Influence of Power Oscillation Damping Assets Reactive Power Capacity on Damping Low-Frequency Power System Oscillations

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Abstract

Over the past ten years, the paradigm has shifted from conventional power generation to renewable generation. Large integration of these renewable energy sources (RES) into the power system poses challenges to system operators, leading them to put stringent requirements for their grid connection. Displacement of synchronous generators by RES reduces system inertia and consequently decreases the system damping capability of electromechanical oscillations. Poorly damped interarea oscillations reduce the transmission line's capacities and may damage power system components. Hence, future grid codes will require wind and solar power plants to provide damping to the system. Several papers have proposed adding an auxiliary damping controller to the wind turbine control algorithm to damp the low-frequency oscillations (LFOs) by modulating active or reactive power. However, these studies have not mentioned if small power plants can damp LFOs in a multimachine system. Therefore, this paper investigates the influence of reactive power capacity on the damping of LFOs and its effects on optimal controller parameters using a simplified SVC model connected at the midpoint of the tie line of a two-area test system. A local feedback signal is selected as the input signal to the SVC damping controller. Controller parameters are optimized using the particle swarm optimization algorithm. Time-domain simulations performed in PowerFactory software demonstrate the damping behavior of the controller at different SVC ratings. The results show a minimum reactive power capacity is required for effective damping of power system oscillations.

Keywords: Electromechanical oscillations, static var compensator (SVC), wind energy, power oscillation damping

1. Introduction

The energy transition necessitated by Fukushima nuclear power plant accident in 2011 has seen a tremendous growth of renewable energy technologies. Wind energy is the fastest and the most developed renewable energy resource, with a global capacity of 837 GW [1]. Another factor contributing to the huge share of renewable energy sources (RES) in the power generation mix is the global call for countries to embrace energy sources that are free from pollutant gases that threaten the climate. Many countries have invested heavily in offshore and onshore wind turbines to achieve their carbon zero targets. For example, Germany plans to close its last nuclear power plant this year (2022) and coal-fired power plants by 2038 [2]. Despite the significant contribution of wind energy to the power generation mix, there is a big concern from the transmission system operators (TSOs) regarding the capability of wind power plants (WPPs) to offer grid ancillary services, especially damping electromechanical oscillations.

Integration of WPPs into the power system has both beneficial and detrimental effects on damping low-frequency power system oscillations [3]. The interaction of wind turbine generators and synchronous generator controllers decreases the damping of electromechanical oscillations. Furthermore, WPPs displace synchronous generators, which leads to a reduction of system inertia. Additionally, critical power system stabilizers (PSSs) associated with displaced generators will be out of service, further deteriorating the damping [4]–[6]. On the other hand, the extensive integration of WPPs can positively impact the damping of power system oscillations; however, the positive damping contribution is dependent on the controller technology used [7]–[9]. The consensus is that WPPs integration reduces the system inertia, consequently decreasing the damping of power system oscillations [10].

The negative effect on system damping by WPPs has necessitated some TSOs of countries such as Sweden, Hydro-Quebec, Australia, and Finland to include power oscillation damping requirements by WPPs in their grid codes [11]–[14]. Traditionally, the PSSs attached to automatic voltage regulators of synchronous generators are used to damp low-frequency oscillations in power systems. Nevertheless, PSSs have limited capability to damp interarea oscillations due to low interarea modes observability in the local input signals [15]. The damping of interarea oscillations can be enhanced by supplementary power oscillation damping controllers attached to control loops of flexible AC transmission systems (FACTS) devices such as static var compensators (SVCs) and static synchronous compensators (STATCOMs).

To ameliorate the negative effect on system damping by wind power plant integration, researchers propose adding a supplementary damping controller to the wind turbine control system, similar to the concept of PSS in synchronous generators. In most of the research works, the authors have used aggregated models of wind farms [16]. But in practical application, each wind turbine converter in the WPP is equipped with a power oscillation damping controller. Therefore, it is essential to determine whether small WPPs with low reactive power capability can damp LFOs in a multimachine system. Thus an SVC equipped with a power oscillation damper (POD) is modelled in this study to investigate the influence of reactive power capacity on the damping of electromechanical oscillations and its effects on optimal controller parameters. The SVC reactive power rating is varied, and corresponding optimal parameters are obtained using the particle swarm optimization algorithm (PSO).

2. Study System Modelling

Modelling of power system components with their controllers, SVC, and POD controller is given below.

2.1 Power System Model

The study power system is the classical two-area-four-machine test system, as depicted in Figure 3. The detailed parameters of the model can be extracted from [17]. The system has been widely used as the benchmark test system for studying electromechanical oscillations in multimachine systems. It inherently exhibits both local and interarea oscillatory modes [17]. An SVC with a POD controller output attached to its voltage control loop is connected at the middle of the tie line 7-9 to enhance voltage stability, increase damping of oscillatory modes, and consequently improve power transmission capacity.

2.2 POD Model

The conventional PSS structure is the most widely adopted structure for implementing FACTS POD because of its simple design and ease of tuning its parameters [18]. The POD modulates the SVC reactive power output to provide the required damping. The POD structure and mathematical description are shown in (1) and Figure 1, respectively.

$$v_{pod} = K_{pod}\left(\frac{sT_W}{1+sT_W}\right)\left(\frac{1+sT_1}{1+sT_2}\right)\left(\frac{1+sT_3}{1+sT_4}\right)POD_{in} \qquad (1)$$

where K_{pod} is the gain, T_w is the washout filter time constant, and T_1, T_2, T_3, and T_4 are the lead-lag phase compensator time constants.

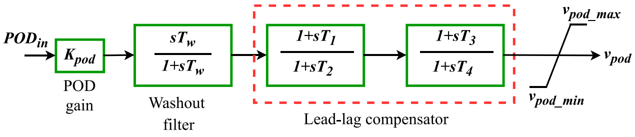

Figure 1. The structure of SVC POD

The SVC POD efficacy depends highly on the input signal; therefore, proper feedback signal selection is crucial. The residue-based method is the most common approach for selecting feedback signals for PODs. The signal with the highest residue magnitude is selected as the input signal [18]. There are two categories of POD input signals, i.e., local and remote. Some examples of local signals are local bus voltage and the transmission line's current or active power. In this study, the current of line2 8-9 is selected as the input signal. The POD controller that utilizes a local signal is called a local controller.

Remote signals are obtained from wide-area measurement systems that gather data from synchronized phasor measurement units located at different parts of the system. The signals are associated with high observability of the oscillatory modes but are prone to communication delays [19]. A POD controller whose input signal is a wide-area signal is called a wide-area controller.

The input signal is fed through a washout block, a high pass filter to remove the steady state component of the input signal so that it is only activated during transients. The gain determines the amount of damping introduced by SVC POD. A second-order lead-lag compensator provides the phase compensation such that the output signal opposes the original low-frequency oscillation. An anti-windup limiter is used to limit the SVC POD output signal to avoid interference with the normal operation of SVC. The output signal is limited to ±0.15 p.u.

2.3 SVC Model

There are different types of FACTS devices used in power systems, i.e., series, shunt, and a combination of series and shunt devices. An SVC system combines a shunt capacitor bank and thyristor-controlled shunt reactance (TCR). The shunt capacitor bank can be manually switched (MSC), or thyristor switched (TSC). The primary function of a static var system is to control the voltage at the directly connected busbar or a remote busbar by providing reactive power compensation [20]. Moreover, an SVC can be equipped with supplemental damping controls to damp power system oscillations, enhancing the power transfer capability [19]. A typical SVC system configuration is shown in Figure 2.

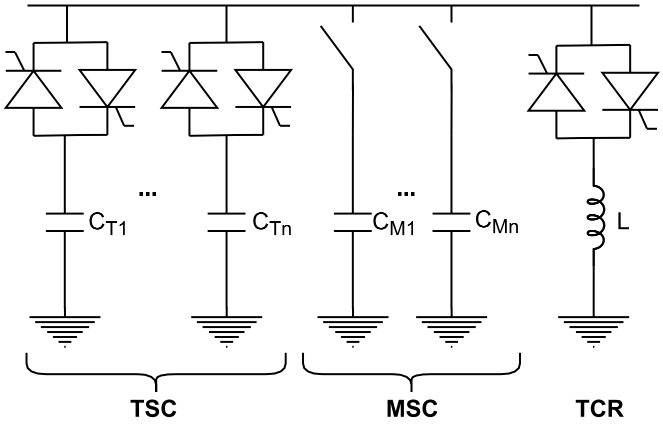

Figure 2. Static var system structure

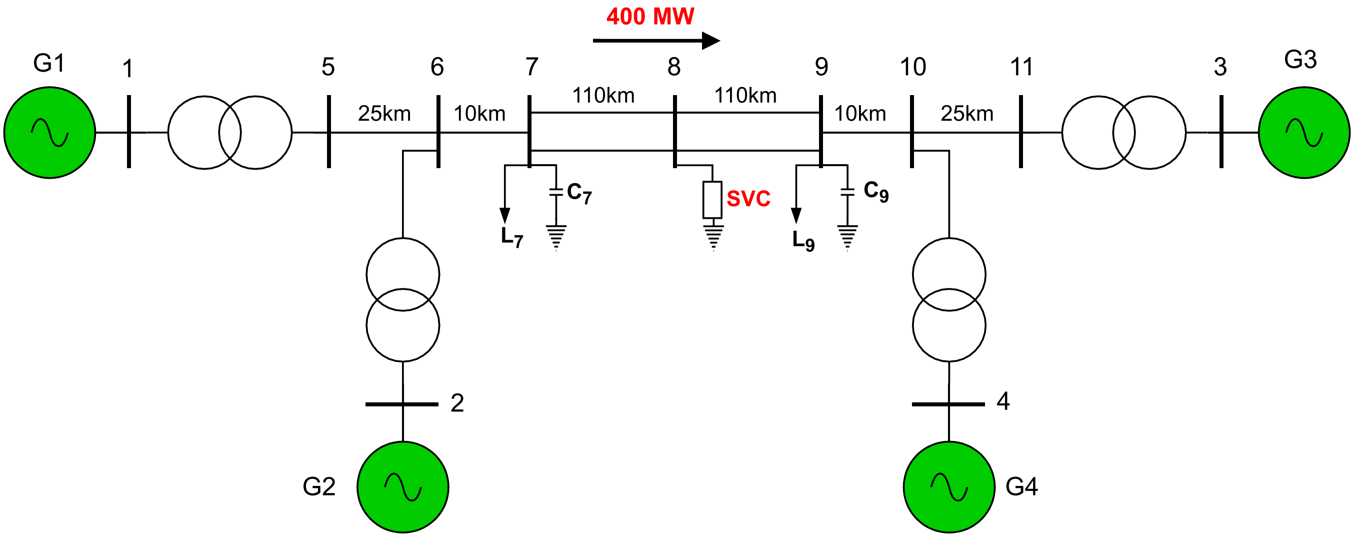

Figure 3. Two-area Four-machine Kundur test system

The SVC needs to change its output for dynamic simulations as the required reactive power changes over time. This paper uses the static var system (SVS) element in DIgSILENT software. The SVS element can be controlled in two ways, i.e., by controlling susceptance or the firing angle and switched capacitors. Control of SVS susceptance is adopted for this work. In this control approach, the SVS is composed of a TCR and fixed capacitors. A PI controller is used to control the SVS input signal b_{svs}. The total susceptance of the model is given by (2) [20].

$$y_{svs} = b_{svs} + Q_{fixcap} * n_{fixcap} \qquad (2)$$

where, b_{svs} is the reactance of TCR, Q_{fixcap} is the rating of fixed capacitor in Mvar and n_{fixcap} is the number of fixed capacitors. The dynamic SVS controller model is depicted in Figure 4. The values of K and T are the proportional gain and integral time constant of the SVS controller; v, v_{ref}, and v_{pod} are the measured system voltage, reference voltage, and supplementary POD signal, respectively. The POD signal provides an additional damping torque effect for low-frequency oscillations.

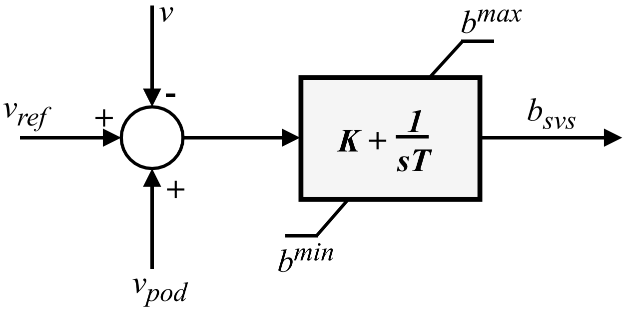

Figure 4. SVC with POD controller structure

The controller parameters K and T must be properly tuned for optimal SVC performance. The different approaches for tuning the controller parameter are described in 2.4.

2.4 SVC POD and Controller Parameter Optimization

The SVC POD and voltage controller parameters must be optimal to damp poorly damped electromechanical oscillations effectively. The modal/eigenvalue analysis technique is used to determine the poorly damped oscillations modes in a power system. Eigenvalue analysis of the study system reveals a poorly damped interarea mode of 0.558 Hz when the system is subjected to a disturbance.

Several techniques can be used to obtain the optimal parameters of the controller. Heuristic algorithms such as particle swarm optimization and genetic algorithm are the most widely used techniques [21]. These algorithms aim to minimize an objective function to increase damping ratios of critical oscillatory modes. The formulated objective function is minimized subject to controller parameter constraints. In this study, the objective is to minimize the low-frequency oscillations in the tie line active power. Therefore the objective function (OF) is formulated as shown in (3). The P_{ref} is the reference value of the tie line active power P.

$$\text{Minimize: } OF = \int_{T1}^{T2} (P - P_{ref})^2 \, dt \qquad (3)$$

Subject to

$$K_{pod,min} \leq K_{pod} \leq K_{pod,max}$$

$$K_{svc,min} \leq K_{svc} \leq K_{svc,max}$$

$$T_{svc,min} \leq T_{svc} \leq T_{svc,max}$$

$$T_{w,min} \leq T_w \leq T_{w,max}$$

$$T_{1,min} \leq T_1 \leq T_{1,max}$$

$$T_{2,min} \leq T_2 \leq T_{2,max}$$

$$T_{3,min} \leq T_3 \leq T_{3,max}$$

$$T_{4,min} \le T_4 \le T_{4,max}$$

The PSO algorithm embedded in PowerFactory software is used to optimize the SVC POD and SVC controller parameters by minimizing the objective function in (3). The lower and upper limits of T_w are set to 5s and 20s, respectively. For other time constants, the lower and upper limits are set to 0.01s and 2s, respectively, whereas the gains range is set from 0.01 to 200.

3. Simulation Results

The time-domain simulations are performed with the power system stabilizers of the four generators disabled. The damping of power oscillations is contributed only by the SVC POD controller. To demonstrate the effectiveness of the POD controller, a 5-cycle three-phase-to ground fault is applied to line1 7-8 at 0.5 seconds. At first, the SVC reactive power capacity is set to 100 Mvar. Parameter identification of both the SVC controller and POD is performed using the parameter identification tool in PowerFactory. SVC POD with optimized parameters effectively damps the electromechanical oscillation, as shown in Figure 5. Optimized controller parameters are summarized in Table 1.

Since this study aims to investigate whether small reactive power assets, such as small WPPs with little reactive power capacity, can damp power system oscillations, the reactive power capacity of the SVC is reduced to 50Mvar. Time domain simulations are repeated with the same parameters. A positive damping effect is noted, as illustrated in Figure 6, but it is not optimal. Hence, the parameter identification process is repeated, and there is a significant improvement in the damping with the newly optimized parameters. However, the damping effect is less than that achieved with 100 Mvar SVC, as shown in Figure 7. The SVC rating is further reduced to 30Mvar, and the parameter optimization procedure is repeated. The damping provided by the 30Mvar SVC POD is not optimal even with optimized controller parameters, as shown in Figure 8. It can be concluded that an increase in SVC reactive power capacity increases the damping capability of the selected modes.

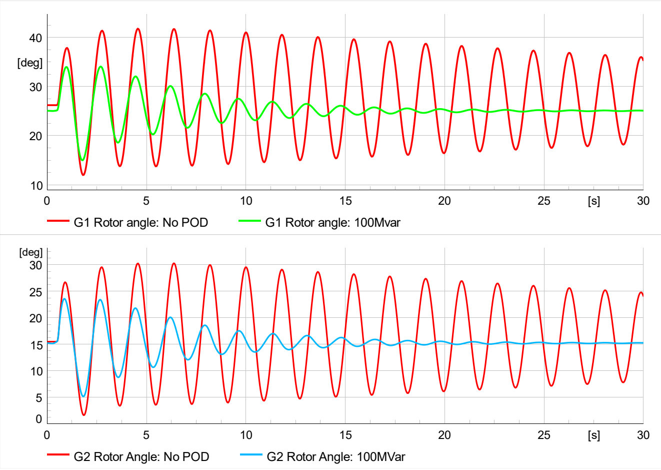

Figure 5. G1&G2 rotor angles with 100 Mvar SVC POD

Besides, a change in the rating of the SVC requires a repeat of POD parameter optimization to achieve optimal damping. It is worth noting that effective damping of power system oscillations is possible with as low as 30Mvar reactive power capacity as long as the controller parameters are appropriately tuned.

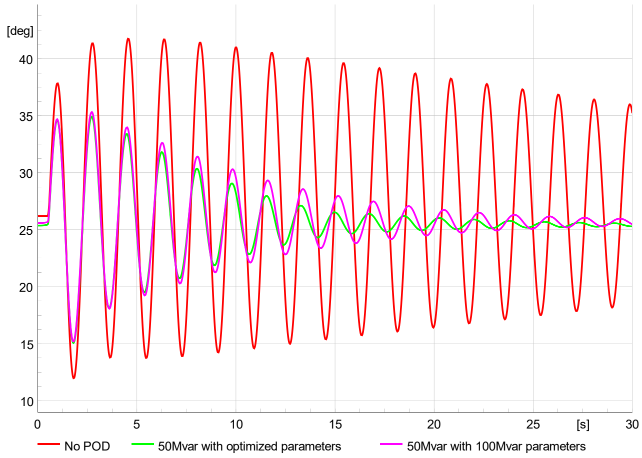

Figure 6. G1 rotor angle with 50 Mvar SVC POD

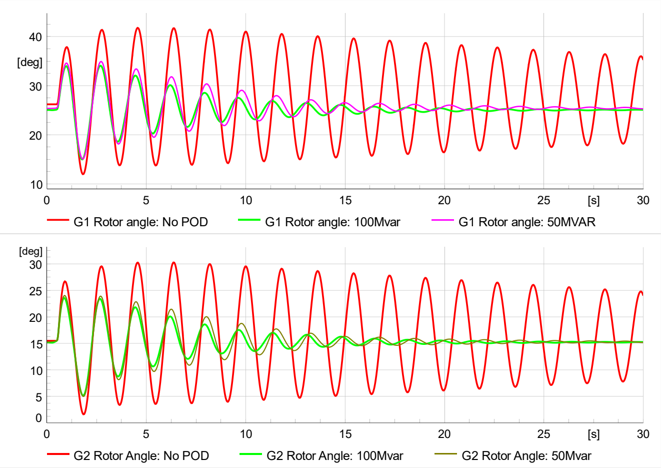

Figure 7. Comparison of 100&50 Mvar SVC POD damping effect

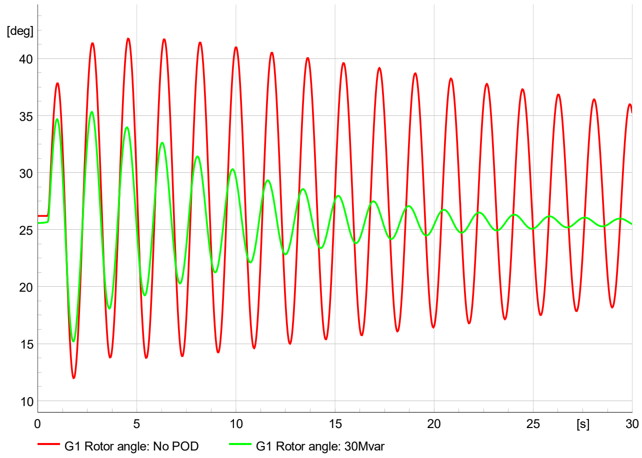

Figure 8. G1 rotor angle with 30 Mvar SVC POD

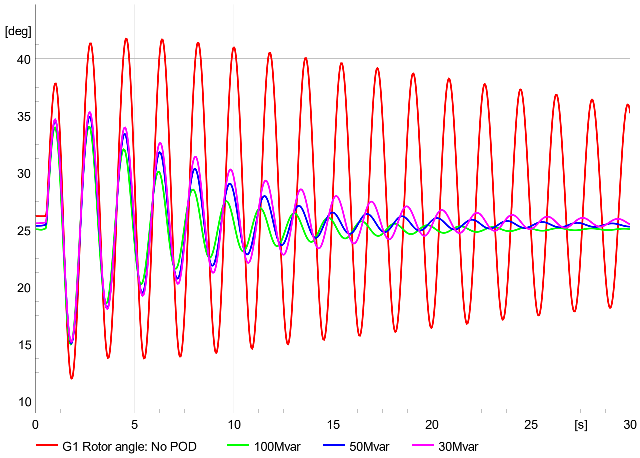

Figure 9. Comparison of 100,50&30 Mvar SVC POD damping effect

Table 1. Optimized parameters of SVC POD controller

Optimized Parameters	**100Mvar**	**50Mvar**	**30Mvar**
K_{pod}	23.22754	36.16678	74.46595
K_{svc}	8.515278	8.570928	9.285521
T_{svc}	0.010703	0.010551	0.010043
T_w	5.002576	5.002971	5.000808
T_1	0.083191	0.083211	0.063007
T_2	1.955276	1.954001	1.999514
T_3	0.010001	0.010002	0.010325
T_4	1.999781	1.999741	1.998637

4. Conclusion

This paper presents the effect of reactive power capacity on damping low-frequency power system oscillation modes in multimachine power systems. The study demonstrates that, with proper tuning of SVC POD parameters, satisfactory damping of electromechanical oscillations in multimachine systems is possible even with low reactive power capacities. In addition, it is shown that controller parameters require retuning each time the SVC rating changes. Retuning controller parameters each time the system undergoes major changes can be avoided by using an adaptive controller design approach that allows the controller to switch to other optimal parameters when the operating point changes. The same technique can be applied to WPPs, where LFOs damping is achieved through reactive power modulation.

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