UTILISATION OF SYNCHRONOUS CONDENSERS FOR IMPROVED DAMPING IN POWER SYSTEMS WITH HIGH RENEWABLE PENETRATION

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Abstract

With ever increasing variable renewable energy (VRE) and subsequent displacement of conventional synchronous generation (CSG), system strength and inertia have been steadily declining in power system grids around the world. A mitigation to the aforementioned problem is installation and operation of synchronous condensers (SC) for provision of system strength and inertia.

While the synchronous condenser is a mature and proven technology, the technology has not been fully utilised, particularly in its ability to provide additional damping to system inter-area modes via Power Oscillation Damper (POD) controllers. Synchronous condensers can provide inertia and modulation of terminal reactive power and voltage (via the excitation system) to impact the system power flows such that it can provide a positive contribution to system damping.

This paper examines the implementation of a synchronous condenser in conjunction with a POD, in a network with high renewable generation, to dampen inter-area modes. Firstly, we investigate a method to determine the ideal location and monitoring Bus of a synchronous condenser, for damping of inter-area modes. Subsequently, the inertia time constant and POD settings are optimised to provide adequate modulation of the SC terminal voltage and reactive power for increased damping of inter-area modes. Finally, large and small-signal disturbances are considered with and without the POD to demonstrate the device effectiveness.

1 Introduction

Australian Energy Market Operator (AEMO) has recently stated that the National Electricity Market (NEM) grid is being transitioned to be capable of operating at 100% instantaneous penetration of renewable energy by 2025 [1].

Due to such large and aggressive renewable generation targets, the system strength is progressively getting weaker. One effective way of increasing the system strength and inertia has been through the installation of SCs.

However, SCs previously installed in the NEM have not been used for damping purposes. Traditionally, SCs have not been equipped with Power System Stabilisers (PSS) due to their lack of ability to dampen the respective local mode. Thus, in this study we investigate the feasibility of equipping SCs with PODs to dampen inter-area modes. To assess the system stability, we employ the IEEE 39 Bus New England Network (NE) in PowerFactory, and demonstrate that the tuning of PODs for SCs can improve damping of inter-area modes.

The aim of this paper is to utilise the IEEE 39 Bus NE Network in PowerFactory and demonstrate that tuning of PODs for SCs can help improve damping of the inter-area modes.

1.1 Existing 39 Bus New England Network

The IEEE 39 Bus NE Network is a publicly available system model. The model consists of 10 generators, 19 loads, 34 lines and 12 transformers. Generator G01 is an equivalent machine that represents the inter-connectors to NYISO and Canada. Generator G02 is selected as the swing node with all other generators dispatched according to their active power and voltage set-points. The network model is demonstrated in Fig. 1. It is worth noting for the purpose of this analysis that the PSS devices on all the existing generators are out of service, due to a lack of information on the PSS lead-lag blocks.

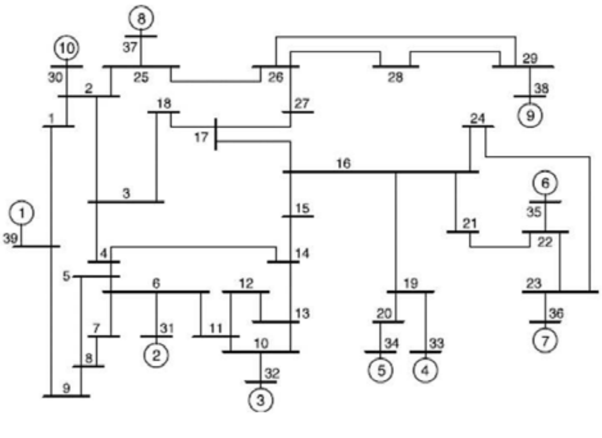

Fig. 1. The New England 39 Bus Model [2].

2 Addition of PV Plant and Synchronous Condenser Sizing

2.1 *PV Plant Displacement of Synchronous Machines*

In order to emulate the renewable generation displacement of conventional synchronous generation, generator G05 (300 MVA) is replaced with a 990 MVA Photovoltaic plant (generator PV01). Similarly, Generator G06 (800 MVA) is replaced with a 1210 MVA PV plant (generator PV02).

The PV inverters are stepped up via 16.5/0.69 kV transformers, connecting to the same Bus, with the generator being replaced. The PV plants are dispatched with the same active and reactive power to maintain the identical power flows and voltages. The PV inverter controls are represented by the generic grid-following WECC PV models (REGCA1 and REECB1).

2.2 *Synchronous Condenser Sizing*

The addition of large PV plants requires the addition of SCs such that the Short-Circuit Ratio (SCR) at the inverter terminal is sufficient to operate correctly. For the intent of this study, it has been assumed that for the PV inverters to operate correctly, a minimum SCR at the inverter terminals of 2.4 is required.

Therefore, a 300 MVA synchronous condenser is included at Bus 20 to facilitate system strength for PV01. Similarly, a 230 MVA synchronous condenser is included at Bus 22 to increase the SCR at PV02 inverters.

The SC machine, transformer and AVR models and corresponding parameters are based on practical examples of operating machines in the NEM network (machine MVA was scaled accordingly to achieve system strength). It is worth noting that the machine unsaturated sub-transient d-axis impedance (Xd”) is 0.135 pu, open-circuit transient d-axis time constant (Tdo’) is 10.5 seconds and inertia constant is 1.92 seconds (no flywheel is considered in this analysis). The AVR and excitation systems are based on the IEEE static excitation system ST6C [3].

2.3 *Critical Fault Clearing Time Assessment*

The replacement of the conventional synchronous generation, with grid-following VRE generators, resulted in a reduction of the equivalent system inertia. The reduction of the equivalent system inertia could have an impact on critical fault clearing times (CFCT); the equivalent synchronous machine inertia time constants are summarised in Table 1.

Table 1 Equivalent System Inertia.

System Scenario	Total Inertia (s)
Original NE 39 Bus network	4.58
NE 39 Bus network with PVs	4.03
NE 39 Bus network with PVs and SCs	4.51

Additionally, the installation of SCs has helped recover the CFCTs to the values calculated in the original IEEE 39 Bus model (i.e. prior to the addition of solar farm generators PV01 and PV02).

The CFCT assessment was carried out on Line 15-16 and Line 16-17 by applying faults, and subsequently clearing them by tripping the faulted line. Table 2 summarises the CFCT results. Case 1 refers to the original network prior to the replacement of G05 and G06 with PVs, Case 2 refer to the scenario where G05 and G06 are retired and PV01 and PV02 are added, while Case 3 represents the addition of SC1 and SC2 for system strength purposes.

Generally, it was observed that the CFCT is recovered by the installation of SCs.

Table 2 Critical Fault Clearing Time Assessment.

Fault location	CFCT (ms)		
	Case 1	Case 2	Case 3
Bus 15 on Line 15-16	390	360	420
Bus 17 on Line 16-17	250	220	250

2.4 *Eigenvalue Assessment*

Eigenvalue analysis was conducted to demonstrate that the overall damping of modes in the network is not significantly reduced by the replacement of synchronous plants with PV generators and synchronous condensers.

Fig. 2 demonstrates the results of modal analysis. The original NE 39 Bus model modes are presented in blue. The red modes represent the NE 39 Bus network with generators G05 and G06 replaced with PV01 and PV02, whilst the green modes represent the network where SC1 and SC2 are installed for system strength purposes. The results indicate that the overall damping of the modes in the network are generally recovered.

One mode of significant importance is the inter-area mode between generator G01 (NYISO/Canada inter-connector) and generators G03, G05, G06, G09 and G10. The frequency of the mode is approximately 0.67 Hz with a damping ratio of 5.7% in the original network (0.72 Hz and damping ratio of 5.69% upon installation of SCs). The SC PODs will attempt to increase the damping of this mode, as discussed in the ensuing sections.

2.5 *Time Domain Assessment*

Time domain analysis was conducted to demonstrate that the provision of SC1 and SC2 recover the inter-area mode damping close to the original values.

In order to excite the aforementioned inter-area mode at around 0.7 Hz, the outage of Line 01-39 and Line 09-39 are simulated. This forces the active power to flow from the NYISO/Canada inter-connector along the remaining line and excite the mode in question.

Fig. 3 demonstrates the active and reactive power flows on Line 09-39 upon disconnection of Line 01-39. Generally, it is observed that the damping of the inter-area mode in question

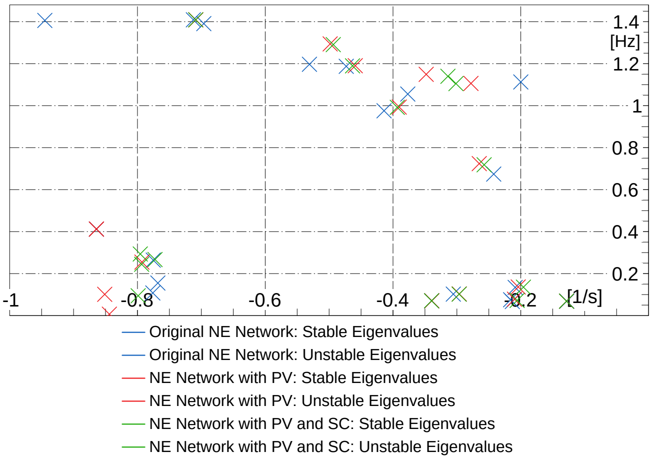

Fig. 2 Eigenvalue analysis of original NE 39 Bus model (blue) vs NE 39 Bus model with PVs (red) vs NE 39 Bus model with PVs and SCs (green; no PODs).

is the same in the original network and the case where generators G05 and G06 are replaced by solar farms PV01 and PV02 (including synchronous condensers SC1 and SC2).

Similar results are observed for tripping of Line 09-39 and monitoring the response on Line 01-39 (see Fig. 4).

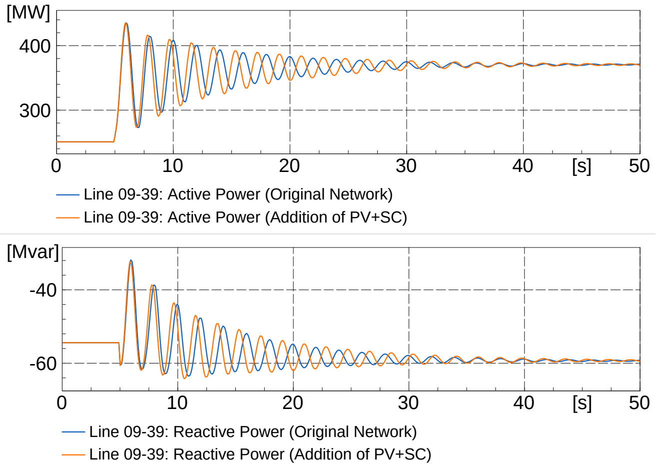

Fig. 3 Outage of Line 01-39; original NE 39 Bus model (blue) vs NE 39 Bus model with PVs and SCs (orange). Active and reactive power flows on Line 09-39.

Based on the analysis carried out in this section (system strength, CFCT, eigenvalue and small disturbance tests), synchronous condensers SC1 and SC2 were shown to be sized correctly. Specifically, the network stability margins (i.e. eigenvalue damping and CFCTs) were recovered upon the replacement of existing synchronous generators G05 and G06 with solar farms PV01 and PV02 and the respective SCs.

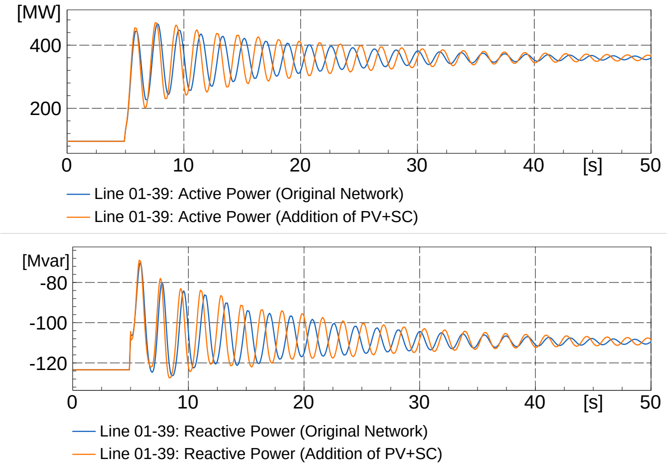

Fig. 4 Outage of Line 09-39; original NE 39 Bus model (blue) vs NE 39 Bus model with PVs and SCs (orange). Active and reactive power flows on Line 01-39.

3 Improvement of Power Oscillation Damping via Synchronous Condenser Excitation Control

Typically synchronous generators are equipped with PSSs to dampen the machine local mode. The damping of the local mode is achieved by deriving the synthesised speed signal (via machine frequency, speed and/or electrical power) and modulating the generator excitation so as to develop components of electrical torque in phase with rotor speed deviation.

Fig. 5 demonstrates the Heffron and Phillips' Small Signal Model of a SMIB system. It is worth noting that all Ki values in the model are constants in the small disturbance approximation domain and depend on machine parameters as well as network operating conditions (i.e loading, system strength and terminal voltage). Typically, when designing a PSS phase compensation is required to compensate for the signal phase shift introduced by the machine and excitation system.

The K2 factor is of considerable importance as it is directly proportional to the internal machine angle (and electrical torque) in the small disturbance approximation domain. Under low loading conditions the K2 factor of the machine is close to zero, and any variation of the machine field voltage does not have a significant impact on the machine electrical torque (subsequently rendering any bias signal from PSS ineffective). Consequently, most manufacturers disable the PSS for low active power operation, or in the case of synchronous condensers the device is permanently disabled .

However, the Heffron and Phillips' Small Signal Model (Fig. 6) of a machine connected to a wide area system (multi-machine network) illustrates that the SCs internal voltage could potentially have an impact on the damping torque of other synchronous generators. It is important to observe that the machine internal voltage (Eq) not only has an effect on its own electrical torque but also the torque of other machines in the system. Therefore, even under low active power operation (i.e. synchronous condensers) the synchronous machine is capable of providing damping of inter-area modes by modulating its internal terminal voltage.

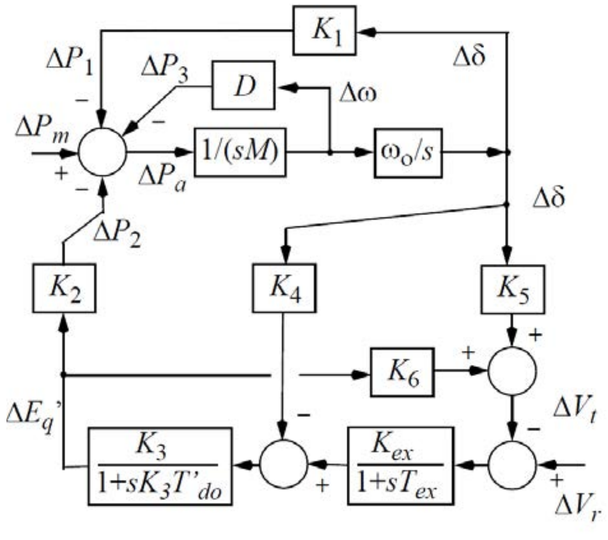

Fig. 5 Heffron and Phillips' Small Signal Model of a SMIB system [4–6].

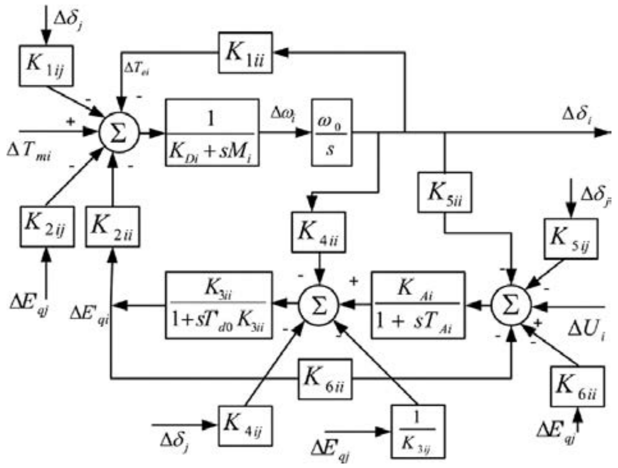

Fig. 6 Heffron and Phillips' Small Signal Model of a Multi-Machine System [7].

In the following section the SCs considered for system strength purposes will be equipped with POD devices and tuned accordingly (to correct for the signal phase shift introduced by the machine, excitation and network), in an attempt to dampen the inter-area modes for a multi machine network.

4 Synchronous Condenser Performance with POD

4.1 POD Settings Design

Based on the theoretical discussion in the previous section, SC1 and SC2 were equipped with the PODs (Fig. 7).

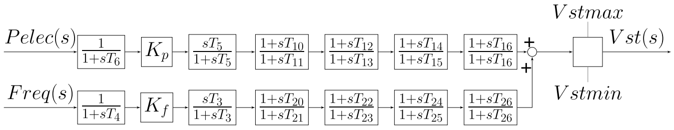

Fig. 7 Power Oscillation Damper Design for SC1 and SC2 in 39-Bus NE system

The SC terminal frequency and active power flows on remote branches are used as the input channels into the PODs.

For SC1 (POC at Bus 20) the active power flow on Line 19-16 is used as the input signal into the POD. By modulating the terminal voltage of SC1 based on the active power oscillations across the Line 19-16, the synchronous condenser is able to improve the damping of inter-area modes.

Similarly, for SC2 (POC at Bus 22) the summation of active power flows on Line 21-16 and Line 24-16 is used as the input signal into the POD. By modulating the terminal voltage of SC2 based on the active power oscillations across Line 21-16 and Line 24-16, the synchronous condenser is able to improve the damping of inter-area modes.

The required phase compensation for the SC1 and SC2 PODs was calculated using the well-established GEP methodology [4–6]. The lead lag constants were chosen to provide phase compensation over the frequency range of interest (0.1-3 Hz).

The POD gain (Kp) for the active power path is chosen to ensure that the PODs are not excessively modulating terminal voltage for large disturbances, while providing sufficient damping to inter-area modes. A Kp value of 7 pu is selected for SC1 and 4 pu for SC2. POD Kf (frequency path gain) of 15 pu is selected for both SCs. Increasing the Kf gain to a large value does not significantly improve damping. However, increasing the Kf gain does assist with the rate-of-change-of-frequency (ROCOF). Thus, a value of 15 pu is chosen as to avoid potential instability or excessive oscillations for large disturbances.

The POD output limiter is chosen to be ±0.075 pu in order to ensure that the POD can only modulate the terminal voltage by 7.5%. A washout time constant of 5 seconds is chosen for both the frequency and active power input channels. A typical value of 10 ms is selected for the frequency transducer time constant; the power transducer is assumed to have a time constant of 50 ms due to the delay in measurement from remote wide-area monitoring devices.

4.2 Critical Fault Clearing Time Assessment with POD

The CFCT assessment was repeated on Line 15-16 and Line 16-17 by applying faults and clearing them by tripping the faulted line. It was observed that the addition of PODs has no significant effect on the overall CFCT. This is expected as the tuned PODs should not affect large-signal system stability margins.

4.3 Eigenvalue Assessment with POD

The POD settings discussed in the previous section were chosen to increase the damping of the inter-area mode between G01 (NYISO/Canada inter-connector) and rest of the NE system.

The frequency of the aforementioned inter-area mode is 0.72 Hz with a damping ratio of 5.69% upon the replacement of G05 and G06 with PV01 and PV02 (and their respective SCs). As previously discussed, the replacement of synchronous generators with PVs and SCs did not result in a significant change of the damping and frequency of the inter-area mode in question.

Fig. 8 demonstrates eigenvalue analysis of the NE 39 Bus network with PVs and SCs (with and without PODs). The results of the eigenvalue analysis indicate that the damping of the inter-area mode is significantly increased with the addition of PODs (damping ratio increased to 10.99% with minor change in mode frequency).

Additionally, generator G04 and G07 speeds are oscillating against one another at a frequency of 1.29 Hz and with a damping ratio of 6.07%, prior to the installation of PODs. Upon addition of POD devices, the damping ratio is increased to 7.53% with negligible change in mode frequency.

Similarly, generator G04 and G07 speeds are oscillating against generator G02, G03, G09 and G10 at a frequency of 1.14 Hz with a damping ratio of 4.38%. The installation of SC1 and SC2 PODs increases the mode damping ratio to 8.03%.

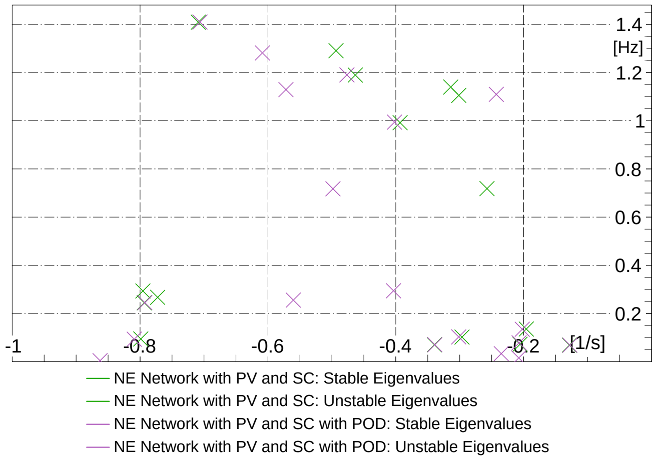

Fig. 8 Eigenvalue analysis of NE 39 Bus model with PVs and SCs (green; no PODs) vs NE 39 Bus model with PVs and SCs (purple; with PODs)

It is worth noting that the damping of the remaining modes are not significantly affected. Thus, it is concluded that the PODs are appropriately designed to only dampen the desired inter-area modes.

The sole exception to this could be argued for a 1.11 Hz mode (caused by the oscillation of the generator G10 speed relative to the rest of the network). It is noted that with the addition of the PODs the damping ratio decreases from 4.33% to 3.48%. However, coordinated tuning is performed with the G10 PSS to recover the aforementioned mode damping to the original network level.

4.4 Time Domain Assessment with PODs

4.4.1 Inter-connector outages: Time domain analysis was conducted to demonstrate the effectiveness of the SC1 and SC2 PODs on damping of the inter-area modes.

In this study, the inter-area mode between G01 (NYISO/Canada inter-connector) and the rest of the NE system is considered the most critical mode. The relatively low damping ratio of the mode limits the overall active power transferability between NYISO/Canada and the NE transmission system.

In order to excite the aforementioned inter-area mode, the lines connecting to G01 (NYISO/Canada equivalent) are tripped. The first case considers a forced outage of Line 01-39. The outage forces the active power to flow from the NYISO/Canada inter-connector towards Load 07, Load 08 and the rest of the network via Line 09-39. Fig. 9 and Fig. 10 demonstrate the active and reactive power flows on Line 09-39 and the SC1 response upon disconnection of Line 01-39.

Similarly, a forced outage of Line 09-39 is simulated, with active and reactive power flows monitored on Line 01-39. Fig. 11 and Fig. 12 demonstrate the response of flows on Line 01-39 and the SC1 terminal quantities for the aforementioned outage of Line 09-39.

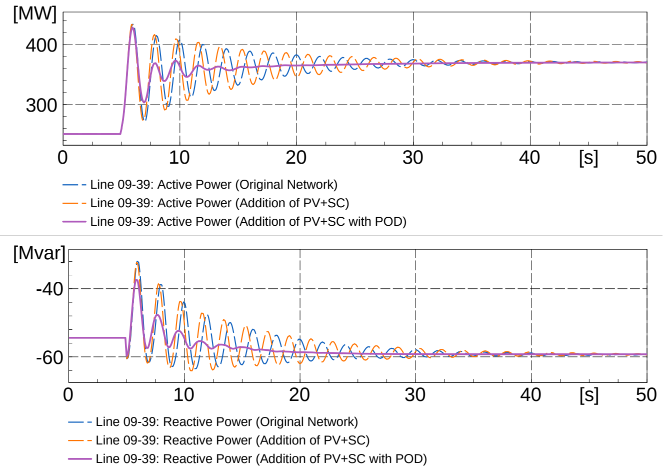

Fig. 9 Outage of Line 01-39; original NE 39 Bus model (blue) vs NE 39 Bus model with PVs and SCs (orange) vs NE 39 Bus model with PVs and SCs with PODs (purple). Active and reactive power flows on Line 09-39.

Generally, it is observed that the inter-area mode in question is significantly more damped with the addition of PODs as compared to the case where the PODs are out of service. Furthermore, it observed that the addition of PODs improves the damping of inter-area modes compared to the original system state (i.e. prior to the replacement of generators G05 and G06 with PV and SCs).

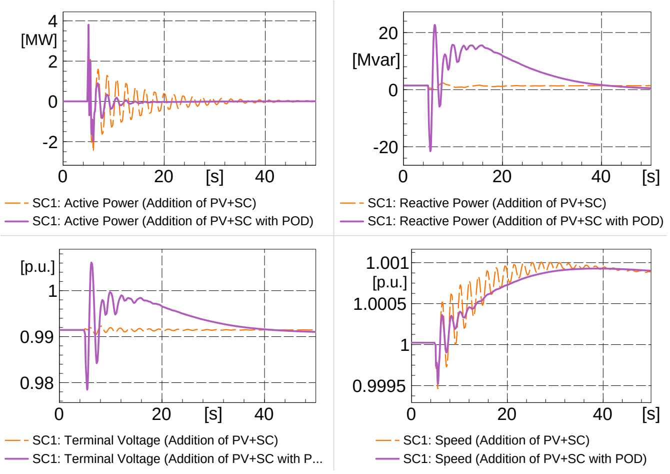

Fig. 10 Outage of Line 01-39; NE 39 Bus model with PVs and SCs (orange) vs NE 39 Bus model with PVs and SCs with PODs (purple). SC1 terminal quantities.

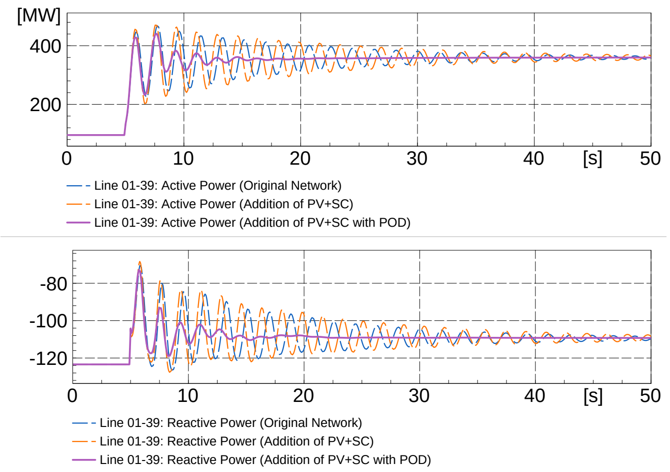

Fig. 11 Outage of Line 09-39; original NE 39 Bus model (blue) vs NE 39 Bus model with PVs and SCs (orange) vs NE 39 Bus model with PVs and SCs with PODs (purple). Active and reactive power flows on Line 01-39.

4.4.2 Frequency Events: To further demonstrate the advantages of equipping SCs with POD devices, frequency events were simulated. In particular, the loss of generator G10 and Load 08 were analysed.

Fig. 13 demonstrates the case where generator G10 is tripped. It is observed that the system is stable with and without the POD devices. However, it should be noted that several seconds after the loss of G10 the ROCOF is significantly reduced due to the installation of PODs.

Similarly, for the loss of Load 08 (Fig. 14), the SC PODs reduce the ROCOF. The reduction of ROCOF (due to the installation of PODs) is attributable to the fact that the Loads are modelled as directly proportional to the system voltage. Therefore, it can be concluded that the addition of the frequency channel onto a SC POD improves ROCOF several seconds after the disturbance, demonstrating a further advantage of installing PODs on SCs.

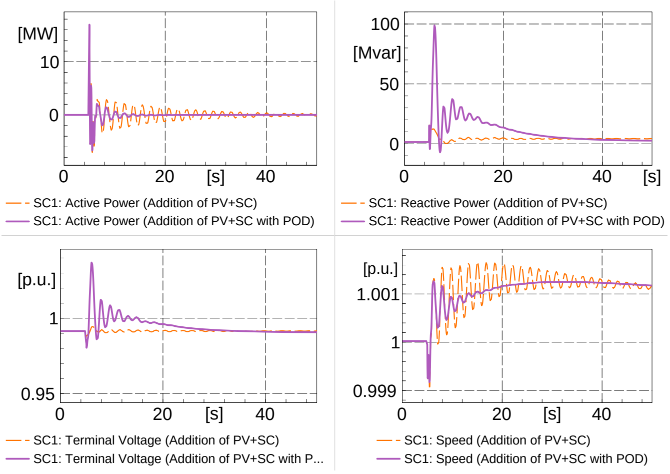

Fig. 12 Outage of Line 09-39; NE 39 Bus model with PVs and SCs (orange) vs NE 39 Bus model with PVs and SCs with PODs (purple). SC1 terminal quantities.

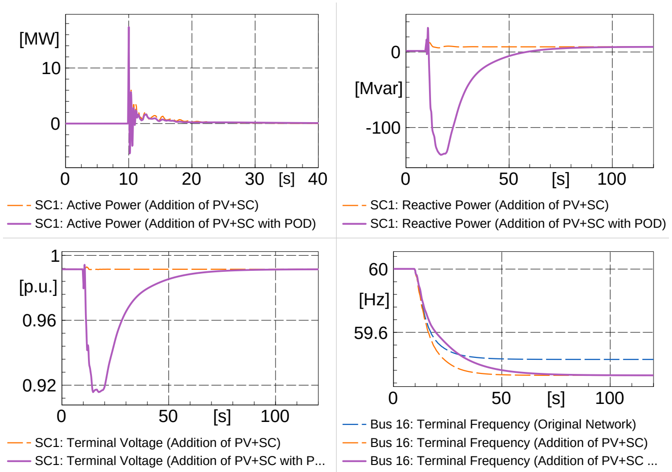

Fig. 13 Outage of generator G10; original NE 39 Bus model (blue) vs NE 39 Bus model with PVs and SCs (orange) vs NE 39 Bus model with PVs and SCs with PODs (purple). SC1 terminal quantities and Bus 16 electrical frequency.

5 Coordination of Generator PSS with SC POD

One of the shortcomings of installing the SC PODs is that the damping of the 1.11 Hz mode is reduced (the mode associated with the G10 speed oscillating with the remainder of the network). This is a common occurrence when tuning PODs and PSSs for damping of inter-area modes.

In order to correct the reduction of damping of the G10 mode, the G10 PSS is enabled and tuned to coordinate with the SC PODs.

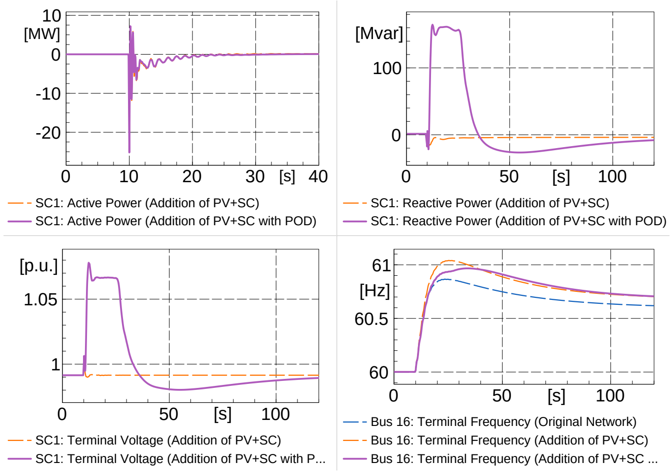

Fig. 14 Outage of Load 08; original NE 39 Bus model (blue) vs NE 39 Bus model with PVs and SCs (orange) vs NE 39 Bus model with PVs and SCs with PODs (purple). SC1 terminal quantities and Bus 16 electrical frequency.

Fig. 15 demonstrates the results of the eigenvalue analysis. It is observed that the damping ratio of the mode is recovered with coordinated tuning of the G10 PSS.

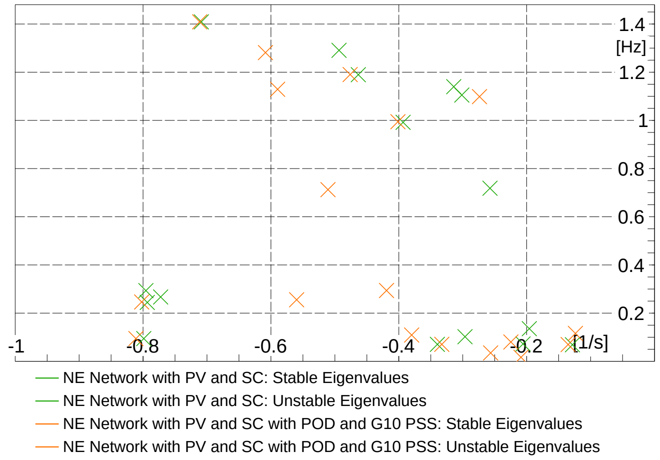

Fig. 15 Eigenvalue analysis for the NE 39 Bus model with G10 PSS and SC PODs in service (orange) vs case with only SC PODs (green).

6 Conclusion

The synchronous condenser is considered as an effective remedial solutions for connecting grid-following inverter based generation to weak grids. Typically, synchronous condensers are not equipped with a PSS due to low active power operation, and in practice, have not been used to dampen the inter-area modes.

This paper presents the utilisation of synchronous condensers for damping of inter-area modes within a multi-machine network by using PODs. The analysis demonstrated that the SC PODs are capable of modulating the system voltage to increase the damping of inter-area modes, by monitoring remote active power and terminal frequency oscillations.

Some coordinated tuning with the PSS devices of other synchronous machines might be required depending on the network. However, this is a common phenomena when tuning PODs and PSS devices for damping of inter-area modes.

Finally, it was observed that an appropriately tuned frequency channel of an SC POD can provide a reduction in ROCOF a few seconds after a frequency event occurs (helping stabilise the overall network).

Therefore, it is highly recommended that the installation of SCs considers the application of a POD for damping wide-area networks, where practically feasible.

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