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Transient Stability Enhancement in Multi-Machine Power System by using Power System Stabilizer (Pss) and Static Var Compensator (Svc)

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***Abstract* - In recent years, power demand has increased substantially while the expansion of power generation and transmission has been severely limited due to limited resources and environmental restrictions. As a consequence, some transmission lines are heavily loaded and the system stability becomes a power transfer-limiting factor. Flexible AC transmission systems (FACTS) controllers have been mainly used for solving various power system steady state control problems. However, recent studies reveal that FACTS controllers could be employed to enhance power system stability in addition to their main function of power flow control.**

This paper presents a fundamental analysis of the application of first generation FACT device i.e., Static VAR compensators (SVCs) and power system stabilizers (PSSs) for stabilizing power systems. Basic SVC control strategies are examined in terms of enhancing the dynamic and transient stabilities. SVC is basically a shunt connected static var generator whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific power variable; typically, the control variable is the SVC bus voltage.

Firstly, to design a controller for SVC devices on transmission lines, a Four Machine Infinite Bus (FMIB) system is modeled. A MATLAB simulation has been carried out to demonstrate the performance of the four machine transmission bus system.

Keywords* - *FACTS, Multi-Machine System, PSS, SVC, Transient Stability.

I. INTRODUCTION

Modern power systems are increasingly complex nonlinear interconnected networks comprising interconnected generator power plants, transformers and transmission lines with differences in loads. The interconnection of smaller subsystems is useful in reducing operating costs (e.g. fuel costs, sharing resources) and variety of loads improves the reliability of the system [1]. However, these possess technical challenges like low frequency electro-mechanical oscillation caused by electrical disturbances [2]. The power system stability is that the ability of the system to come back to its original operating condition after the disturbance [3]. In modern power systems, increased in the power demand results the overloading in long transmission lines (above normal limits), exacerbating the problem of transient stability, which has become a serious limiting factor in electrical engineering.

The transient stability of a system is defined as the ability of the system to maintain the system in stable condition after occurrence of the large disturbances, like fault and switching of lines. There are many ways for improving transient stability, including circuit breakers, fast-acting exciters and reduction within the transfer reactance of the system [1]. Under small disturbances, to remain synchronization the machine requires positive damping, generally from a power system stabilizer (PSS) provides positive damping to the system, which is one of the most common controls used to damp out oscillations.

The main role of PSS is to introduce modeling signal acting through the excitation system for oscillation damping [4]. It should be capable of providing stabilization signals over a broad range of operating conditions and disturbances; however, within nonlinear systems, the function of PSS is limited [5]. Many complex power systems are now stabilized using Flexible Alternating Current Transmission System (FACTS), which can control network conditions with optimum speed and enhance transient, voltage and steady state stabilities [6].

There are numerous classes of FACTS controllers, including shunt, series, combined series-series and combined series-shunt types. FACTS devices include a group of multiple controllers used to regulate system parameters like damping oscillation at different frequency, phase angle, voltage, current and impedance [7]. In this paper, SVC is discussed. It is a shunt type, used to connect as a controller which enhances the transient stability and damping the power oscillation with more reliable operation [8], [9].

The organization of this paper is as follows: Section II power system stabilizer PSS structure and the effect of damping oscillation; Section III models of static Var compensator SVC and explains SVC principles and its effectiveness to improve damping oscillation and explain the structure of the SVC controller; and Section IV presents the conclusion of the work.

II. POWER SYSTEM STABILIZER (PSS)

These are controllers with the ability to control synchronous machine stability through the excitation system by employing high-speed exciters and continuously acting voltage regulators. The PSS (Fig.1) adds damping to the generator unit’s characteristic electromechanical oscillations by modulating the generator excitation to develop components of electrical torque in phase with rotor speed deviations. The PSS thus contributes to the enhancement of small-signal stability of power systems. Fixed structure stabilizers generally provide acceptable dynamic performance.

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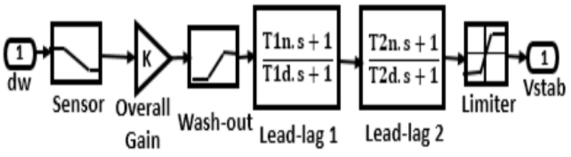

Fig.1. Block diagram of the PSS.

A. Speed-Based (Δω) Stabilizer

These are stabilizers that employ a direct measurement of shaft speed. Run-out compensation must be inherent to the method of measuring the speed signal to minimize noise caused by shaft run-out (lateral movement) and other sources.

While stabilizers supported direct measurement of shaft speed is used on several thermal units, this kind of stabilizer has many limitations. The primary disadvantage is the need to use a torsional filter to attenuate the torsional components of the stabilizing signal. This filter introduces a phase lag at lower frequencies which has a destabilizing effect on the "exciter mode", thus imposing a maximum limit on the allowable stabilizer gain. In several cases, this is often restrictive and limits the overall effectiveness of the stabilizer in damping system oscillations. In addition, the stabilizer has to be custom-designed for each type of generating Power-Based (ΔP) PSS unit depending on its torsional characteristics.

B. Power-Based (ΔP) Stabilizer

Due to the simple structure of power measurement and its relationship to shaft speed, it had been thought-about to be a natural candidate as an input signal to early stabilizers. The equation of motion for the rotor is written as follows:

$$\frac{\partial}{\partial t}\Delta\omega = \frac{1}{2H}(\Delta P_m - \Delta P_e)$$

(1)

Where, H = inertia constant; ΔPm = change in mechanical power input; ΔPe = change in electric power output and Δω = speed deviation

If variations of mechanical power are neglected, this equation implies that, signals are proportional to shaft acceleration (i.e. one that leads speed changes by 90°) is available from the scaled measurement of electrical power. This principle was implemented as the basic for many several stabilizer designs. In combination with both high and low-pass filtering, the stabilizing signal derived in this manner might provide pure damping torque at specifically one electromechanical frequency.

But at a same time this design has two major disadvantages. First, it can't be set to produce a pure damping contribution at more than one frequency and thus for units affected by both local and inter-area modes a compromise is needed. The second limitation is that an unwanted stabilizer output is made whenever mechanical power changes occur. This severely limits the gain and output limits that will be used with these units. Even modest loading and unloading rates produce large terminal voltage and reactive power variations, unless stabilizer gain is severely restricted. Many power-based stabilizers are still in operation though they're rapidly replaced by units supported the integral-of-accelerating power design.

C. Integral-of-Accelerating Power (ΔPω) Stabilizer

The limitations inherent in the other stabilizer structures led to the development of stabilizers that measure the accelerating power of the generator. Due to the complexity of the design, and the need for customization at each location, a method of indirectly deriving the accelerating power was developed as shown in fig.2.

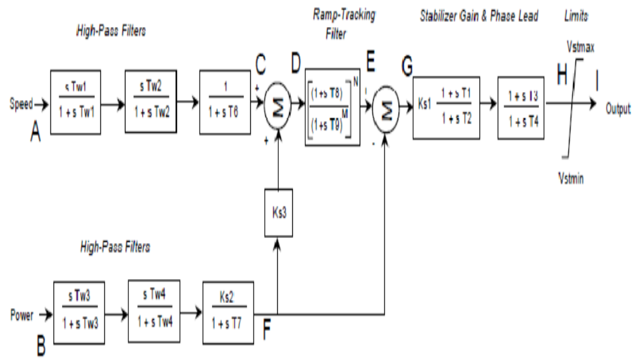

Fig.2. Accelerating Power PSS Model.

The principle of this stabilizer is illustrated by rewriting equation (1) in terms of the integral of power.

$$\Delta\omega = \frac{1}{2H}\int(\Delta P_m - \Delta P_e)\,\partial t$$

(2)

The integral of mechanical power is related to electrical power and shaft speed as given bellow:

$$\int \Delta P_m\,\partial t = 2H\Delta\omega + \int \Delta P_e\,\partial t$$

(3)

The ΔPω stabilizer makes use of the (3) simulate a signal proportional to the integral of change in mechanical power by adding signals proportional to shaft-speed change and integral of electrical power change. On horizontal shaft units, this signal will contain torsional oscillations unless a filter is used. Because mechanical power changes are relatively slow, the derived integral of mechanical power signal can be conditioned with a low-pass filter to attenuate torsional frequencies. The overall transfer function for deriving the integral-of accelerating power signal from measurement of electrical power and shaft speed is given bellow

$$\int \frac{\Delta P_a}{2H}\,\partial t = -\frac{\Delta Pe}{2Hs} + G(s)\left[\frac{\Delta P_e(s)}{2Hs} + \Delta\omega(s)\right]$$

(4)

Where, G(s) is the low-pass filter's transfer function.

The major advantage of a ΔPω stabilizer is that there is no requirement for a torsional filter in the main stabilizing path including the ΔPe signal. This alleviates the exciter mode stability problem, thereby permitting a higher stabilizer gain that result in better damping of system oscillations. A conventional end-of-shaft speed measurement or compensated frequency signal can be used with this structure.

III. STATIC VAR COMPENSATORS (SVCS)

The single-line diagram of a SVC and a simplified block diagram of its control system is shown in fig 3. Static Var compensators (SVCs) rated at 50 ~ 300 MVar, consisting of voltage source inverters using gate-turn-off (GTO) thyristors, are employed in improving power factor and stabilizing

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transmission systems. By controlling the amount of reactive power injected into or absorbed from the power system the SVC regulates voltage at its terminals. The SVC generates reactive power (SVC capacitive) when system voltage is low and absorbs the reactive power (SVC inductive) when the system voltage is high. The SVC can adjust the amplitude of the ac voltage of the inverters by pulse-width modulation (PWM) or by controlling the dc bus voltage, thus producing either leading or lagging reactive power.

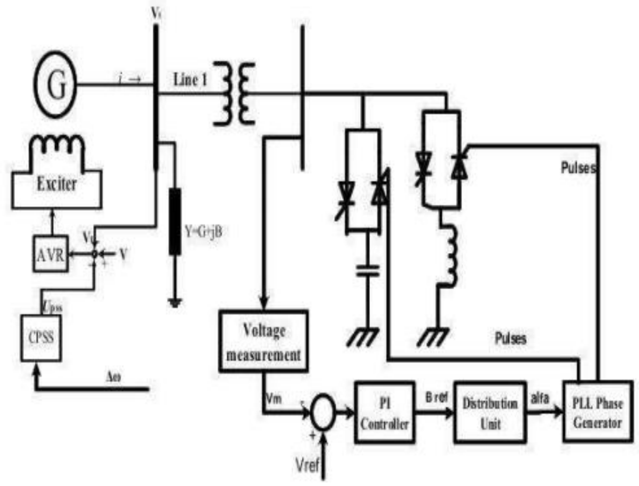

Fig.3. single-line diagram of a SVC and a simplified block diagram of its control system.

A pulse-width-modulated SVC, in which the dc voltage is controlled to remain at a constant value, responds rapidly to a change in reactive power at the expense of increasing the switching and snubbing losses. High efficiency and high reliability are a priority in practical power system applications of the SVCs. On the other hand, a dc voltage-controlled SVC, which directly controls the dc capacitor voltage by causing a small amount of active power to flow into or out of the voltage-source inverters, results in less switching and snubbing losses because the switching frequency is low. However, the dc voltage-controlled SVC is inferior to the Pulse Width Modulated (PWM) SVC in the transient response of reactive power. A model of the SVC based on the pq theory [17] is developed, and has the ability to deal with the power flow between the ac and dc sides in a transient state.

A. *Modelling of the SVC*

The following assumptions are made in modelling the SVC: first, any harmonic voltage caused by the switching operation of the inverters is excluded from the synthesized ac voltage of the SVC; second, the instantaneous amplitude of the fundamental component of the ac voltage is proportional to the instantaneous voltage of the dc capacitor; third, no power loss occurs in the inverters, therefore the active power on the ac side is equal to the active power on the dc side. The assumptions mean that the harmonic voltage caused by fluctuation of the dc voltage is included in the synthesized ac voltage. Assume an ideal three-phase power supply given by:

$$\begin{bmatrix} v_{su} \\ v_{sv} \\ v_{sw} \end{bmatrix} = \sqrt{\frac{2}{3}}\, Vs \begin{bmatrix} \cos\omega_0 t \\ \cos(\omega_0 t - 2\pi/3) \\ \cos(\omega_0 t + 2\pi/3) \end{bmatrix} \quad (5)$$

Where, VS is the rms voltage of the supply and ωO is its angular frequency. The above assumptions lead to the following ac voltage of the SVC:

$$\begin{bmatrix} v_{su} \\ v_{sv} \\ v_{sw} \end{bmatrix} = \sqrt{\frac{2}{3}}\, kVc \begin{bmatrix} \cos(\omega_0 t + \emptyset) \\ \cos(\omega_0 t - 2\pi/3 + \emptyset) \\ \cos(\omega_0 t + 2\pi/3 + \emptyset) \end{bmatrix} \quad (6)$$

Where, φ is the angle of the fundamental ac voltage with respect to the supply voltage, and K is the ac to dc voltage ratio of the SVC.

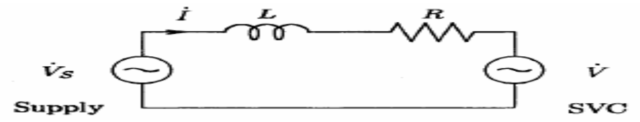

Fig.4. Model of the SVC: Single-Phase Equivalent.

Using Fig. 2.10, one obtains the following equation:

$$\begin{bmatrix} v_{su} \\ v_{sv} \\ v_{sw} \end{bmatrix} = R + L\frac{d}{dt}\begin{bmatrix} i_u \\ i_v \\ i_w \end{bmatrix} + \begin{bmatrix} v_u \\ v_v \\ v_w \end{bmatrix} \quad (7)$$

Invoking Assumption 3 results in the following equation for active power:

$$p = v_u i_u + v_v i_v + v_w i_w = \frac{d}{dt}\frac{c}{2} v_c \frac{dv_c}{dt} \quad (8)$$

The pq theory can be used to transform,

$$\begin{bmatrix} L\frac{d}{dt} + R & -\omega_0 L \\ \omega_0 L & L\frac{d}{dt} + R \end{bmatrix}\begin{bmatrix} i_p \\ i_q \end{bmatrix} = \begin{bmatrix} Vs - kvc\ \cos\emptyset \\ -kvc\ \sin\emptyset \end{bmatrix} \quad (9)$$

$$\frac{dVc}{dt} = \frac{k}{c} i_{p(\cos\emptyset + i_q \sin\emptyset)} \quad (10)$$

In (9) and (10), ip is an instantaneous active current and iq is an instantaneous reactive current. The instantaneous reactive power which is drawn from the supply, qs is given as:

$$qs = vsp.i_q - vsq.i_p = V_s.i_q \quad (10)$$

B. *SVC Control*

The SVC can be operated in two different modes: In voltage regulation mode (the voltage is regulated within limits) and in var control mode (the SVC susceptance is kept constant). The block diagram of the control circuit is shown in fig.5. Due to the use Reactive power feedback using a PI controller; it is possible to improve the transient response of the reactive power. The pq transform circuit calculates the instantaneous reactive power qs from the three-phase supply voltages and the three-phase currents. The calculated reactive power qs and the reference reactive power q*s are applied to the proportional-integral (PI) controller. The output of the PI controller is a reference signal representing the phase angle φ*.

The counter produces the phase information, ω0t, from a signal generated by the phase locked loop (PLL) circuit. The phase comparator compares Φ with ω0t, and determines the time at which the corresponding switching device is turned on or off. The gate control circuit prevents each switching device from being switched-on more than once in one cycle due to fast changes in Φ.

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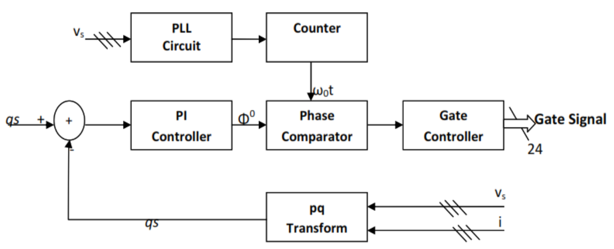

Fig.5. Block Diagram of SVC Control Circuit.

IV. Simulation Results

The comparison between PSS and SVC was conducted in a multi-machine system, as shown in Fig. 6. This system consists of 4 machines and 6 buses. The system was originally available in MATLAB with two machines and three buses, but in order to consider more cases in this work, the number of machines and buses were increased. Two types of stabilizers can be selected, a generic model using the acceleration power (Pa= difference between mechanical power Pm and output electrical power Peo) and a Multi-band stabilizer using the speed deviation (dw). The stabilizer type can be selected by specifying a value (0=No PSS 1=Pa PSS or 2= dw MB PSS) in the PSS constant block. The disturbance applied is three phase fault to ground near a generator 1 on bus 1 at t= 5s; SVC is used as a controller is phaser type, connected to B1 and taking those cases:

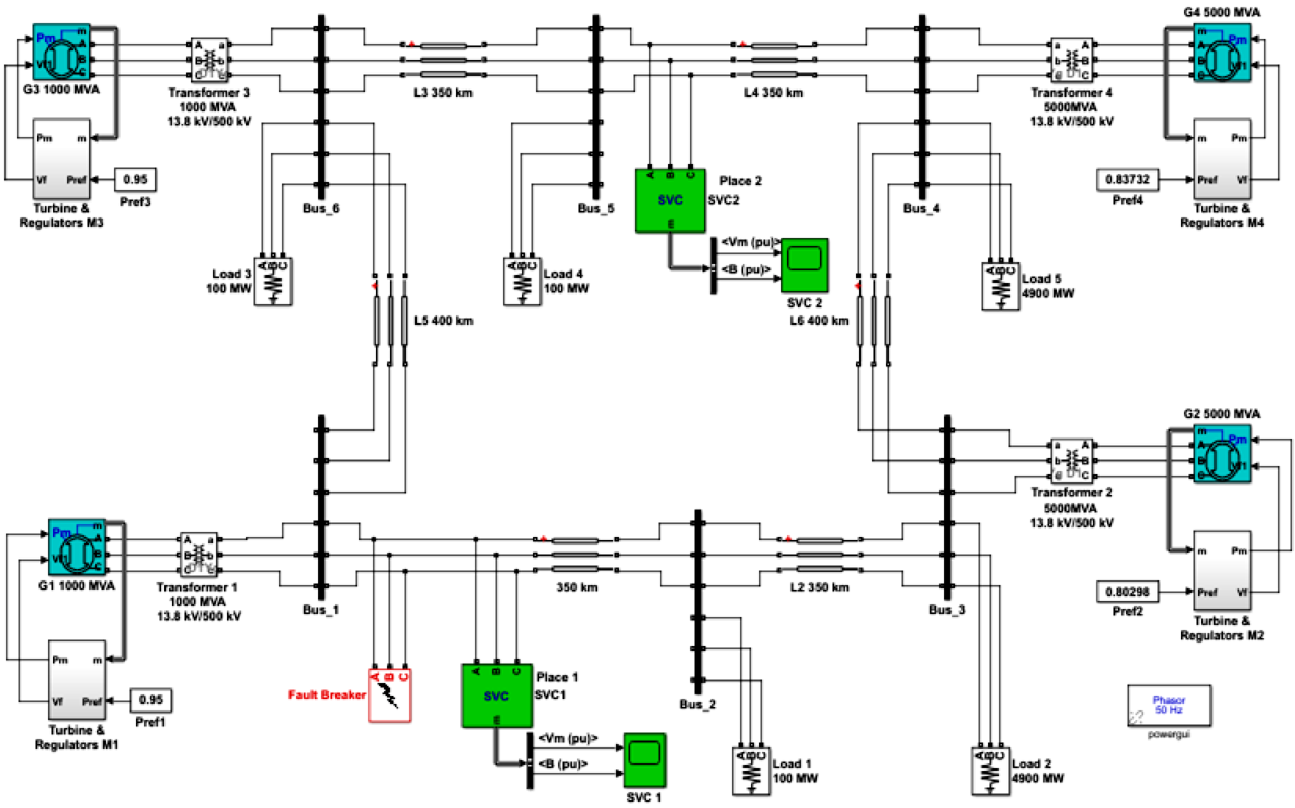

Fig.6. Test system (4 machine, 6 bus) modeled in Simulink/MATLAB.

A. Case 1

When comparing between using without PSS and PSS only for a critical clearing time (tc =148 ms), the results show that the system loses stability when utilizing PSS alone, while it remains stable using both SVC and PSS. Fig 7-10 show the rotor angle difference of G1-G2 of the test system, rotor angle difference of G3-G4, the terminal voltage on B1 and transmission line active power of G1.

B. Case 2

Using PSS solely and PSS with SVC (to enhance transient stability and dampen the oscillation), the system remained stable, at clearing time (tc = 147 ms). Table I lists the performance comparison between using (PSS) and (PSS with SVC). Furthermore, Fig 11 and 12 shows the rotor angle difference of G1 and rotor angle difference of G3; SVC settled faster with settling time is (11s and 10.3s) than with only PSS (13s and 13.3s), and the peak amplitude of both rotor angle with SVC reduced with value is 79 and 67 degrees, respectively. With only PSS, the corresponding values are 87 and 70 degrees. Fig 13 and 14 show that the terminal voltage on B1 and B6 with SVC oscillated less and stabilized with peak amplitudes of 1.15 p.u and 1.126 p.u, and settling times of 9s and 9s, compared to only PSS with peak amplitudes of 1.29 p.u and 1.222 p.u and settling times of 12s and 12s. Fig 15 and 16 shows the transmission line active power values of G1 and G3; it can be seen that the line with SVC has less oscillation and greater stabilization than that with only PSS.

C. Case 3

In this case the comparison between using PSS alone and two SVC with PSS in two different locations was made. The first SVC was connected to the system in a location the same as the previous one, and the second was connected near G3 with bus 6. Additionally, Fig 17 and 18 show that

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rotor angle difference of G1 and rotor angle difference of G3 with SVC settled faster with settling time is (9s and 9s) than with only PSS (13s and 12.3s), and the peak amplitude of both rotor angle with SVC reduced with values of 78 and 63 degrees. With only PSS the settling time is 13 and 13.3s and the peak amplitude is 86 and 70 degrees. Fig 19 and 20 shows that the terminal voltage on B1and terminal voltage on B6 with SVC oscillates less and stabilizes with peak amplitude (1.145p.u and 1.118p.u) and settling time (8s and 8s) compared to only PSS, where the peak amplitude is (1.29p.u and 1.222p.u) and settling time (12s and 12s). Fig 21 and 22 shows the transmission line active power of G1 and G3.

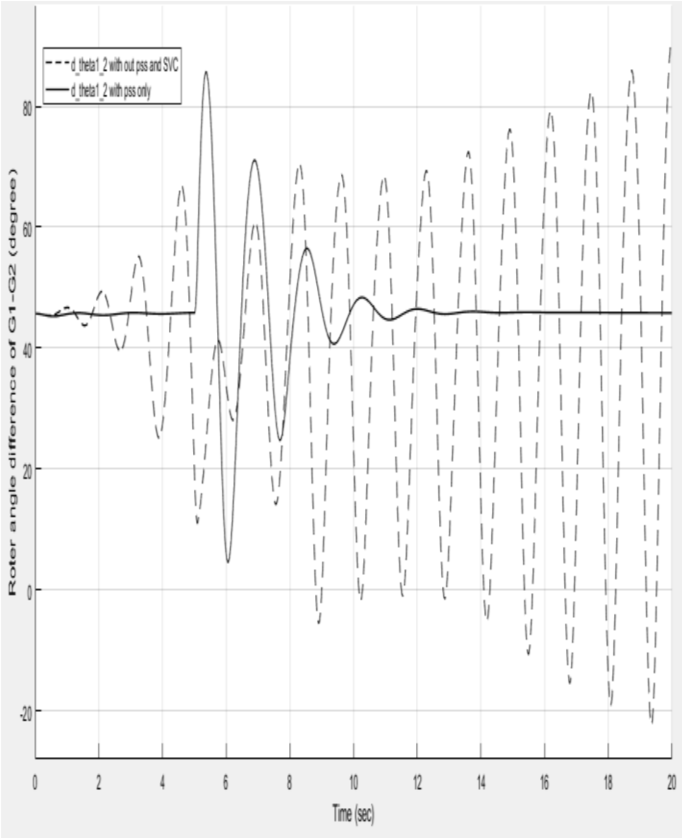

Fig. 7. Rotor angle difference of G1 to G2.

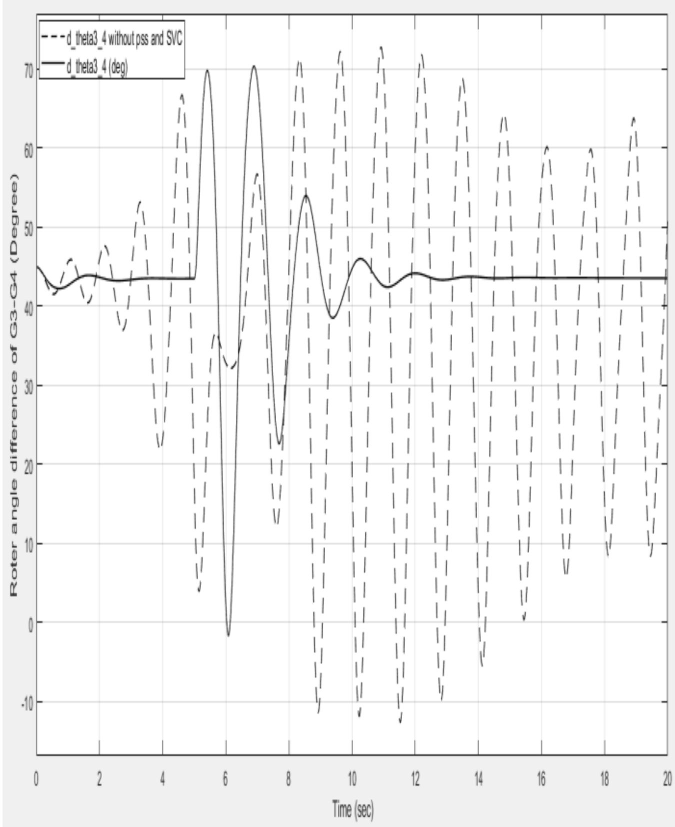

Fig. 8. Rotor angle difference of G3 to G4.

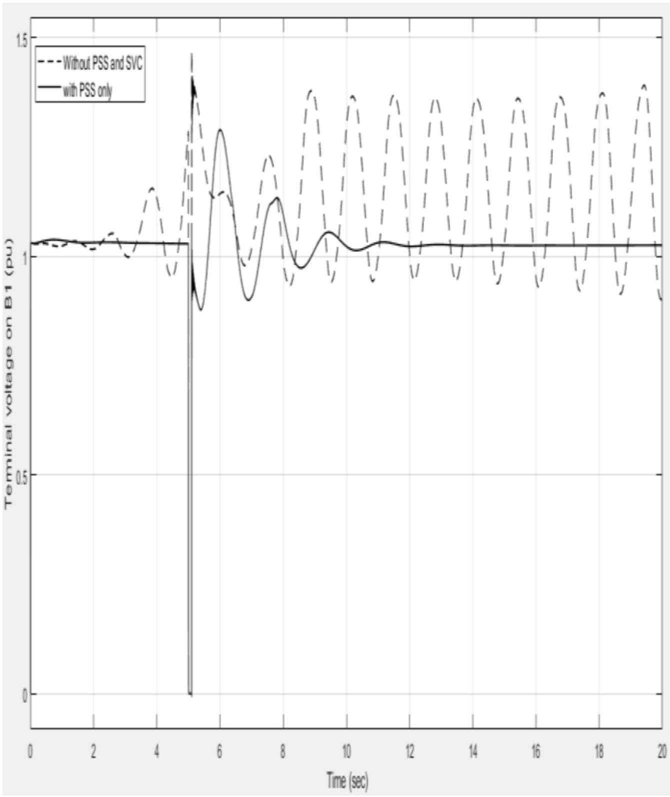

Fig. 9. Terminal voltage on B1.

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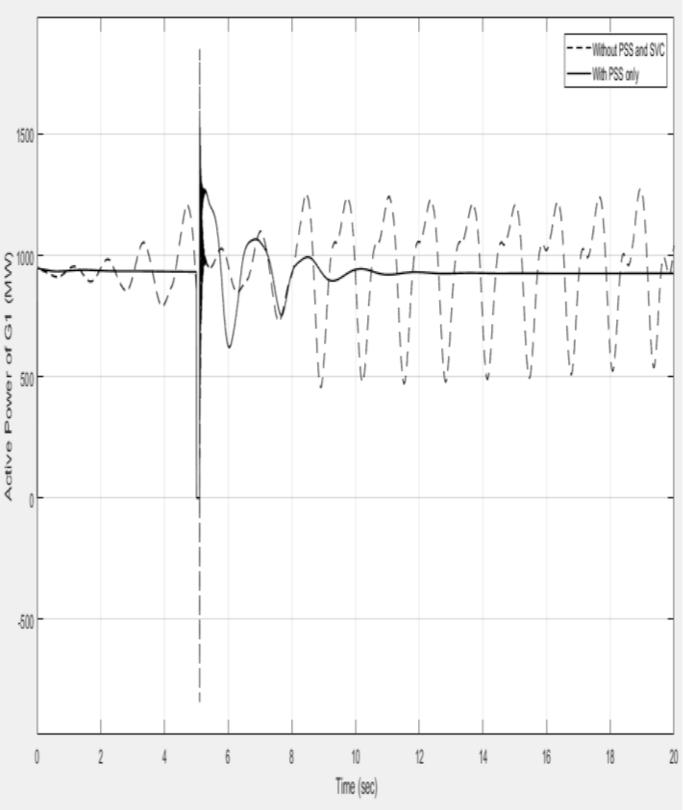

Fig. 10. Transmission line active power of G1.

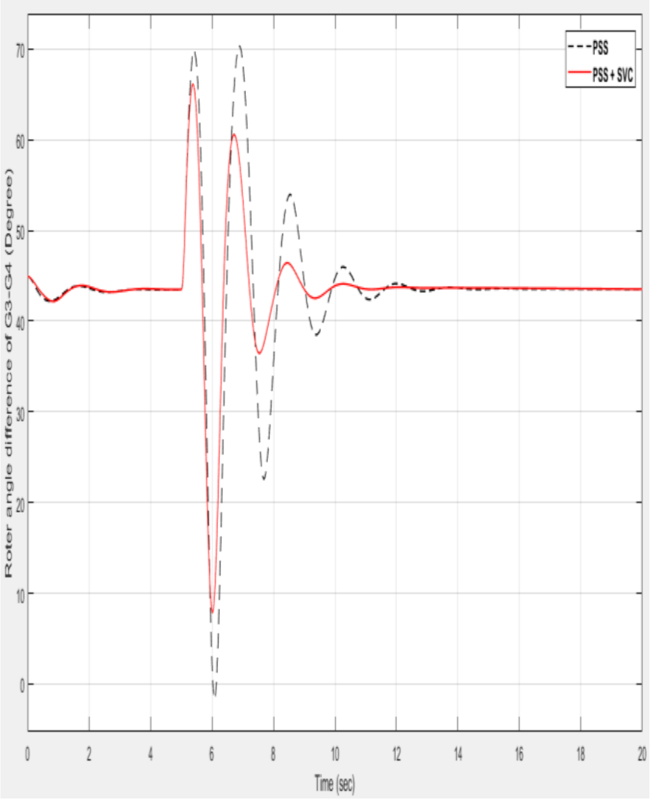

Fig. 12. Rotor angle difference of G3 to G4.

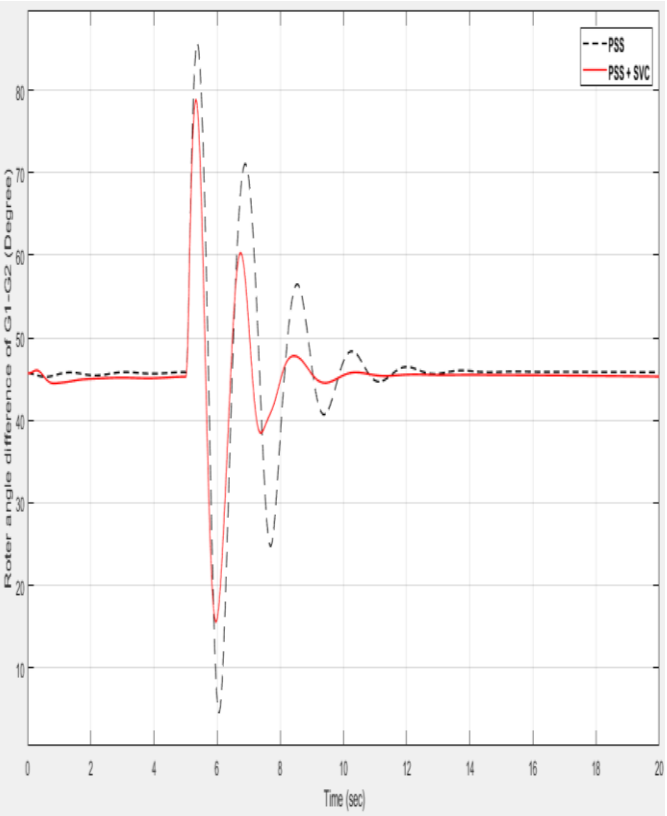

Fig. 11. Rotor angle difference of G1 to G2.

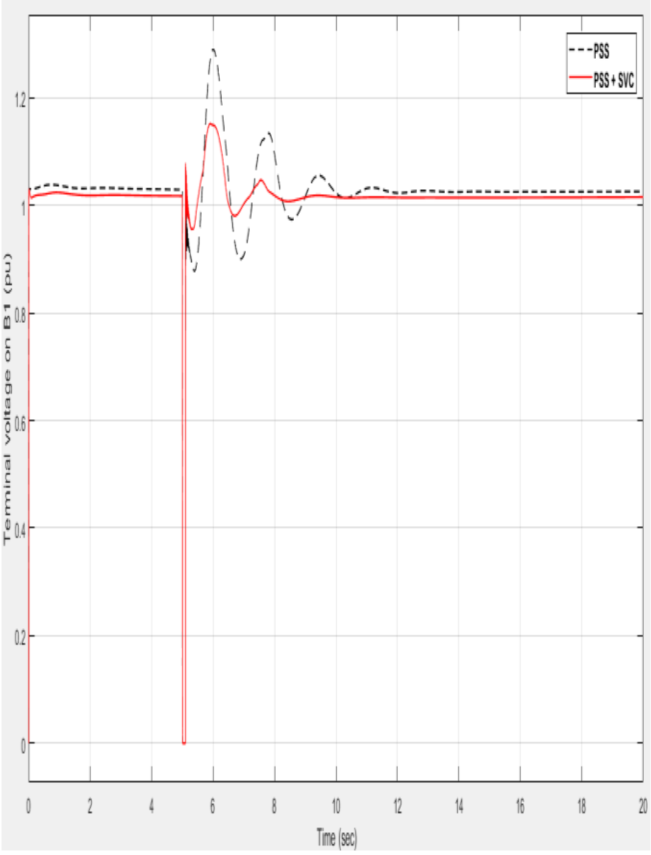

Fig. 13. Terminal voltage on B1.

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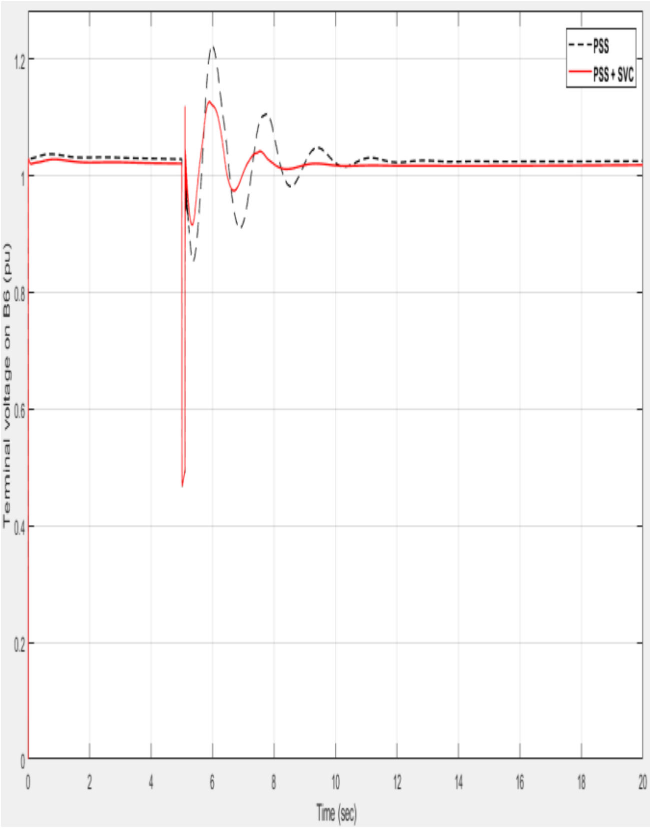

Fig. 14. Terminal voltage on B6.

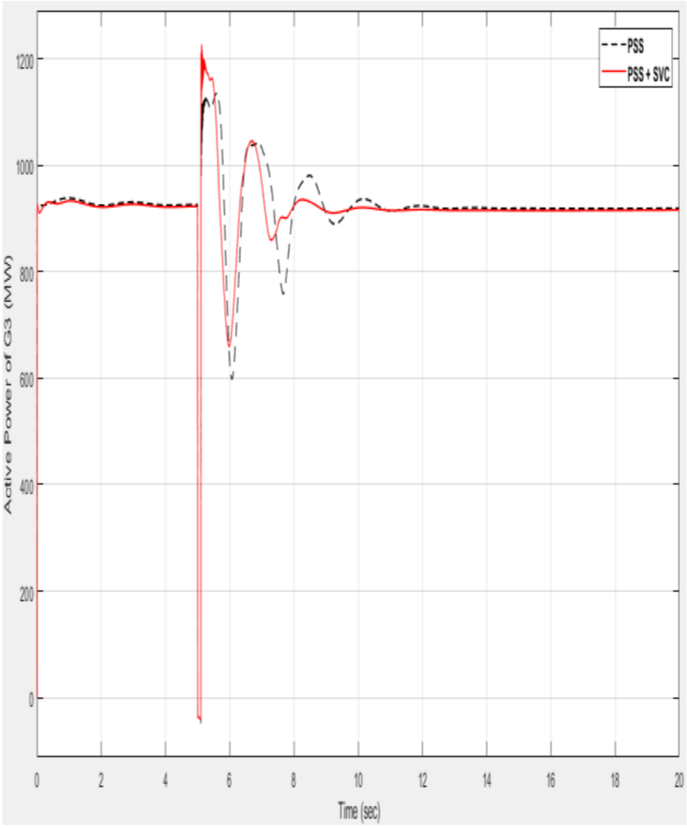

Fig. 16. Transmission line active power of G3.

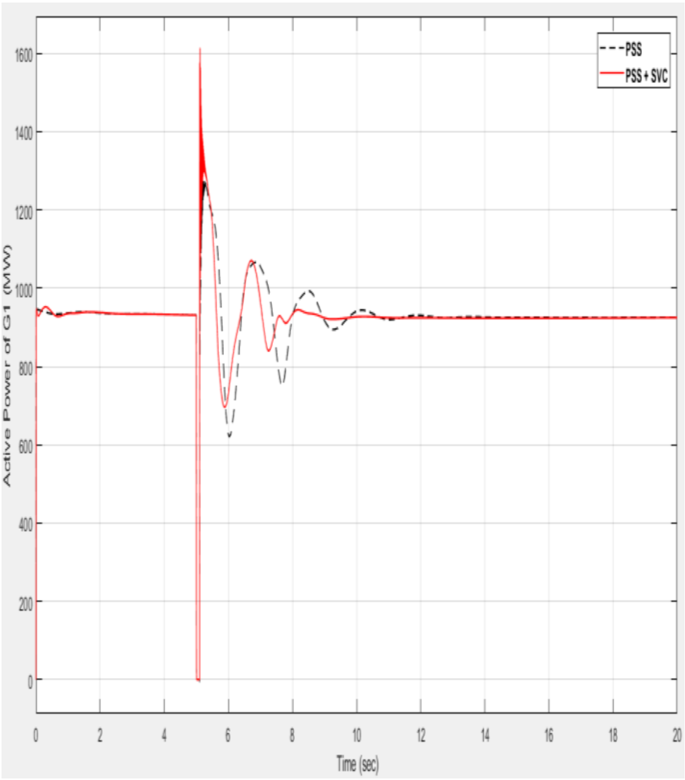

Fig. 15. Transmission line active power of G1.

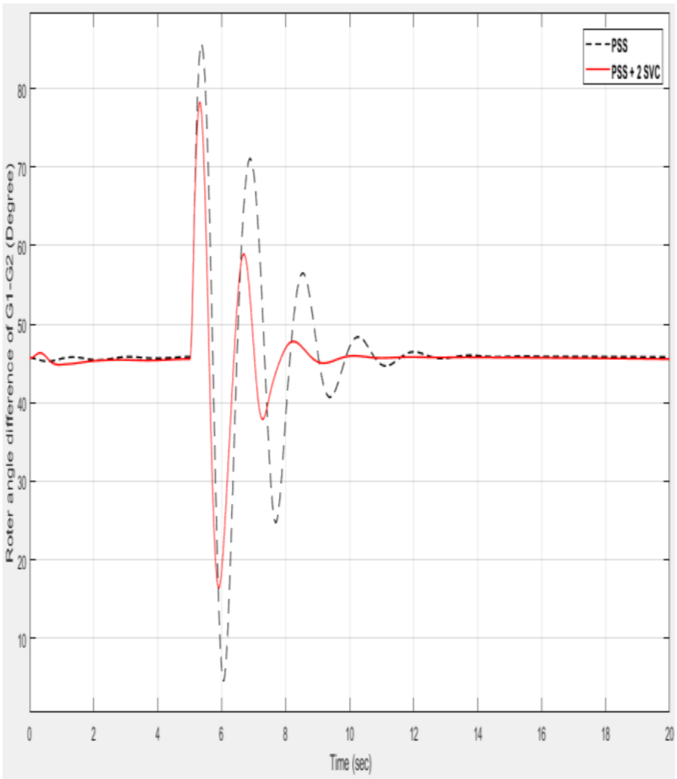

Fig. 17. Rotor angle difference of G1 to G2.

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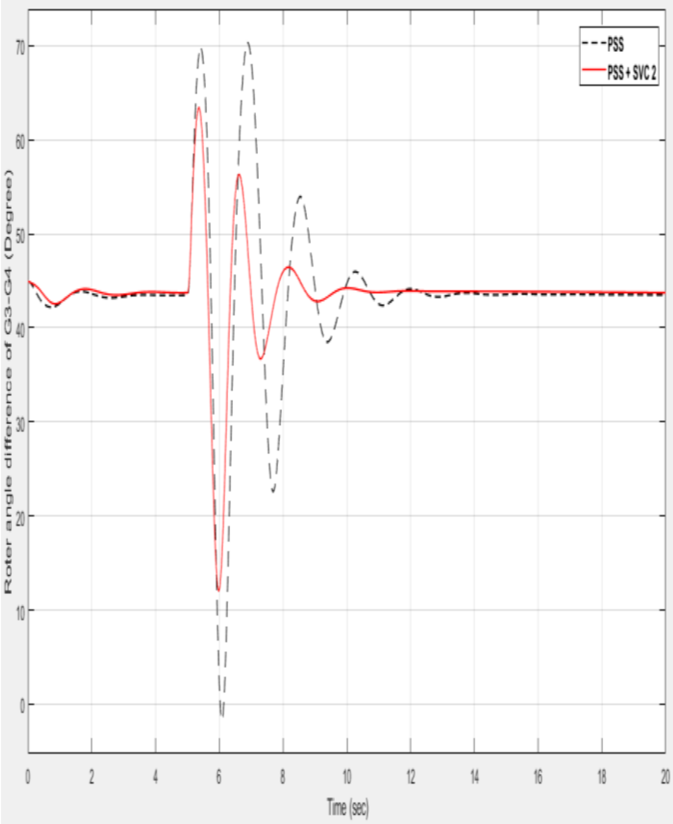

Fig. 18. Rotor angle difference of G3 to G4.

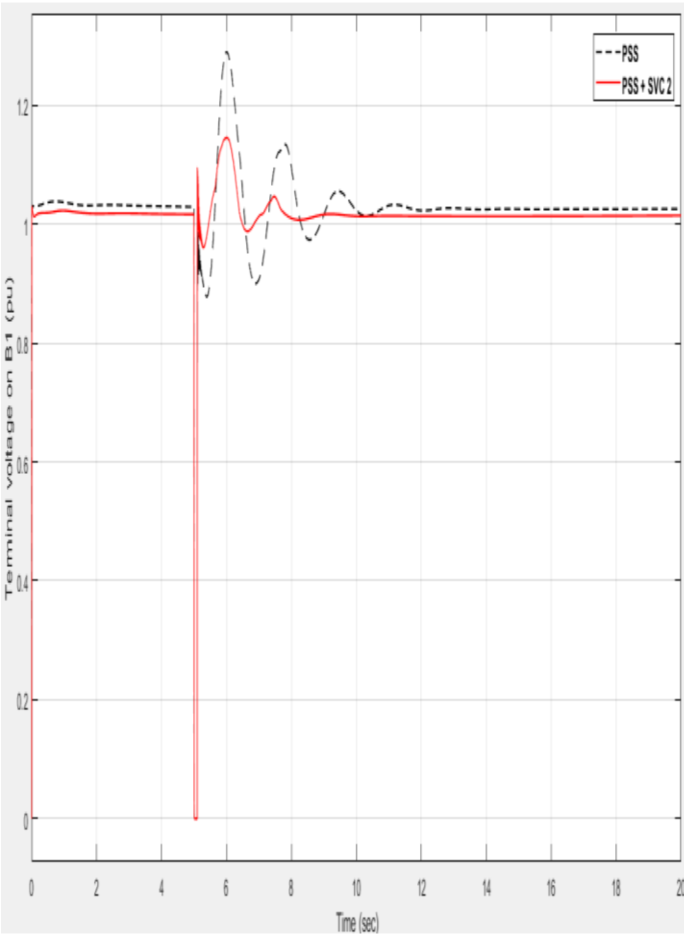

Fig. 19. Terminal voltage on B1.

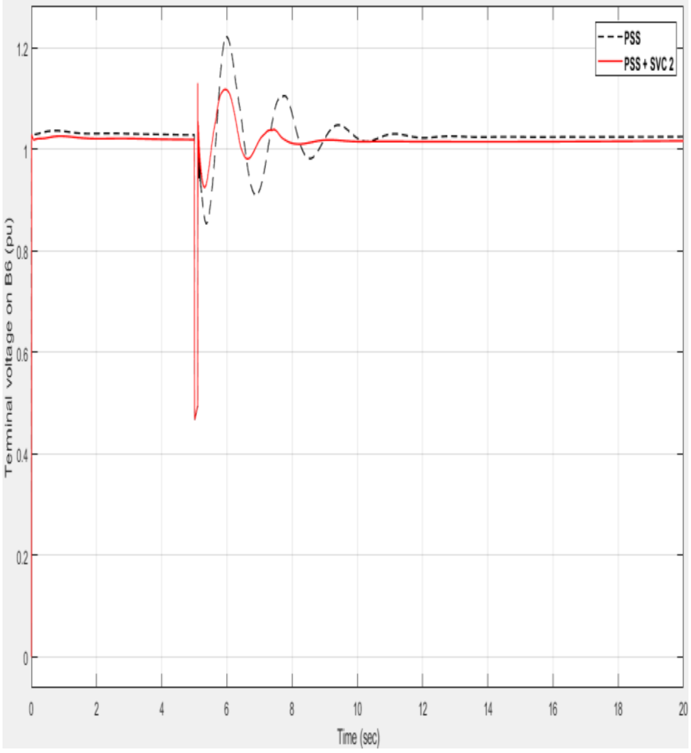

Fig. 20. Terminal voltage on B6.

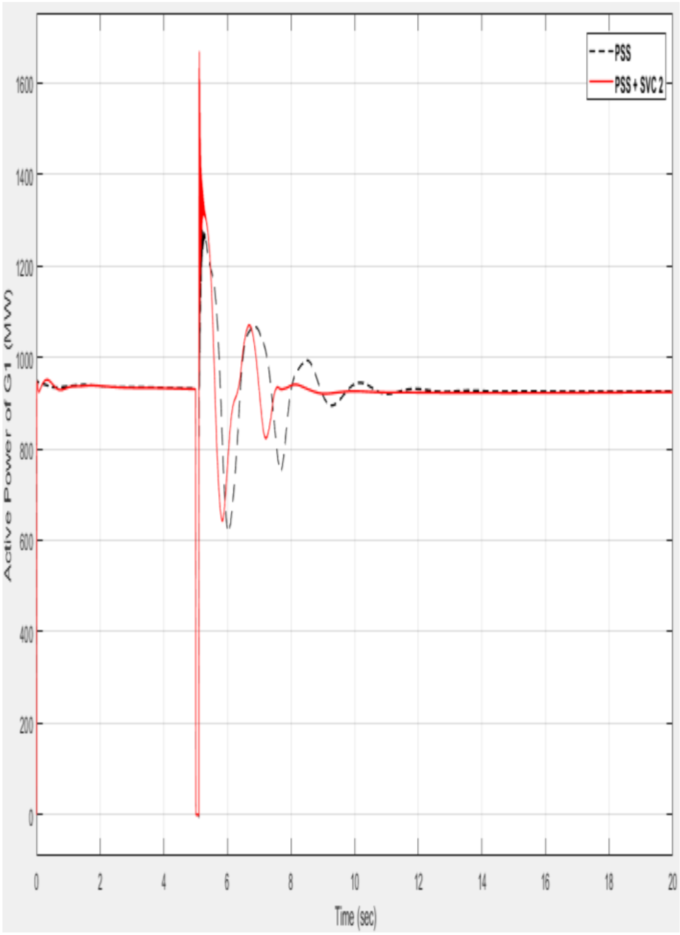

Fig. 21. Transmission line active power of G1.

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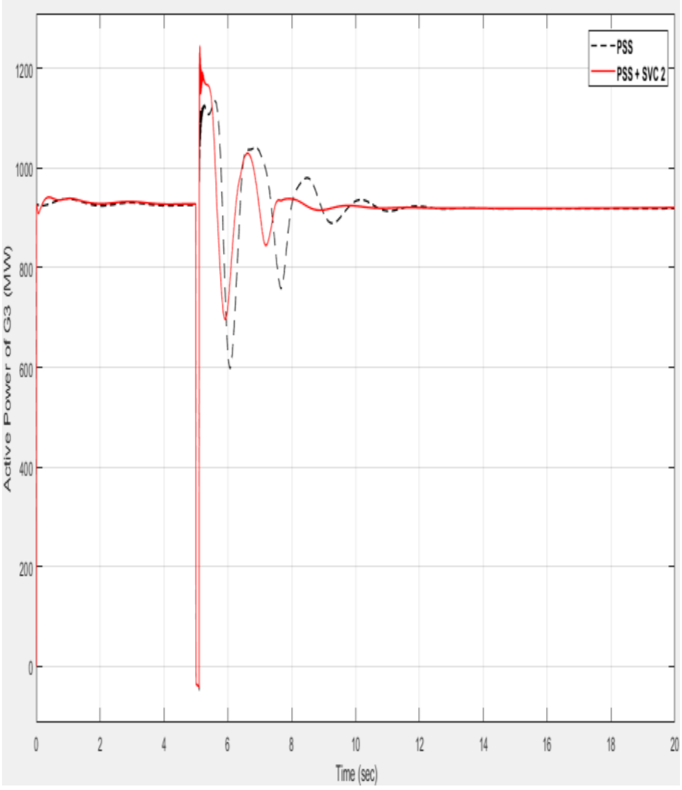

Fig. 22. Transmission line active power of G3.

V. CONCLUSION

The SVC enhances system stability by controlling the amount of reactive power injected into or absorbed from the power system. On the other hand, the PSS has for a long time found application in the exciters of synchronous machines as an effective means of damping the generator unit's characteristic electromechanical oscillations by modulating the generator excitation. Thus, PSSs and FACTS are fast becoming a necessity in power system stability enhancement rather than an option to be considered.

This paper discussed and investigated the transient stability enhancement by using a power system stabilizer PSS and static Var compensator. The study has compared the independent application of PSS and its combination with SVC using a multi-machine testing system consisting of four machines and six buses in MATLAB Simulink. During three phases to ground fault on generator 1 three cases were considered to identify the differences between PSS and SVC, and their ability to fix transient stability. Firstly, at the critical clearing time the system lost the synchronism when using PSS only, and it retained synchronism when SVC was connected with the system as a controller. In a second case with a clearing time of 147 ms, the system remained stable with both PSS only and PSS with SVC; however, the result was much better when utilizing SVC for damping oscillation. In the final case, two SVCs were used, and in comparison with previous cases the results indicated improved transient stability and damping oscillation of several parameters, such as rotor angle and terminal voltage and transmission lines active power.

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