

Article

SVC Control Strategy for Transient Stability Improvement of Multimachine Power System

Anica Šešok * and Ivica Pavić

Department of Energy and Power Systems, University of Zagreb Faculty of Electrical Engineering and Computing, 10000 Zagreb, Croatia; ivica.pavic@fer.hr

* Correspondence: anica.sesok@fer.hr

Abstract: The increase in renewable energy sources (RESs) in power systems is causing significant changes in their dynamic behavior. To ensure the safe operation of these systems, it is necessary to develop new methods for preserving transient stability that follow the new system dynamics. Fast-response devices such as flexible AC transmission systems (FACTSs) can improve the dynamic response of power systems. One of the most frequently used FACTS devices is the Static Var Compensator (SVC), which can improve a system's transient stability with a proper control strategy. This paper presents a reactive power control strategy for an SVC using synchronized voltage phasor measurements and particle swarm optimization (PSO) to improve the transient stability of a multimachine power system. The PSO algorithm is based on the sensitivity analysis of bus voltage amplitudes and angles to the reactive power of the SVC. It determines the SVC reactive power required for damping active power oscillations of synchronous generators in fault conditions. The sensitivity coefficients can be determined in advance for the characteristic switching conditions of the influential part of the transmission network, and with the application of the PSO algorithm, enable quick and efficient finding of a satisfactory solution. This relatively simple and fast algorithm can be applied in real time. The proposed control strategy is tested on the IEEE 14-bus system using Dlg-SILENT PowerFactory. The simulation results show that an SVC with the proposed control strategy effectively minimizes the rotor angle oscillations of generators after large disturbances.

Keywords: voltage phasor measurement; power oscillations damping; reactive power control; rotor angle; SVC; transient stability

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1. Introduction

The dynamic stability of power systems has long been recognized as an important factor for the safe operation of these systems; therefore, many solutions have been found over time to preserve it. However, the increasing integration of devices based on power electronics into power systems has caused major changes in their dynamic behavior, which is becoming increasingly dependent on the fast response of said devices [1]. For this reason, new solutions are needed that will contribute to preserving the dynamic stability of such systems, with an emphasis on transient stability, which mostly depends on the fast response of system elements. Transient stability, also called large-disturbance rotor angle stability, deals with the ability of a power system to maintain synchronism when subjected to a large disturbance, such as a short circuit on a transmission line. The time frame of interest for transient stability studies is typically from 3 to 5 s after the disturbance [2].

Flexible AC transmission system (FACTS) devices are considered to be effective solutions for reactive power control and transient stability [3]. Although their application is mostly based on solving steady-state stability issues such as voltage and power flow control, or increasing transmission capacities, FACTSs can significantly dampen

electromechanical oscillations and improve a power system's dynamic response during large disturbances [4–6]. FACTS devices are based on power electronics, which enables them to react quickly to system changes, thus participating in maintaining transient stability. Different types of FACTSs have different contributions to transient stability improvement [7], and can generally be divided into serial, shunt, and combined devices.

The primary role of FACTS shunt devices is voltage control by injecting or absorbing the reactive power at the connection bus. Reactive power compensation increases the flow of synchronizing power between synchronous generators in the system, thus raising the power system's transient stability limit. By adding auxiliary control circuits, power oscillations that occur during large disturbances can be dampened more effectively, further improving the transient stability of the system. The SVC oscillation damping controller is often tuned using different optimization algorithms, some of which are described in [8–12].

Various SVC control strategies for transient stability improvement are described in [13–16]. In [13], a PI controller is added to the control loop of the SVC to improve oscillation damping and voltage control. The input signal is the rotor speed deviation $\Delta\omega$. In [14], an increase in transient stability is obtained by enhancing the steady-state power-transfer limit provided by the SVC voltage controller. In [15], the author proposes a control strategy for FACTS shunt devices to improve the first swing stability limit by maximizing the decelerating area. This is achieved using a locally available voltage control signal. In [16], the authors consider different locally available control signals to enhance the SVC interarea oscillation damping using observability indices.

For a long time, most research focused on SVC control strategies was based on local measurements and decentralized control. Due to changes in power systems' dynamic behavior and the development of measurement technologies in the last few years, control strategies based on wide area monitoring systems (WAMSs) have become an increasingly active area of research in the field of power system stability [17,18]. An essential part of WAMSs are phasor measurement units (PMUs), which collect synchronized and precise voltage or current measurements that enable real-time system monitoring. Measurements collected by PMUs can be used to develop new control strategies that extend the operation areas of devices such as SVCs to dampen large-disturbance power oscillations and improve the transient stability of power systems [19].

Various SVC control strategies for transient stability improvement using WAMSs are described in [20–23]. Ref. [20] proposes a control strategy that minimizes the current magnitude along the SVC-compensated transmission line and dampens inter-area power oscillations using the voltage measurement and voltage oscillation frequencies. In [21], SVC controllers use the estimated area angles and angular velocities to improve the system's first swing stability and oscillation damping following a large disturbance. The control algorithm is based on the maximum reduction in the total kinetic energy of the system. Ref. [22] presents the design of a nonlinear external damping controller using the speed deviations of generators estimated through wide-area measurements. In [23], the authors chose the speed deviations and angular differences of generators as input signals for the SVC supplementary controller based on the residue ratio method to dampen inter-area oscillations.

In this paper, an SVC control strategy using a WAMS to improve the transient stability of a power system is presented. The proposed strategy is based on collecting voltage phasor measurements which serve as SVC controller inputs to dampen generator power and rotor angle oscillations. This is achieved by minimizing the generator's electrical and mechanical power differences that occur during large disturbances using the particle swarm optimization (PSO) algorithm to calculate the SVC optimal reactive power injection. The novelty of the proposed strategy lies in the sensitivity coefficients used to express the generators' active power dependence on the SVC reactive power in disturbance conditions. Thus, the SVC directly affects the damping of target generator oscillations, unlike the traditional approach, where the SVC dampens local oscillations. Although it is

designed and tested for SVCs, the same strategy could be applied to static synchronous compensators (STATCOMs). The proposed strategy can be used to simultaneously dampen multiple generator oscillations, and it is tested on the IEEE 14-bus system. It is also efficient in terms of computation time and system requirements, which makes it suitable for real-time control.

The paper is divided into nine sections, the first of which is the introduction. The power system simulation model is described in Section 2. Section 3 compares the transient stabilities of a system with installed renewable energy sources (RESs) and a conventional system with synchronous generators. In Section 4, the SVC working scheme is described, and in Section 5, the control strategy for the SVC to improve the transient stability of the system is proposed. Section 6 and Section 7 describe the simulation procedure and the obtained results. The discussion with a conclusion is given in Section 8.

2. Simulation Model

The IEEE 14-bus system shown in Figure 1 was used as the simulation model. The system data that were primarily used for the steady-state analysis were expanded and modified according to [24] for transient stability analysis. The model consisted of two transmission voltage levels, 220 kV and 110 kV, and five synchronous machines, with G1 as a reference machine. In the initial model, three of the five machines were synchronous compensators used for the system's reactive power control. In the modified simulation model, these three compensators were converted into synchronous generators, and reactive power control was performed by the SVC installed on the 220 kV bus 4. Bus 4 was chosen as the SVC connection bus to affect as many generators in the system as possible. The rated power of the SVC was 250 Mvar capacitive and 200 Mvar inductive.

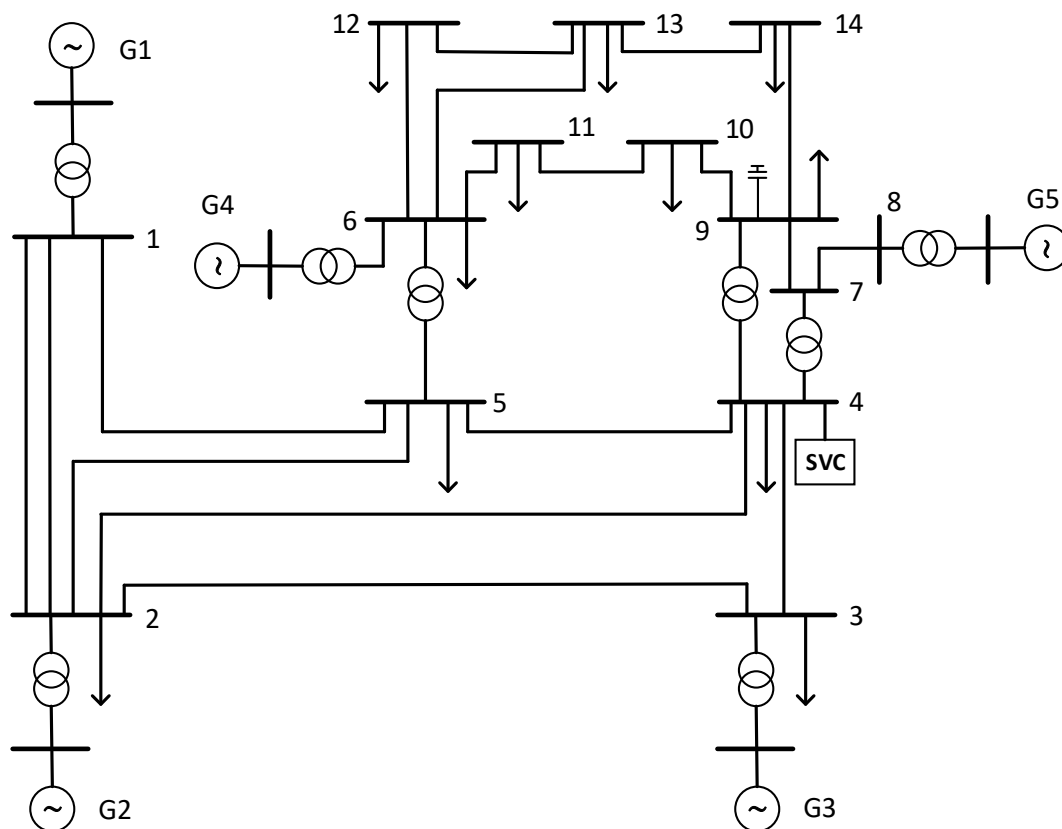


Figure 1. IEEE 14-bus system with SVC.

3. RESs' Impact on Transient Stability

Transient stability analysis is a basic dynamic calculation, based on which a system's behavior under large disturbances can be determined. The term generator stability refers to its ability to maintain synchronism with other generators in the system during large disturbances. In the case of an unstable response, the generator rotor angle continuously increases until the synchronism is lost, which usually happens in the generator's first swing. This loss of synchronism is associated with the critical clearing time (CCT), defined as the longest fault duration for which the synchronous operation is still maintained. The higher the CCT, the more stable the system.

Due to the increasing integration of renewable energy sources (RESs) into power systems, their impact on the transient stability of these systems should be analyzed. The analysis is carried out for two scenarios using the simulation model from Figure 1 with the SVC switched off. In the first scenario (Scenario I), the entire production consists of synchronous generators and amounts to 270 MW. In the second scenario (Scenario II), the synchronous generators G4 and G5 connected to the 110 kV voltage level are replaced with wind turbines of the same production connected to the grid via a full-size converter. In this case, the production of these wind turbines amounts to slightly more than 20% of the total system's production. For the mentioned two scenarios, a three-phase short circuit on the 220 kV transmission line 2-3 with different durations is simulated to determine the CCT of the generator G3, which is most affected by the fault. Due to the test network's high inertia, the short circuit's duration must be quite long for the generator to lose its stability. As a criterion for maintaining this stability, the first swing stability criterion is used; therefore, the duration of the simulations is 3 s. Figure 2 shows the generator G3's rotor oscillations for the two scenarios. For the same fault duration, the generator remains stable in Scenario I, while in Scenario II, it falls out of synchronism and loses its stability. Further simulations determine that the CCT of the generator G3 in Scenario I is 590 ms, while in Scenario II, it is 500 ms, which is 90 ms less. This makes Scenario I, with only synchronous generators, more stable compared to the system with RESs installed. The impact of RESs on transient stability can be improved by adding a control system to the converter to provide active and reactive power support to the system during faults, or by installing other devices such as SVCs. With the SVC switched on in the simulation model, the CCT of the generator G3 is extended by 40 ms in both scenarios.

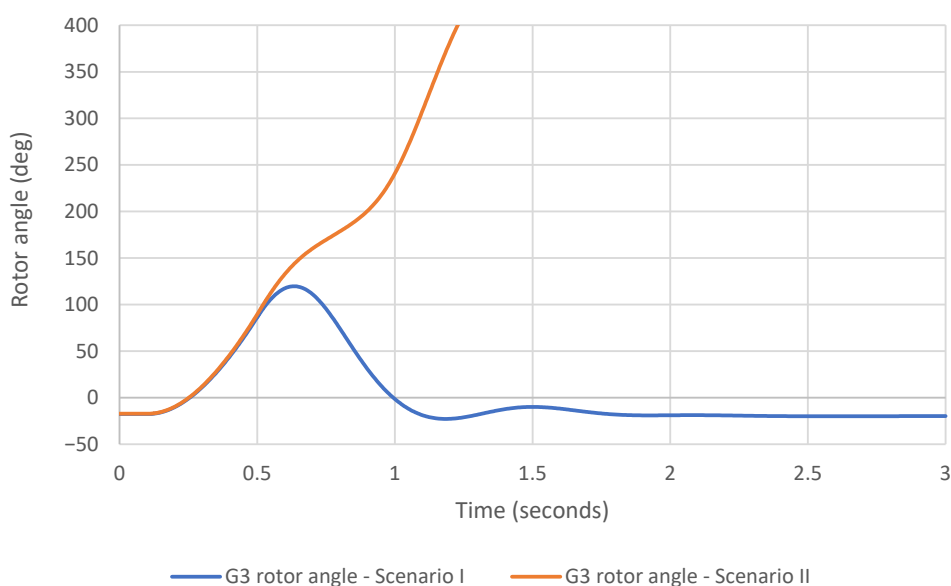


Figure 2. RESs' impact on G3 rotor angle oscillations.

4. SVC

Static var compensators (SVCs) are some of the most used FACTS devices in power systems, which belong to the first generation of thyristor-based FACTSs. Their primary goal is to support the bus voltage by injecting or absorbing reactive power. They consist of a combination of two different devices: a TCR (thyristor-controlled reactor) and a TSC (thyristor-switched capacitor). TCRs consist of a shunt-connected reactor controlled by two parallel, reverse-controlled thyristors. TSCs have a similar composition to TCRs, but the reactor is replaced by a capacitor. While TCRs have the possibility of continuous reactive power control through the firing angle input, TSCs offer control in steps determined by the number of capacitor banks. By connecting suitable variable and fixed reactors and capacitors in parallel, SVCs can have the possibility of continuous reactive power control in their connection point [7,25]. A circuit diagram of an SVC is shown in Figure 3.

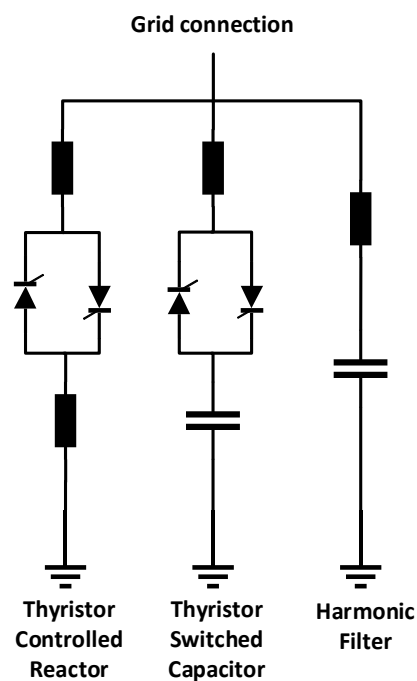


Figure 3. Circuit diagram of an SVC.

5. Proposed Control Strategy

The proposed SVC control strategy is shown in Figure 4. The first step of the proposed strategy consists of collecting synchronized voltage phasor measurements on the synchronous generator buses and their adjacent buses. The collected measurements then serve as inputs for the optimization algorithm, which determines the amount of SVC reactive power required to dampen the active power and rotor angle oscillations of the synchronous generators. The new reference voltage is calculated from the reactive power and adjusted on the SVC by a simple previously tuned PI controller. Particle swarm optimization (PSO) was chosen as the optimization algorithm due to its reliability and precision in obtaining results. It also has a short calculation time. If there are no active power oscillations in the system, the SVC reference point remains as initially set. The same applies after the transient condition passes, and if the mechanical power of the generator remains unchanged, the SVC returns to the initial setting.

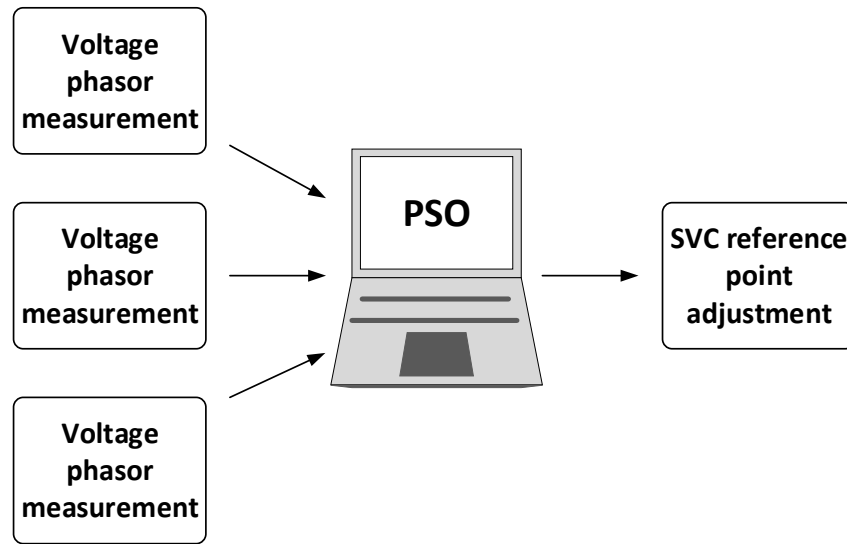


Figure 4. Proposed SVC control strategy.

Before applying the proposed strategy, it is necessary to determine the line admittances that enter the calculation of the synchronous generators' active power oscillations, as well as the sensitivity coefficients of the voltages that enter the same calculation to the amount of injected reactive power of the SVC.

5.1. Particle Swarm Optimization

PSO is a stochastic algorithm based on a population of solutions, inspired by the behavior of flocks of birds and schools of fish. A swarm consists of a series of particles that search for a possible solution within a defined space. In each iteration, the velocity and position of these particles are adjusted to find the optimal solution of the given objective function [26]. The swarm behavior in PSO is described by two equations, which make this algorithm simple and accessible for use. The velocity vector v_i^{k+1} and the position vector x_i^{k+1} of the particles in every iteration are calculated using the following expressions [27]:

$$v_i^{k+1} = \omega v_i^k + c_1 r_1 (pbest_i^k - x_i^k) + c_2 r_2 (gbest_i^k - x_i^k) \quad (1)$$

$$x_i^{k+1} = x_i^k + v_i^{k+1} \quad (2)$$

where ω , c_1 , and c_2 are constants, r_1 and r_2 random numbers between 0 and 1, and $pbest_i^k$ and $gbest_i^k$ are the best local and global particle positions in the previous iteration.

Another important feature of the PSO algorithm is that it is largely unaffected by the size and non-linearity of a problem and can converge to the optimal solution in most cases. For this reason, it is applied to various optimization problems in power systems [26].

In this paper, PSO is used to determine the optimal amount of the SVC reactive power required for damping the oscillations of the synchronous generators' active power at certain moments. The optimization algorithm calculates the minimum of the following objective function:

$$\Sigma |P_{ei} - P_{mi}| \quad (3)$$

where P_{ei} is the active power of the synchronous generator i in the system and P_{mi} is its mechanical power. In the event of a disturbance, an imbalance between these two powers will occur on swinging generators. According to the swing Equation (4), which describes the dynamic behavior of a synchronous generator during a disturbance by reducing power oscillations, the swinging generators' rotor angle oscillations will also be reduced. The swing equation is given by the following expression [28]:

$$\frac{2H_i}{\omega_0} \frac{d^2\delta_i}{dt^2} = P_{ei} - P_{mi} \quad (4)$$

where H is an inertia constant, ω_0 is the synchronous speed, δ is the rotor angle, and P_{ei} and P_{mi} are the active and mechanical power of the synchronous generator i . The active power of an individual generator is calculated according to the expression [28]:

$$P_{ei} = |U_i|^2 \text{real}(Y_{ii}) + \sum_{j \neq i} |U_i| |U_j| |Y_{ij}| \cos(\delta_i - \delta_j - \theta_{ij}) \quad (5)$$

where U_i is the voltage of the generator bus, U_j is the voltage of its adjacent buses, Y is the admittance matrix of the observed system, and δ_i , δ_j , and θ_{ij} are the voltage and admittance angles. For calculating Equation (5), only the admittances of the synchronous generator buses and the admittances of the lines by which they are connected to adjacent buses are needed. All equations are expressed in the per-unit system.

5.2. Sensitivity Analysis

A sensitivity analysis is performed to determine the influence of the SVC reactive power injection on the bus voltages that enter the PSO algorithm. To determine the optimal amount of SVC reactive power injection for damping the synchronous generators' active power oscillations, it is necessary to consider the sensitivity coefficients of the voltage amplitude U_i and angle δ_i in Equation (5), according to the expressions:

$$U_i = U_{mi} + K_{Ui} \Delta Q \quad (6)$$

$$\delta_i = \delta_{mi} + K_{\delta i} \Delta Q \quad (7)$$

where U_{mi} and δ_{mi} are measured values of the voltage amplitude and angle at a certain moment, ΔQ is the change in the SVC reactive power injection, and K_{Ui} and $K_{\delta i}$ are the sensitivity coefficients of the voltage amplitude and angle to ΔQ . Thus, Equation (5) becomes:

$$P_{ei} = |U_{mi} + K_{Ui} \Delta Q|^2 \text{real}(Y_{ii}) + \sum_{j \neq i} |U_{mi} + K_{Ui} \Delta Q| |U_{mj} + K_{Uj} \Delta Q| |Y_{ij}| \cos(\delta_{mi} + K_{\delta i} \Delta Q - (\delta_{mj} + K_{\delta j} \Delta Q) - \theta_{ij}) \quad (8)$$

When Equation (8) is combined with the objective function in Equation (3), the PSO algorithm can calculate the optimal ΔQ for damping the synchronous generators' power and rotor angle oscillations at any given moment, which is then used to adjust the SVC setting.

The conditions during a fault are different from those in a steady state, therefore, the sensitivity coefficients during the transient condition are different from those during normal system operation. During a disturbance, such as a short circuit, a voltage drop occurs on nearby buses, and generators must meet the high reactive power demand. For this reason, it is not possible to calculate the sensitivity coefficients for generator buses using classical methods based on power flows. In this paper, the coefficients are determined through a certain number of simulations and are calculated for different power injections, according to the expressions:

$$K_{Ui} = \frac{\Delta U_i}{\Delta Q} \quad (9)$$

$$K_{\delta i} = \frac{\Delta \delta_i}{\Delta Q} \quad (10)$$

6. Simulation Procedure

Simulations are carried out in the DigSILENT PowerFactory 2022 software package to test the proposed SVC control strategy during transient conditions. A loss of transient stability mainly occurs due to a continuous increase in the rotor angle due to insufficient synchronizing torque. In this case, the generator often falls out of synchronism in the first swing of the rotor angle. This loss of synchronism can also occur after a stable first swing due to insufficient damping of the rotor angle oscillations [28]. The proposed control strategy reduces the amplitude and slope of the rotor angle oscillation curve of the synchronous generators in the system. This reduced angle curve slope means reduced speed deviations of the generators. The time frame of interest in transient stability analysis ranges between 3 and 5 s from the onset of the disturbance.

As already stated in the introduction, an SVC without auxiliary controls does not contribute to oscillation damping. For this reason, the performance of the SVC without a damping function was compared with that of the SVC with the proposed control strategy. The simulation procedure will be explained on the generator G3 from the simulation model shown in Figure 1. The three-phase short circuit in this scenario is on the 220 kV transmission line 2-3 and lasts 100 ms. The start of the short circuit is at 0.1 s and the line is disconnected at 0.2 s.

Before the simulation, it is necessary to carry out a sensitivity analysis for the observed short circuit. The sensitivity coefficients are calculated for the voltage amplitude and angle according to Equation (9) and Equation (10) during the transient condition in 80 ms intervals, with ΔQ ranging from -120 Mvar to 125 Mvar. Their average value is then used in Equation (8). Figures 5 and 6 show some of the calculated voltage amplitude and angle sensitivity coefficients during the transient condition for 220 kV buses 1-5 of the simulation model. Coefficient values are shown for the first 500 ms of the calculation. In all simulations, the observed generators are those connected to the 220 kV voltage level, to which the SVC is also connected, due to their much higher sensitivity to the SVC reactive power injection compared to the generators connected to the 110 kV voltage level. This was concluded from the performed voltage sensitivity analysis.

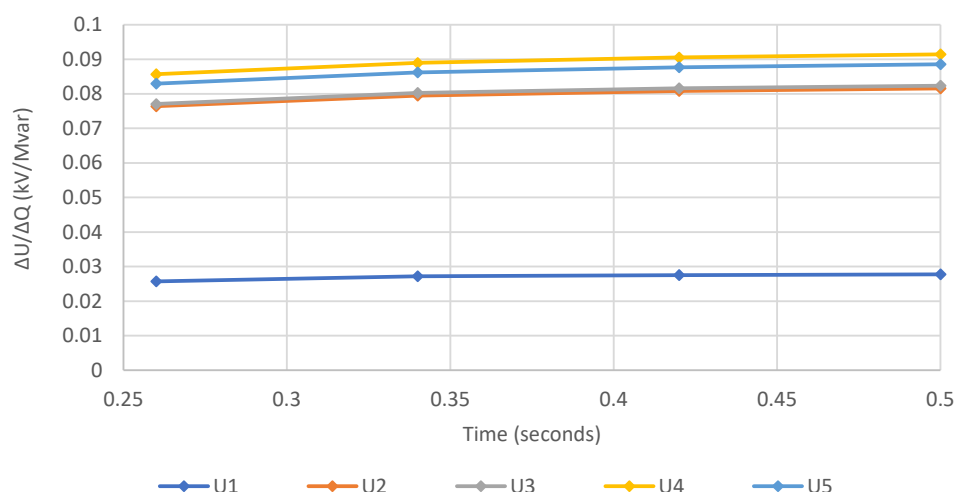


Figure 5. Voltage amplitude sensitivity coefficients.

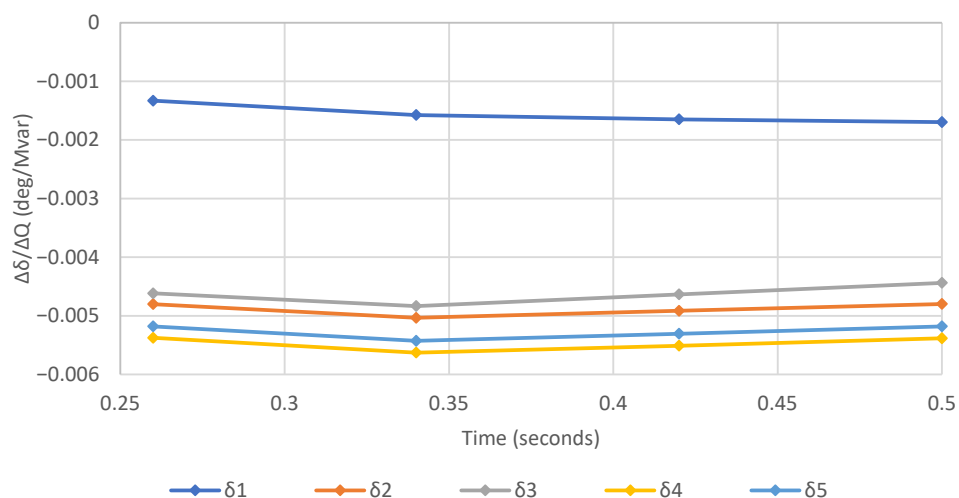


Figure 6. Voltage angle sensitivity coefficients.

The first step of the simulation procedure is to collect the voltage amplitude and angle values required for the calculation of P_{e3} according to Equation (5). In a real power system, this step would be conducted by collecting synchronized voltage phasor measurements from PMUs. The collected data enter the PSO algorithm written in the Python programming language, which determines the amount of ΔQ needed to obtain the minimum of the objective function in Equation (3). The swarm consists of 20 particles, the usual number for problems of small dimensions [29], and the global optimum is determined after 100 iterations. The PSO algorithm calculation time is around 10 ms. From the ΔQ determined by the optimization, a new reference voltage setting U_{ref} is calculated and adjusted on the SVC according to the expression:

$$U_{ref} = U_{m4} + K_{U4}\Delta Q \quad (11)$$

where U_{m4} is the voltage amplitude of the SVC connection bus measured at certain moments and K_{U4} is its voltage amplitude sensitivity coefficient to ΔQ . The process is repeated every 80 ms to collect the necessary data, execute the optimization algorithm, and send the setting command to the SVC. The specified interval can be shorter, depending on the speed of the used technology. Table 1 shows the obtained U_{ref} values that are adjusted on the SVC at the indicated times. During a short circuit due to a voltage drop on the SVC, it is determined that it is optimal to keep U_{ref} at the initial setting, the same as before the short circuit occurrence.

Table 1. Calculated SVC reference voltage settings.

Time (s)	U_{ref} (pu)	Time (s)	U_{ref} (pu)
0.18	1.00	0.66	1.05
0.26	0.80	0.74	1.07
0.34	0.75	0.82	1.07
0.42	0.88	0.90	1.05
0.50	1.02	0.98	1.02
0.58	1.05	1.06	1.00

Figures 7 and 8 show how the SVC affects the active power and rotor angle oscillations of the observed generator. Each figure shows two curves. The blue curve represents

the case of the SVC with the proposed control strategy, and the red curve represents the case of the SVC with no auxiliary control.

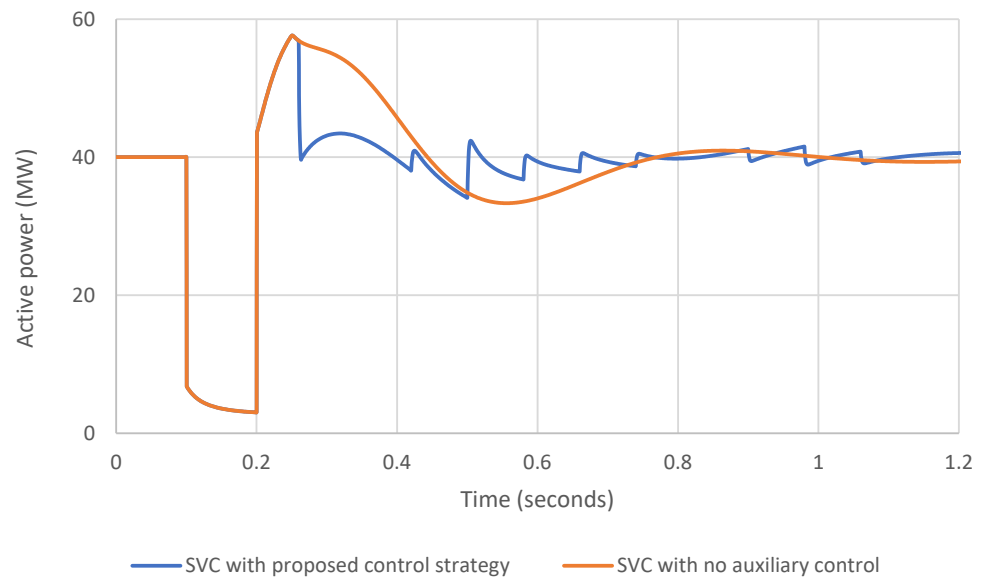


Figure 7. SVC impact on G3 active power oscillations.

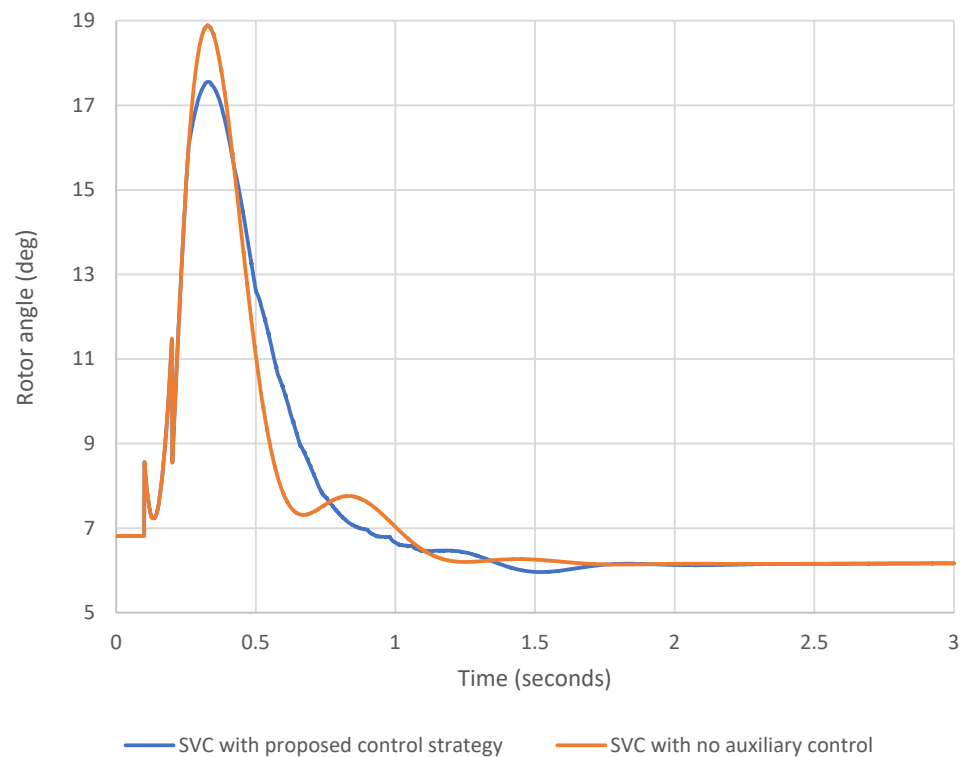


Figure 8. SVC impact on G3 rotor angle oscillations.

From Figure 7, it is evident that the SVC with U_{ref} adjusted according to Table 1 reduces the difference between the generator's mechanical and active power at given

moments, and it can be seen from Figure 8 that it successfully reduces the amplitude and slope of the generator rotor angle oscillation curve.

7. Simulation Results

7.1. Three-Phase Short Circuit on Line 2-3

The simulation results described below show the case of damping the oscillations of the generators G2 and G3 connected to bus 2 and bus 3 of the simulation model from Figure 6. The location of the short circuit is the same as in the demonstration example, with the same duration of 100 ms. In this case, the SVC setting is also adjusted every 80 ms. Oscillation damping for multiple generators is performed according to the object function in Equation (3), in which the sum of the absolute differences between the active and mechanical power of individual generators is minimized, where the active power of an individual generator is calculated according to Equation (8).

The obtained SVC settings for damping the oscillations of the generators G2 and G3 are shown in Table 2. When compared with the results from Table 1, it can be seen that the oscillations last longer in the case of damping the oscillations of multiple generators. Despite this, the mentioned oscillations are of a small amplitude and do not endanger the generators.

Table 2. Calculated SVC reference voltage settings for short circuit on line 2-3.

Time (s)	U_{ref} (pu)	Time (s)	U_{ref} (pu)
0.18	1.00	0.90	1.06
0.26	0.78	0.98	1.05
0.34	0.75	1.06	1.04
0.42	0.88	1.14	1.03
0.50	0.97	1.22	1.03
0.58	1.00	1.30	1.02
0.66	1.03	1.38	1.02
0.74	1.05	1.46	1.01
0.82	1.06	1.54	1.00

Figures 9 and 10 show how the SVC affects the rotor angle oscillations of the generators G2 and G3. In both figures, the blue curve represents oscillations in the case of the SVC with the proposed control strategy, and the red curve represents oscillations in the case of the SVC with no auxiliary control. The SVC with the obtained voltage reference settings from Table 2 successfully dampens the oscillations of both generators, especially during the first swing, which is the most important for preserving transient stability.

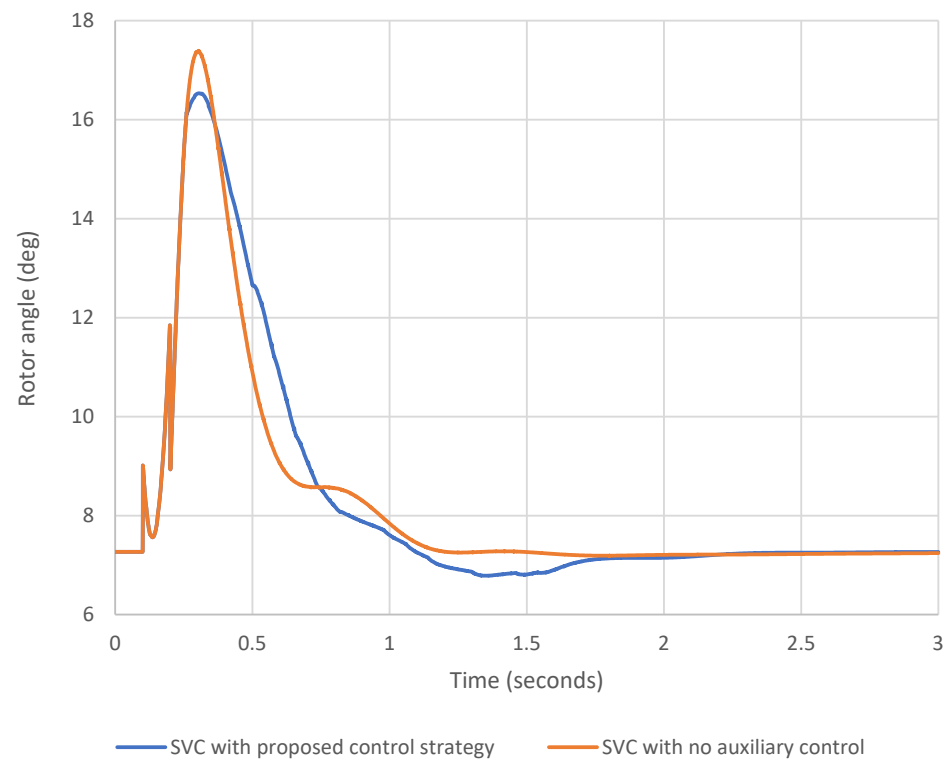


Figure 9. SVC impact on G2 rotor angle oscillations.

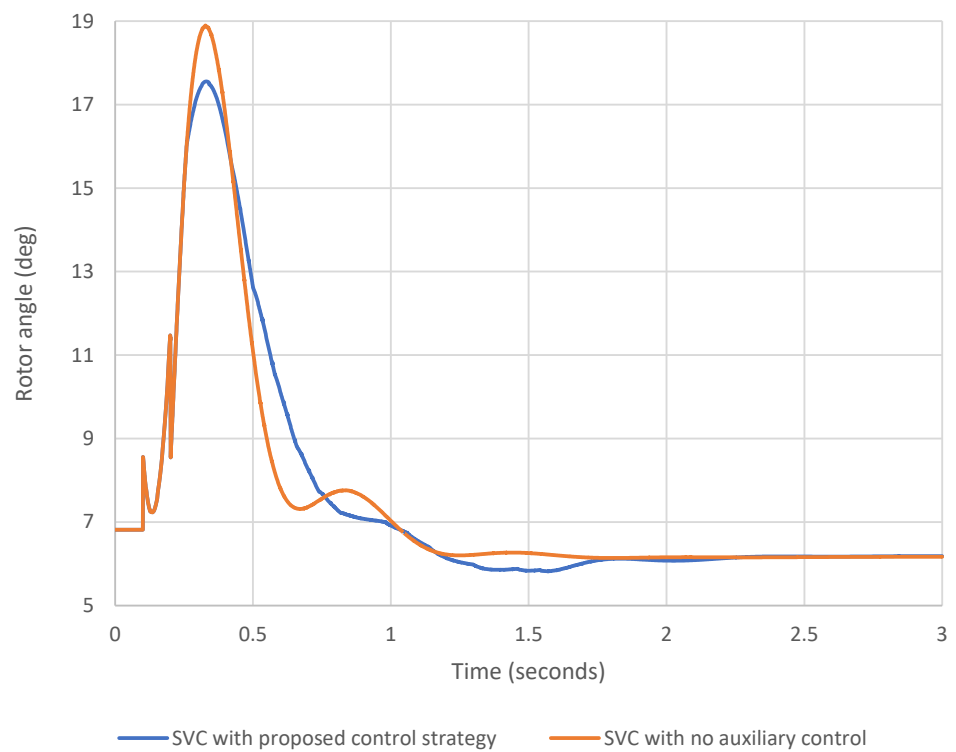


Figure 10. SVC impact on G3 rotor angle oscillations.

7.2. Three-Phase Short Circuit on Line 3-4

In this simulation scenario, there is a short circuit on transmission line 3-4, and the oscillations of the generators G2 and G3 are damped. The duration of the short circuit is 100 ms, starting at 0.1 s. After 100 ms, line 3-4 is disconnected. Considering the change in the system topology compared to the previous scenario, it is necessary to calculate the new sensitivity coefficients of the voltage amplitude and angle to the injected reactive power of the SVC. The biggest difference between the new and previously used coefficients is calculated for bus 3 and bus 4 due to the disconnection of the lines connecting them. The other sensitivity coefficients are approximately equal to those from previous simulations. The simulation is then performed according to the same procedure as the previous ones.

The obtained SVC settings for damping the oscillations of the generators G2 and G3 are shown in Table 1, while Figures 11 and 12 show the damping of the rotor angle oscillations of the generators G2 and G3, with cases with the proposed SVC control strategy shown in blue and those without the proposed SVC control strategy shown in red. It can be concluded from the figures that the SVC with the obtained voltage reference settings from Table 3 successfully dampens the oscillations of both generators.

Table 3. Calculated SVC reference voltage settings for short circuit on line 3-4.

Time (s)	U_{ref} (pu)	Time (s)	U_{ref} (pu)
0.18	1.00	0.74	1.06
0.26	0.81	0.82	1.07
0.34	0.77	0.90	1.06
0.42	0.86	0.98	1.05
0.50	0.98	1.06	1.03
0.58	1.01	1.14	1.02
0.66	1.04	1.22	1.00

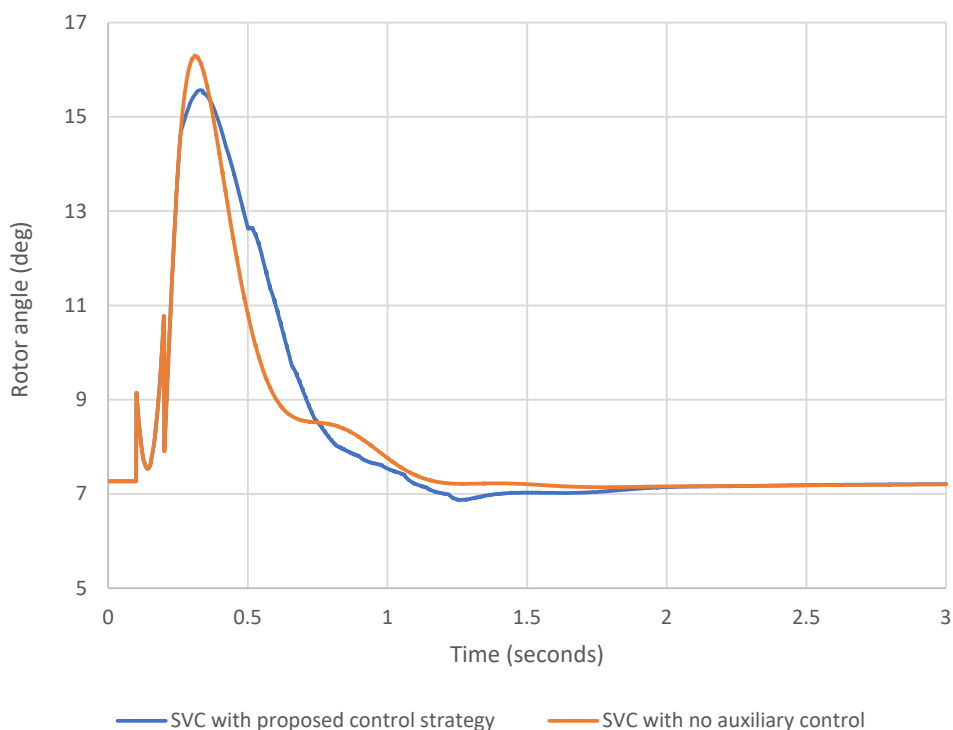


Figure 11. SVC impact on G2 rotor angle oscillations.

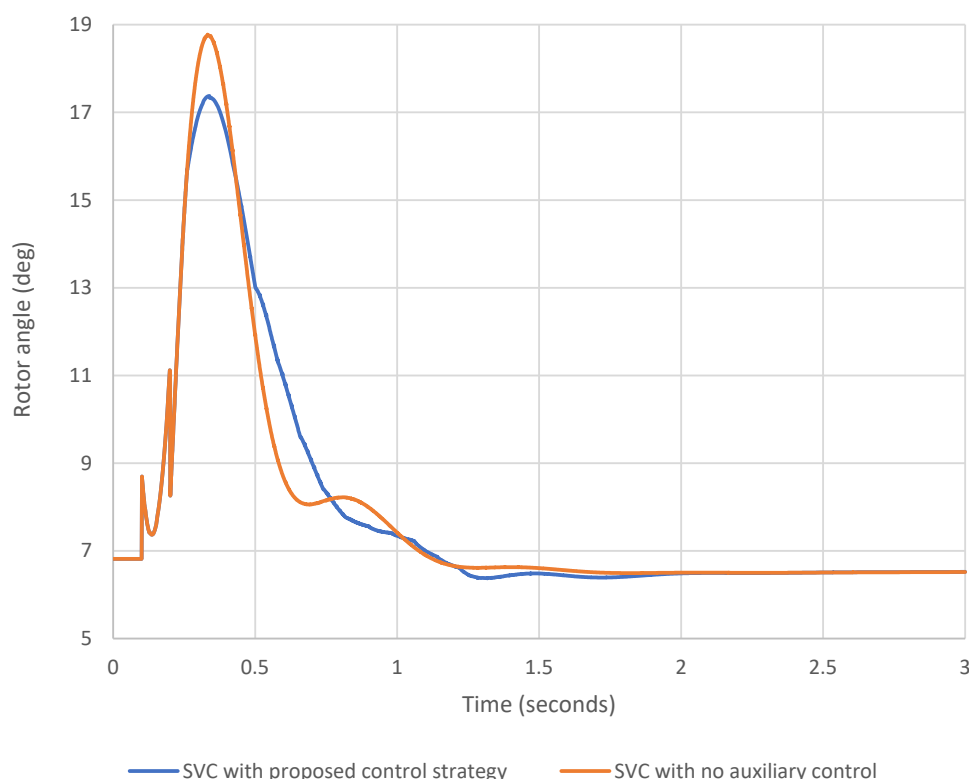


Figure 12. SVC impact on G3 rotor angle oscillations.

8. Discussion

This paper presents an SVC control strategy based on collecting voltage phasor measurements through PMUs and calculating the device's optimal reactive power injection using particle swarm optimization. The PSO algorithm is based on the sensitivity coefficients used to determine the SVC reactive power required for damping the active power oscillations of synchronous generators in fault conditions. This kind of use of sensitivity coefficients was not found in the researched literature.

The main advantage of the proposed strategy is the use of a relatively simple and fast PSO algorithm suitable for real-time SVC control. Another advantage is that the control strategy can be used to simultaneously dampen the rotor angle oscillations of multiple generators in the system by utilizing already installed SVCs and PMUs. The main limitations of the proposed strategy are the sensitivity coefficients that need to be calculated in advance, depending on the network topology in the area of the SVC's operation. Also, potential delays in PMU measurements can have a negative impact on the accuracy of the PSO output data.

The proposed strategy was tested through simulations in the DIgSILENT PowerFactory 2022 software package on the IEEE 14-bus system. The simulation results showed that an SVC with the proposed control strategy effectively minimized the amplitude of power oscillations during large disturbances, resulting in reduced speed deviations and rotor angle oscillations of generators. Although demonstrated for SVC control, the given strategy can also be used for STATCOM control. To determine the true extent of an SVC's influence on transient stability, the strategy should be tested on a larger, more realistic system, which will be the focus of future works.

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A.Š and I.P.; data curation, A.Š and I.P.; writing—original draft preparation, A.Š.; writing—review and editing, A.Š and I.P.; visualization, A.Š and I.P.; supervision, I.P. All authors have read and agreed to the published version of the manuscript.

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References

- Hatziargyriou, N.; Milanovic, J.; Rahmann, C.; Ajarapu, V.; Canizares, C.; Erlich, I.; Hill, D.; Hiskens, I.; Kamwa, I.; Pal, B.; et al. Definition and Classification of Power System Stability—Revisited & Extended. *IEEE Trans. Power Syst.* **2021**, *36*, 3271–3281. <https://doi.org/10.1109/tpwrs.2020.3041774>.
- Kundur, P.; Paserba, J.; Ajarapu, V.; Andersson, G.; Bose, A.; Canizares, C.; Hatziargyriou, N.; Hill, D.; Stankovic, A.; Taylor, C.; et al. Definition and classification of power system stability IEEE/CIGRE joint task force on stability terms and definitions. *IEEE Trans. Power Syst.* **2004**, *19*, 1387–1401. <https://doi.org/10.1109/tpwrs.2004.825981>.
- Hingorani, N.G.; Gyugyi, L. *Understanding FACTS: Concepts and Technology of Flexible AC Transmission Systems*; Wiley-IEEE Press: Hoboken, NJ, USA, 2000.
- Dahat, S.A.; Dhabale, A. Analysis of the combined effects of SVC and SSSC controllers to improve power system stability. *Energy Rep.* **2023**, *9*, 445–454. <https://doi.org/10.1016/j.egy.2023.09.064>.
- Singh, R.K.; Singh, N.K. Power system transient stability improvement with FACTS controllers using SSSC-based controller. *Sustain. Energy Technol. Assess.* **2022**, *53*, 102664. <https://doi.org/10.1016/j.seta.2022.102664>.
- Vetoshkin, L.; Muller, Z. Dynamic Stability Improvement of Power System by Means of STATCOM with Virtual Inertia. *IEEE Access* **2021**, *9*, 116105–116114. <https://doi.org/10.1109/access.2021.3106236>.
- Siddique, A.; Xu, Y.; Aslam, W.; Rasheed, M. A Comprehensive Study on FACTS Devices to Improve the Stability and Power Flow Capability in Power System. In Proceedings of the 2019 Asia Power and Energy Engineering Conference, APEEC 2019, Chengdu, China, 29–31 March 2019; pp. 199–205. <https://doi.org/10.1109/APEEC.2019.8720685>.
- Welhazi, Y.; Guesmi, T.; Alshammari, B.M.; Alqunun, K.; Alateeq, A.; Almalaq, Y.; Alsabhan, R.; Abdallah, H.H. A Novel Hybrid Chaotic Jaya and Sequential Quadratic Programming Method for Robust Design of Power System Stabilizers and Static VAR Compensator. *Energies* **2022**, *15*, 860. <https://doi.org/10.3390/en15030860>.
- Farah, A.; Belazi, A.; Alqunun, K.; Almalaq, A.; Alshammari, B.M.; Ben Hamida, M.B.; Abbassi, R. A New Design Method for Optimal Parameters Setting of PSSs and SVC Damping Controllers to Alleviate Power System Stability Problem. *Energies* **2021**, *14*, 7312. <https://doi.org/10.3390/en14217312>.
- Guesmi, T.; Alshammari, B.M.; Almalaq, Y.; Alateeq, A.; Alqunun, K. New Coordinated Tuning of SVC and PSSs in Multimachine Power System Using Coyote Optimization Algorithm. *Sustainability* **2021**, *13*, 3131. <https://doi.org/10.3390/su13063131>.
- Benayad, K.; Zabaoui, T.; Bouafassa, A. Wide-Area Based SVC-Fractional Order PID Controller For Damping Inter-Area Oscillations. In Proceedings of the 2020 6th IEEE International Energy Conference (ENERGYCon), Gammarth, Tunisia, 28 September–1 October 2020; pp. 610–615. <https://doi.org/10.1109/ENERGYCon48941.2020.9236492>.
- Kamari, N.A.M.; Musirin, I.; Ibrahim, A.A. Swarm Intelligence Approach for Angle Stability Improvement of PSS and SVC-Based SMIB. *J. Electr. Eng. Technol.* **2020**, *15*, 1001–1014. <https://doi.org/10.1007/s42835-020-00386-w>.
- Keskes, S.; Bouchiba, N.; Sallem, S.; Chrifi-Alaoui, L.; Kammoun, M. Transient stability enhancement and voltage regulation in SMIB power system using SVC with PI controller. In Proceedings of the 2017 6th IEEE International Conference on Systems and Control (ICSC), Batna, Algeria, 7–9 May 2017; pp. 115–120. <https://doi.org/10.1109/ICoSC.2017.7958729>.
- Kumar, A.; Dubey, S.B. Enhancement of Transient Stability in Transmission Line Using SVC Facts Controller. *Int. J. Recent Technol. Eng. (IJRTE)* **2013**, *2*, 2277–3878. Available online: www.ijrte.org (accessed on 10 July 2024).
- Haque, M. Improvement of First Swing Stability Limit by Utilizing Full Benefit of Shunt FACTS Devices. *IEEE Trans. Power Syst.* **2004**, *19*, 1894–1902. <https://doi.org/10.1109/tpwrs.2004.836243>.
- Mithulananthan, N.; Canizares, C.; Reeve, J.; Rogers, G. Comparison of PSS, SVC, and STATCOM controllers for damping power system oscillations. *IEEE Trans. Power Syst.* **2003**, *18*, 786–792. <https://doi.org/10.1109/tpwrs.2003.811181>.
- Mira-Gebauer, N.; Rahmann, C.; Alvarez-Malebrán, R.; Vittal, V. Review of Wide-Area Controllers for Supporting Power System Stability. *IEEE Access* **2023**, *11*, 8073–8095. <https://doi.org/10.1109/access.2023.3237576>.
- Khan, M.T.; Siddiqui, A.S. FACTS device control strategy using PMU. *Perspect. Sci.* **2016**, *8*, 730–732. <https://doi.org/10.1016/j.pisc.2016.06.072>.
- Karavas, C.-S.G.; Plakas, K.A.; Krommydas, K.F.; Kurashvili, A.S.; Dikaiakos, C.N.; Papaioannou, G.P. A Review of Wide-Area Monitoring and Damping Control Systems in Europe. In Proceedings of the 2021 IEEE Madrid PowerTech, Madrid, Spain, 28 June–2 July 2021; pp. 1–6. <https://doi.org/10.1109/PowerTech46648.2021.9495037>.
- Espazza, A.; Segundo, J.; Nuñez, C.; Visairo, N.; Barocio, E.; García, H. Transient Stability Enhancement Using a Wide-Area Controlled SVC: An HIL Validation Approach. *Energies* **2018**, *11*, 1639. <https://doi.org/10.3390/en11071639>.

21. Vahidnia, A.; Ledwich, G.; Palmer, E.W. Transient Stability Improvement Through Wide-Area Controlled SVCs. *IEEE Trans. Power Syst.* **2016**, *31*, 3082–3089. <https://doi.org/10.1109/tpwrs.2015.2473670>.
22. Venayagamoorthy, G.; Jetti, S. A Dual function neuron based external controller for a static var compensator. In Proceedings of the 2008 IEEE Power and Energy Society General Meeting—Conversion and Delivery of Electrical Energy in the 21st Century, Pittsburgh, PA, USA, 20–24 July 2008; p. 1. doi: 10.1109/PES.2008.4596659.
23. Chang, Y.; Xu, Z. A novel SVC supplementary controller based on wide area signals. *Electr. Power Syst. Res.* **2007**, *77*, 1569–1574. <https://doi.org/10.1016/j.epsr.2006.11.002>.
24. Demetriou, P.; Asprou, M.; Quiros-Tortos, J.; Kyriakides, E. Dynamic IEEE Test Systems for Transient Analysis. *IEEE Syst. J.* **2017**, *11*, 2108–2117. <https://doi.org/10.1109/jsyst.2015.2444893>.
25. Igbinoia, F.O.; Fandi, G.; Svec, J.; Muller, Z.; Tlustý, J. Comparative review of reactive power compensation technologies. In Proceedings of the 2015 16th IEEE International Scientific Conference on Electric Power Engineering (EPE), Kouty nad Desnou, Czech Republic, 20–22 May 2015; pp. 2–7. <https://doi.org/10.1109/EPE.2015.7161066>.
26. del Valle, Y.; Venayagamoorthy, G.K.; Mohagheghi, S.; Hernandez, J.-C.; Harley, R.G. Particle Swarm Optimization: Basic Concepts, Variants and Applications in Power Systems. *IEEE Trans. Evol. Comput.* **2008**, *12*, 171–195. <https://doi.org/10.1109/tevc.2007.896686>.
27. AlRashidi, M.R.; El-Hawary, M.E. A Survey of Particle Swarm Optimization Applications in Electric Power Systems. *IEEE Trans. Evol. Comput.* **2009**, *13*, 913–918. <https://doi.org/10.1109/tevc.2006.880326>.
28. Kundur, P. *Power System Stability and Control*; McGraw-Hill: New York, NY, USA, 1994.
29. Piotrowski, A.P.; Napiorkowski, J.J.; Piotrowska, A.E. Population size in Particle Swarm Optimization. *Swarm Evol. Comput.* **2020**, *58*, 100718. <https://doi.org/10.1016/j.swevo.2020.100718>.

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