

Stability Enhancement for a Superconducting Generator in Multi-machine Power System Using STATCOM

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Abstract: - This paper investigates the multi-machine power systems stability enhancement by means of STATCOM-based stabilizers. To demonstrate the influence of the introduction of the STATCOM to the power systems, a comparative study is implemented by attaching a single SVC or a single STATCOM to the studied power system. The under-study power system includes a superconducting generator (SCG) and nine conventional units of different types and ratings. In view of control, various types of control systems are used such as Proportional Integral Derivative (PID) controller and power system stabilizers (PSSs). The system's nonlinear model is established by achieving a satisfactory degree of accuracy and tested for various types of contingency. The simulation results reveal that, the introduction of STATCOM is achieving further enhancement of the system performance in terms of damping increase and fast return of system variables to their nominal values under different disturbances such as 3-phase short circuit, step increase in load, and line outage compared to the SVC-based stabilizers.

Key-Words: - Multi-machine power systems, Control systems, Superconducting generator, Static var compensator, STATCOM, PID controller.

1 Introduction

SCGs is the optimum choice to overcome the up-rating problems of conventional synchronous generators, which adversely affect the system stability [1]. SCGs have many advantages such as the capability of generating greater power with higher efficiency, possibility of generation at transmission line voltages, reduced size and weight and low p.u. reactance as well as environmental advantages due to reduced oil consumption and CO₂ emissions [2]. Conversely, SCGs have high hunting frequency and low inherent damping, that requires a special attention and more considerations due to the field winding zero resistance and the corresponding extreme long time constant, which makes the SCG excitation control ineffective [3, 4]. Hence, the governor control loop is the only permissible loop to enhance performance of the SCG.

Flexible AC transmission systems (FACTS) got in the recent years as well-known term for higher controllability in power systems by means of power electronic technologies that introduce new degrees of freedom into the operation of power system. Several FACTS-devices have been introduced for various applications worldwide. Some of them such

as the thyristor based static var compensator (SVC) which is a widely applied technology; others like the voltage source converter (VSC) based static compensator (STATCOM) or the VSC-HVDC is being used in a growing number of installations worldwide [5, 6].

Even though excitation and governor control systems are widely used to suppress the generators electromechanical oscillations and enhance the overall stability of power systems, it is noticed that in some cases it is difficult to effectively damp the oscillatory modes using these controller alone, especially when they are acting through slow acting exciters [7, 8]. Continuous advances in power electronic technologies have made the application of FACTS devices very popular in power systems. Most FACTS devices are installed on transmission lines for the purposes of increasing the damping of low frequency oscillations [9].

This paper discusses the impact of attaching the FACTS-based stabilizer to the multi-machine power systems, especially the STATCOM. The considered power system includes one SCG and nine conventional units forming the New England power system. The system is tested for various types of

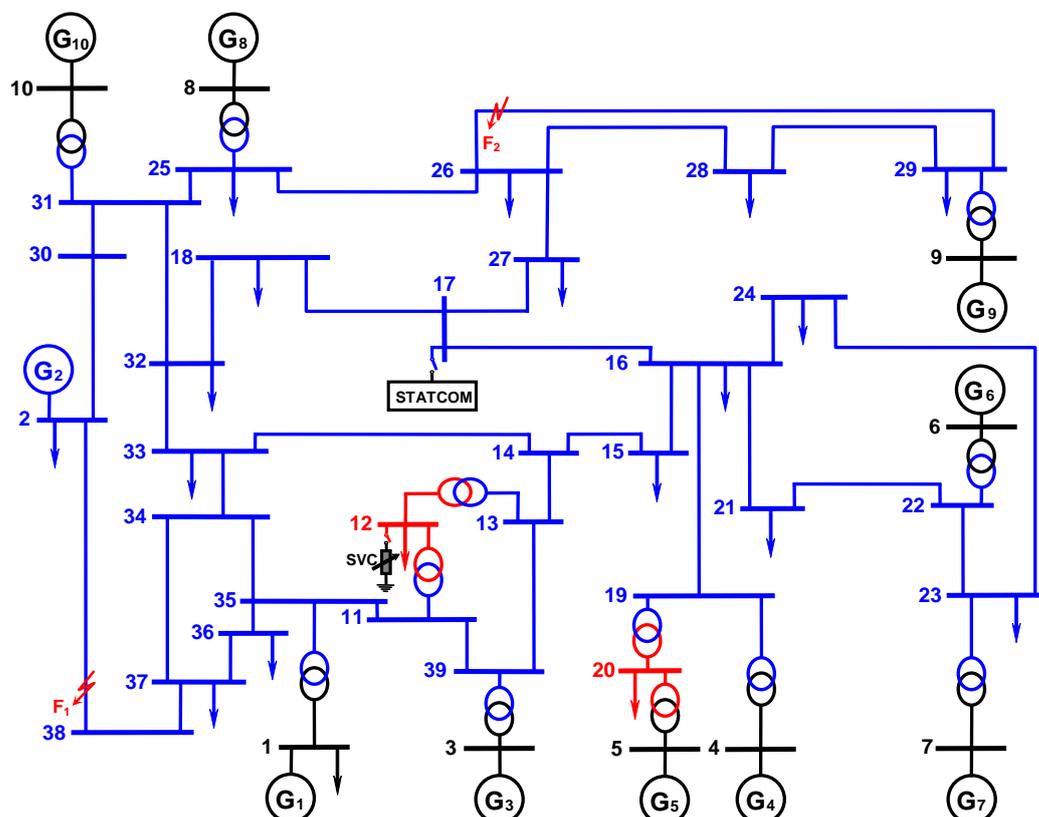


Fig.1 Single line diagram for the New England power system

Table 1 The generating units' arrangement

Generator No.	Type	Rating (MVA)	Generator No.	Type	Rating (MVA)
1	Nuclear	920.35	6	Steam	896
2	SCG	2000	7	Steam	835
3	Steam	835	8	Hydro-Electric	615
4	Steam	835	9	Nuclear	1070
5	Hydro-Electric	615	10	Steam	410

disturbances and its response is obtained in a comparative form with SVC to demonstrate the effectiveness the entrance of the STATCOM. In view of control, the SCG is controlled by PID designed according to pole placement technique, implemented in its governor control loop. While, conventional generating units are controlled by different conventional excitation control systems using adequate PSSs. On the other hand, SVC and STATCOM are equipped with various types of PID controller designed according to optimization technique. The simulation results illustrate that, the existence of the STATCOM in multi-machine power improves its performance and increases the stability margins.

2 POWER SYSTEM DESCRIPTION

The considered multi-machine power system is the New England power system: 10 machines, 39

buses and 19 load areas [10]. The single line diagram of the studied power system is represented in Fig.1. The power system is involving FACTS-devices such as the SVC or the STATCOM. All loads treated as lumped impedances and the transmission system is expressed as nominal π double-circuit lines. The generating units are different types and ratings, nine conventional units and a SCG unit, as illustrated in Table 1. The generating units parameters are listed in Appendix-A. In view of modeling, the conventional generating unit are represented by its reduced third-order model. However, a detailed representation for the SCG model, control systems, and transmission lines are considered. This detailed model is important especially for the SCG which has different construction criterions [1]. The rotor screens are the most critical parts in the modeling of the SCG. Each screen is represented by two fixed parameters coils, one on each axis [11]. Also, all nonlinearities and constraints of valve movements are taken into

consideration. The system generating units are equipped with various types of exciters as slow and fast acting thyristor exciters with different ceiling voltages.

3 SYSTEM MODELLING

This section describes the mathematical model for each component of the studied power system. These models involve generating units, network solution, excitation systems and FACTS-devices.

3.1 SCG Model

The SCG is represented by a detailed non-linear model. The order of the mathematical model is nine equations for the SCG (to cater the doubly screened rotor) and six for the turbine system that consists of a three stage turbine with reheat and parallel governing system [1]. The IEEE technical committee report illustrates the various models that represent the turbine dynamics [12]. The SCG is a low inertia unit so, it is equipped with fast valving routine to improve its stability [13]. The SCG's mathematical model is described in Appendix-B.

3.2 Conventional Generators Models

Based on park's *d-q axes*, a third-order nonlinear mathematical model representation is established to represent each conventional machine. The differential equations are arranged as a set of first order equations as following [16]:

I- Mechanical equations:

$$\dot{\delta}^i = \omega^i \tag{1}$$

$$\dot{\omega}^i = \frac{\omega_o}{2H^i} (T_m^i - T_e^i - K_d^i \omega^i) \tag{2}$$

II- Electrical equation:

$$\dot{E}_q^i = \frac{1}{T_{do}^i} (E_{fd}^i - I_d^i (X_d^i - X_d^i) - E_q^i) \tag{3}$$

where,

$$T_e^i = E_q^i I_q^i - I_d^i I_q^i (X_d^i - X_q^i) \tag{4}$$

$$\left. \begin{aligned} V_d^i &= I_q^i X_q^i \\ V_q^i &= E_q^i - I_d^i X_d^i \end{aligned} \right\} \tag{5}$$

III- Terminal power:

$$P_t^i = V_d^i I_d^i + V_q^i I_q^i \tag{6}$$

IV- Terminal voltage

$$V_t^i = \sqrt{V_d^i{}^2 + V_q^i{}^2} \tag{7}$$

To reduce the system order, the mechanical input torques are assumed to be fixed for conventional machines.

3.3 FACTS-Devices Model

Any multi-machine power system including FACTS-devices can be represented as shown in Fig.2. The study firstly considers these devices as generators which inject current I_s as shown in Fig.2. then, this current is used to determine the individual reference voltage for each generator. Then, the individual reference current is calculated from the generator model and transformed to the common reference current. The common reference current is calculated from the FACTS-device model. These values are used to calculate the common reference voltage for the FACTS-device and for each generator and so on.

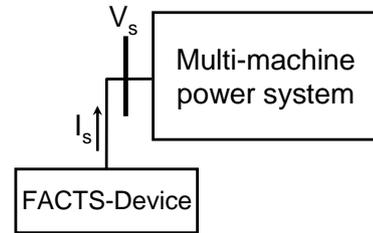


Fig.2 The representation of the shunt FATS-Device

3.3.1 SVC Model

SVC is basically a shunt connected variable reactance whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific power system variables [17]. The SVC equivalent circuit is shown in Fig.3.

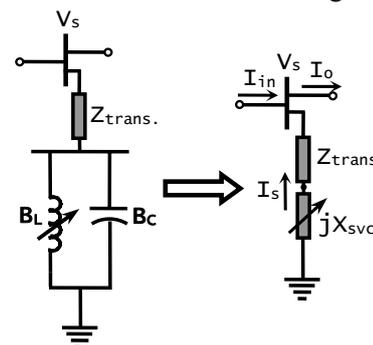


Fig.3 The SVC equivalent circuit

Based on *d-q axes* rotate with the common reference *D-Q axes*, the SVC nonlinear first-order differential equations are:

$$\dot{I}_{SD} = \frac{\omega_o}{X_S} (-V_{SD} - I_{SD} R_S + I_{SQ} X_S) \tag{8}$$

$$\dot{I}_{SQ} = \frac{\omega_o}{X_S} (-V_{SQ} - I_{SQ} R_S - I_{SD} X_S) \tag{9}$$

where,

$$I_s = I_{SD} + jI_{SQ} \quad (10)$$

The thyristor firing angle first-order differential equation:

$$\dot{\alpha}_{svc} = \frac{K_s (\alpha_{ref} + u_{svc} - u_v) - \alpha_{svc}}{T_s} \quad (11)$$

The SVC model produces the current injected to its bus. This current is used in network calculation as mentioned in previous section. This model of SVC is shown in Fig.4.

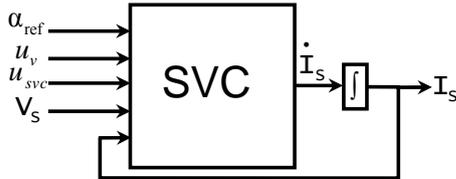


Fig.4 SVC model representation

3.3.2 STATCOM Model

The STATCOM is a versatile shunt injection FACTS device, based on a voltage source converter (VSC). This acts as a sinusoidal voltage source of variable phase and magnitude, the manipulation of which permits the control of the real and reactive power flow. The STATCOM equivalent circuit is shown in Fig.5.

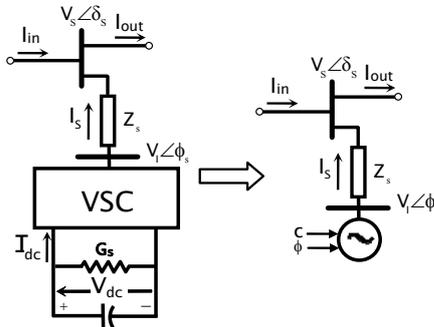


Fig.5 The STATCOM equivalent circuit

Based on $d-q$ axes rotate with the common reference $D-Q$ axes, the STATCOM nonlinear first-order differential equations [18]:

$$\dot{I}_{SD} = \frac{\omega_o}{X_s} (V_{ID} - V_{SD} - I_{SD} R_s + I_{SQ} X_s) \quad (12)$$

$$\dot{I}_{SQ} = \frac{\omega_o}{X_s} (V_{IQ} - V_{SQ} - I_{SQ} R_s - I_{SD} X_s) \quad (13)$$

The DC link capacitor will exchange energy with the system and its voltage will be varied through the first-order differential equation:

$$\dot{V}_{dc} = -\frac{1}{C_s} \left(\frac{P_{ac}}{V_{dc}} + G_s V_{dc} \right) \quad (14)$$

where,

$$P_{ac} = V_{ID} I_{SD} + V_{IQ} I_{SQ} \quad (15)$$

The STATCOM model produces the current injected to its connected bus. This current is used in network calculation using the system admittance matrix. The model of STATCOM is shown in Fig.6.

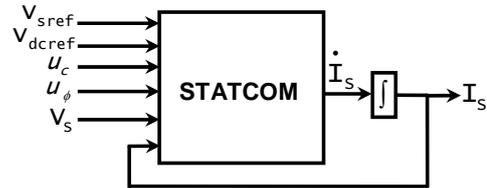


Fig.6 STATCOM model representation

4. CONTROL SYSTEMS

This section illustrates the used control systems for each component of the studied power system.

4.1 Conventional Generators' Control Systems

In this study, conventional generators are controlled via typical excitation systems using Various types of exciters with different ceiling voltages. In this control scheme the generators 1 and 6 are equipped with fast acting thyristor exciters with negligible time lag. The other conventional machines are equipped with rotary exciter types. High gains automatic voltage regulators (AVRs) are used with the exciters to control the generators' terminal voltages. The block diagram of the excitation systems for conventional generators is shown in Fig.7. The excitation system parameters are listed in Appendix-A according to the IEEE standardization.

Under heavy load conditions the continuously acting of excitation systems produce a negative damping to the system oscillations. To eliminate this undesired effect and in general to improve the system damping, an artificial network producing torque in the speed phase is introduced. The network used to add a signal that control the synchronous machine terminal voltage is called power system stabilizer (PSS) network [19]. The PSS is a lead-lag network with two time constants T_1 and T_2 and gain G_s . The PSS attached to the excitation system is shown in Fig.7. The PSS transfer function is given by:

$$\frac{y_s}{\omega} = G_s \frac{1+T_1 s}{1+T_2 s} \quad (16)$$

where, y_s is the control signal, and ω is the deviation in machine speed. The ratio T_1/T_2 is 10

[19]. A number of iterations have been taken to obtain the suitable gains for PSS for different generating units. Parameters of excitation systems and PSSs for conventional generating units are listed in Appendix-A.

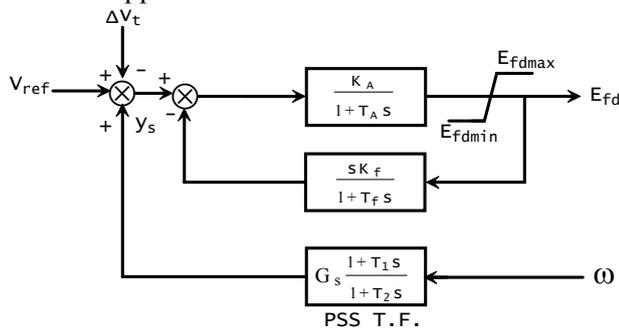


Fig.7 Excitation system for conventional generating units

4.2 SCG Control System

Excitation control is ineffective in improving the performance of the SCG due to the very long time constant of its field winding and the shielding effects of the two rotor screens, which is designed to protect the superconducting field winding from armature transients, also prevents any events in the field winding to be effective at the stator winding. Moreover, the magnitude and rate of change of the excitation current and field flux must not exceed certain limits, otherwise the superconducting element goes normal (quench) [20]. So, this renders the necessity of considering only the governor control loop to enhance the system's performance. Adding positive damping via the governor loop is very difficult and requires a great deal of attention [3]. The SCG is driven by a three stages steam turbine system with reheat and fast acting electrohydraulic governor. In this study the PID controller, designed according to pole placement technique, is used as a control system for the SCG in its governor control loop as shown in Fig.8. The PID controller parameters' values are obtained as $K_p=0.182668$, $K_i=0.000125366$, and $K_d=0.072285$ respectively [21].

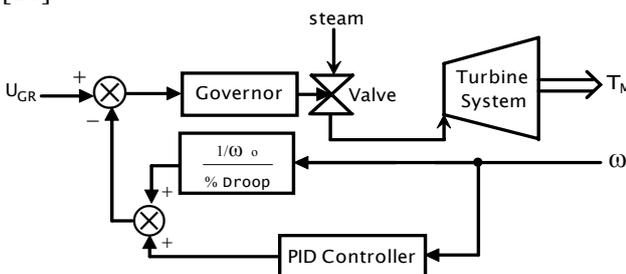


Fig.8 The SCG's governor control system

4.3 SVC Control System

One of the major reasons for installing a SVC is to improve dynamic voltage control and thus increases system load-ability. The SVC is equipped by PID controller to set the firing angle value of the thyristors and hence the SVC shunt susceptance setting [22]. The PID controller attached to the SVC is shown in Fig.9.

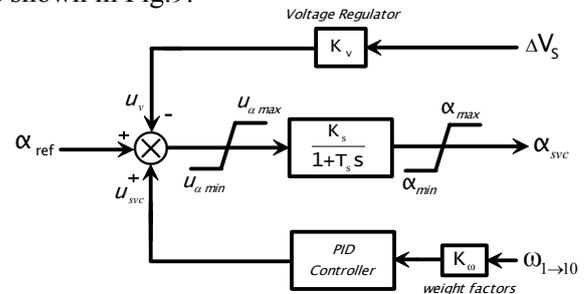


Fig.9 The SVC firing angle control system
The PID controller, the controller transfer function is given by:

$$H_{svc}(s) = K_{ps} + \frac{K_{is}}{s} + K_{ds}s \quad (17)$$

4.3 STATCOM Control Systems

The STATCOM may be represented in the same way as a controlled synchronous condenser, which its output voltage magnitude and angle are determined by control systems. The STATCOM is equipped with PID controllers to set its output voltage. The STATCOM control system shown in Fig.10.

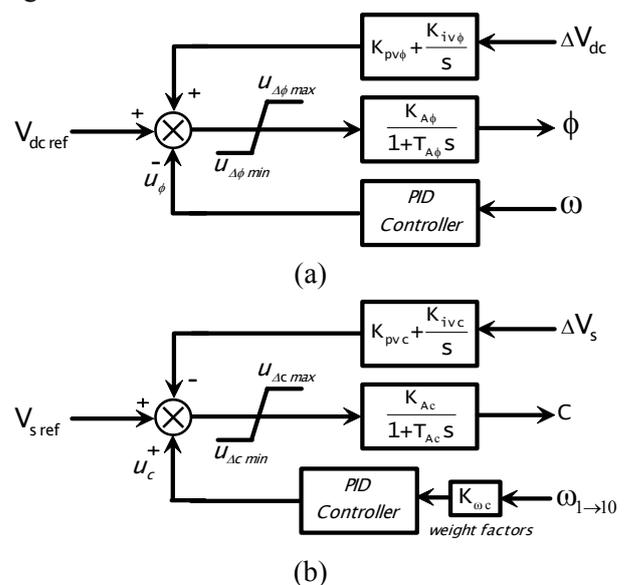


Fig.10 The STATCOM control system
(a) phase control (b) Magnitude control
The PID controllers' transfer functions are given by:

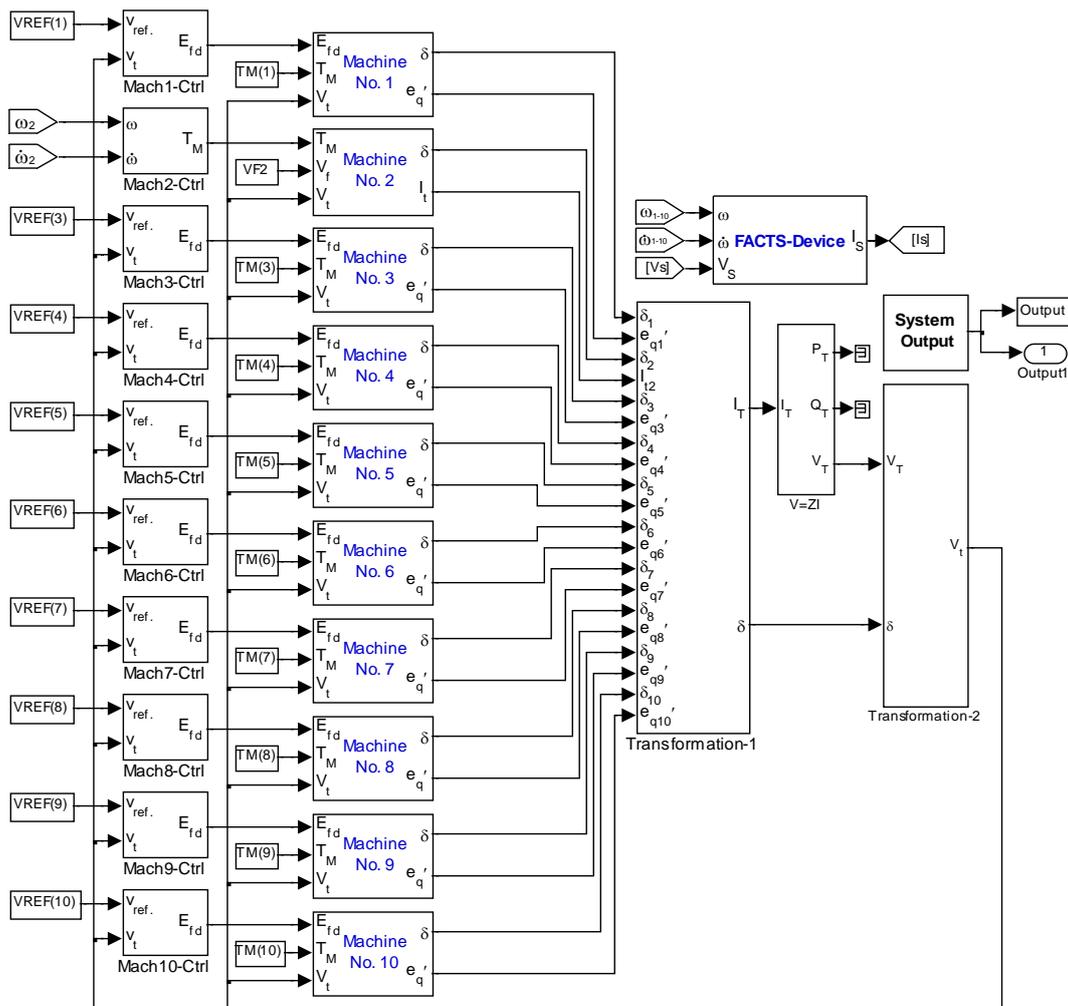


Fig.11 The SIMULINK model of the multi-machine power system

$$\left. \begin{aligned} H_c(s) &= K_{pc} + \frac{K_{ic}}{s} + K_{dc} s \\ H_\phi(s) &= K_{p\phi} + \frac{K_{i\phi}}{s} + K_{d\phi} s \end{aligned} \right\} \quad (18)$$

5. Digital Simulation

The SIMULINK model of a multi-machine power system including a SVC/STATCOM is shown in Fig.11. The differential equations describe each generator model are represented by separate blocks. The FACTS-device is also represented by a single block that describes its dynamic behavior. FACTS-device's sub-system and generators' sub-systems are linked together through the block that represents the electrical network to configure the whole system. The system initial flow calculation is computed by a m-file that accepts all system data and returns the system initial conditions. The loads have been replaced with a constant impedance-type model. The system model is tested before applying the disturbance for a

certain period (200 ms) then it is subjected to a disturbance and tested for 5 s using numerical integration technique.

5.1 Optimal Location of FACTS-devices

FACTS-devices are placed at a suitable bus to enhance the power system stability and to improve the damping characteristics of the power system. The system performance index technique is applied to choose the optimal location. The power system transient performance is obtained when it is subjected to a 3-phase short circuit. Fig.12 shows the values of performance index for different buses location when the SVC is equipped with PID controller with feedback signal of the speed deviations for all generators. According to the values of performance index, the optimal location for the SVC is at bus 28. Also, Fig.13 shows the values of performance index for different buses location when the STATCOM is attached to the system. This figure results in, the optimal location is bus No. 30.

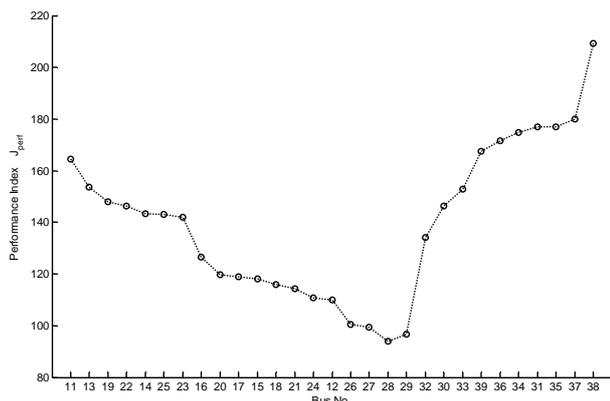


Fig. 12 The system's performance index versus the SVC location

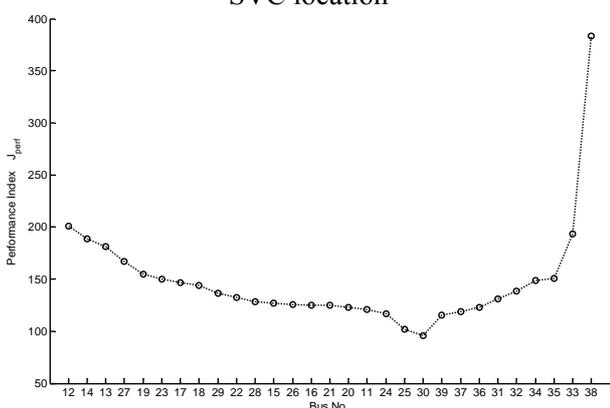


Fig. 13 The system's performance index versus the STATCOM location

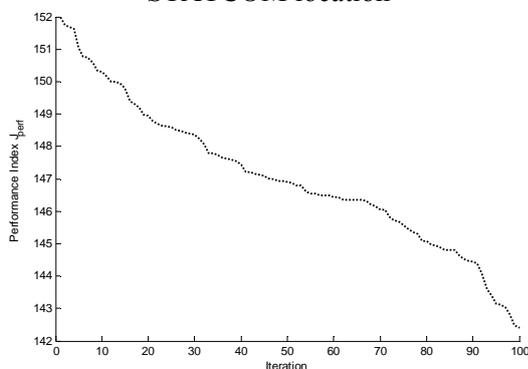


Fig. 14 The system performance versus the iteration in case of SVC

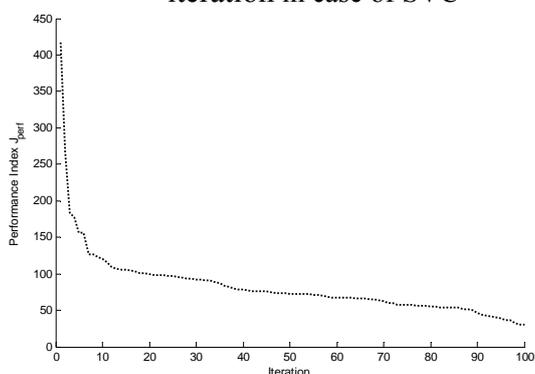


Fig. 15 The system performance versus the iteration in case of STATCOM

5.2 FACTS-devices controller parameters

After choosing the best location for the SVC/STATCOM, with the MATLAB optimization toolbox the control systems parameters of the FACTS-devices are determined by minimizing the system performance (J_{perf}), which is given by:

$$J_{perf} = \int_0^{\infty} e(t) * t^2 \tag{19}$$

where, $e(t) = \Sigma \{ \text{All of the system output deviations. Such as speed, rotor angle, valve position, etc.} \}$, t : is the time.

The system performance versus the iteration of the optimization is shown in Fig.14 for the case of SVC. And Fig.15 shows the case of attaching the STATCOM. With the help of MATLAB optimization toolbox the parameters of the SVC/STATCOM PID controllers are given in Appendix-A.

6. Simulation Results

The time response of the studied multi-machine power system involving a SVC/STATCOM is illustrated when it is subjected to different disturbances. The FACTS-based stabilizers' parameters are optimally designed when coordinated with the power system controllers with fixed parameters by the help of MATLAB optimization techniques.

The generators' rotor angles and the SCG valve position are used to evaluate the effectiveness of the proposed nonlinear model-based optimization process. The simulation results are obtained in a comparative form to show the effectiveness of FACTS-devices on the system performance.

Fig.16 shows the response when the system is subjected to a 3-phase short circuit at F_1 . This figure illustrates that, SVC positively affects the system's performance and adds more damping to it. For Fig.17, the comparison is focused on the effect of FACTS-devices only. The figure shows that, the system's response with STATCOM is more damped. So, all system variables return to their initial values quickly in case of STATCOM compared with SVC. Fig.18 through Fig.20 show the dynamic response of the system such as load increase, one line outage, or disconnection of a transformer. these results confirm the ability of STATCOM to increase the system's damping.

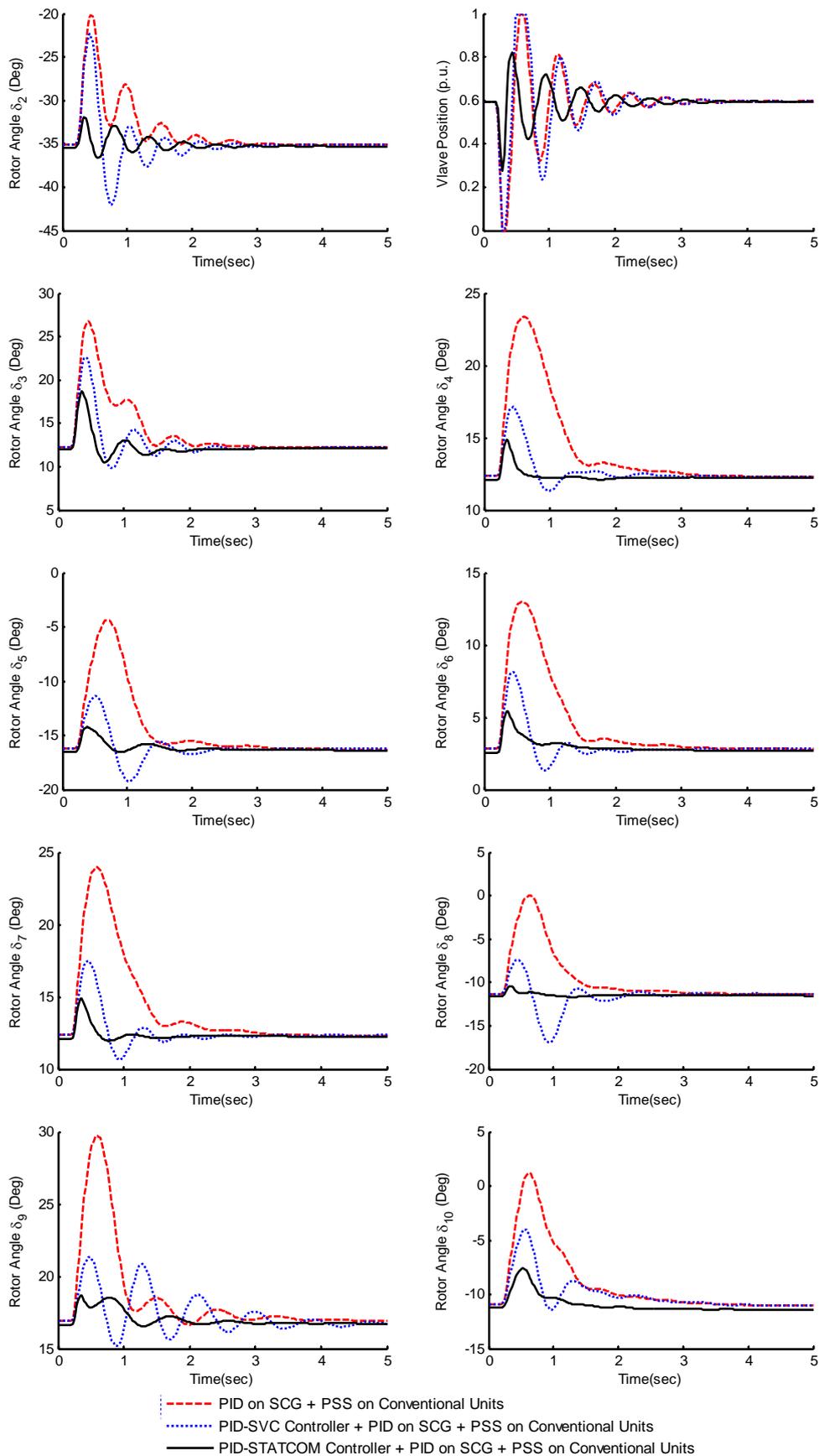


Fig.16 System transient response to a 3-phase short circuit for a 100 ms at F_1

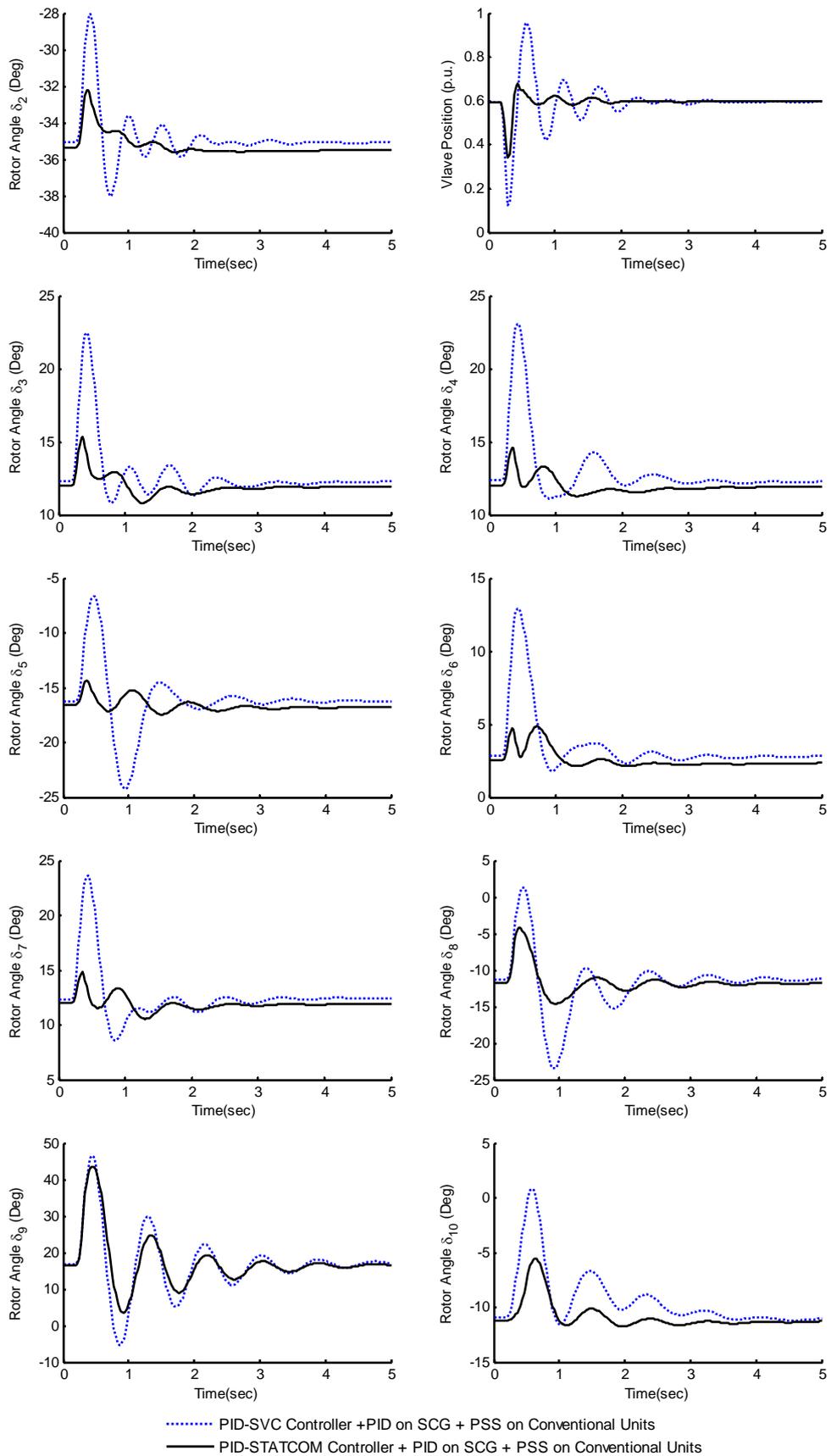


Fig.17 System transient response to a 3-phase short circuit for a 100 ms at F₂

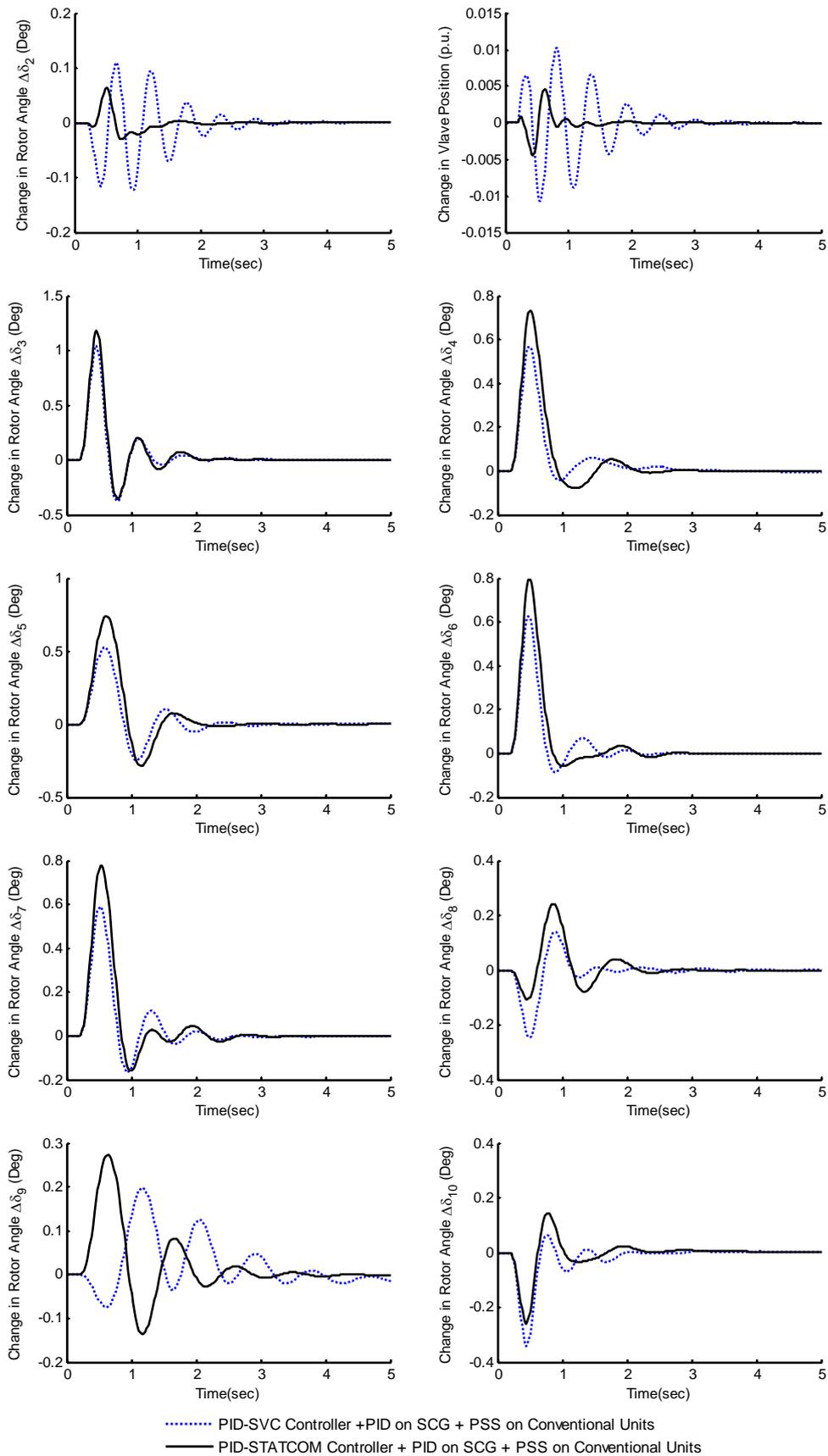


Fig.19 Dynamic response to one line outage (14-33) for 200 ms

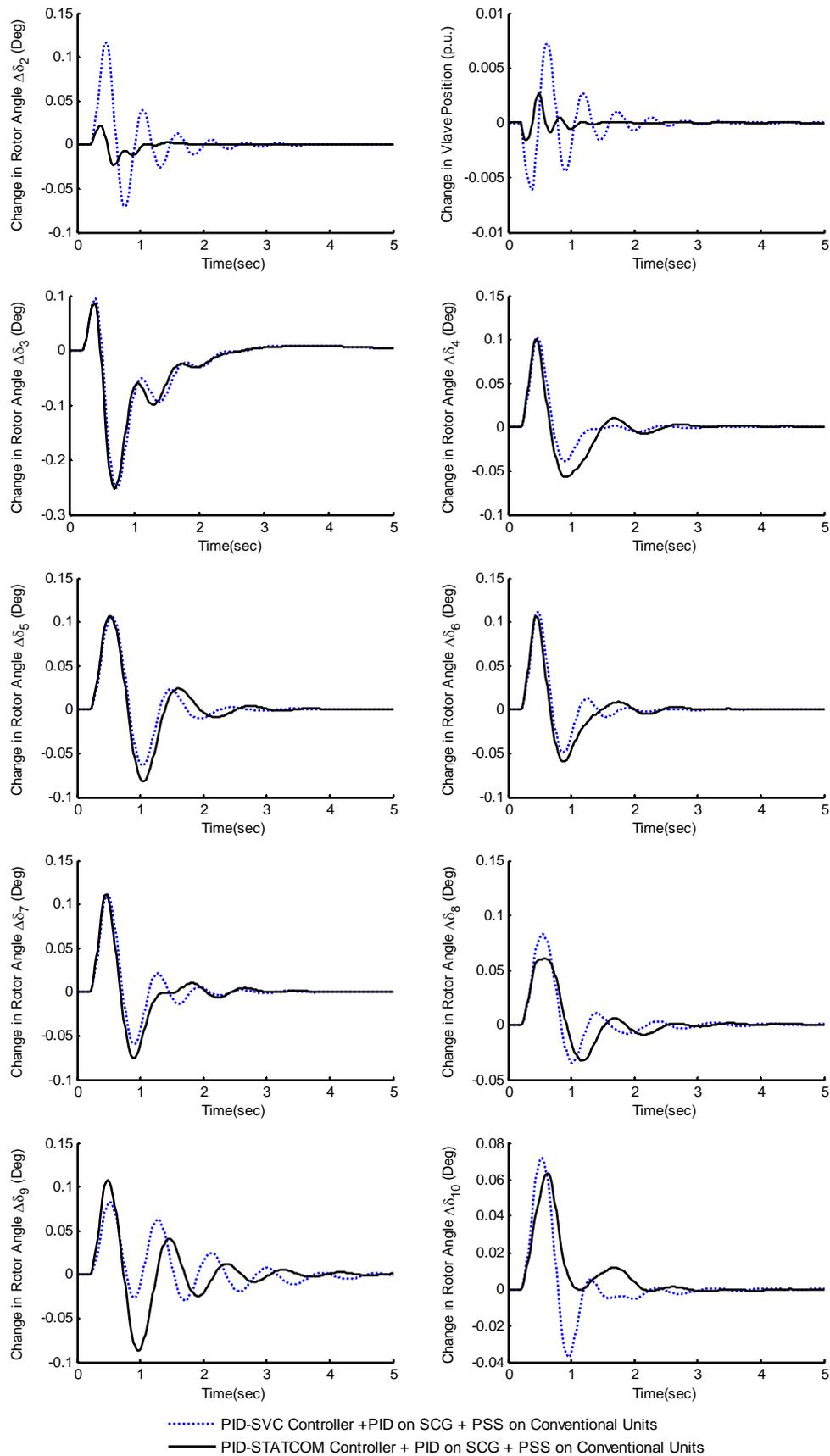


Fig.20 Dynamic response to a disconnection of transformer (11-12) for 200 ms

7. CONCLUSIONS

The paper presents FACTS stabilizers based PID controllers as a approach to improve the performance of SCGs in multi-machines power systems. Conventional generating units are equipped with excitation control systems. While, SCG is equipped with PID controller, designed using pole placement technique, in its governor loop. The FACTS-device are equipped with PID controllers designed using the system performance minimization. The simulation results, show the effectiveness of the STATOM-based controller over the SVC-based controller for various disturbances in terms of damping increase, system variables fast return to their nominal values and less movements of the SCG governor valve.

8. APPENDICES

Appendix-A

SCG parameters:

2000 MVA, 1700 MW, 3000 rpm
 $X_d=X_q=0.5457$ p.u.
 $X_{D1}=X_{Q1}=0.2567$ p.u.
 $X_{D2}=X_{Q2}=0.4225$ p.u., $X_f=0.541$ p.u.
 $X_{fd}=X_{fd1}=X_{dD1}=X_{dD2}=X_{D1D2}=0.237$ p.u.
 $X_{qQ1}=X_{qQ2}=X_{Q1Q2}=0.237$ p.u., $X_{fD2}=0.3898$ p.u.
 $R_a=0.003$ p.u., $R_{D1}=R_{Q1}=0.1008$ p.u.
 $R_{D2}=R_{Q2}=0.00134$ p.u.
 Field time constant=750 s
 $H=3$ KW.s/KVA

Turbines and governor system parameters

$T_{HP}=T_{GM}=0.1$ s, $F_{HP}=26\%$, $T_{IP}=0.1$ s, $F_{IP}=42\%$
 $T_{LP}=0.3$ s, $F_{LP}=32\%$, $T_{HR}=10$ s, $P_o=1.2$ p.u.

SVC parameters

$R_{trans}=0.01$ p.u., $X_{trans}=0.145$ p.u., $B_C=B_{L0}=1.0$ p.u.
 $\alpha_{svco}=90^\circ$, $60^\circ \leq \alpha_{svc} \leq 135^\circ$, $K_s=1$, $T_s=0.05$ s.,
 $|u_a|=10$, $K_v=50$.
 $K_{ps}=0.0683$, $K_{is}=8.0165$ and $K_{ds}=0.0483$.

Table 3 Conventional machines parameters

Unit	G ₁	G _{3,4,7}	G _{5,8}	G ₆	G ₉	G ₁₀
Rated (MVA)	920.35	835	615	896	1070	410
X _d (p.u.)	1.7900	2.1830	0.8979	1.7900	1.933	1.7668
X' _d (p.u.)	0.3550	0.4130	0.2995	0.2200	0.4670	0.2738
X _q (p.u.)	1.6600	2.1570	0.6460	1.7150	1.7430	1.7469
X' _q (p.u.)	0.5700	1.2850	0.6460	0.4000	1.1440	1.0104
T' _{do} (s)	7.9000	5.6900	7.4000	4.3000	6.6600	5.4320
H (s)	3.7638	2.6424	5.148	2.9297	3.0953	3.7041
K _d (p.u.)	2.00	2.00	2.00	2.00	2.00	2.00

Table 3 Excitation systems and PSSs parameters

Unit	G ₁	G _{3,4,7}	G _{5,8}	G ₆	G ₉	G ₁₀
K _A (p.u.)	25.000	400	200	250	400	400
T _A (s)	0.20	0.02	0.02	0.20	0.02	0.02
K _F (p.u.)	0.084	0.030	0.010	0.036	0.060	0.030
T _F (s)	1.00	1.00	1.00	1.00	1.00	1.00
E _{fdmax} (p.u.)	4.31	5.02	7.32	5.15	4.80	3.29
E _{fdmin} (p.u.)	-4.31	0.00	0.00	-5.15	0.00	0.00
G _S (p.u.)	0.03	0.03	0.03	0.03	0.03	0.03
T ₁ (s)	0.15	0.15	0.15	0.15	0.15	0.15
T ₂ (s)	0.015	0.015	0.015	0.015	0.015	0.015

STATCOM parameters

$G_s=1/28$ p.u.; $C_s=1$ p.u., $K_s=0.9$ p.u.
 $K_{pc}=0.19024$, $K_{ic}=0.39253$, $K_{dc}=0.00207$
 $K_{p\phi}=0.44093$, $K_{i\phi}=0.71248$, $K_{d\phi}=0.0063$
 $K_{pv\phi}=0.71002$, $K_{iv\phi}=0.33503$
 $K_{pvc}=0.39921$, $K_{ivc}=0.62223$

Appendix-B

SCG model

Based on Park's model used d-q axes transformation, the SCG nonlinear first-order differential equations are [14]:

I-Stator Representation:

$$\dot{\Psi}_d = \omega_o (v_{td} + i_d R_a + \Psi_q) + \omega \Psi_q \quad (20)$$

$$\dot{\Psi}_q = \omega_o (v_{tq} + i_q R_a - \Psi_d) - \omega \Psi_d \quad (21)$$

II-Outer Screen Representation:

$$\dot{\Psi}_{D1} = -\omega_o i_{D1} R_{D1} \quad (22)$$

$$\dot{\Psi}_{Q1} = -\omega_o i_{Q1} R_{Q1} \quad (23)$$

III-Inner Screen Representation:

$$\dot{\Psi}_{D2} = -\omega_o i_{D2} R_{D2} \quad (24)$$

$$\dot{\Psi}_{Q2} = -\omega_o i_{Q2} R_{Q2} \quad (25)$$

IV-Field Circuit Representation:

$$\dot{\Psi}_f = \omega_o (v_f - i_f R_f) \quad (26)$$

The currents are obtained as a function of flux linkages as:

$$\begin{bmatrix} i_f \\ i_d \\ i_{D1} \\ i_{D2} \end{bmatrix} = \begin{bmatrix} X_f & -X_{fd} & X_{fD1} & X_{fD2} \\ X_{fd} & -X_d & X_{dD1} & X_{dD2} \\ X_{fD1} & -X_{dD1} & X_{D1} & X_{D1D2} \\ X_{fD2} & -X_{dD2} & X_{D1D2} & X_{D2} \end{bmatrix}^{-1} \begin{bmatrix} \Psi_f \\ \Psi_d \\ \Psi_{D1} \\ \Psi_{D2} \end{bmatrix} \quad (27)$$

and

$$\begin{bmatrix} i_q \\ i_{Q1} \\ i_{Q2} \end{bmatrix} = \begin{bmatrix} -X_q & X_{qQ1} & X_{qQ2} \\ -X_{qQ1} & X_{Q1} & X_{Q1Q2} \\ -X_{qQ2} & X_{Q1Q2} & X_{Q2} \end{bmatrix}^{-1} \begin{bmatrix} \Psi_q \\ \Psi_{Q1} \\ \Psi_{Q2} \end{bmatrix} \quad (28)$$

V-Mechanical Equations:

$$\dot{\delta} = \omega \quad (29)$$

$$\dot{\omega} = \frac{\omega_o}{2H} (T_m - T_e) \quad (30)$$

where,

$$T_e = \psi_d i_q - \psi_q i_d \quad (31)$$

VI-Terminal power:

$$P_t = v_{td} i_d + v_{tq} i_q \quad (32)$$

VII-Terminal voltage:

$$v_t = \sqrt{v_{td}^2 + v_{tq}^2} \quad (33)$$

The model of the three stages steam turbine with reheat and electro-hydraulic governor is the IEEE standard representation as described in the model shown in Fig.21.

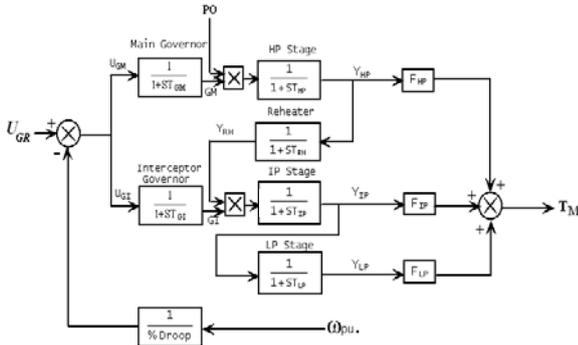


Fig.21 Representation of turbine and governor system

The mathematical model of the governor and turbine system is represented by a set of first order differential equations as:

I-The Electro-Hydraulic Governors Equations:

$$\dot{G}_M = \frac{U_{GM} - G_M}{T_{GM}} \quad (34)$$

$$\dot{G}_I = \frac{U_{GI} - G_I}{T_{GI}} \quad (35)$$

The valves travel and velocity limits are:

$$0 \leq G_M \leq 1, \quad -6.7 \leq \dot{G}_M \leq 6.7 \quad \text{and} \quad 0 \leq G_I \leq 1, \quad -6.7 \leq \dot{G}_I \leq 6.7.$$

These rate change limits are based on the time required to reach the valves positions to 100% which is 150 ms [15].

II-Turbines Equations:

$$\dot{Y}_{HP} = \frac{G_M P_o - Y_{HP}}{T_{HP}} \quad (36)$$

$$\dot{Y}_{RH} = \frac{Y_{HP} - Y_{RH}}{T_{RH}} \quad (37)$$

$$\dot{Y}_{IP} = \frac{G_I Y_{RH} - Y_{IP}}{T_{IP}} \quad (38)$$

$$\dot{Y}_{LP} = \frac{Y_{IP} - Y_{LP}}{T_{LP}} \quad (39)$$

The mechanical torque is given by:

$$T_m = F_{HP} Y_{HP} + F_{IP} Y_{IP} + F_{LP} Y_{LP} \quad (40)$$

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