency, ω_m is the angular frequency of the modulating signal, σ is the exponential change rate of the modulating signal and $u(t)$ is the step function indicating the start of the oscillation. The damping ratio of the signal is defined as:

$$\xi = \frac{-\sigma}{\sqrt{\sigma^2+\omega_m^2}} \quad (2)$$

With the above, the damping ratio can be calculated if two distinct points on the exponential curve are known:

$$Z = \frac{\ln(\frac{y_1}{y_2})}{\omega_m \cdot (t_2 - t_1)} \quad (3)$$

$$\xi = \sqrt{\frac{Z^2}{Z^2+1}} \quad (4)$$

Where y_1 and y_2 are the oscillation magnitudes recorded at t_1 and t_2, respectively.

When σ is a negative number, the damping ratio ξ becomes positive which means that the oscillation is positively damped where the magnitude of oscillation decreases over time. Conversely, if σ is a positive number, the damping ratio ξ turns negative, indicating a negatively damped oscillation where the magnitude of oscillation increases with time.

C. Detecting of Positive or Negative Contribution

1. Positive or negative contributor

With a high concentration of inverter-based resources (IBRs) and large electrical distances from synchronous machine, power systems are prone to instabilities due to lack of available system strength. These instabilities could manifest themselves in different forms. In recent years, the National Electricity Market (NEM) of Australia has experienced sustained post-disturbance voltage oscillations in several regions of its grid. An analysis performed by the Australian Energy Market Operator (AEMO) has concluded that all such oscillations can be attributed to subsynchronous interactions among closely situated IBRs [12].

Renewable generation is injecting reactive power during voltage deviation to support system voltage during disturbance. The change of the injected reactive current and eventually reactive power can be approximated by the following equation:

$$\Delta I_Q = k \cdot \Delta V_S \quad (5)$$

where ΔI_Q is the change of the output reactive current, ΔV_S is the change of the measured system voltage and k is reactive compensation parameter. It should be noted that the change of the output reactive current can be positive (injection of the reactive power) or negative (absorption of the reactive power) depending on the change of the system voltage.

Figure 4 below illustrates in a simplistic way the impact of the output reactive power Q_{OUT} being in phase or out of phase with a system voltage V_S, where both voltage and reactive power are oscillating at the $f_{OSC}=1/T_{OSC}$ oscillation frequency.

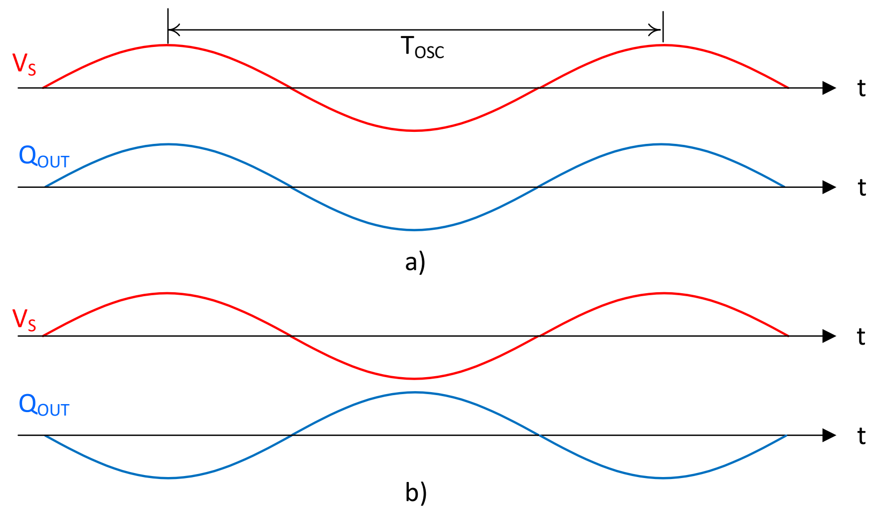


Figure 4. a) Phase of the output reactive power Q_{OUT} is in phase with system voltage V_S, b) Phase of the output reactive power Q_{OUT} is out of phase with system voltage V_S

In general, change of the voltage on the bus connecting renewable generation plant is proportional to the injection/absorption of the output reactive power, can be defined by:

$$\Delta V \propto \frac{\Delta Q_{OUT}}{Q_{SC}} \times 100\% \tag{6}$$

where Q_{SC} is 3-phase system short circuit MVA at the plant location

If at the positive peak of the oscillation voltage, the reactive power is also approximately at positive peak (in phase) as shown in the Figure 4a, it means reactive power contribution has negative effect and is accelerating oscillation as plant is trying to increase the bus voltage. On the contrary, when oscillation voltage is at positive peak, but reactive power is at negative peak (out of phase) as shown in the Figure 4b, the reactive power contribution has positive damping effect.

Because there are inherent delays in the voltage measurements and changing the IBR reactive control and oscillation frequency being at wide range, it's difficult to predict and adjust controls to always have a damping effect for renewable generation. However, detection of positive or negative contribution can help in mitigating oscillation by increasing or reducing certain plants outputs or disconnecting plants causing sustained oscillations.

Based on the description above, a new method has been proposed in [12] to determine whether the IBR is a positive contributor or a negative contributor by comparing the angle difference between the reactive power injected by the IBR and the phase of the voltage oscillation.

- For a positive contributor, the reactive power oscillations introduced by the IBR exhibit an approximate out-of-phase difference from voltage oscillations. This implies that a voltage increase results in a decrease of the IBR's reactive power reaction, and vice versa, which assists in mitigating voltage oscillations at the plant side.

- For a negative contributor, the reactive power injected by the IBR varies almost in phase with voltage oscillations. This means that with increasing voltage magnitude the reactive power also increases, and vice versa which exacerbates voltage oscillations.

Based on the above suggested approach, AEMO further demonstrated how the phase angle difference between voltage measured at the connection point and reactive power from a generating system could be used as a foundation for evaluating whether the generating system is damping or exacerbating voltage oscillations. The ability to differentiate between power plants that dampen these oscillations and those that amplify them would aid in prompt interventions to prevent adverse impacts on the power system or the generating system.

2. Oscillation detection contributor implementation

To incorporate the above suggested new approach with V-Q angle checking into the MSOD algorithm, the reactive power needs to be calculated first. As described in the block diagram of the MSOD algorithm in section III.A, for Band I-III, the input signals include the RMS magnitude of voltage and 3 phase reactive power, so there are no difficulties to apply this new approach. But for Band IV, since the input signals are instantaneous samples, we need to calculate reactive power in time-domain.

A method described in [13] defines a way to calculate instantaneous real and reactive power based on direct (d) and quadrature (q) coordinates, as shown below:

$$P = V_d I_d + V_q I_q \quad (7)$$

$$Q = V_d I_q - V_q I_d \quad (8)$$

In which V_d, V_q and I_d, I_q are the voltages and currents in d-q coordinates.

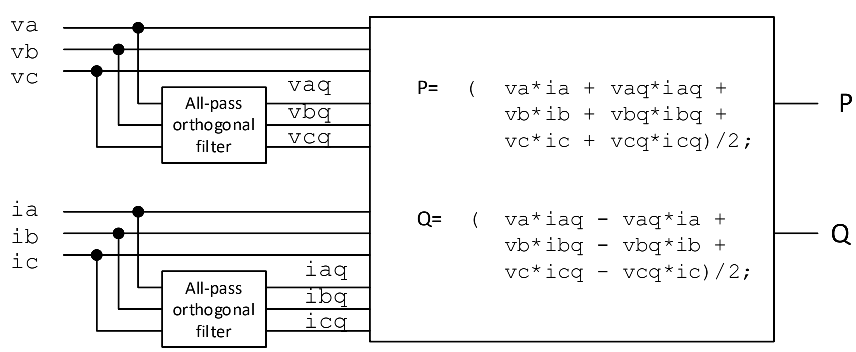


Figure 5. Instantaneous 3-phase real power and reactive power calculation via d-q coordinates

The d-component can be obtained by using the original samples directly, but the q-component needs to be calculated separately, where its phase must be shifted by +90 degrees from the d-component. In our MSOD implementation, an orthogonal all-pass filter has been used to shift the phase of the original samples by +90 degrees at the nominal frequency, at the same time, pass all frequencies equally in gain without any attenuation. The magnitude and phase frequency response of this orthogonal filter is shown in Figure 6.

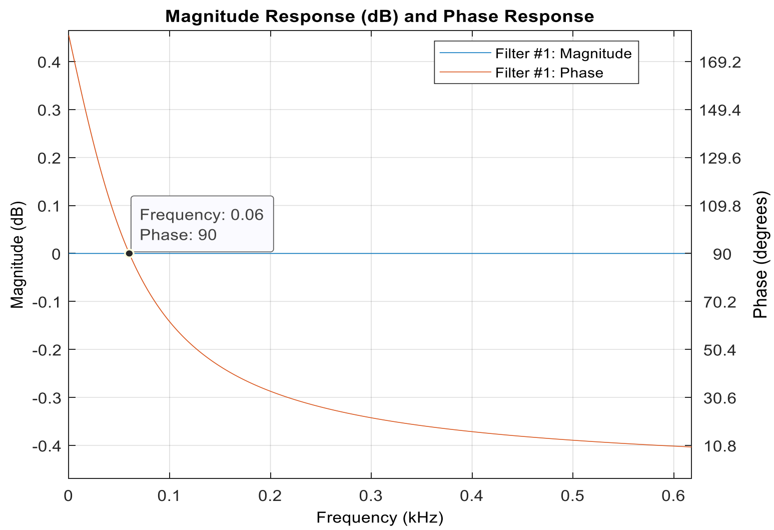


Figure 6. Magnitude and phase frequency response of the orthogonal all-pass filter

IV. Field oscillation cases

Several field cases from Australia, involving renewable generation were analyzed to validate oscillation detection algorithm.

A. Australia HWF and PAREP sites

On June 23, 2023, two renewable sites within the National Electricity Market (NEM) grid of Australia, namely HWF and PAREP, experienced a sustained oscillation of approximately 6.25Hz following a disturbance.

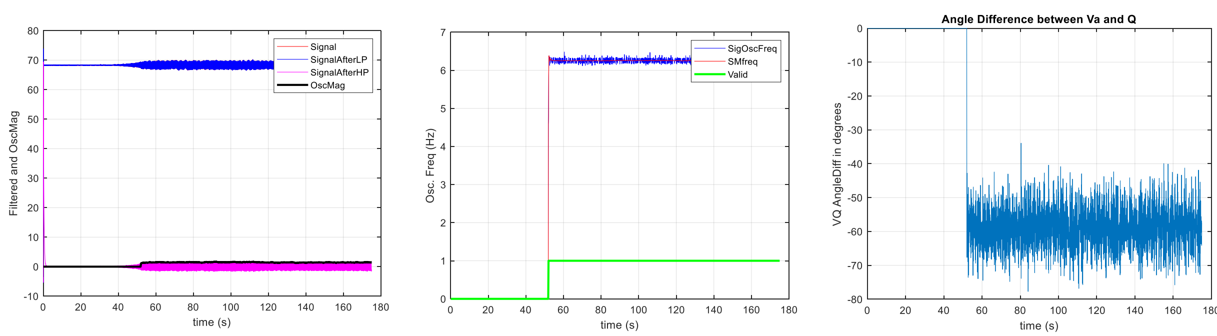


Figure 7. Analysis Result for the Oscillation at HWF Site: Left-Oscillation Input Signal Va Magnitude, Middle-Oscillation Frequency Detected ~6.25 Hz, Right-Angle Difference between V and Q

The phase relationships between V-Q of these two sites are shown in Figure 7 and Figure 8 respectively, in which site PAREP was more in phase (at average -23 degrees) compared to site HWF (at average -60 degrees).

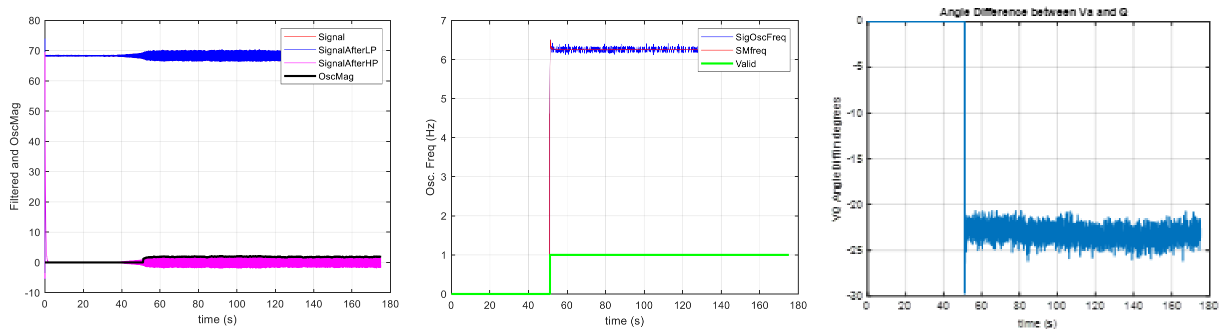


Figure 8. Analysis Result for the Oscillation at PAREP Site: Left-Oscillation Input Signal Va Magnitude, Middle-Oscillation Frequency Detected ~6.25 Hz, Right-Angle Difference between V and Q

As such, site PAREP was identified as a bigger contributor to the oscillation, while site HWF exhibited a much lesser impact to the oscillation.

B. YARRANLEA solar farm

An oscillation event occurred on June 8, 2020, subsequent to the outage of one of the two 110kV Feeders. These feeders were linked to two solar plants, namely Yarranlea Solar Farm (YSF) and Maryrorough Solar Farm (MSF). Notably, Yarranlea Solar Farm has documented this oscillation, and MSOD analysis results are shown in Figure 9 below.

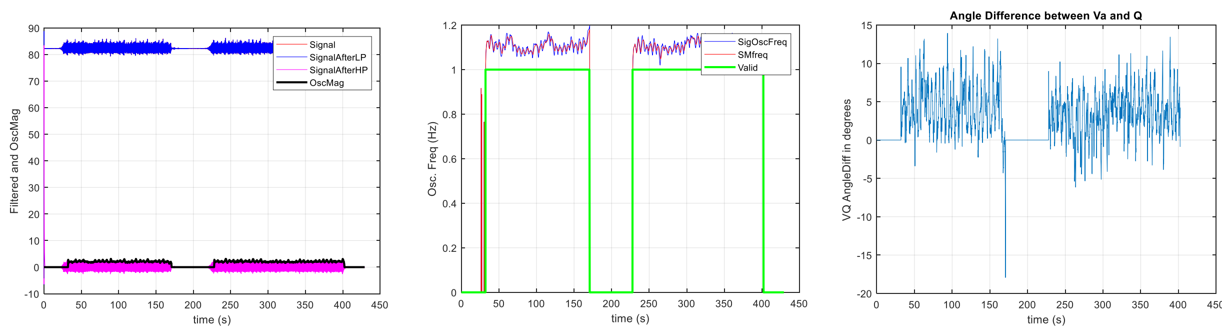


Figure 9. Analysis Result for the Oscillation at Yarranlea Solar Farm Site: Left-Oscillation Input Signal Va Magnitude, Middle-Oscillation Frequency Detected ~1.1 Hz, Right-Angle Difference between V and Q

From the MSOD analysis results, it can be seen that this is a sustained (not damped) post-disturbance voltage oscillation at approximately 1.1 Hz. The phase relationship between V-Q in Figure 9 indicated this site (YSF) was a very strong contributor to the oscillation because the V-Q angle almost in phase.

C. HVDC case

High Voltage Direct Current (HVDC) installations can impact the behavior of the power system as far a stability is concerned. Depending on the control algorithms of the HVDC link, the technology used and the network topology the link can improve or degrade the stability of the complete system. When considering the impact of HVDC link on the network stability it is important to take into account not only the current topology but also any future extensions to the network.

It is recognized that HVDC installations can be responsible for subsynchronous torsional interactions (SSTI) [14]. This is mostly applicable to the Line Commutated Converters (LCC) operating in rectifier mode where the adverse effect is caused by the subsynchronous currents injected by the converter. The biggest risk of STTI is linked with HVDC installation connected to steam turbine generators by a short, radial line. When evaluating the risk of STTI it is important to assess whether the generator can be considered nearby. This is usually done by using the Unit Interaction Factor (UIF). The method defines UIF=0.1 as a threshold for the generator to be in the vicinity of the HVDC installation. UIF can be calculated using the following equation:

$$UIF_i = \frac{MW_{HVDC}}{MVA_i}\left(1 - \frac{SC_i}{SC_{tot}}\right)^2 \quad (9)$$

Where:

UIF_i: Unit interaction factor of the i:th unit (generator/machine)

MW_{HVDC}: MW rating of the HVDC system

MVA_i: MVA rating of the i:th unit

SC_i: Short circuit capacity at the HVDC connection point excluding the i:th unit

SC_{tot}: Short circuit capacity at the HVDC connection point including the i:th unit.

If UIF is close to the threshold of 0.1 for any generator, in any topology, then additional measure must be taken to prevent the oscillations. The most common approach is to implement a dedicated Subsynchronous Damping Controller function (SSDC). The SSDC is responsible for providing a positive damping to oscillations in a subsynchronous frequency bandwidth associated with the nearby generators, typically in the range of 15-40 Hz. The output of the function is provided as a feedback loop to the main scheme current control loop.

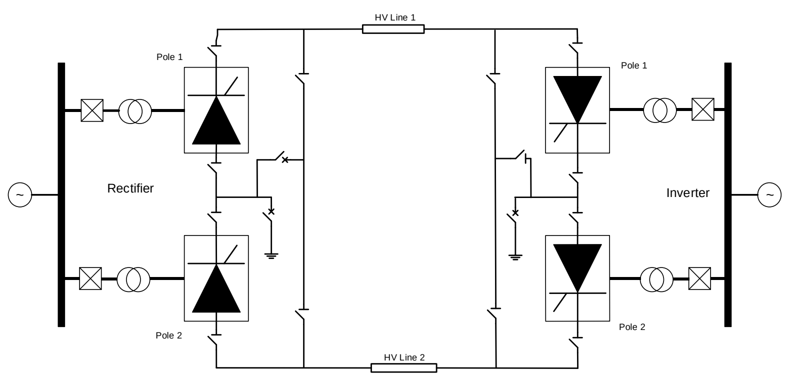


Figure 10. HVDC installation with SSDC function enabled

This subsynchronous oscillation event was obtained from one of the bi-pole HVDC installations as shown in Figure 10, in which a Subsynchronous Damping Controller function (SSDC) was incorporated into the HVDC control system.

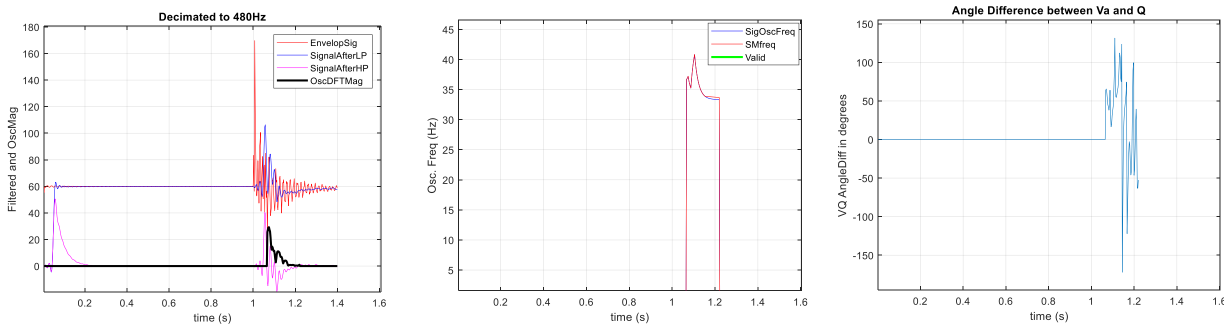


Figure 11. Analysis Result for the Oscillation at HVDC Site: Left-Oscillation Input Signal Va Magnitude, Middle-Oscillation Frequency Detected ~35 Hz, Right-Angle Difference between V and Q

The MSOD analysis results presented in Figure 11 revealed that this subsynchronous oscillation occurred at approximately 35Hz. The SSDC acted quickly which increased the damping ratio and resulted in the oscillation amplitude reducing rapidly. The phase relationship between V-Q shown in Figure 11 indicated that this HVDC site was not a big contributor to the oscillation because the V-Q angle was quite large (at 50 to 100 degrees range) following the commencement of the oscillation.

V. Conclusions

Subsynchronous oscillations is not a new phenomenon in the power system and were presenting challenges even with a conventional synchronous generation. The range of oscillation frequency can be very wide, from 0.1Hz to near system nominal frequency. Depending on which power system components are oscillating against each other, the dominant oscillating frequency can vary and oscillations can occur faster or slower. In conventional synchronous generation the damping of the subsynchronous oscillations in conventional synchronous system are well understood and damped by means of the synchronous machine inherent characteristics and power system stabilizers (PSSs).

With the fast deployment of the renewable generation of the different types and with power electronics converters and their controllers, the issue of the subsynchronous oscillations and their mitigation is becoming even more important, because new sources and modes of oscillations are added to the existing ones.

Detection of subsynchronous oscillations and detection of the contributors to these oscillations is essential to ensure reliable operation of the power system.

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VII. Bio

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