A new control strategy for SSSC to improve low-frequency oscillations damping

J. Gholinezhad, M. Ebadian, M. R. Aghaebrahimi

Abstract -- When power systems are expanded and connected together with weak tie lines, the low-frequency oscillations are increased and the stability margin of the power system decreases. Therefore, when designing the transmission system to be used, it is necessary to maintain the dynamic stability of the power system, and to make sure to have the most possible stability margin. SSSC is a FACTS device connected in series with power transmission lines. SSSC can control power flow very effectively and can inject series inductive or capacitive voltages into the line. In this paper, a new control strategy based on voltage measurement for the SSSC is proposed. The commonly used strategy for SSSC is based on line current measurement; consequently, the injected voltage is in quadrature with the line current. But in the proposed strategy, the injected voltage is in quadrature with the ac voltage at the point of common coupling (PCC) of SSSC. With modifications done in the proposed strategy, compared with the conventional control method, it can be adjusted easily to control the power flow of the transmission line. The simulation is performed in single-machine and multi-machine power systems. The analysis of the results under different disturbances show that the proposed strategy has an appropriate response with respect to the changes in the system states and it is relatively faster in damping power system oscillations, compared with the conventional strategy.

Index Terms - Static Synchronous Series Compensator (SSSC), voltage frame strategy, current frame strategy, damping controller, dynamic stability.

I. INTRODUCTION

BECAUSE of the expansion in power systems, the low-frequency oscillations are increased. If enough damping does not exist in the power system, these oscillations will remain and grow until the system breaks down [1]. The rapid progress of power electronic devices has made the use of Flexible AC Transmission Systems (FACTS) possible in controlling power systems. FACTS controllers are able to quickly control the network situation in different operating conditions and this ability of FACTS controllers can improve the power system stability [2]. SSSC is a FACTS device connected in series with power transmission lines. SSSC can control power flow very effectively and can inject series inductive or capacitive voltages into the transmission line. The performance of SSSC in improving the stability and power system oscillations damping can be seen in many references [3-6].

In [7,8] the controller parameters are adjusted so that the un-damped and damped modes under different load conditions are taken directly to the specified area, without worsening the other system modes. Elsewhere, through "phase control" and "magnitude control", the effectiveness of SSSC has been compared for both control methods [9-11]. In [12] SSSC with adaptive controller is used in a single machine infinite bus (SMIB) power system. The controller parameters determine the magnitude and the phase of the injected voltage and the eigenvalue analysis has been used for linear SMIB with SSSC.

In [13,14] the effect of performance modes of SSSC on transient stability and small signal swing is investigated. In these references, two modes of control for the SSSC, i.e. "Constant voltage" and "Constant reactance" modes, are introduced. For damping inter-area oscillations, hybrid compensation has been used by series capacitors for two phases and by SSSC series with a fixed capacitor for the third phase [15]. In all the above papers, SSSC controller produces injected voltage based on the transmission line current measurement.

In this paper, a new control strategy based on voltage measurement for the SSSC is proposed. Two control strategies (the commonly used and the proposed strategies) for SSSC are given in below. In the first strategy, which is commonly used for the SSSC, since the injected voltage is based on transmission line current measurement and perpendicular to the line current, it is called the current frame SSSC controller. The second control strategy is inspired by UPFC controllers and since the injected voltage is based on transmission line voltage measurement, this method is called voltage-frame method. UPFC, which can independently control the active and reactive powers in the power system, is actually a combination of STATCOM and SSSC. Since STATCOM is a

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shunt compensator, it can inject/absorb reactive power to/from the grid by the injected current which is perpendicular to the voltage of the point of common coupling (PCC). Reactive power exchange controls the voltage of the PCC and increases the stability margin.

In present paper, the proposed strategy and the conventional strategy for SSSC are used in single-machine and multi-machine power systems and the results are compared.

II. POWER SYSTEM MODELING

A. Generator Model

Synchronous generators are one of the main components of any power system. Three sets of differential equations are required to represent the dynamic behavior of a synchronous generator. These sets of equations include the electrical equations (the field, damper bar and stator windings), mechanical equations (the rotor) and dynamic equations related to different control loops (such as AVR and turbine-governor control).

In this paper, Fourth-order model has been used and the stator and network dynamics have been ignored. Dynamic equations are as follows [16]:

$$\dot{\delta}_i = \omega_i - \omega_s \qquad (1)$$

$$M_i\dot{\omega}_i = P_{mi} - (I_{di}E_{di} + I_{qi}E_{qi}) + (X_{qi} - X_{di})I_{di}I_{qi} - D(\omega_i - \omega_s) \qquad (2)$$

$$T'_{d0i}\dot{E}'_{qi} = E_{FDi} - E'_{qi} + (X_{di} - X'_{di})I_{di} \qquad (3)$$

$$T'_{q0i}\dot{E}'_{di} = -E'_{di} - (X_{qi} - X'_{qi})I_{qi} \qquad (4)$$

B. SSSC Model

Figure 1 shows the general structure of a transmission line with SSSC. In this figure, V_{inja}, V_{injb} and V_{injc} are the injected voltages into different phases, R and X_e are resistance and reactance of the transmission line, V_{DC} is the DC link voltage and R_p is the resistance representing converter losses.

Assuming a balanced network, the AC power is as follows:

$$P_{ac} = \frac{3}{2}(V_{injD}I_D + V_{injQ}I_Q) \qquad (5)$$

It is assumed that the injected voltage is as follows:

$$V_{inj} = V_{injD} + jV_{injQ} = kmV_{dc}\angle\varphi = kmV_{dc}\cos\varphi + jkmV_{dc}\sin\varphi \qquad (6)$$

As a result:

$$P_{ac} = \frac{3}{2}(I_D kmV_{dc}\cos\varphi + jI_Q kmV_{dc}\sin\varphi) \qquad (7)$$

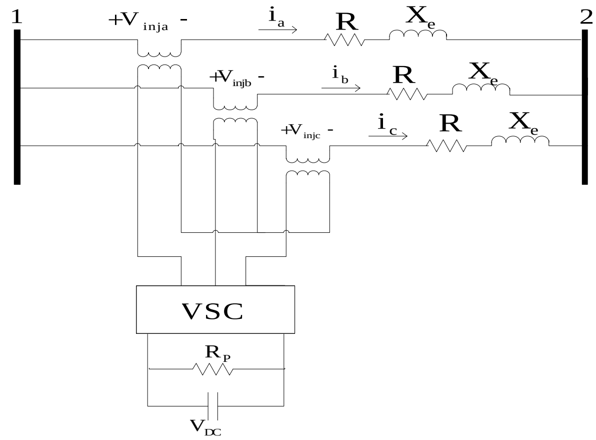


Fig 1. Transmission Line Compensated by SSSC

The DC capacitor differential equation can be expressed as below [17]:

$$\frac{dV_{dc}}{dt} = \frac{3}{2C}km(I_D\cos\varphi + I_Q\sin\varphi) - \frac{V_{dc}}{CR_P} \qquad (8)$$

The compensated transmission line inductors' dynamic equations are:

$$\begin{bmatrix} \frac{dI_D}{dt} \\ \frac{dI_Q}{dt} \\ \frac{dI_0}{dt} \end{bmatrix} = \begin{pmatrix} -\frac{R}{L_e} & \omega_s & 0 \\ -\omega_s & -\frac{R}{L_e} & 0 \\ 0 & 0 & -\frac{R}{L_e} \end{pmatrix} \begin{bmatrix} I_D \\ I_Q \\ I_0 \end{bmatrix} + \frac{1}{L_e}\begin{bmatrix} V_{1D} - V_{2D} - V_{injD} \\ V_{1Q} - V_{2Q} - V_{injQ} \\ V_{1o} - V_{2o} - V_{injo} \end{bmatrix} \qquad (9)$$

Ignoring the last sentence and since the SSSC has fast internal controllers, these dynamics are neglected and the equations are written algebraically:

$$0 = -\frac{R}{X_e}\omega_s I_D + \omega_s I_Q + \frac{\omega_s}{X_e}(V_{1D} - V_{2D} - V_{injD}) \qquad (10)$$

$$0 = -\omega_s I_D - \frac{R}{X_e}\omega_s I_Q + \frac{\omega_s}{X_e}\left(V_{1Q} - V_{2Q} - V_{injQ}\right) \quad (11)$$

III. THE PROPOSED STRATEGY

In this section, each of the control strategies will be described.

A. The conventional control strategy based on current measurement

According to Fig. 2, the power control loop (the difference between the active power, P_{line}, and the desired active power transmission line, P^*_{ine}) determines the reference internal reactive power (q^*_c).

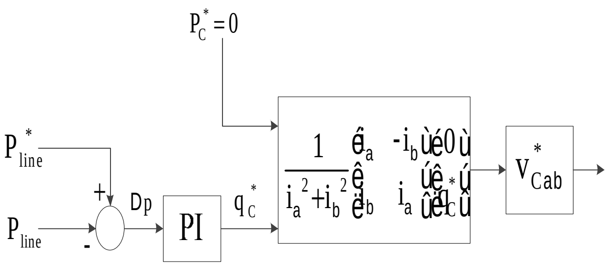


Fig 2. Current frame strategy

According to the instantaneous power theory (dual p-q theory), the series injected voltage is obtained as [18]:

$$\begin{bmatrix} v_a \\ v_b \end{bmatrix} = \frac{1}{i_a^2 + i_b^2}\begin{bmatrix} i_a & -i_b \\ i_b & i_a \end{bmatrix}\begin{bmatrix} p \\ q \end{bmatrix} \quad (12)$$

If the reference active power (p^*_c) is considered equal to zero, the injected voltage is determined by line current and the reference reactive power as:

$$\begin{bmatrix} v^*_{Ca} \\ v^*_{Cb} \end{bmatrix} = \frac{1}{i_a^2 + i_b^2}\begin{bmatrix} i_a & -i_b \\ i_b & i_a \end{bmatrix}\begin{bmatrix} 0 \\ q^*_C \end{bmatrix} \quad (13)$$

Since $p^*_c = 0$, SSSC only exchanges reactive power with the line, thus the injected voltage is perpendicular to the line current. But, if the losses of various components are considered, the active power will be exchanged between SSSC and transmission line. In this case, according to Fig. 3, the other control loop is added to generate the amount of lost power ($p^*_c = p_{losses}$). Accordingly, the injected voltage will not be perpendicular to the line current and will have some deviation from the line current and the DC link capacitor will be charge and discharged.

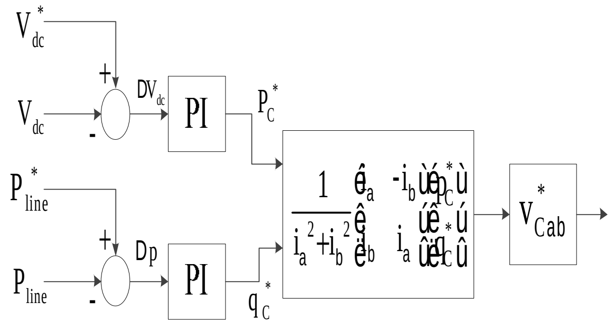


Fig 3. Current frame strategy considering losses

B. The proposed control strategy based on voltage measurement

Considering the small angle variation between the line current and the voltage of the point of common coupling (PCC), which is dependent on the reactive power of the PCC, it is suggested that the connection point's voltage is measured rather than the line current. This method is similar to the conventional method, except that the series injected voltage is perpendicular to the voltage of the converter junction instead of being perpendicular to the line current.

Since the injected voltage is perpendicular to the voltage of the PCC, in addition to modifying the active transfer power, the reactive power is affected too. Thus, the DC link voltage is changed and since the DC link of SSSC is not connected to a power source, it seems that this method is not applicable. However, with the following modifications, this method can be implemented in SSSC.

The controller based on voltage measurement is used for SSSC as shown in Fig. 4. The power control loop determines the reference internal reactive power (q^*_c) similar to the conventional strategy. But here, according to the p-q theory, the injected voltage is obtained as:

$$\begin{bmatrix} v^*_{Ca} \\ v^*_{Cb} \end{bmatrix} = \frac{1}{v_a^2 + v_b^2}\begin{bmatrix} v_a & v_b \\ v_b & -v_a \end{bmatrix}\begin{bmatrix} 0 \\ q^*_C \end{bmatrix} \quad (14)$$

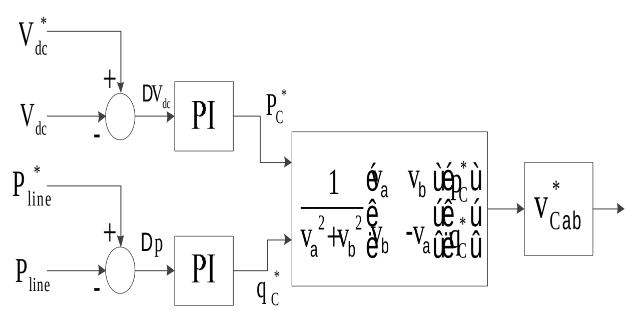


Fig **4.** Voltage frame strategy

If $p^*_c = 0$, the injected voltage is perpendicular to the voltage of the PCC. In addition to the power flow control, the injected voltage changes the dc link voltage. As a result, the DC link needs to be connected to a power source or energy storage system. In this strategy, the DC link voltage control loop modifies the injected voltage deviation to make it to the perpendicular to the line current.

In the current frame controller, the DC link voltage control loop is used to compensate losses, while here this loop has another duty, i.e. to modify the injected voltage angle so that the active power is not exchanged with the network continually. As described, the DC link control loop not only compensates the losses of the DC link, it also changes the injected voltage angle automatically to keep it perpendicular to the line current to protect the DC link voltage. In Figure 5, both control strategies are shown, neglecting power losses.

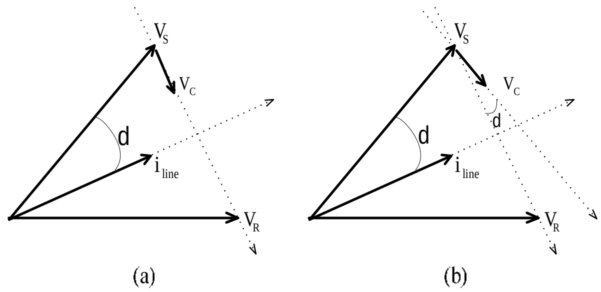


Fig 5. Phasor diagram ignoring losses (a) The current frame (b) The voltage frame

IV. SSSC DAMPING CONTROLLER

A. The Structure of SSSC Controller

The configuration of SSSC damping controller is displayed in Fig. 6. According to [19], the rotor speed deviation is an appropriate alternative input signal for FACTS device controllers compared with the local signals, i.e. the line current and the transferred active power. Consequently, the rotor speed deviation is used as the input signal in this paper and the output signal is the injected voltage V_q. The structure consists of a gain K_S, a washout signal block and a two-stage lead-lag block.

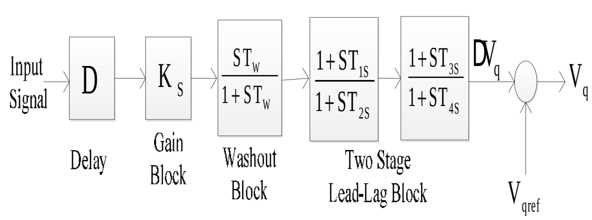


Fig 6. The structure of SSSC Controller

The washout signal block, with a time constant T_W, is used as a high-pass filter. T_W is large enough to pass the input signal, including fluctuations, unchanged. The amount of T_W is not critical and can be in a range from 1 to 20 seconds. The lead-lag blocks (time constants T_{1S}, T_{2S}, T_{3S} and T_{4S}) provide the appropriate specified phase-lead for the phase-lag offset between the input and the output. In Figure 6, V_{qref} shows the reference injected voltage, which is obtained from the steady state power flow calculations.

B. Problem Definition

In the lead-lag controller structure, the time constant T_W is normally a predetermined amount. $T_W = 10s$ is used in this paper. The controller gain K_S, and the time constants are determined using Particle Swarm Optimization (PSO) algorithm. In steady state conditions, V_{qref} is a constant value and ΔV_q is equal to zero, while in dynamic conditions, the injected series voltage, V_q, is adjusted so that to damp oscillations of the power system. The effective value of V_q is calculated as follows:

$$V_q = V_{qref} + \Delta V_q \tag{15}$$

The parameters of SSSC controller are designed to damp power system oscillations after a large disturbance. These oscillations can be observed by changes in the rotor angle, the rotor speed and the transmission lines power.

Since the power system operating conditions are varying, a performance index for a wide range of set points is defined as follows:

For single-machine power system:

$$J = \int_{t=0}^{t=t_1} |\Delta\omega| . t . dt \tag{16}$$

For two-machine power system:

$$J = \int_{t=0}^{t=t_1} |\omega_1 - \omega_2| . t . dt \tag{17}$$

Where, $\Delta\omega$ is the speed deviation in SMIB, ω_1 and ω_2 are the first and second generator speeds, respectively, and t_1 is the simulation time. To calculate the objective function, a time-domain simulation has been undertaken and for improved power system oscillations damping and improved stability, minimization of the objective function is performed. Problem constraints are the range of SSSC damping controller parameters. As a result, the design of the SSSC damping controller can be considered as an optimization problem as:

$$\text{Minimize } J \tag{18}$$

Subject to:

$$\begin{aligned} K_{MIN} &\le K \le K_{MAX} \\ T_{1_{MIN}} &\le T_1 \le T_{1_{MAX}} \\ T_{2_{MIN}} &\le T_2 \le T_{2_{MAX}} \\ T_{3_{MIN}} &\le T_3 \le T_{3_{MAX}} \\ T_{4_{MIN}} &\le T_4 \le T_{4_{MAX}} \end{aligned} \tag{19}$$

Typical ranges of the optimized parameters are [0.01–100] for K and [0.01–1] for T_1, T_2, T_3 and T_4 [20]. The process of optimizing the objective function by PSO algorithm and the time-domain simulation for setting the parameters are performed. In PSO, the search for the optimal parameters to achieve a unique solution is continued. Because of the strength of this algorithm, the parameters are set and the solution is not trapped in a local minimum. The optimized parameters based on the proposed and conventional strategies and specified by the PSO algorithm are shown in Table 1 for SMIB and Two-machine power systems. The SSSC controllers were designed by the mentioned strategies and tested under different disturbances and the results are presented in next section.

TABLE I

TABLE 1. THE OPTIMIZED PARAMETERS OF SSSC IN SMIB

Parameters	I Frame		V Frame	
	SMIB	Two-machine	SMIB	Two-machine
K	22.75	63.4	87.42	56.01
T1	0.02	0.12	0.01	0.05
T2	0.73	0.34	0.967	0.21
T3	0.876	0.76	1	0.891
T4	0.447	0.19	0.994	0.245

V. SIMULATION RESULTS

The proposed control strategy for the SSSC and the conventional strategy have been simulated in single-machine and two machine power systems under different disturbances and the results have been compared with each other. For simplicity, the proposed strategy with (V Frame) and the conventional strategy with (I Frame) are presented.

A. Single Machine Infinite Bus Power System

Single machine infinite bus system with SSSC is shown in Fig. 7. The system includes a synchronous generator, the coupling transformer, SSSC and two parallel transmission lines. In this figure, T represents the transformer, V_T and V_B are the terminal voltage of the generator and the infinite bus voltage, respectively, V_1, V_2, V_{DC}, V_q and I are the bus voltages, DC link voltage, the injected voltage of SSSC and the line current, respectively.

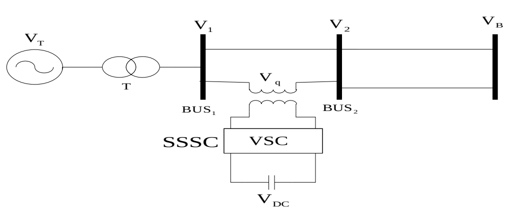
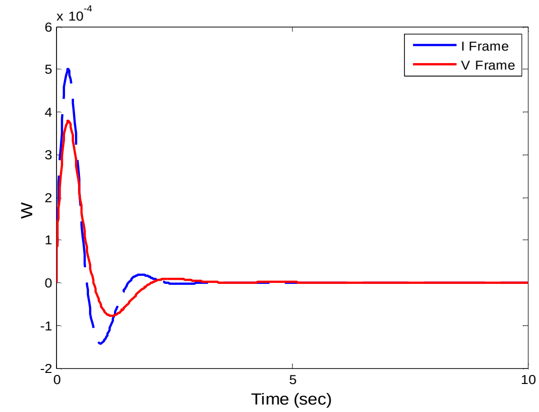


Fig 7. SMIB with SSSC

1) 3-phase fault disturbance

A three-phase to ground short circuit on the line between buses 1 and 2, close to the bus 2 in parallel transmission line with SSSC has happened and lasts for 100 ms. After clearing the fault, the system is restored to its initial state. The simulation results are shown in Fig. 8. According to Fig. 8, when SSSC damping controller is not used, the low frequency oscillations are not damped and the power system becomes unstable, while both control strategies damp the oscillations well and improve the dynamic stability. Compared with the conventional strategy, it is clear that the proposed strategy effectively increases the power system damping and stability by adjusting the injected voltage of SSSC. Also, the added DC link voltage control loop in the proposed strategy has prevented the DC capacitor from discharging, and with a very small voltage swing reaches the steady state value. Therefore, it does not require any energy storage system or power source connected to the DC link.



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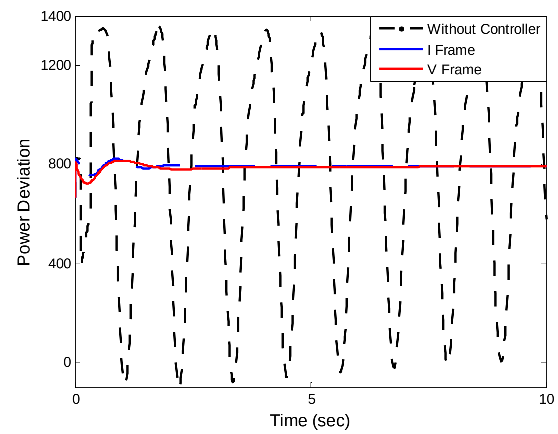

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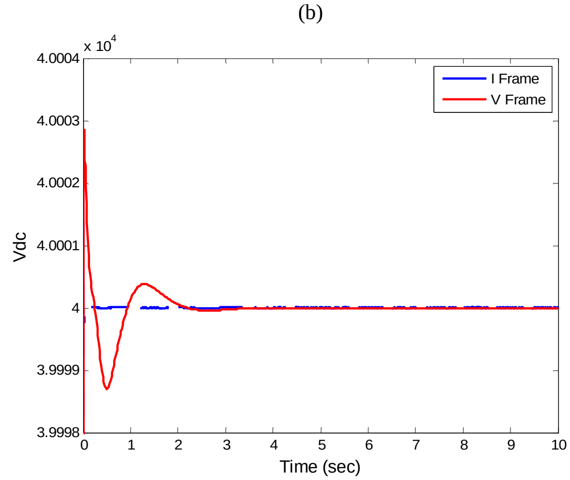


(c)

Fig 8. System response for 3-phase fault for 100 ms: (a) Speed Deviation (b) Power Deviation (c) DC link voltage

B. Two-machine power system

Figure 9 shows the single line diagram of the two-machine power system [21]. The parameters of the two generators, transformers, excitation system and transmission line are given in the Appendix. A SSSC is located between buses 3 and 4 on mid-point of the tie-line, to improve the stability of the power system. The speed difference between the first and the second generator ($W_1 - W_2$) is used as the input signal of the SSSC controller. The simulation results are obtained under the following condition.

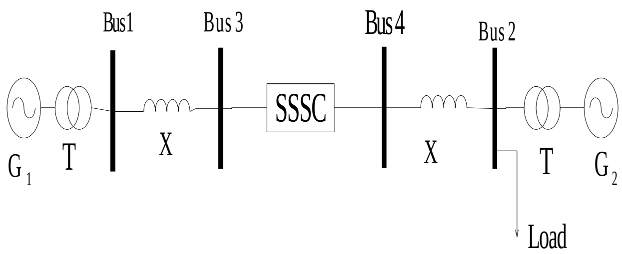
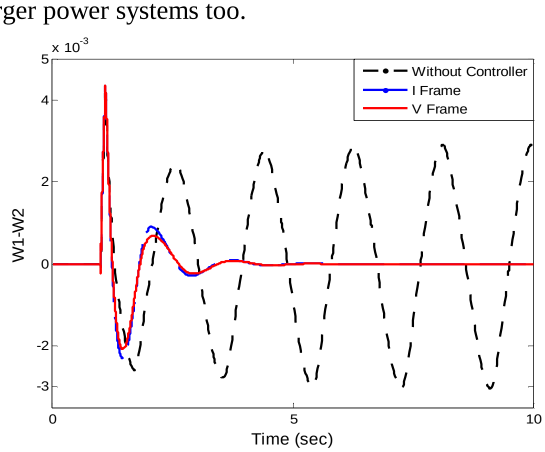


Fig 9. Two-machine power system

1) Single phase fault disturbance

A single-phase to ground short circuit on the line between buses 1 and 3, close to the bus 1 has happened and lasts for 100 ms. After clearing the fault, the system is restored to its initial state. Simulation results are shown in Fig. 10. According to this figure, both local and inter-area modes of oscillations in the absence of controllers are highly unstable. Again, the proposed strategy efficiently increases the power system damping by adjusting the injected voltage of SSSC. Compared to the conventional strategy, it is clear that the proposed strategy has a relatively better performance. Also here, with the modifications described, the DC link voltage is maintained. Considering the better efficiency of the proposed strategy in the two-machine power system, this strategy can be extended to larger power systems too.



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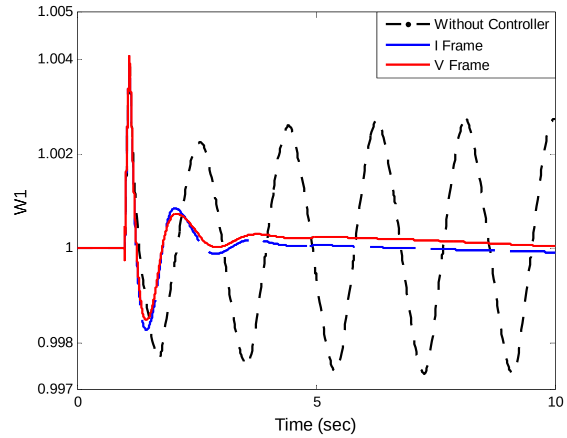

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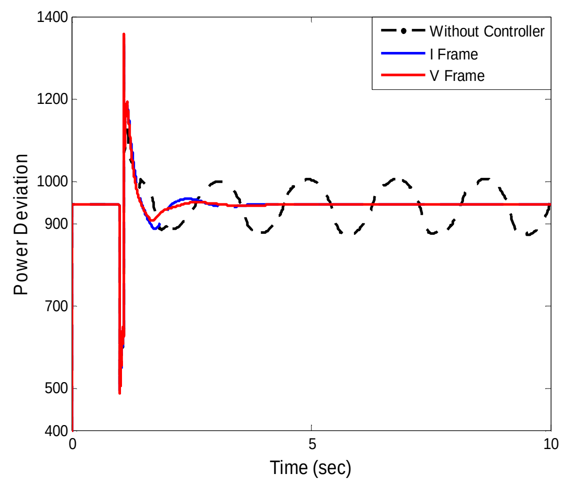

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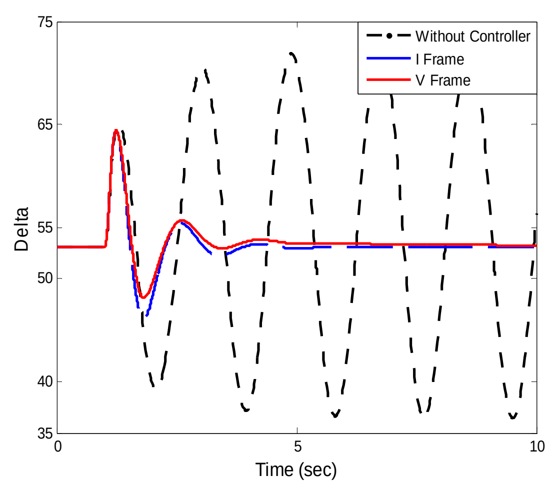

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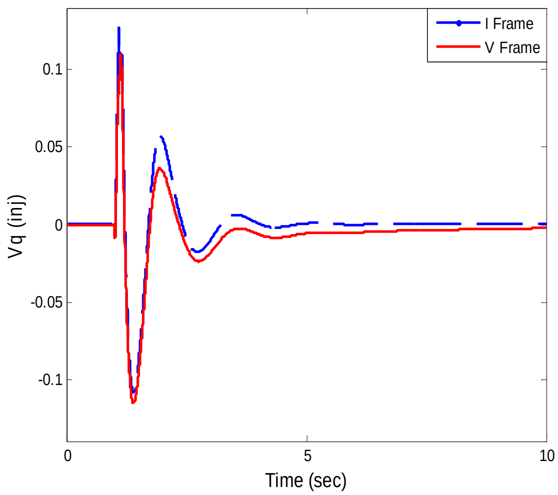

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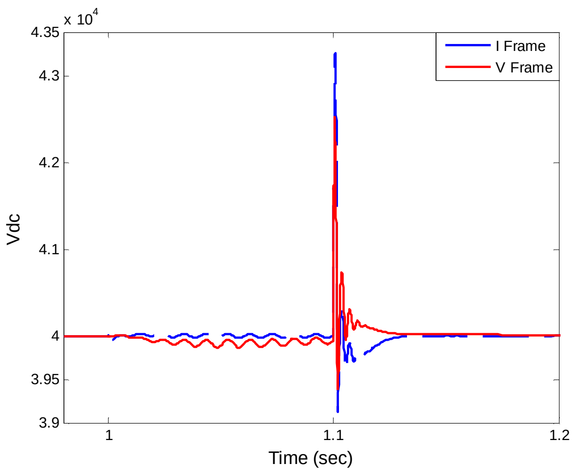

(f)

Fig 10. System response for single-phase fault for 100 ms: (a) Inter-area mode of oscillation (b) Local mode of oscillation (c) Tie-line power flow (d) Power angle deviation (e) SSSC injected voltage (f) DC link voltage

VI. Conclusions

The conventional control strategy for SSSC is based on an injected voltage perpendicular to the transmission line current. As a result, for the regulation and control of the active power flow, only reactive power is exchanged with the transmission line. In this paper, a control strategy based on measurement of the SSSC junction voltage, rather than the line current, was given. Both of the control strategies were simulated in single-machine and two machine power systems and the results were compared. For both strategies, the time domain simulation in order to minimize the objective function was performed and the results were carefully evaluated. Basically, the harmonic content of the current is more than the voltage harmonics. Consequently, the controller based on voltage has a better performance than the controller based on the current. The simulation results under different disturbances in both power systems indicate the effectiveness of the proposed control strategy for SSSC. The SSSC controller with the proposed strategy has damped the local and inter-area oscillations well, and has improved the dynamic stability.

VII. Appendix

Generator

$$S_{B_1} = S_{SMIB} = 2100\text{MVA},\ S_{B_2} = 5000\text{MVA},$$

$$H = 3.7\text{s},\ V_B = 13.8\text{kv},\ f = 60\text{Hz}$$

$$R_S = 2.8544\text{e-}3,\ X_d = 1.305,\ X_d' = 0.296,\ X_d'' = 0.252,\ X_q = 0.474,$$

$$X_q' = 0.243,\ X_d = 0.1,\ T_d = 1.01\text{s},\ T_d' = 1.01\text{s},\ T_{q0}'' = 0.1\text{s}$$

The excitation system

$$K_A = 200,\ T_A = 0.001\text{s},\ E_{f\,min} = 0,\ E_{f\,max} = 7$$

$$K_e = 1,\ T_e = 0,\ T_b = 0,\ T_c = 0,\ K_f = 0.001,\ T_f = 0.1\text{s}$$

Turbine and Governor

$$K_a = 3.33,\ T_a = 0.07,\ G_{min} = 0.01,\ G_{max} = 0.9751$$

$$V_{g\,min} = -0.1\text{pu/s},\ V_{g\,max} = 0.1\text{pu/s},\ R_P = 0.05,\ K_P = 1.163$$

$$K_i = 0.105,\ K_d = 0,\ T_d = 0.01\text{s},\ b = 0,\ T_W = 2.67\text{s}$$

Transmission line

$$3\text{-Ph},\ 60\text{Hz},\ L = 300\text{km}$$

$$R_1 = 0.02546\ \text{W/km},\ R_0 = 0.3846\ \text{W/km},\ L_1 = 0.9337\text{e-}3\text{H/km}$$

$$L_0 = 4.1264\text{e-}3\text{H/km},\ C_1 = 12.74\text{e-}9\text{F/km},\ C_0 = 7.751\text{e-}9\text{F/km},\ \text{Load} = 2500\text{MW}$$

SSSC

$$S_{nom} = 100\text{MVA},\ V_{nom} = 500\text{kv},\ f = 60\text{Hz},\ V_{DC} = 40\text{kv}$$

VIII. References

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