Research Article

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Power flow control and power oscillation damping in a 2-machine system using SSSC during faults

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Abstract: With the rapidly growing population, energy demand is increasing. The power supply to consumers must be free from distortions. By injecting voltage in quadrature with line current and varying the magnitude, the SSSC offers series compensation to the line. The injected voltage, which offers the effect of inserting an inductive or else capacitive reactance in series with the transmission line, is in quadrature with the line current. Using MATLAB/Simulink software, a phasor model of a 2-machine device with SSSC integration and POD as a subsidiary controller is simulated in this paper to evaluate efficient power flow regulation. The simulation has been used to study the time domain behavior of SSSC under normal and faulty conditions. The SSSC is implemented for correcting the voltage and analyzing power responses during a low voltage fault in the power system, whereas in normal conditions, the power system's voltage stability for maintaining steady acceptable voltages at every bus is analyzed. It has been revealed that POD controller assists SSSC by supplying the reference voltage signal to damp out the low frequency power oscillations. The objective of this study is to reduce the crest outreach and clearing time during the fault thus improving the transient stability.

Keywords: 2-machine power system; FACTS; power flow control; power oscillation damping (POD); series compensation; static synchronous series compensator (SSSC); voltage-sourced converter.

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1 Introduction

With the rising population, there is a rise in electricity demand progressively. To match this ever rising demand, the generation needs to be extended. In that regard, the renewable generation trend has given a significant boost. The power electronics device revolution has helped utilities to tackle the effects that occur in power system while fulfilling this demand. The power electronic control devices provide quick and definitive switching which provide an opportunity to improve the power quality. Renewable energy has now become popular and its incorporation into the traditional grid includes the usage of power electronic converters. The interconnected power system are intended to serve continuously varying load demand. Furthermore, the complexities encountered in constructing new transmission lines may escalate. The transmission line operating close to stability limit may be dangerous for the entire system, as even a single disruption may lead to voltage instability. At that moment, a sudden rise or fall in voltage takes place. If the condition worsens, voltage failure or system blackout may result. The key causes of voltage instability are the imbalance between demand and supply of reactive power (Kundur, Balu, and Lauby 1994). Therefore, in order to maintain system reliability and protection, adequate power control flow via existing transmission systems is necessary. The power flow control is to be achieved at a very high speed. It is not possible to achieve such fast control by mechanically controlled switching devices (Ramanujam 2010). The ideal solution to the problem outlined above is the evolution of FACTS (Flexible AC Transmission System) controls based on power electronics. The FACTS allows for power management and improvement of power transmission capability. The possibility of regulating current across a line at a reasonable cost opens up a lot of possibilities for enhancing transmission capability by using one of the FACTS controllers (Hingorani and Gyugyi 2000). Several variations of compensation are offered by the FACTS controllers. The incapacitated line is the appropriate point for FACTS installation (Hridya et al. 2015). Furthermore, employing SSSC reduces the amount of reactive power delivered by the generator and reduces reactive power demand fluctuations. Self-tuning PID control SSSC is found to have better damping characteristics than fixed gain control (Therattil and Panda 2011). For improved system stability, increased power transfer capability, along with quick management of power flow, a hybrid series compensation employing SSSC and passive series capacitor is used (Agrawal, Bansal, Sisodia et al; Thirumalaivasan, Janaki, and Prabhu 2013). It uses a filter to provide a simple way for extracting sub-synchronous components (Amar Kanta and Arvind Kumar 2021). Sub synchronous current suppressor is a technique for suppressing sub synchronous line current. The use of PSS and SSSC controllers for enhancing low voltage ride through and transient stability in power system is reviewed (Agrawal, Bansal, and Sisodia 2020; Movahedi, Halvaei Niasar, and Gharehpetian 2019). The SSSC integrated with the power system model is linearized, and alternative approaches for designing the SSSC damping controller have been given based on this research (Abou et al. 2020; Wang 2000). By adjusting the equivalent line impedance, SSSC augments the power transfer capability regarding power system; while, they are highly controllable devices and provide further functionalities and services to the energy system. Power quality is critical in the distribution system, particularly in deregulated electrical markets, because it affects demand power consistency (Devi and Geethanjali 2014; Wang, Xu, and Xing 2019). Controlling SSSC for any objective-specific compensation can be done in a variety of ways (Kundur, Balu, and Lauby 1994; Movahedi, Halvaei Niasar, and Gharehpetian 2019; Shakarami and Kazemi 2011; Vicky 2020). The impact of several control methods on system performance is investigated (Castro et al. 2007). To provide variable compensation, the magnitude and phase angle must be regulated (Shakarami and Kazemi 2011; Shruti and Sincy 2021). In order to dampen inter-area oscillations, an SSSC-centric stabilizer is used in both directions. The residue analysis method is applied to determine the perfect position and relevant input indicator for SSSC. The difficulty of sub synchronous resonance can be solved by modifying the amount of compensation and the control schemes (Ajay Lileshwar and Patil 2019; Widyan 2013). The FACTS controllers can compensate for series, shunt, mixed series-series, or series-shunt. SSSC may increase transient stability limits, manage power flow, quick control to minimize the influence of disruption, minimize voltage difference, lessen power swinging, and so on, by using series compensation (Abou et al; Lv et al. 2017; Parvathy, Sindhu Thampatty, and Padmanabhan Nambiar 2018; Thirumalaivasan, Janaki Muneappa, and Yunjian 2017). To manage power flow and dampening power oscillations, MVA size series, Conventional power system stabilizers (CPSS), along with damping controllers are the appropriate controllers employed for implementing SSSC. The MOL-centric optimization is wielded for optimizing the recommended optimal controller parameters. The recommended controller's dynamics performance is measured under enormous loading conditions to demonstrate its efficacy and resilience in the face of various disturbances and operating conditions (Asit kumar, Sangram Keshori, and Sanat 2020; Bidyadhar and Pati 2018; Ritika, Vijay Kumar, and Singh 2017; Sanat Kumar, Sangram Keshori, and Asit Kumar 2018). The impact of SSSC on distant relay's performance on transmission lines has been studied in earlier publications.

1.1 Problem statement

The existing models developed to improve the power system performance have major problems such as.

- The damping controllers used for damping out the oscillations that couldn't offer the essential damping in complex power system.
- For augmenting oscillation efficacy, damping in the power system, a supplementary controller has to be built as unnecessary oscillations might lead to huge power quality disturbances and stability issues.
- Due to voltage unbalance, harmonics, or else the surges that come as of the operation of protection relays, reference wave's generation defining required voltages across the load is hugely distorted.

However, only a few studies have looked at the effect of combining a POD controller with an SSSC on faults. With this motivation, this article focused on SSSC performance analysis with and without a POD controller under several symmetrical and unsymmetrical failures. The contributions of this paper are,

- To integrate a phasor model of a 2-machine device with SSSC.
- To suppress oscillations in power system using Power Oscillation Damping Controller as a subsidiary controller.
- To study the time domain behavior of SSSC under various conditions.

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2 Literature survey

Jamnani and Maulikkumar (2019) implemented a Particle Swarm Optimization (PSO) for constructing coordinated parameters of static VAR compensator (SVC) along with Thyristor Controlled Series Capacitor (TCSC). With the assistance of MATLAB, simulation is done on the IEEE-14 bus system. As per the outcomes, the system's efficacy was attained by the coordination of FACTS devices with each other to revamp power flows. However, the PSO algorithm's low convergence rate causes high dimensional and complex problems.

Kush et al. (2019) presented the modeling together with the simulation of SSSC used in a multimachine power system. The model was simulated under symmetrical and unsymmetrical faults. When SSSC is deployed, the settling time of oscillations together with the transient peak of bus voltages along with line power after fault occurrence were minimized. Large variations of loads affect the system's stability.

Ojaswani and Barkha (2020) developed an SSSC-centric controller for eliminating the power oscillation damping in the power system along with enhancing the transient stability. Moreover, to control SSSC, a hysteresis controller was deployed and a lead-lag controller was deployed for augmenting the system's dynamic response. The outcomes depicted the controller's efficacy with SSSC for power system stability enhancement under various fault conditions. But, inter area oscillations are not effectively damped.

Agrawal, Bansal, and Sisodia (2020) presented an intelligent and optimized SSSC design with the incorporation of the differential evolution technique. The disturbance and phase variation were evaluated; in addition, the angular change in phase along with enhancement in the signal amplitude was offered. As per the outcomes, the stability was enhanced; also, the voltage fluctuation was minimized. However, owing to huge interconnections, instability takes place in the power system.

Prabha, Rohit, and Manju (2019) implemented a fuzzy logic controller for applying an appropriate control signal to STATCOM. The controller built employing fuzzy logic, which deploys human reasoning, was programmed into fuzzy logic language. For the optimized implementation of the controlled signal to the real system, fuzzy logic was employed. The outcomes were analogized to the conventional energy function-centric controllers. However, fuzzy logic is limited to handle imprecise data.

3 Static synchronous series compensator

A synchronous voltage source can provide a set of three alternating, stable sinusoidal voltages with controlled magnitude and phase inclination at the desired frequency. A set of balanced 3-phase voltages with the same magnitude are generated by the synchronous voltage source, which is displaced by 120°. In this configuration, for generating the final output, a compatible set of 3-phase, quasi-square output voltage waves that are fused through an apt magnetic structure, are generated by the 6-phase inverters functioning as of a usual dc bus. It generates or consumes reactive electricity. When a synchronous voltage source is connected to DC storage, it gains the capacity to barter real power. As a result, SVS functions as a self-contained compensator, with just a modest DC link condenser (Elenilson et al. 2020). The SVS functions to offer some operating features and functional performance are controlling the network parameters like (A) transmission line voltage, (B) impedance, along with (C) angle uniformly by offering (i) reactive shunt compensation, (ii) series compensation, together with (iii) phase shifting. If Synchronous Voltage Source (SVS) has an additional DC source, it can interchange independently regulated active power with an AC system. SVS functionalities are shown in Figure 1. The SSSC is a series compensator emanated from a voltage-sourced converter. SSSC has the same basic functionality as a Synchronous Voltage Source based on a voltage-sourced converter (Preeti Ranjan, Prakash Kumar, and Sidhartha 2018). By the usage of an SVS, the effective impedance of transmission lines is changed by the SSSC. An ideal 60 Hz generator, which interfaces with the energy storage device for negotiating real power exchange with the AC system and generating internally the reactive power essential for network compensation is termed the SVS. SSSC could supply voltage either 90° lagging or else leading the line current. While the SSSC injects voltage, which causes the line current, it is equal to a capacitive reactance linked in series with the power line; in addition, it augments the line current along with the power flow. With a variable line current, a fixed compensating voltage can be maintained. This is achievable because the compensating injected voltage amplitude is controlled independently of the line current amplitude (Pierre et al. 2021). The injected voltage could be managed independently as it is not associated with the line impedance. That is, since the voltage across the line reactance in every practical case is greater than, and limited by the SSSC's voltage, the SSSC might not be tuned with any finite line inductance to have a classical series resonance at the fundamental frequency.

Normal inductive compensation is supplied if the SVS output voltage is 90° ahead of the line current. SVS' output voltage polarity can be easily changed to lag or lead the line current by 90° (Roman, Maria, and Andrey 2021). SSSC is depicted in a single line diagram in Figure 2. A modest amount of real power is pulled from the line to keep the capacitor charged and compensate for transformer and VSC losses. The DC voltage source is constant in a PWM inverter-based VSC, V_{conv} is adjusted by varying the modulation index of the PWM. Figure 3 shows a block diagram representation of the SSSC control system. The VSC's DC link voltage V_{dc} is filtered out using the same type of measurement technique. V_{dVSC} and V_{qVSC} are the two components provided by regulators implanted with a PI controller (Difei, Aihong, and Shuyuan 2020). The voltage-sourced converter in this case is made up of IGBTs, and the gate pulses to the converter are controlled by a PWM modulator.

In SSSC's control system, PLL's output is deployed to obtain the d and q components of the AC and DC sequence voltages (V_{dVsc}, V_{qVSC}). The 2-machine system's active and reactive power can be equated as,

$$P = \frac{V^2}{X_L^2 + R^2}\left[X_L \sin\delta - \mathrm{R}(1 - \cos\delta)\right] \tag{1}$$

$$q = \frac{V^2}{X_L^2 + R^2}\left[\mathrm{R}\sin\delta - X_L(1 - \cos\delta)\right] \tag{2}$$

Here, P and Q are the active and reactive powers, X_L, R are the line reactance and resistance, and δ is the transmission angle.

Hence, the procedure and time frame for the design model includes, designing a simulink test system of two machine phasor models, and insertion of SSSC at 10 s of the simulation period. Simulate the three-phase faults for 30 s. Record the time taken by the flow of power approaching the main load after clearing the faults.

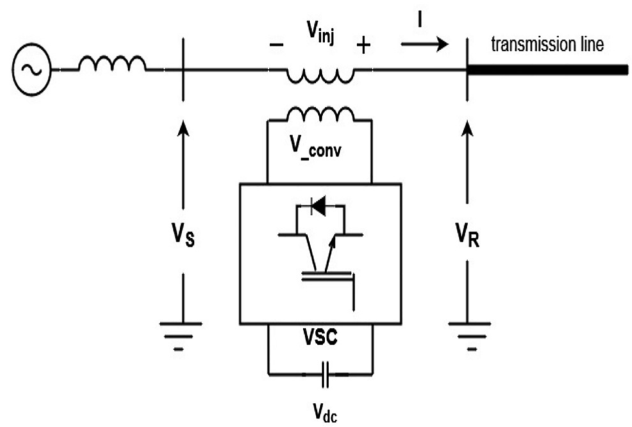

Figure 2: Single-line diagram of SSSC.

4 MATLAB phasor model

In MATLAB software, a two-machine phasor model was simulated, as illustrated in Figure 4. One synchronous machine has a 210 MVA rating, while the other has a 140 MVA rating. 230 kV is the nominal line voltage. A 250 km line connects the SSSC phasor block in series. The SSSC has a 10 MVA rating and 10% maximum injected voltage limit. A POD controller is used in conjunction with SSSC to lessen low

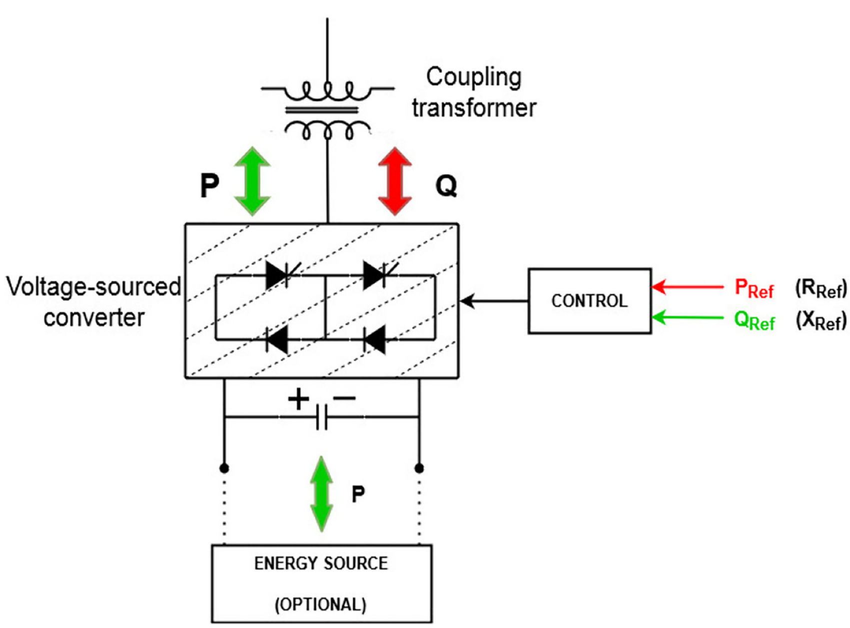

Figure 1: Voltage-sourced converter based functional representation of SVS.

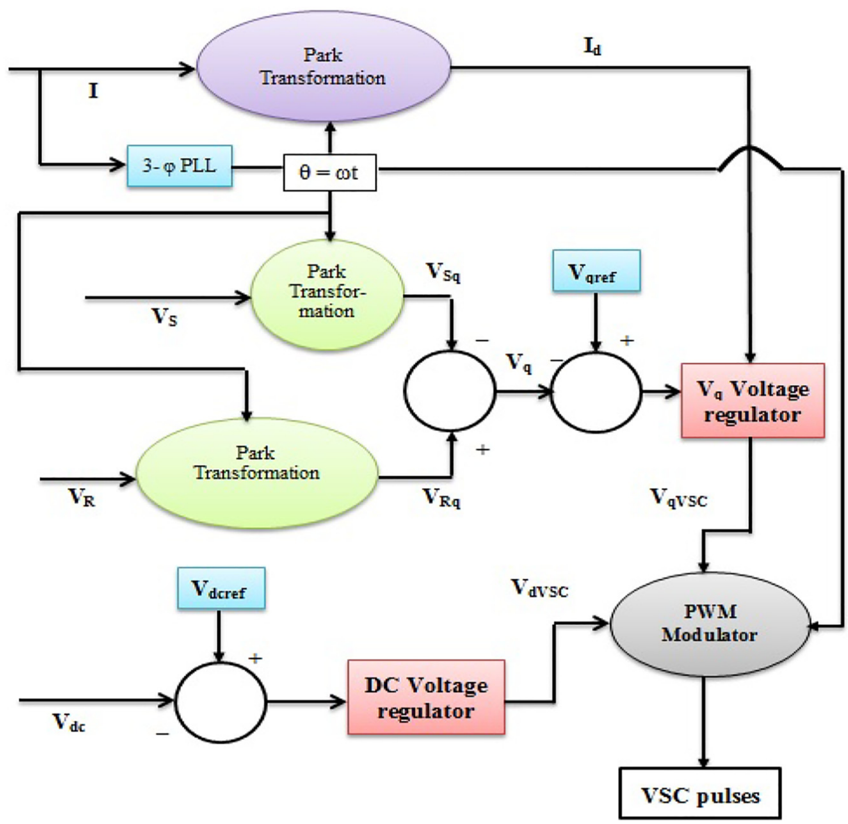

Figure 3: Block representation of the SSSC control system.

frequency disruptions at bus B2. The POD controller provides a reference injected voltage signal to dampen the oscillations. The damping of an oscillation can be caused by various factors, such as friction or aerodynamic drag. Damping in an oscillator circuit takes place since a little electrical energy is lost. This leads to the amplitude of the oscillation to decay over time. Then, a stair generator is used to bypass SSSC for the first 2 s. The stair generator is used to supply reference signals to the POD controller. The stair generator generates a reference signal based on the values specified in the time and amplitude parameters. These signals are delivered in such a way that the SSSC acts as inductor for 2 s–6 s, and as capacitor for 6 s–10 s. Bus B3 has a significant three-phase dynamic load. Since an unbalanced system could cause minimized efficiency, tripped circuit breakers, along with a useful life of equipment, 3-phase load balancing is desirable. The dynamic load block could permit to design an electrical fault as an open circuit. Initially, the real and reactive power levels are set at 250 MW and 50 MVAR, respectively.

5 Simulation results

Figures 5 and 6 show the dynamic reaction of SSSC with and without a POD controller. It comprises of active power flow measured at Bus B2 over a 250 km line. Figure 5 depicts the active power flow at bus 2, as well as the reference voltage V_{qref} and the injected voltage V_{qinj}. The phasor model is often used to simulate symmetrical and asymmetrical faults. In high voltage systems, asymmetrical faults are more complicated to analyze as they drop voltage near to zero dramatically influencing converters. The dynamic phasors are capable of accurately representing symmetrical and unsymmetrical faults with and without the occurrence of synchronous interactions. Hence, the phasor model represents systems' dynamic behavior during symmetric along with asymmetric faults on the ac side; in addition, it is also apt for the dc-side faults and is appropriate for the simulation analysis. Symmetrical faults are those faults that include all the three phases. But, unsymmetrical faults are those faults in which either one or two phases are involved. In unsymmetrical faults, the three phase lines become unbalanced. The symmetrical fault is much more severe when analogized to the unsymmetrical fault at the transmission lines, as it affects all the 3 phases, unlike unsymmetrical faults. Such fault is balanced; that is, the lines are displaced by an equal angle and it is the severe sort of fault encompassing the largest current. The findings are compared with and without the use of POD controller. At t = 5 s, SSSC is used to perform the inductive reactance function (V_{qref} = –0.08 pu); also, at t = 15 s, it is used to perform the capacitive reactance function (V_{qref} = +0.08 pu). When the POD controller is turned on, the power oscillations are dampened. The oscillations

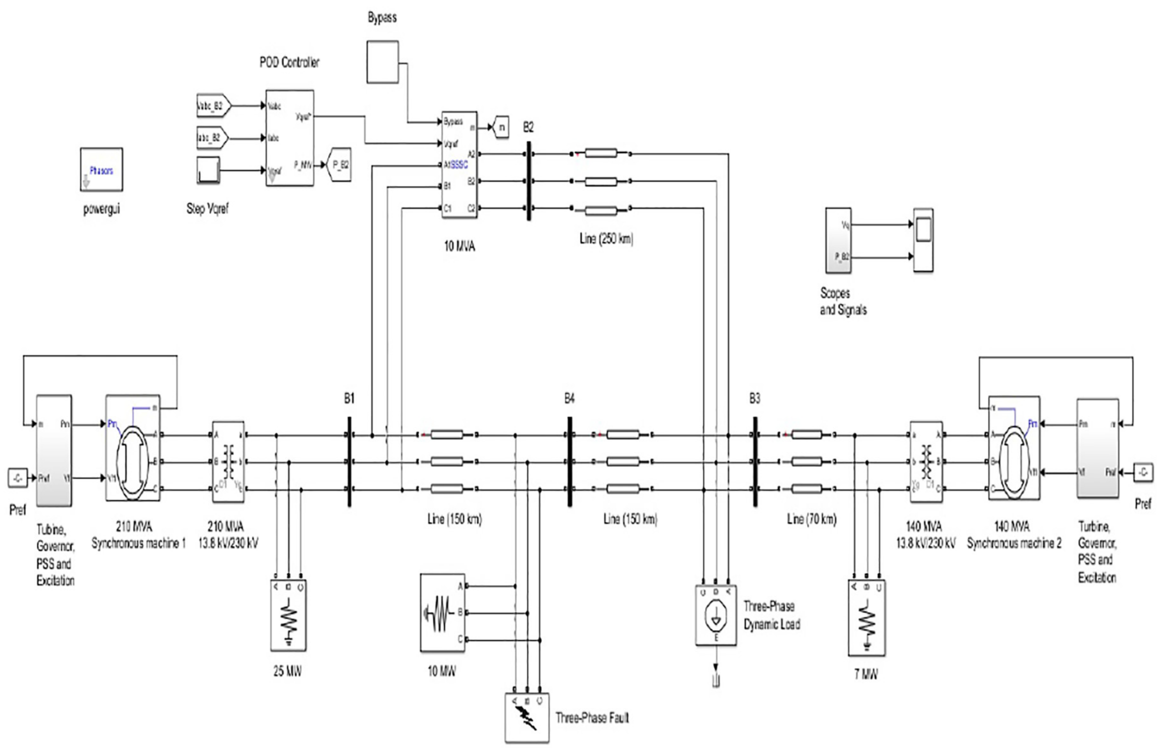

Figure 4: MATLAB/Simulink two-machine SSSC integrated phasor model.

become damped out while the damping augments; also, there are no oscillations with a damping factor; in addition, the output augments over time to the steady state output value. To attain the steady state value, the output takes a longer time if the damping augments. Hence, the POD controller damping is the only factor contributing to the steady state value. The analysis is carried out in the system under normal, healthy settings. During faults, the POD feature is also noticed.

Symmetrical faults are computed by determining the calculation of following. (A) the detection of the voltage at any point in the network, (B) the current in any branch along with (C) the value of reactance essential to limit the fault current to any required value. (A) Single line-to-ground fault (LG), (B) Line to line fault (LL), (C) Double Line-to-ground fault (LLG), (D) Three-phase short circuit fault (LLL), along with (E) Three-phase-to-ground fault (LLLG) are the classifications of unsymmetrical faults. For the selection of circuit breakers and design of the protective scheme, the essential data are offered by such estimations. The faults in the power system are identified by monitoring the changes in 3-phase currents and voltages of one end.

Figure 5 depicts the dynamic output of SSSC without the POD controller. The injected voltage follows the reference value flawlessly in the absence of POD controller. During inductive reactance mode, the power flow settles in 8.93 s, but in capacitive, it settles at 20.63 s. (5.63 s delaying the disruptions).

With POD switched ON, the injected voltage V_{qinj} exactly tracks the reference voltage V_{qref}, as shown in Figure 6. At 7.35 s, the settled power flow in inductive mode is achieved. In capacitive mode, the power flow settles in 19.83 s (4.83 s delaying the disruption), which is significantly faster than in the absence of a POD controller. This is because the POD offers stabilizing signals to the SSSC and the SSSC with POD includes the enhanced potential to dampen the network oscillations than in the absence of a POD controller. Also, the network's load balancing is enhanced since SSSC-POD rises the system's real and reactive power. The peak overshoot is also significantly decreased.

At t = 1.33–1.5 s, L-G fault is applied to phase A depicted in Figure 7. The reference voltage wave shape is perfectly followed by the injected voltage wave shape. The oscillations reach a high of 103.9 MW during the incident and clear out around 4.95 s after the fault is cleared. At 4.95 s, the power flow reaches its steady-state value in the inductive reactance mode. In the absence of a POD controller, the power flow in capacitive reactance mode reaches steady-state in 20.91 s (5.91 s after the disruption).

The consequences of L-G fault applied to phase A are presented in Figure 8. In this scenario, the oscillation peaks at 100.7 MW during the fault, and the oscillations dwindle

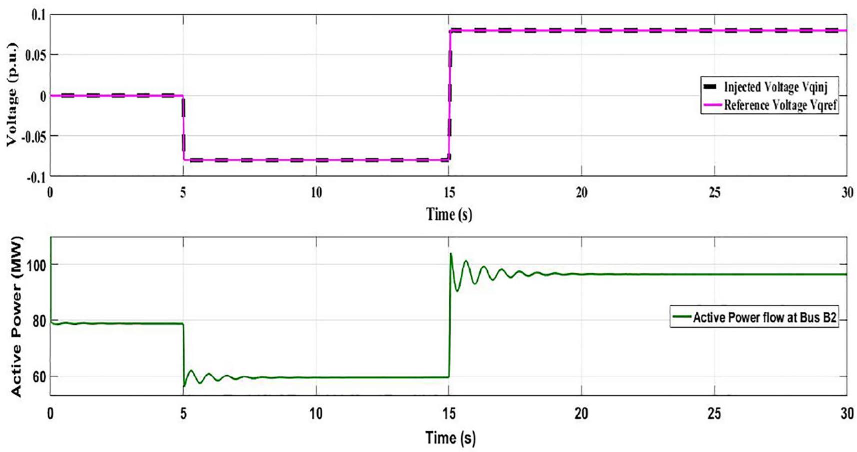

Figure 5: Dynamic response of SSSC without POD controller.

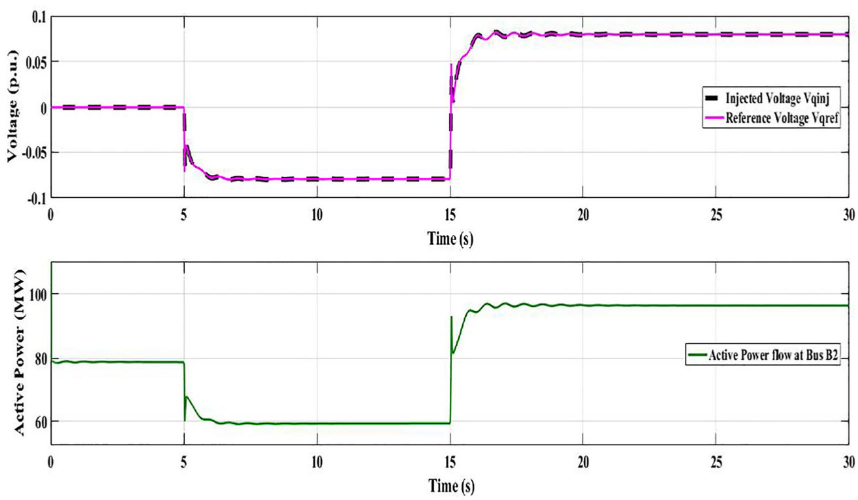

Figure 6: Dynamic response of SSSC with POD controller.

out at 4.85 s after the fault is cleared. Inductive mode, the settled power flow recorded at Bus B2 is obtained after 8.75 s. The settled power flow is attained in capacitive mode at 19.92 s (4.92 s after the disruption). As a result, the POD controller's damping is the only reason for the rapid achievement of steady state value.

When L-L-G fault is put on the A and B phases, the outcomes depicted in Figure 9 are seen. First and foremost, the

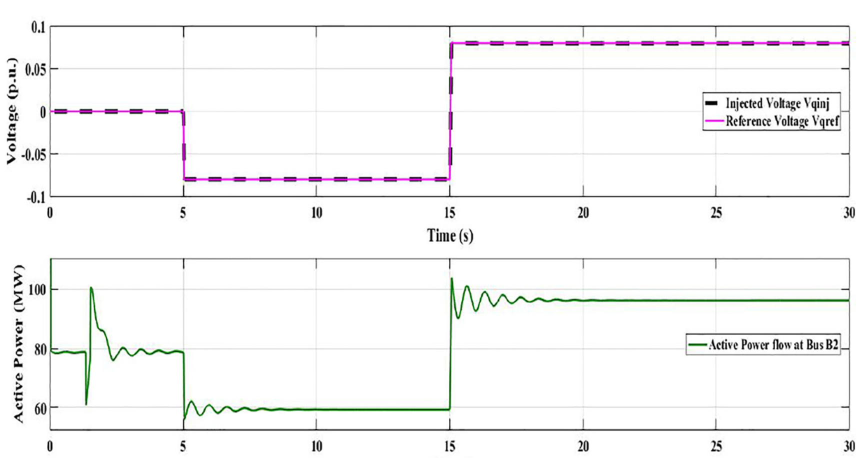

Figure 7: Waveforms during L-G fault without POD controller.

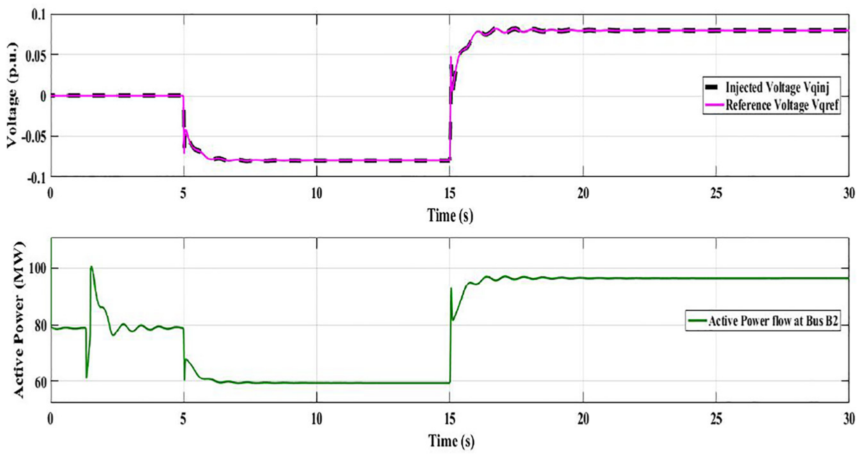

Figure 8: Waveforms during L-G fault with POD controller.

POD controller is turned off in this scenario. The oscillation peaks at 106.1 MW during the fault, and the oscillations dwindle out around 4.96 s after the fault is cleared. Inductive mode, the settled power flow recorded at Bus B2 is obtained at 8.85 s whereas in capacitive mode, it is recorded at 20.90 s (5.9 s after the disruption). The insufficient dampening of power flow oscillations causes this delay in reaching the steady-state value. In order to prevent this, the POD controller is wielded as a supplementary control action for sustaining the frequency at the nominal value in a steady state and to avoid time delay due to a lack of damping in the generator.

Figure 10 shows the outcomes of L-L-G fault when introduced at phase A while the phase B POD controller is ON. In this scenario, the oscillation peaks at 106.2 MW during the fault, and the fluctuations dampen out at around 4.82 s after the fault is cleared. Inductive mode settled power flow recorded at Bus B2 takes 7.35 s whereas in capacitive mode, it is obtained at 19.35 s (4.35 s after the disruption).

On phases A, B, and C, L-L-L-G is applied. Without turning on the POD controller, the results indicated in Figure 11 are obtained. In this scenario, the oscillation peaks at 108.5 MW during the fault, and the fluctuations fade out at 4.99 s after the fault is cleared. Inductive mode settled power flow recorded at Bus B2 is obtained at 8.65 s whereas in capacitive mode at 20.53 s (5.35 s after the disruption).

With POD ON, the results for L-L-L-G fault applied on phases A, B, and C are displayed in Figure 12. The oscillation peaks at 108.7 MW during the fault, and the oscillations fade out around 4.85 s after the fault is cleared. Inductive mode settled power flow recorded at Bus B2 takes 7.52 s whereas in capacitive mode at 19.24 s (4.24 s after the disruption). In series with the transmission line, this offers the ability to reproduce an inductive or else capacitive reactance in which the device is connected; hence, permitting effectual control of the active along with reactive power flows in the line in which SSSC is installed.

Figure 13 analyses the settling time taken by the proposed and existing method to reach the transient stability. From Figure 13 it can be said that the proposed system has attained power system stability efficiently with a minimum time of 13.65 s compared to the existing models. This is owing

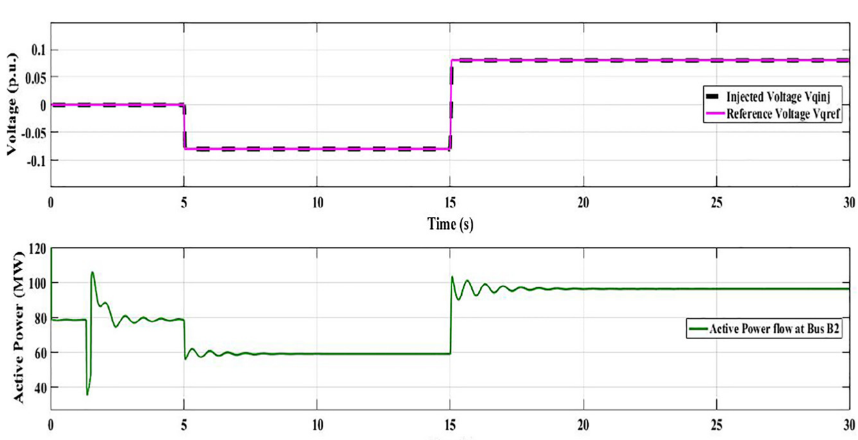

Figure 9: Waveforms during LLG fault without POD controller.

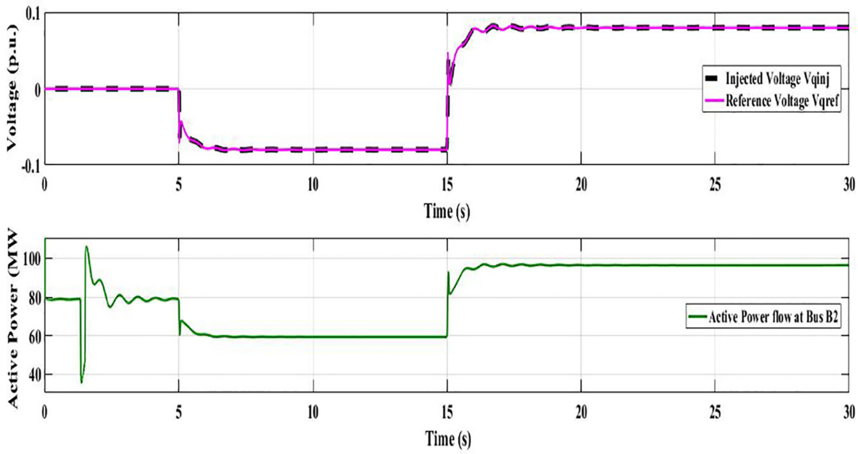

Figure 10: Waveforms during LL-G fault with POD controller.

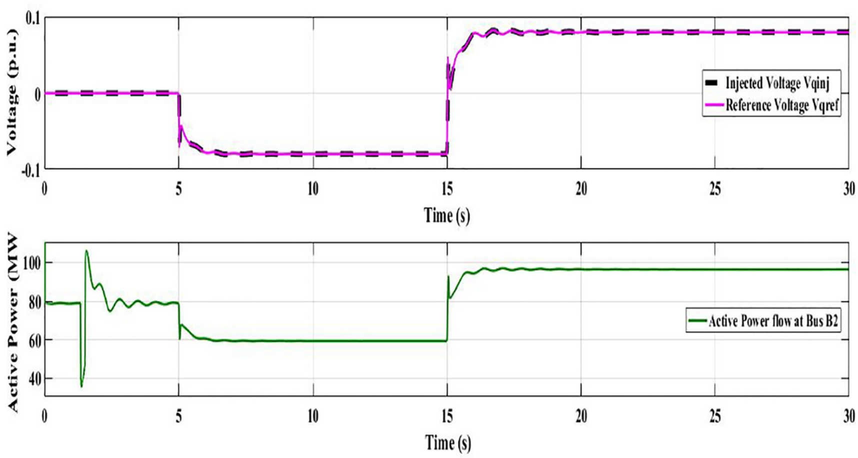

Figure 11: Waveforms during LLL-G fault without POD controller.

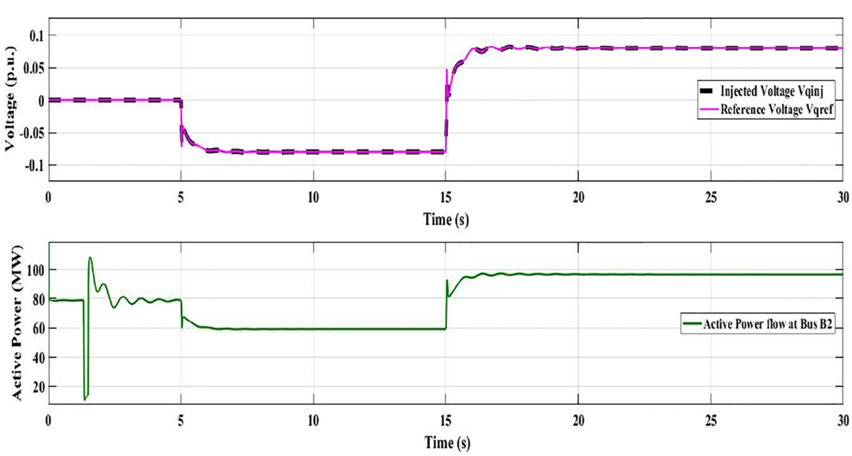

Figure 12: Waveforms during LLL-G fault with POD controller.

to that by injecting an opposing active power drawn as of their respective ac grids, the POD participating in the dc voltage regulation reacts to the voltage distortion. The results showed that the POD controllers used for SSSC processed the model dynamically and settled down very quickly due to the injection of active and reactive power.

6 Conclusions

This paper studied the SSSC's impact in controlling the power flow, along with lessens low-frequency power oscillations in the system. The 2-machine system is taken for the objective of the work. A POD controller is used in conjunction with SSSC to

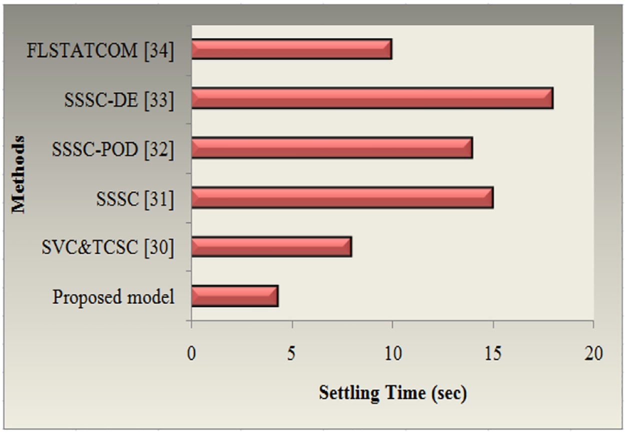

Figure 13: Comparative Analysis.

lessen low-frequency disruptions at bus B2. The POD controller provides a reference injected voltage signal to dampen the oscillations in such a way that the SSSC acts as an inductor and as a capacitor for a certain period. In the simulation results, the time domain characteristics of the model are studied with and without the POD controller. When the POD controller is absent, the oscillations prevail for a longer time. As the POD controller is turned 'ON', the low frequency oscillations in the power flow are damped out faster than in the case of the absence of the POD controller. As per the outcomes, SSSC with a POD controller could damp power oscillations in both inductive along with capacitive modes. It could also lessen the power oscillations with the help of the POD controller during both normal and faulty conditions. These functions of SSSC are well supported by the different simulation results and confirm its applicability in a real power system. This study may be extended in the future for a wide area network and integrating power generation system to provide further improvement for higher damping during power oscillation.

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