

SCG Stability Enhancement Using STATCOM Based-ANN Controller

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Abstract: - Artificial neural network (ANN) control of static compensator (STATCOM) to improve the damping of power systems is presented. The proposed control strategy is applied on a STATCOM attached to a single machine-infinite bus (SMIB) and a multi-machine power systems that include a superconducting generator (SCG). The proposed control method, ANN-STATCOM is designed based on proportional integral derivative (PID) by means of minimization of the system's deviations. The damping provided by the ANN-STATCOM controller is compared with a fixed-parameter PID-STATCOM controller. In view of power systems control, various conventional types of control systems are employed such as PID controller for SCG and power system stabilizers (PSSs) for conventional units. The simulation results demonstrate the effectiveness of the proposed ANN-STATCOM controller in stabilizing the power systems performance for various disturbances at multiple operating points.

Key-Words: - Power system control, Superconducting generator, Static compensator, ANN control.

1 Introduction

The rapid development of power electronic switching technology provides opportunities to develop fast power converters to improve the dynamic performance of power systems [1]. During the last decade, Flexible AC transmission systems (FACTS) technologies have been proposed and implemented for power flow control, voltage stabilization and damping oscillation and harmonic filtering damping of power oscillations [2]. 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 based voltage source converter (VSC) such as static compensator (STATCOM) is being used in a growing number of installations worldwide [3, 4].

STATCOM is a shunt-connected FACTS device based synchronous generator that generates three-phase voltage using VSC from a DC capacitor [5]. The magnitude control of the STATCOM voltage, provides a shunt compensation by exchanging reactive power between the STATCOM and the transmission system. In addition to reactive power exchange, STATCOM can also improve stability and increase damping characteristics of the power systems, if a proper damping controller is designed [6]. To maximize the benefits of STATCOM, much

effort has been put to investigate the control capability of such devices to improve system stability [7].

Although Superconducting generators (SCGs) have many advantages such as high efficiency, generation at transmission line voltages, reduced size and weight as well as environmental advantages due to reduced oil consumption and CO₂ emissions [8, 9], the SCGs require 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 is not effective. Hence, the governor control loop is the only permissible control loop for the system performance enhancement [10, 11].

Various conventional controllers with fixed parameters have been employed for STATCOM as lead-lag compensator and PID [12]. These conventional controllers are designed at a certain operating condition using the system linearized model at this condition. Due to the load changes, other disturbance or the power system operating conditions daily changes, the fixed parameters of the controller which insure good performance under a certain operating condition may be not suitable for other conditions. To maintain better performance under a wide range of operating conditions, self

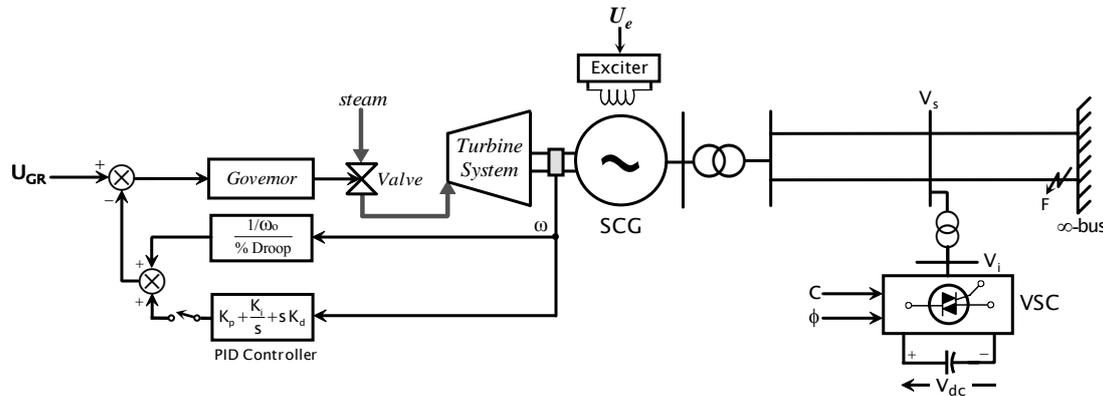


Fig.1 The studied electrical power system including a STATCOM

tuning adaptive controllers have been developed [13].

Since 1989, ANNs methodology has captured interest in electrical power engineering and has promised to ensure effective system performance enhancement [14, 15]. The use of artificial neural networks (ANNs) offers an attractive alternative for the STATCOM's control. The ANNs are able to model on-line nonlinear, MIMO (multiple inputs-multiple outputs), and non-stationary systems. The ANNs' nature makes them robust, adaptive, optimum, and hybrid control techniques, with attractive features to power system control [16].

This paper presents an alternative control approach using the ANN control strategy for STATCOM to improve the performance of power systems that include a SCG. The ANN scheme was trained by on-line unsupervised (self learning) ANN based PID controller using an optimization technique to minimize the system deviations in most common operating conditions. The ANN system consists of one input, one hidden and one output layers for each parameters. The system performance with ANN-STATCOM controller is compared with others using conventional PID-STATCOM controller. The simulation results reveals that the ANN controller is more flexible and robust for the system when subjected to various disturbances in a wide range of operating conditions.

2. single machine-infinite bus (SMIB)

The first considered power system is a SMIB consists of a SCG connected to an infinite bus through a double circuit transmission line using a step-up transformer. The SCG is driven by a three stages steam turbine system with reheat and fast acting electro-hydraulic governor. In addition to that, a STATCOM connected at the mid-line via a step-down transformer as shown in Fig.1.

2.1 SYSTEM MODELLING

A detailed model representation for SCG, STATCOM, control systems, and transmission lines is considered. This detailed model is important especially for the SCG which has different construction criterions [8]. 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 considered.

2.1.1 STATCOM model

The STATCOM is a flexible shunt injection FACTS device, 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.2

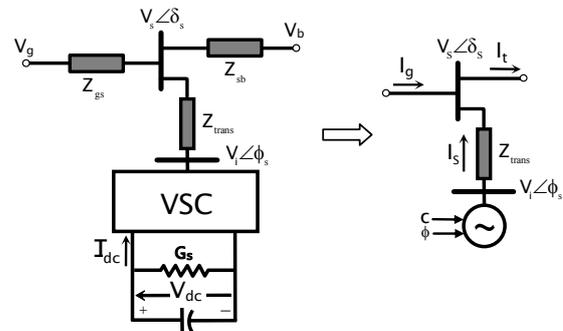


Fig.2 The STATCOM equivalent circuit

Based on *d-q* axes rotate with the SCG rotor speed, the STATCOM's AC side detailed nonlinear model is formed from the first-order differential equations [17]:

$$\dot{I}_{sd} = \frac{\omega_o}{X_s} (V_{id} - V_{sd} - I_{sd} R_s + I_{sq} X_s) + \omega I_{sq} \quad (1)$$

$$\dot{I}_{sq} = \frac{\omega_o}{X_s} (V_{iq} - V_{sq} - I_{sq} R_s - I_{sd} X_s) - \omega I_{sd} \quad (2)$$

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

$$\dot{V}_{dc} = -\frac{1}{C_s} \left(\frac{P_{ac}}{V_{dc}} + G_s V_{dc} \right) \quad (3)$$

where,

$$P_{ac} = V_{di} I_d + V_{qi} I_q = \text{real}(V_i I_s^*) \quad (4)$$

The d-q STATCOM's bus voltage components related to the infinite bus are:

$$\left. \begin{aligned} V_{sd} &= V_{bd} + I_{td} R_{sb} - I_{tq} X_{sb} \left(1 + \frac{\omega}{\omega_o}\right) + \dot{I}_{td} L_{sb} \\ V_{sq} &= V_{bq} + I_{td} X_{sb} \left(1 + \frac{\omega}{\omega_o}\right) + I_{tq} R_{sb} + \dot{I}_{tq} L_{sb} \end{aligned} \right\} \quad (5)$$

where, $X_s = X_{trans}$, $R_s = R_{trans}$, $Z_{trans} = R_{trans} + jX_{trans}$, $I_t = I_g + I_s$, and $I_t = I_{td} + jI_{tq}$.

Due to the fact that the STATCOM is placed on high-voltage transmission lines a step-down transformer is required in order to allow the use of power electronics devices as shown in Fig.1. The relationships between the converter DC and AC sides are obtained by applying the Pulse Width Modulation (PWM) technique, the VSC allows representation of the STATCOM with a voltage at fundamental frequency as:

$$V_i = c V_{dc} \angle \phi \quad (6)$$

where c is the amplitude modulation ratio of the VSC.

2.1.2 SCG Model

The SCG is a low inertia unit so, it is equipped with fast valving routine to improve its stability [18]. The IEEE technical committee report illustrates the various models that represent the turbine dynamics. The SCG's mathematical model is described in [19]. Based on Park's model used *d-q axes* transformation, The system nonlinear first-order differential equations are:

$$\dot{\delta} = \omega \quad (7)$$

$$\dot{\omega} = \frac{\omega_o}{2H} (T_m - T_e) \quad (8)$$

$$\dot{\Psi}_d = \omega_o (V_{sd} + I_{gd} (R_a + R_{gs}) + \Psi_q) + \omega \Psi_q \quad (9)$$

$$\dot{\Psi}_q = \omega_o (V_{sq} + I_{gq} (R_a + R_{gs}) - \Psi_d) - \omega \Psi_d \quad (10)$$

$$\dot{\Psi}_{D1} = -\omega_o I_{D1} R_{D1} \quad (11)$$

$$\dot{\Psi}_{Q1} = -\omega_o I_{Q1} R_{Q1} \quad (12)$$

$$\dot{\Psi}_{D2} = -\omega_o I_{D2} R_{D2} \quad (13)$$

$$\dot{\Psi}_{Q2} = -\omega_o I_{Q2} R_{Q2} \quad (14)$$

$$\dot{\Psi}_f = \omega_o (V_f - I_f R_f) \quad (15)$$

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

$$\begin{bmatrix} I_f \\ I_{gd} \\ I_{D1} \\ I_{D2} \end{bmatrix} = \begin{bmatrix} X_f & -X_{fd} & X_{fD1} & X_{fD2} \\ X_{fd} & -(X_d + X_{gs}) & X_{dD1} & X_{dD2} \\ X_{fD1} & -X_{dD1} & X_{D1} & X_{D1D2} \\ X_{fD2} & -X_{dD2} & X_{D1D2} & X_{D2} \end{bmatrix}^{-1} \begin{bmatrix} \Psi_f \\ \Psi_d \\ \Psi_{D1} \\ \Psi_{D2} \end{bmatrix} \quad (16)$$

and

$$\begin{bmatrix} I_{gq} \\ I_{Q1} \\ I_{Q2} \end{bmatrix} = \begin{bmatrix} -(X_q + X_{gs}) & X_{qQ1} & X_{qQ2} \\ -X_{qQ1} & X_{Q1} & X_{Q1Q2} \\ -X_{qQ2} & X_{Q1Q2} & X_{Q2} \end{bmatrix}^{-1} \begin{bmatrix} \Psi_q \\ \Psi_{Q1} \\ \Psi_{Q2} \end{bmatrix} \quad (17)$$

where,

$$T_e = \Psi_d i_{gq} - \Psi_q i_{gd} \quad (18)$$

2.1.3 Turbine and Governor System Model

The mathematical model of the governor and turbine system is represented by a set of first order differential equations as shown in Fig.3. Each stage in the mechanical system is represented by a first order differential equation and the hydraulic valves limits are imposed on the valves position and velocities [8].

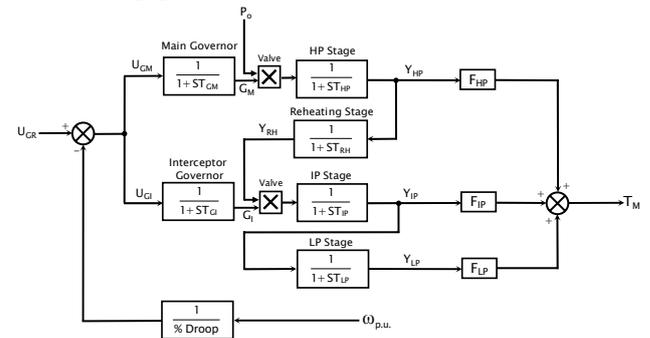


Fig.3 Representation of turbine and governor system

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

$$\dot{G}_M = \frac{U_{GM} - G_M}{T_{GM}} \quad (19)$$

$$\dot{G}_I = \frac{U_{GI} - G_I}{T_{GI}} \quad (20)$$

$$\dot{Y}_{HP} = \frac{G_M P_o - Y_{HP}}{T_{HP}} \quad (21)$$

$$\dot{Y}_{RH} = \frac{Y_{HP} - Y_{RH}}{T_{RH}} \quad (22)$$

$$\dot{Y}_{IP} = \frac{G_I Y_{RH} - Y_{IP}}{T_{IP}} \quad (23)$$

$$\dot{Y}_{LP} = \frac{Y_{IP} - Y_{LP}}{T_{LP}} \quad (24)$$

The mechanical torque is given by:

$$T_m = F_{HP} Y_{HP} + F_{IP} Y_{IP} + F_{LP} Y_{LP} \quad (25)$$

The valves' velocities limits are based on the time required to reach the valves positions to 100% which is 150 ms [19]:

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

After the initial conditions calculation step from the phasor diagram shown in Fig.4, a digital MATLAB-SIMULINK model has been built to simulate the studied power system. The system non-linear equations are solved using Runge-Kutta integration technique with integration step 0.2 ms and the system is tested after normal operation period of 200ms. The SCG, the STATCOM, the transmission and the mechanical system parameters are mentioned in Appendix A.

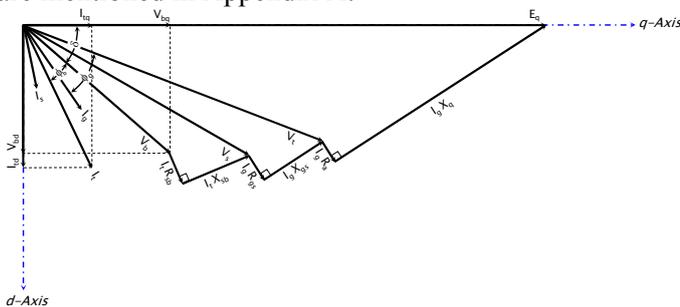


Fig.4 Phasor diagram of power system including a STATCOM device

2.2 SCG CONTROL system

The performance of the SCG is improved by incorporating controllers in the governor loop such as phase advance network or PID controller [19]. The used controller in this paper is the PID controller whose parameters are determined using pole placement technique and these values are reported in Appendix A [20].

2.3 STATCOM CONTROL systems

One of the major reasons for installing a STATCOM is to improve dynamic voltage control and thus increases system load-ability and enhances the transient stability. The STATCOM is equipped either by conventional controller such as lead-lag or adaptive controller such as ANN controller to set the modulation ratio and the phase angle and hence the STATCOM output voltage magnitude and phase. In this study, the conventional controller used is the PID and the adaptive one is the ANN, selector has been employed to connect the desired controller to the STATCOM as shown in Fig.5.

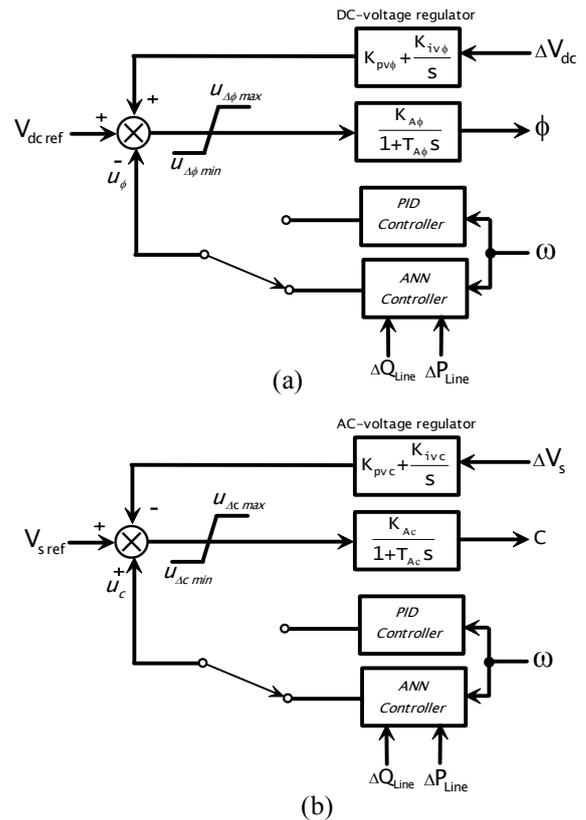


Fig.5 The STATCOM control systems (a) phase control (b) Magnitude control

2.4 Conventional PID-STATCOM Controller

The PID controller is relatively simple in practical implementation and can enhance the system performance particularly to minimize post fault oscillations. Pole placement technique is used in order to determine the controller parameters [21].

The selected roots are the SCG's dominant roots at lagging p.f. of the system time invariant model. The dominant eigenvalues of the system with PID-STATCOM compared with the STATCOM-voltage regulators only are illustrated in Table 1. The results illustrate the voltage regulators add a negative damping, as the dominant roots are worse than the system without STATCOM. The objective of the damping control systems is concentrated on the movement of these modes towards the left-hand side of the s-plane. From the pole placement technique the STATCOM regulators and controllers are listed in Appendix A.

Table 1 The system dominant eigenvalues

At lagging p.f.			
Modes	Without STATCOM	PI _φ and PI _c -regulators	PID _φ and PID _c
Rotor	-4±j13	-3.96 ± j14.28	-5.5 ± j11
Field	-0.00147	-0.0015047	-0.001503

2.5 ANN NETWORK controller design

The conventional PID controller is designed according to a certain operating point and its parameters are fixed. To overcome the drawbacks of conventional controllers, ANN strategies are proposed due to its simple structure, adaptability, robustness and considering the power grid nonlinearities. To obtain the optimal values of ANN based PID controller parameters, two ANNs are established to take the place of PID_{ϕ} and PID_c damping controllers. The inputs to the ANNs are the deviation in the transmission line active and reactive powers and its output is only one PID parameter. So, the proposed ANN construction is repeated three times for each controller parameter (three for PID_{ϕ} and three for PID_c).

Fig.6 shows the construction of one network of these ANNs group, which consists of one input layer, one hidden layer (3-neurons) with a hyperbolic tangent sigmoid activation function and one output with a pureline activation function. The complete ANN controller system is illustrated in Fig.7.

The ANNs' weights and biases are adjusted by minimizing the system performance index, which indicates the systems' deviations. The system performance index (J), which is the total sum of the system deviations multiplied by the square of the time as:

$$J = \int_0^{\infty} e(t) * t^2 \quad (26)$$

where, $e(t) = \sum \{ \text{deviations in } \delta, \omega, \text{ valve position, } |V_t|, V_{dc}, \text{ and } |V_s| \}$, t: is the time.

The minimization of the performance index is implemented by the use of MATLAB optimization toolbox.

2.6 Eigenvalues Analysis

To demonstrate the effect of ANN-STATCOM controllers on the eigenvalues, The system is linearized using the system SIMULINK model. The system dominant eigenvalues with ANN-STATCOM compared with the PID-STATCOM are illustrated in Table 2. It can be concluded from table, the introduction of ANN-STATCOM controllers increase significantly the system damping.

Table 2 The system dominant eigenvalues

At lagging p.f.		
Modes	PID-STATCOM controllers	ANN-STATCOM controllers
Rotor	$-5.5 \pm j11$	$-9.47087 \pm j10.2629$
Field	-0.0015034	-0.0015035

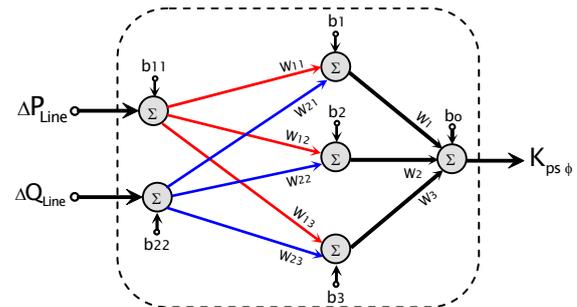


Fig.8 The architecture of one ANN

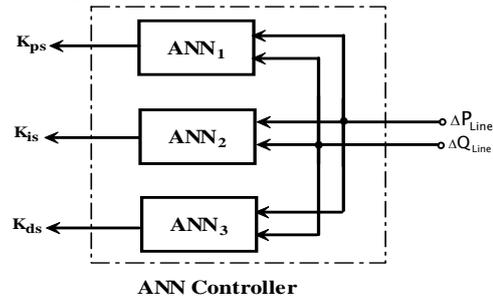


Fig.7 The ANN controller with all components

2.7 SMIB SIMULATION RESULTS

To study the robustness characteristics of the designed ANN-STATCOM damping controllers to all the operating conditions, simulation tests have been carried out using MATLAB-SIMULINK model of the system. The system performance is examined for various types of disturbances at different operating conditions. The simulation results are obtained in comparative form with conventional PID-STATCOM controllers. The time response of the system when the SCG is equipped by speed governor only for a symmetrical three-phase short circuit for 120 ms duration is shown in Fig.8. Starting from Fig 9 the results are focused on the comparison between ANN-STATCOM and conventional PID-STATCOM controllers. The time response of the system when the SCG is equipped by speed governor only for a symmetrical three-phase short circuit for 120 ms duration is shown in Fig.9. Fig. 10 shows the effectiveness of ANN-STATCOM to restore the system to its normal state after a major fault is applied. the System response to 3-phase short circuit followed by one line outage is shown in Fig.11. From Fig.12 to Fig.14 the system dynamic response is illustrated for 10% step increase U_{GR} , V_s ref, V_{dc} ref for 200 ms. These results illustrate that the ANN-STATCOM controllers is more reliable than conventional controllers as it provides a good damping to the electro-mechanical modes of oscillations and all system variables quickly return to their initial values.

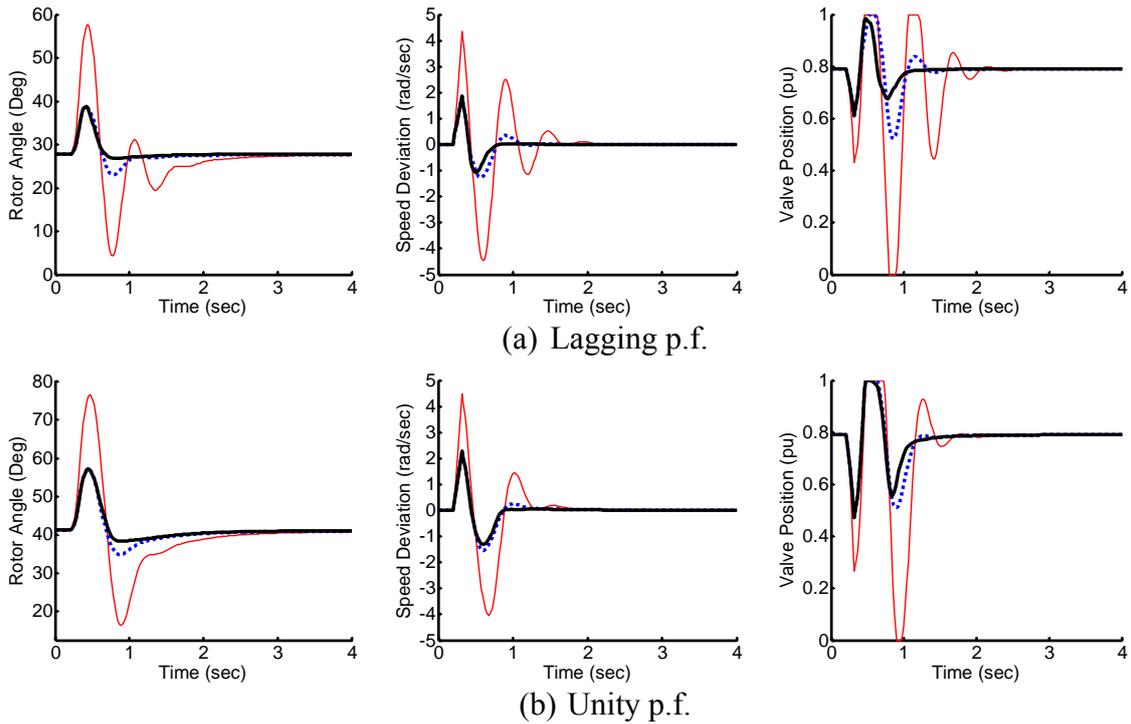


Fig.8 System response to a 3-phase short circuit for 120 ms, SCG equipped with PID controller

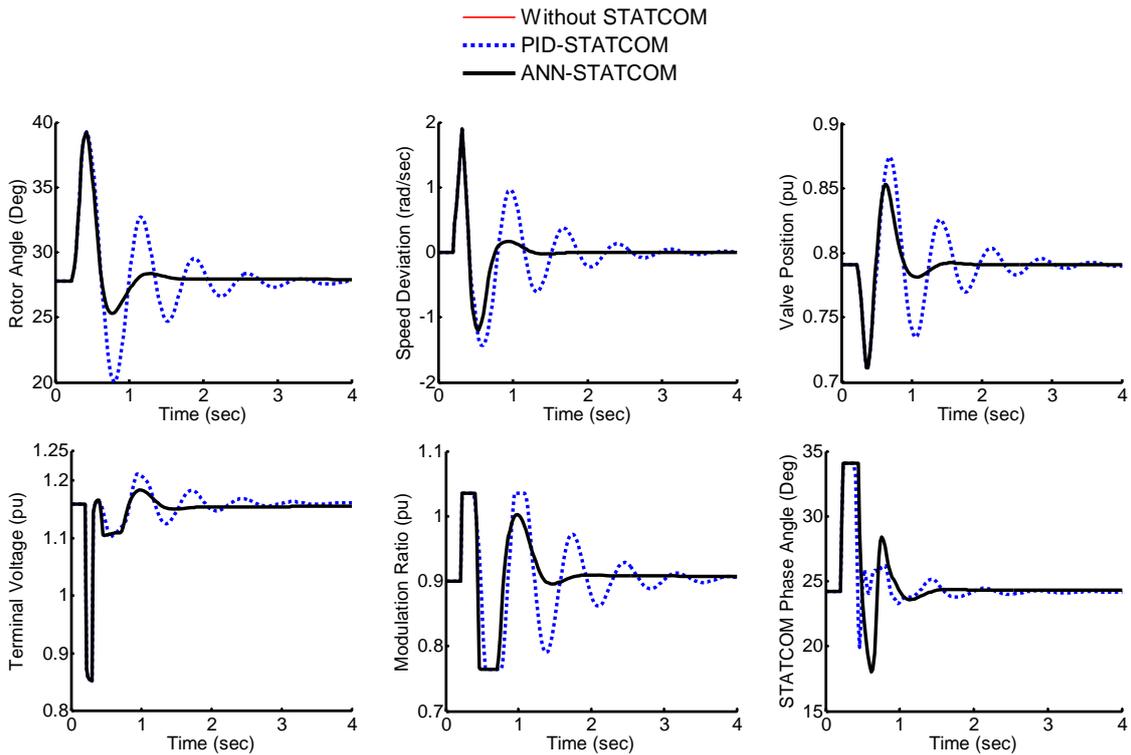


Fig.9 System response to a 3-phase short circuit for 120 ms at lagging p.f., SCG equipped with speed governor only

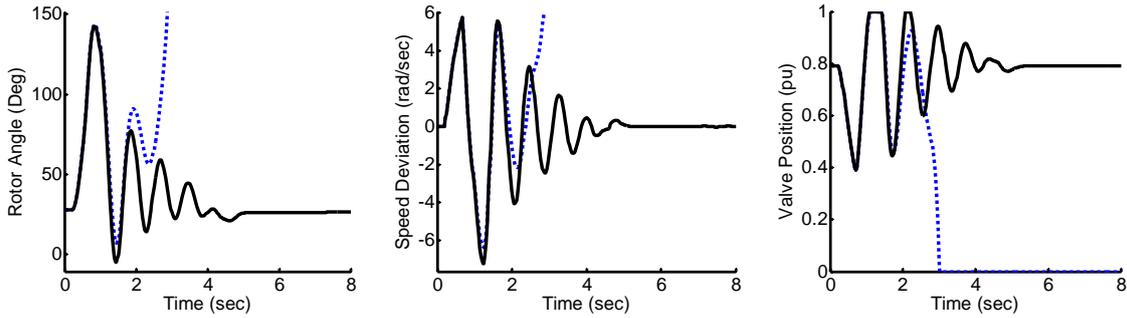


Fig.10 System response to a 3-phase short circuit for 490 ms at lagging p.f., SCG equipped with speed governor only

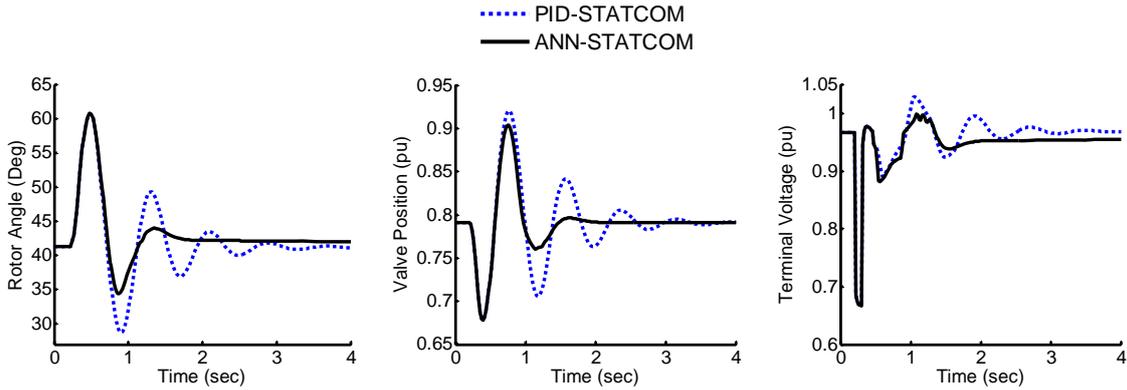


Fig.11 System response to 3-phase short circuit for 120 ms followed by one line outage for 200 ms at Unity p.f., SCG equipped with speed governor only

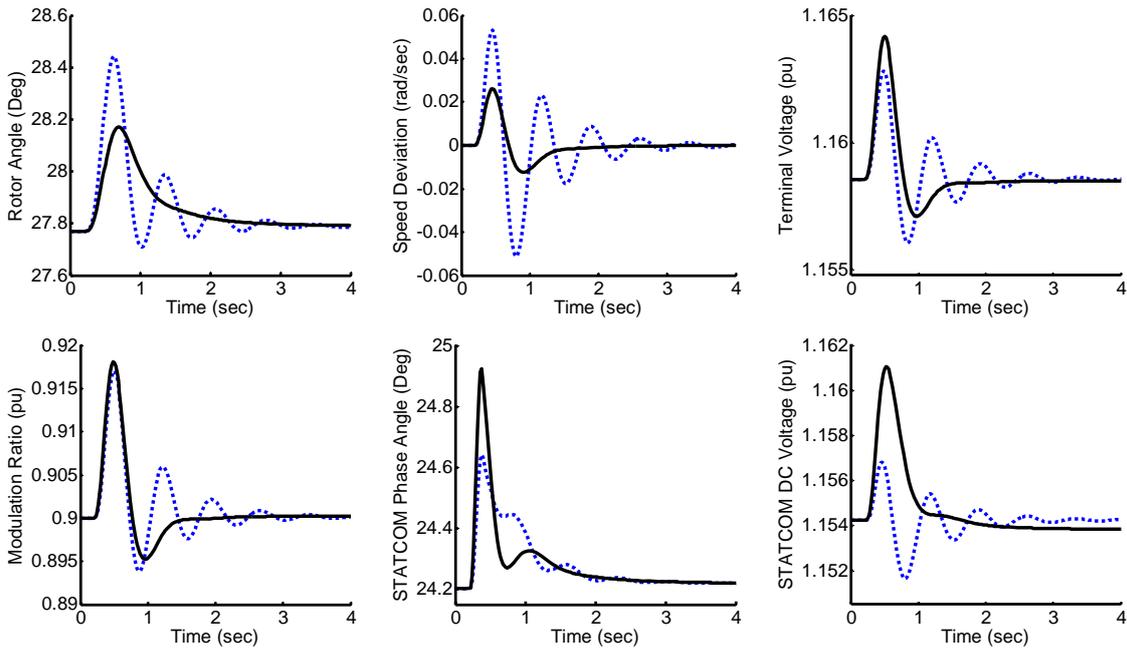


Fig.12 System response to a 10% step increase in mechanical input for 120 ms at lagging p.f. , SCG equipped with speed governor only

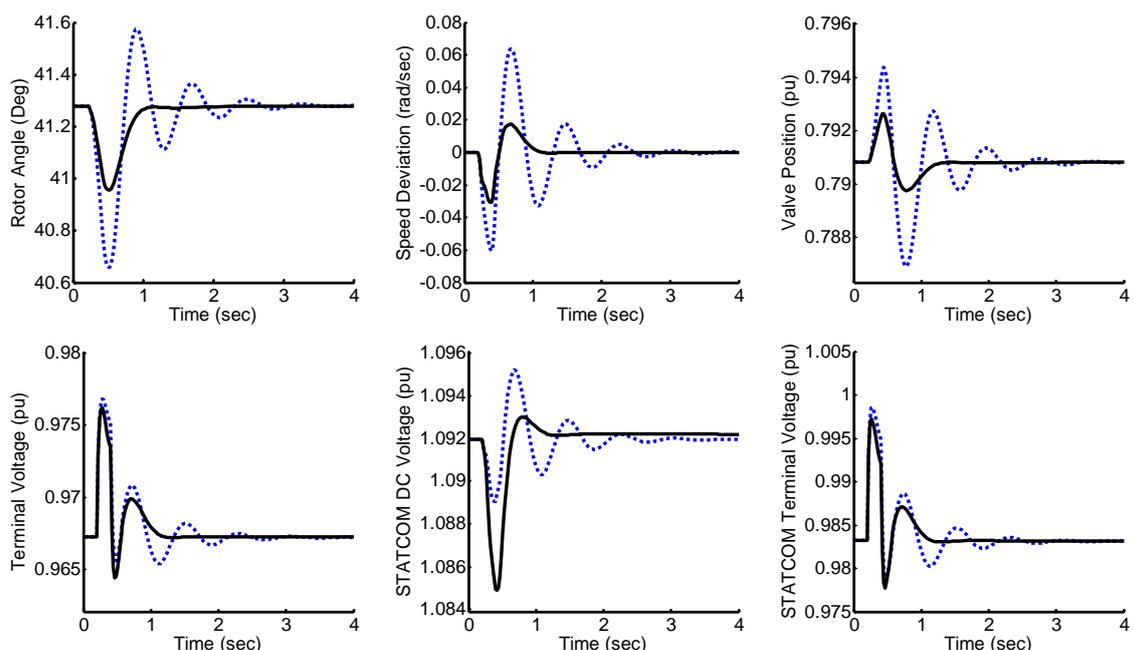


Fig.13 System response to a 10% step increase in $V_{s\text{ref}}$ for 200 ms, at unity p.f.

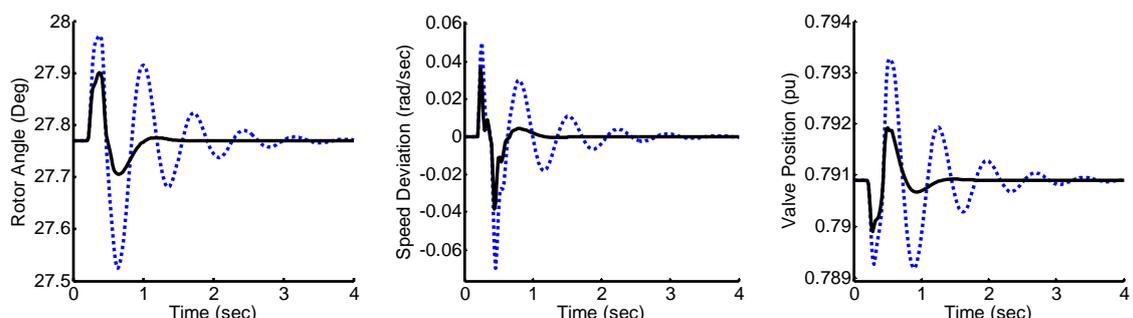


Fig.14 System response to a 10% step increase in $V_{dc\text{ref}}$ for 200 ms, at lagging p.f.

..... PID-STATCOM
 ——— ANN-STATCOM

3. Multi-Machine Power System

To verify the performance of the proposed ANN-STATCOM controller, a multi-machine power system is considered. The studied multi-machine power system is the New England power system: 10 machines, 39 buses and 19 load areas [22]. The single line diagram of the studied power system is represented in Fig.15. 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 3. 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, STATCOM, control systems, and transmission lines are considered. The

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

3.1 Conventional Generators

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 [23]:

I- Mechanical equations:

$$\dot{\delta}^i = \omega^i \tag{27}$$

$$\dot{\omega}^i = \frac{\omega_o}{2H^i} (T_m^i - T_e^i - K_d^i \omega^i) \tag{28}$$

$$\dot{E}_q^i = \frac{1}{T_{do}^i} (E_{fd}^i - I_d^i (X_d^i - X_d^i) - E_q^i) \tag{29}$$

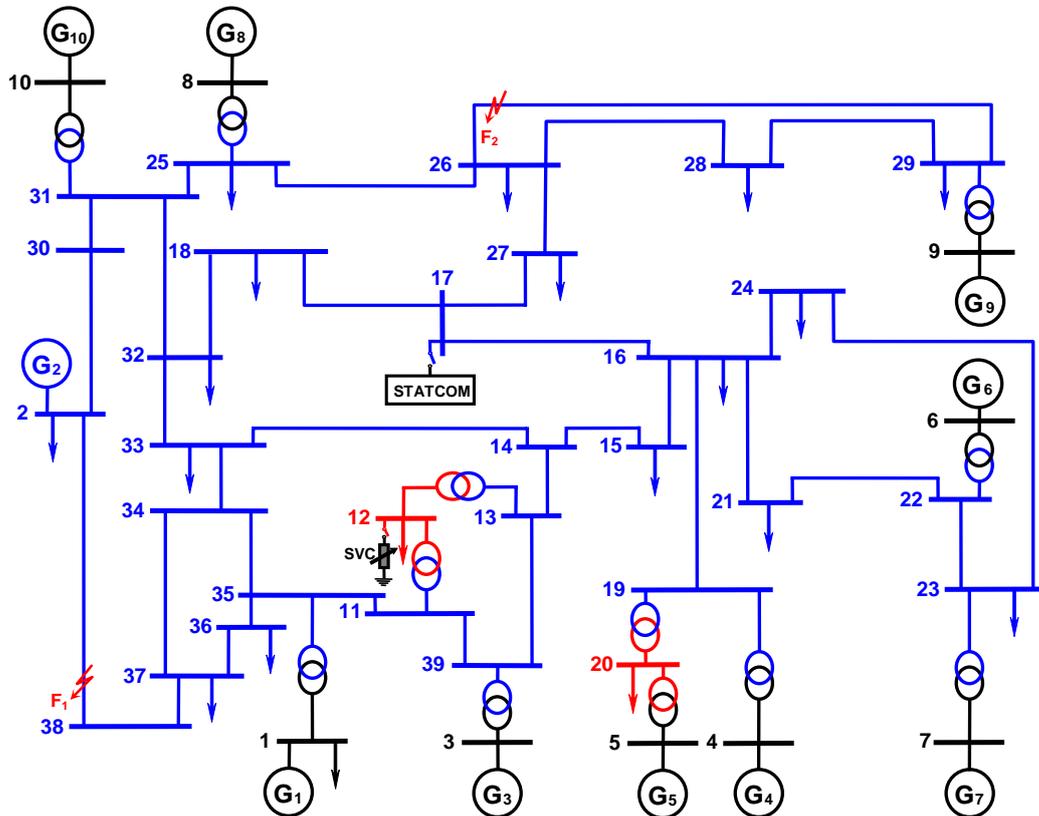


Fig.15 Single line diagram for the New England power system

Table 3 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

where,

$$T_e^i = E_q^i I_q^i - I_d^i I_q^i (X_d^i - X_q^i) \quad (30)$$

To reduce the system order, the mechanical input torques are assumed to be fixed for conventional machines. 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.16. 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 [24]. 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.16. The PSS transfer function is given by:

$$\frac{y_s}{\omega} = G_s \frac{1+T_1 s}{1+T_2 s} \quad (31)$$

where, y_s is the control signal, and ω is the deviation in machine speed. The ratio T_1/T_2 is 10 [24]. 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

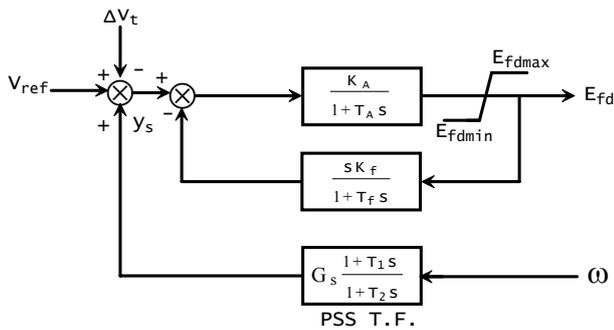


Fig.16 Excitation system for conventional generating units

3.2 Optimal Location of STATCOM

STATCOM is 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.17 shows the values of performance index for different buses location when the STATCOM 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 STATCOM is bus 30.

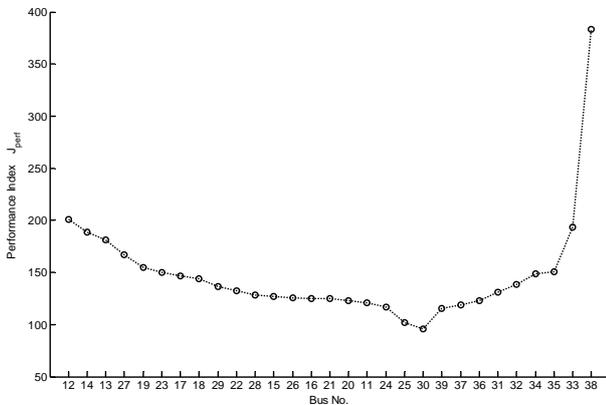


Fig.17 The system's performance index versus the STATCOM location

3.3 Multi-Machine Power System Simulation Results

The time response of the studied multi-machine power system involving a STATCOM is illustrated when it is subjected to different disturbances. The STATCOM-based stabilizers (PID and ANN) parameters are optimally designed when coordinated with the power system controllers 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 positive effect of the ANN-STATCOM on the system performance.

Fig.18 shows the response when the system is subjected to a 3-phase short circuit at F₁. This figure illustrates the significant improvement of the system's performance resulting from adding the STATCOM as it adds more damping. For Fig.19, the comparison is focused on the effect of STATCOM-controllers only. The figure shows that, the system's response with ANN-STATCOM is more damped. So, all system variables return to their initial values quickly in case of ANN-STATCOM compared with PID-STATCOM. Fig.20 and Fig.21 show the dynamic response of the system such as 10% increase in U_{GR} or load increase. These results confirm the ability of ANN-STATCOM to increase the system's damping.

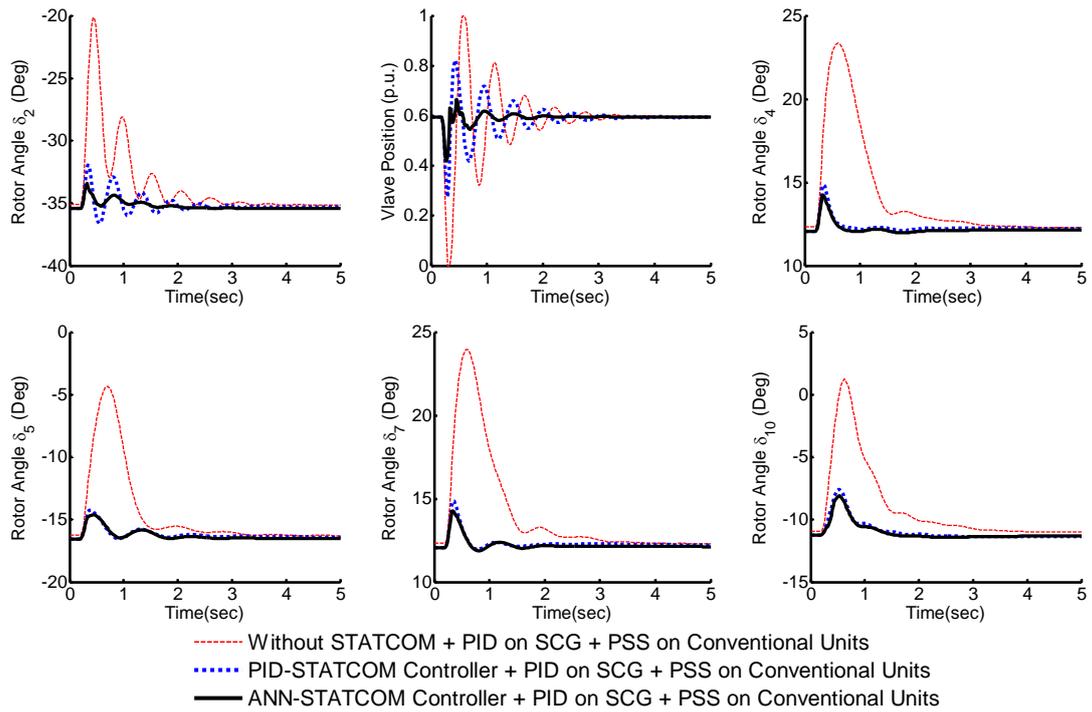


Fig.18 System transient response to a 3-phase short circuit for a 100 ms at F₁

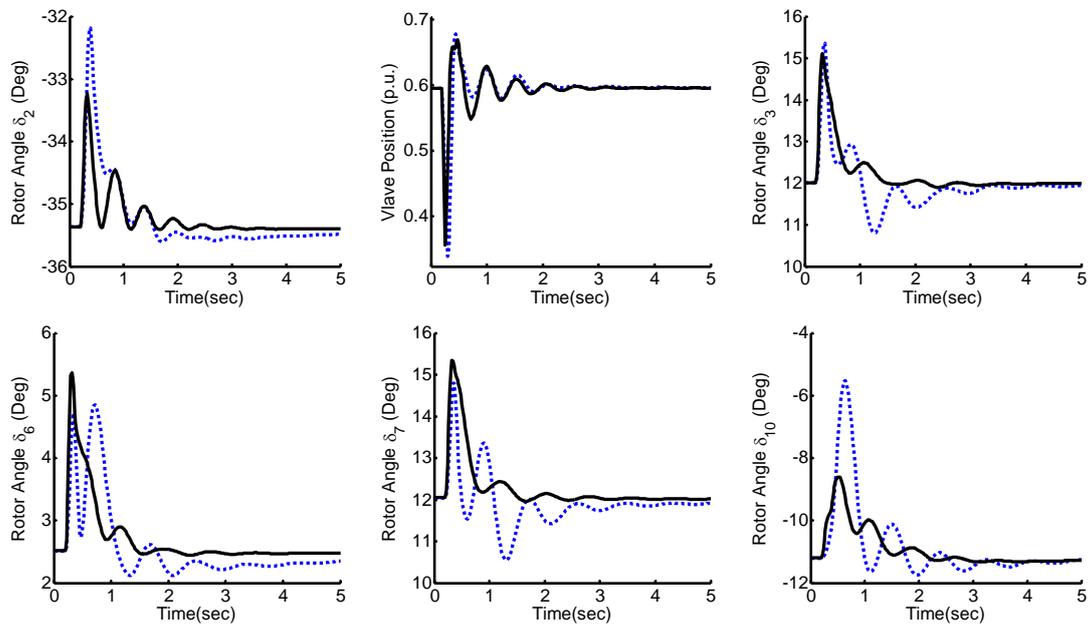


Fig.19 System transient response to a 3-phase short circuit for a 100 ms at F₂

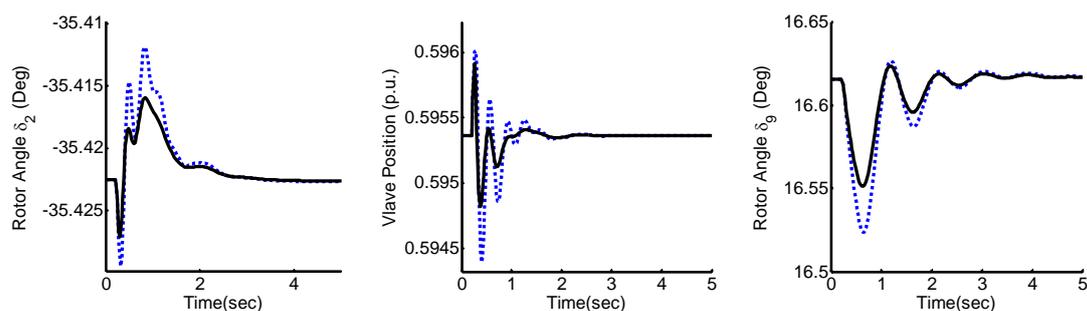


Fig.20 Dynamic response to a 10% load increase at bus 16 for 100 ms

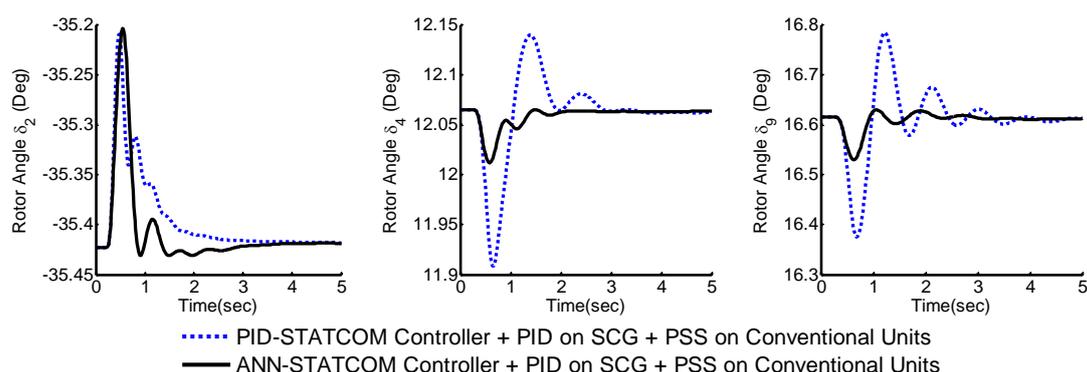


Fig.21 Dynamic response to 10% increase in SCG mechanical input for 100 ms

4. CONCLUSION

This paper presents the design of the ANN-STATCOM controllers based PID-STATCOM for stabilization the power systems. The control strategy has been implemented on a STATCOM attached to a SMIB and the New England power systems. In this study the SCG is equipped with PID controller in the governor loop and other units are equipped with PSS. For SMIB, the PID-STATCOM is designed using pole-placement technique. However, in case of multi-machine power system, it is designed using the system deviations optimization. The STATCOM output voltage is controlled either by conventional PID or by ANN controllers to compare the results. The ANNs main task is to adapt the controller parameters to the operating condition. The simulation results show the adaptability, robustness, reliability and the effectiveness of the ANN-STATCOM controller to provide significant damping characteristics over the conventional controller

for various disturbances at a wide range of operating conditions.

5. APPENDICES

Appendix-A

Superconducting Generator 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., $R_a=0.003$ 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.
 $R_{D1}=R_{Q1}=0.1008$ p.u., $R_{D2}=R_{Q2}=0.00134$ p.u.
 Field time constant=750 sec., $H=3$ KW.s/KVA.

Transmission line parameters:

$X_l=0.15$ p.u., $R_l=0.003$ p.u., $X_L=0.195$ p.u.,
 $R_L=0.0075$ p.u.

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.

SCG's PID Controller Parameters:

$K_p=0.18266$, $K_i=0.0001257$, $K_d=0.072285$.

STATCOM Parameters in SMIB System:

$G_s=1/28$ p.u.; $C_s=1$ p.u., $K_s=0.9$ p.u.

DC voltage regulator: $K_{pv\phi}=20.642$, $K_{iv\phi}=13.359$

AC voltage regulator: $K_{pvc}=2.0273$, $K_{ivc}=0.1592$

damping controller PID_{ϕ} : $K_{p\phi}=1.0351$, $K_{i\phi}=1.1995$, $K_{d\phi}=0.00456$

damping controller PID_c : $K_{pc}=0.4372$, $K_{ic}=1.6878$, $K_{dc}=0.01096$

STATCOM parameters in multi-machine System

$G_s=1/28$ p.u.; $C_s=1$ p.u., $K_s=0.9$ p.u.

$K_{pc}=0.19024$, $K_{ic}=0.39253$, $K_{dc}=0.00207$

$K_{p\phi}=0.44093$, $K_{i\phi}=0.71248$, $K_{d\phi}=0.0063$

$K_{pv\phi}=0.71002$, $K_{iv\phi}=0.33503$

$K_{pvc}=0.39921$, $K_{ivc}=0.62223$

Table 4 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 5 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

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