

POWER SYSTEM STABILIZATION USING ANN CONTROLLED STATCOM-SMES

Anil K. DAHIYA

Dept. of Electrical Engg.
National institute of technology,
Kurukshetra, India.
anildau@yahoo.co.in
Tel: +91-9416039964

Ratna DAHIYA

Dept. of Electrical Engg
National institute of technology,
Kurukshetra, India.
ratna_dahiya@yahoo.co.in
Tel: +91-9896848509

D. P. KOTHARI

Adviser Vellore Institute of
Technology University, Vellore,
India
(dpk0710@yahoo.co.in,)
Tel: +91-9443311334

Abstract- *An Static Compensator integrated with Superconducting magnetic Energy Storage (SMES) device using Artificial Neural Network (ANN) controller to stabilize the Single Machine Infinite Bus (SMIB) system is proposed in the present work. The active power exchanged by SMES plays a major role in improving the dynamic performance of power system during changes in operating conditions. The application of ANN controller enhances the performance of STATCOM-SMES system significantly. The use of PI controller to control the rate of active power exchange between a power system and superconducting coil of STATCOM-SMES has been reported already. In the present work, PI controller is replaced by artificial neural network controller. The dynamic performance of STATCOM-SMES in term of power system stabilization, using ANN controllers is evaluated through the simulation by using SimPowerSystems of SIMULINK/MATLAB.*

Index term– Power system stabilization, artificial neural network, oscillation damping, STATCOM, SMES.

1. Inrtoduction

A large power system is subjected to various disturbances very changes in operating conditions cause's oscillations and electromagnetic torque in the system [1]. The system variables such as frequency, load angle, active and reactive power of generator should be maintained within permissible limits and oscillations should be damped out as quickly as possible for a secured operation of a power system [2-3]. SMES is very effective to improving dynamic performance of power system due to its large energy storage capacity, fast response and negligible losses. A STATCOM, on the other hand, can only exchange reactive power and is effective for improving voltage

stability [9]. The integration of SMES and STATCOM is capable of exchanging active and reactive power simultaneously, and hence is most suitable to improve the dynamic problems of power system effectively [10-11]. The model of STATCOM-SMES comprises of voltage source inverter based STATCOM integrated with SMES through a chopper.

The effectiveness of STATCOM-SMES for improving the dynamic performance of power system depends mainly on the rate of exchange of active power during changing operating conditions. The nonlinear controllers such as ANN are the most suitable and effective tools to deal simultaneously with the uncertainty, nonlinearity and transient conditions of a power system [12]. The conventional PI controlled STATCOM-SMES has already been used to improve the dynamic performance of power system.

ANNs are computing architectures that consist of massive parallel interconnections of simple neural processor. They have the ability to approximate an arbitrary nonlinear mapping [13]. The effectiveness of ANN controller depends upon the training and the training parameters. An ANN feed-forward, multi-layer neural network has been designed by proper training and implemented in integrated STATCOM-SMES to enhance the dynamic performances of SMIB.

The simulation is carried out to improving dynamic performance of SMIB system with STATCOM-SMES using various controllers. The performance of STATCOM-SMES with each controller has also been compared.

2. System Model

A functional model of a STATCOM-SMES consists of STATCOM integrated with SMES through an interface between both devices and control system as shown in Fig. 1. The STATCOM comprises of voltage source inverter, the DC bus capacitors and the step up coupling transformer. The interfacing device between SMES coil and dc bus is a dc-dc chopper. The active power is exchanged between SMES and power system through DC bus of STATCOM and controlled by chopper interface.

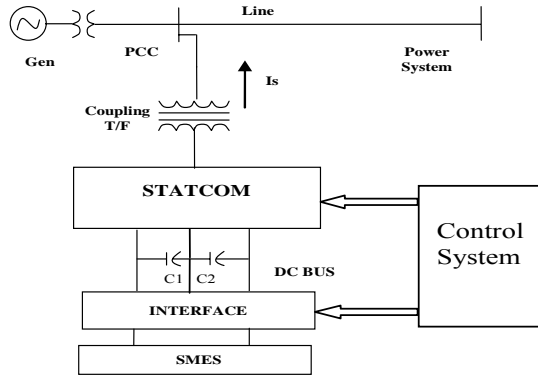


Fig. 1 System functional model

A. STATCOM

STATCOM controls reactive power and hence the voltage profile at the point of common coupling (PCC). The basic component of a STATCOM is a 48-pulse, three levels, neutral point clamped (NPC), voltage source inverter (VSI) using gate turn off thyristors (GTO) and DC capacitors. The total harmonic distortion (THD) level of used VSI is below the objectionable limits and eliminates the requirement of harmonic filtering [11].

B. SMES

The main component of SMES system is the superconducting coil of high conductance made of alloy. The superconducting coil is contained in a cryostat. A helium vessel encloses the superconducting coil and keeps the temperature well below the critical temperature. A power conversion system (PCS) is interconnected between ac system and superconducting coil of SMES to control the energy flow rapidly. STATCOM and three level dc-dc chopper has been used as ac/dc power conversion system to convert electrical energy from ac to dc or vice-versa [11]. The current in the coil continuously

circulates during steady state operation (in standby mode). When a disturbance is sensed, the controller directs the PCS to exchange the real power between SMES coil and power system. The systematic exchange of energy between SMES coil and power system, stabilizes the power system quickly and hence maintained interruption free operating condition for optimum performance of critical processes. The current and voltage of the superconducting inductor are related as given in eqn. (1).

$$i_L = \frac{1}{L} \int_{i_0}^t V_L dt + I_{L0} \quad (1)$$

where L is the equivalent inductance of the SMES coil and I_{L0} is the initial current of the inductor.

The inductively stored energy (E in Joule) and the rated power (P in Watt) of SMES can be expressed as follows:

$$P = V_L I_L \quad (2)$$

$$W = \frac{1}{2} L I_L^2$$

The minimum operating SMES coil current is limited to be 20% of maximum rating of SMES to prevent the dc-dc chopper from operating in discontinuous conduction mode. The state of charge of the SMES coil is set at 60% of the rating capacity. The coil protection consists of by-pass switches and arresters and protects the coil from thyristors failure and other faults. The by-pass switches also reduce energy losses when the coil is in standby mode.

C. DC Chopper

A two quadrant, three level chopper is used to control the rate of charging/discharging of SMES coil as shown in Fig. 2. The main advantages of three-level chopper are: reduction in harmonics, voltage stress of thyristors, switching losses and higher rating of power devices. In addition, the three-level chopper enhances the dynamic performance of STATCOM by regulating the current flowing from the SMES coil to the inverter of the STATCOM. In the charge mode, thyristors G_1 and G_2 are always kept on, while thyristors G_3 and G_4 are modulated to obtain the appropriate output voltage across the SMES coil. In standby mode, thyristors G_3 and G_4 are switched off, while thyristors G_1 and G_2 are kept on all the time. In the discharge mode, thyristors G_3 and G_4 are constantly kept off, while thyristors G_1 and G_2 are controlled. A general expression relating the chopper average output voltage V_L to the VSI

average dc bus voltage V_d can be given through eq. (3).

$$V_L = m V_d \quad (3)$$

$m = (D_1 + D_2)$ is the chopper buck mode.

$m = -(1 - D_1 - D_2)$ is the chopper boost mode.

where m is modulation index, D_1 and D_2 is the duty cycle for buck and boost mode respectively.

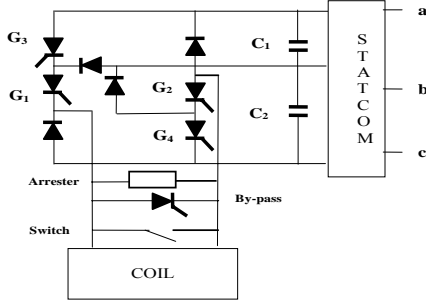


Fig. 2 Model of DC Chopper

2. Test Power System

The test power system consists of a synchronous generator feeding an infinite bus having a short circuit rating of 10000 MVA, through a double circuit line. The modeled generator is powered by tandem compound steam turbine prime mover including speed governor system. The performance of the proposed STATCOM-SMES controller is analyzed through simulation using SimPowersystems of SIMULINK/MATLAB. To this aim, a three phase to ground (3-LG) fault is applied at line #2 of power system at time $t = 5.2$ s and cleared at $t = 5.3$ s, by isolating the faulty line. The integrated STATCOM-SMES system is placed at generator bus aiming to enhance the dynamic security of the power system. The major test system data related to transformer, synchronous machine, lines and STATCOM-SMES are summarized in Appendix.

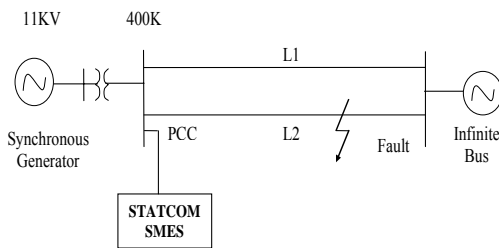


Fig. 3 Test power system

3. Control strategy

The nonlinear controller and advanced technology plays a vital role in the efficient and secured operation of modern power system. This section develops control strategy for STATCOM-SMES using two input variables i.e. deviation of angular frequency and derivative of angular frequency. The controlling action forces the SMES coil to operate in three basic modes, namely, charging, discharging and standing by mode. In charging mode SMES absorb active power from the power system when system frequency is high and it is rising. In discharging mode SMES inject active power in the power system when power system frequency is low and decreasing. And in standby mode during the steady state condition of power system and maintain its coil current level constant. The STATCOM regulates voltage at PCC by exchanging reactive power with power system almost independently. The output of phase lock loop (PLL) of STATCOM is modified to control the phase angle of STATCOM-SMES terminal voltage for smooth flow of energy between power system and STATCOM-SMES as shown in Fig. 4.

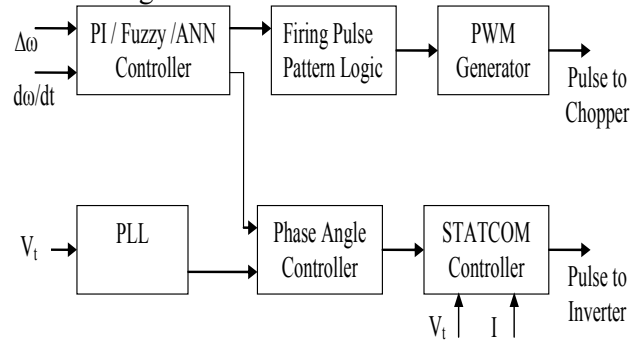


Fig. 4 The control algorithm of STATCOM-SMES

The advantage of designing advanced nonlinear controller is that it doesn't need detailed information about the system. In nonlinear controller, the input variables $d\omega/dt$ acts as a predictive parameter in the control action. The artificial neural network controller has been designed with the help of "neural network tool" of MATLAB. The controller is implemented in STATCOM-SMES system and its performances have been compared with conventional PI controlled STATCOM-SMES system. The parameters of PI controller has been optimized by using "response

optimization tool” of MATLAB and the gain values obtained are $K_p=180$ and $K_f=54$.

3. Artificial Neural Network Controller

ANN presents two principal characteristics, i.e. it's not necessary to establish specific input-output relationship, but they are formulated through a learning process or through an adaptive algorithm and it can be trained online without requiring large amounts of offline data. The major advantages of the ANN are the simplicity of controller's design and their compromise between the complexity of conventional nonlinear controller and its performance. The back propagation algorithm is most commonly used for the training of feed-forward neural networks. It updates the network weights and biases in the direction that the performance function, usually the sum of square errors, decreases most rapidly. The implementation consists of a feed-forward Artificial Neural Network which is trained for two input variables, i.e. deviation of frequency and derivative of frequency, and required signals at its output. The control objective of the ANN is to provide the input to the firing pulse pattern logic circuit for proper firing patterns for GTO's. The output signal of firing pulse pattern logic circuit is fed to PWM generator to generate the desired firing pulse for GTO's. The ANN controller is trained with the help of neural network tool box “nntool” of MATLAB using the TRAINLIM Transfer function, and LERNGDM Adaptation learning function. The Network has 2 layers and 10 neurons, and has been trained using 5000 epochs. The basic topology of neural network is given in Fig. 5.

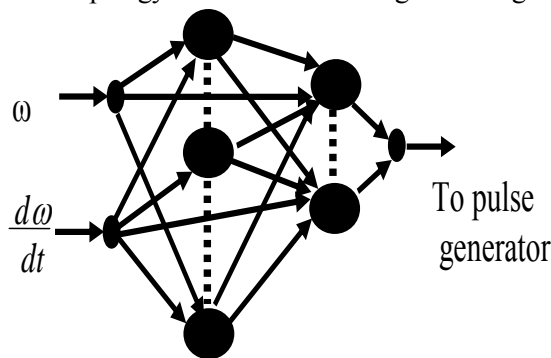


Fig. 5. The ANN Topology

5. Results and Discussion

The performance of STATCOM-SMES using different controllers to stabilize the power system has been analyzed through the simulation results. The various simulation results of SMIB power system without compensation and with PI controlled and ANN controlled STATCOM-SMES have been compared in Figs. 6 -11. The rotor speed deviation of generator has been compared in Fig.6; settling time and peak overshoot of rotor speed are compared in Table 1 and Table 2 respectively. The analysis of figure Fig.6 and Tables 1-2 shows that the oscillations in the speed has been damp out effectively with ANN controlled STATCOM-SMES as compare with PI controlled STATCOM-SMES. The rotor angle of generator has been compared in Fig.7; settling time and peak overshoot of rotor angle are compared in Table 3 and Table 4 respectively. It is evident from the Fig. 7 and Table 3-4 that the effects of the disturbances on rotor angle are mitigated in shorter time with ANN controlled STATCOM-SMES than in the case with PI controlled STATCOM-SMES. The active power output of generator has been compared in Fig.8; settling time and peak overshoot of active power are compared in Table 5 and Table 6 respectively. The active power oscillations have been damp out quickly with ANN controller. The voltages at generator bus and reactive power output of generator using different controllers have also been compared as shown in Fig. 9 and Fig. 10 respectively. The performance of advanced controlled STATCOM-SMES is found marginally better as compared to PI controlled STATCOM-SMES to restore the generator bus voltage quickly as shown in Fig. 9. The DC current in SMES coil using various controllers are shown in Fig.11. The examination of Figs. 6-9 and Tables 1-6 reveals that the overall dynamic performance of power system has been improved effectively with ANN controlled STATCOM-SMES as compared with PI controlled STATCOM-SMES.

The controller output signal, phase angle of STATCOM terminal voltage, control pulse to chopper GTO,s, output current of SMES coil, circulating current in SMES coil, stored energy in SMES coil, with PI controlled and ANN controlled STATCOM-SMES are shown in Fig. 12 and Fig. 13 respectively.

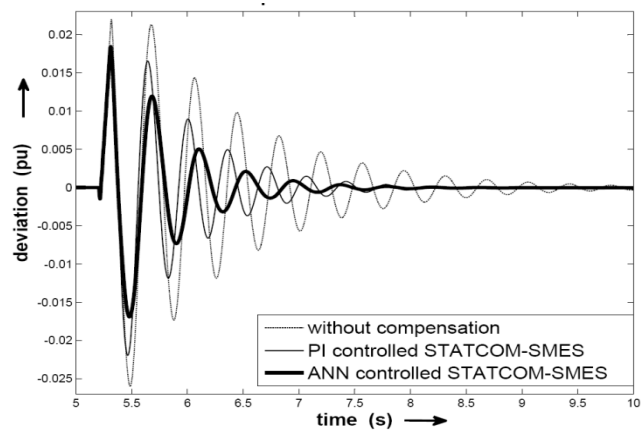


Fig. 6 Rotor speed deviation at generator output with PI controlled and ANN controlled STATCOM-SMES.

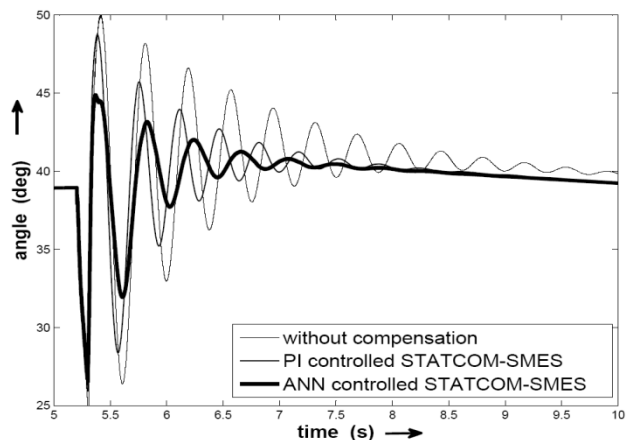


Fig.7 Rotor angle deviation of generator with PI controlled and ANN controlled STATCOM-SMES.

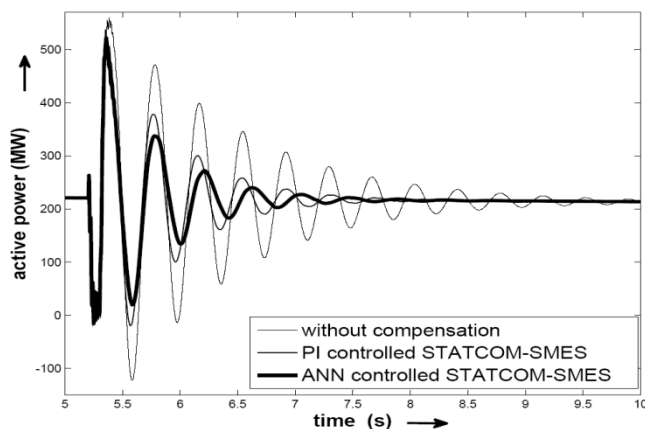


Fig.8 Active power output of generator with PI controlled and ANN controlled STATCOM-SMES.

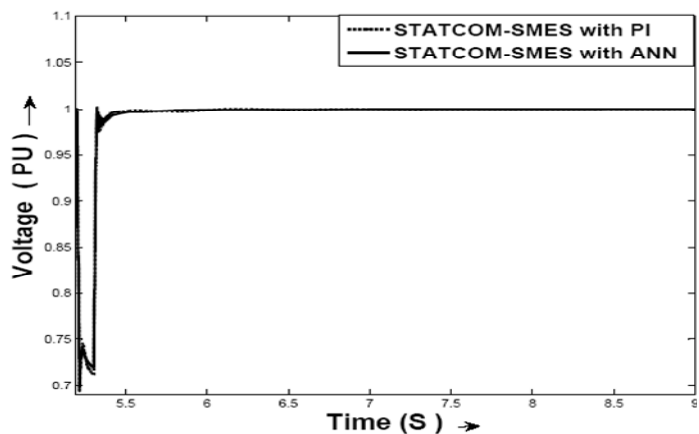


Fig.9 Voltage at PCC with PI controlled and ANN controlled STATCOM-SMES.

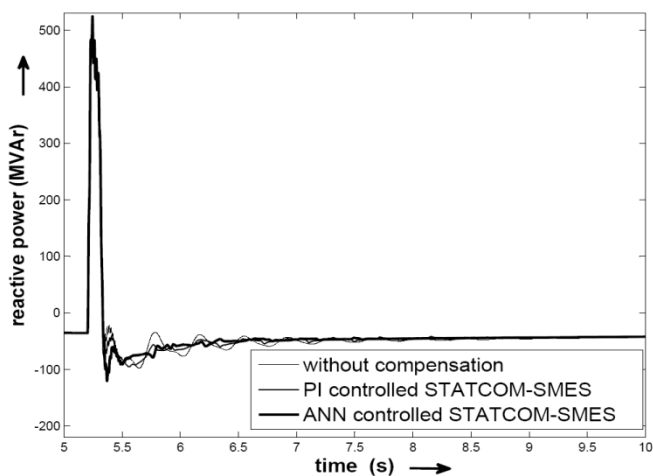


Fig.10 Reactive power exchanged by PI and ANN controlled STATCOM-SMES.

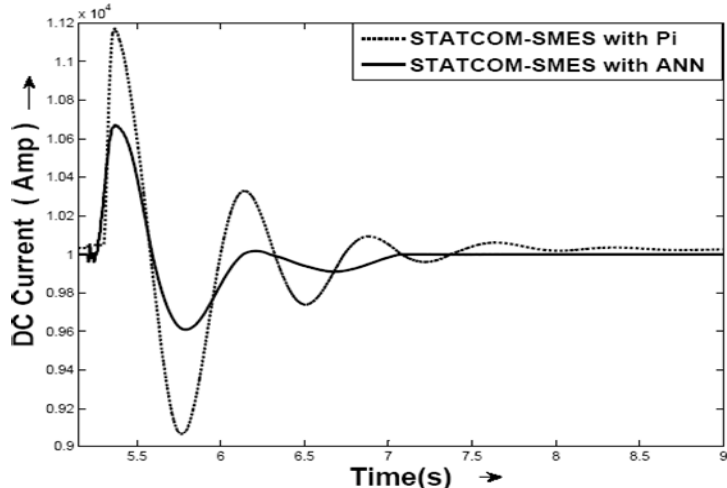


Fig. 11 DC current of SMES coil with PI controlled and ANN controlled STATCOM-SMES

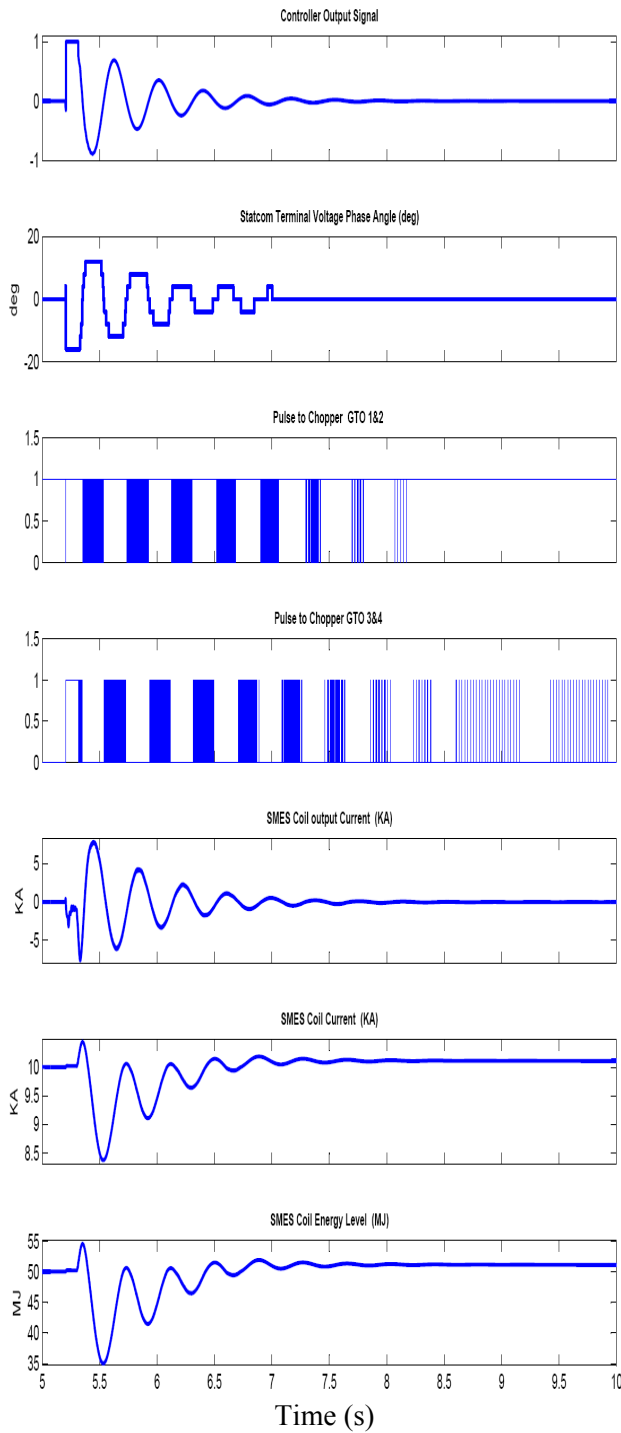


Fig. 12. Controller output signal, phase angle of STATCOM terminal voltage, control pulse to chopper GTO,s, output current of SMES coil, circulating current in SMES coil, stored energy in SMES coil with PI controlled STATCOM-SMES.

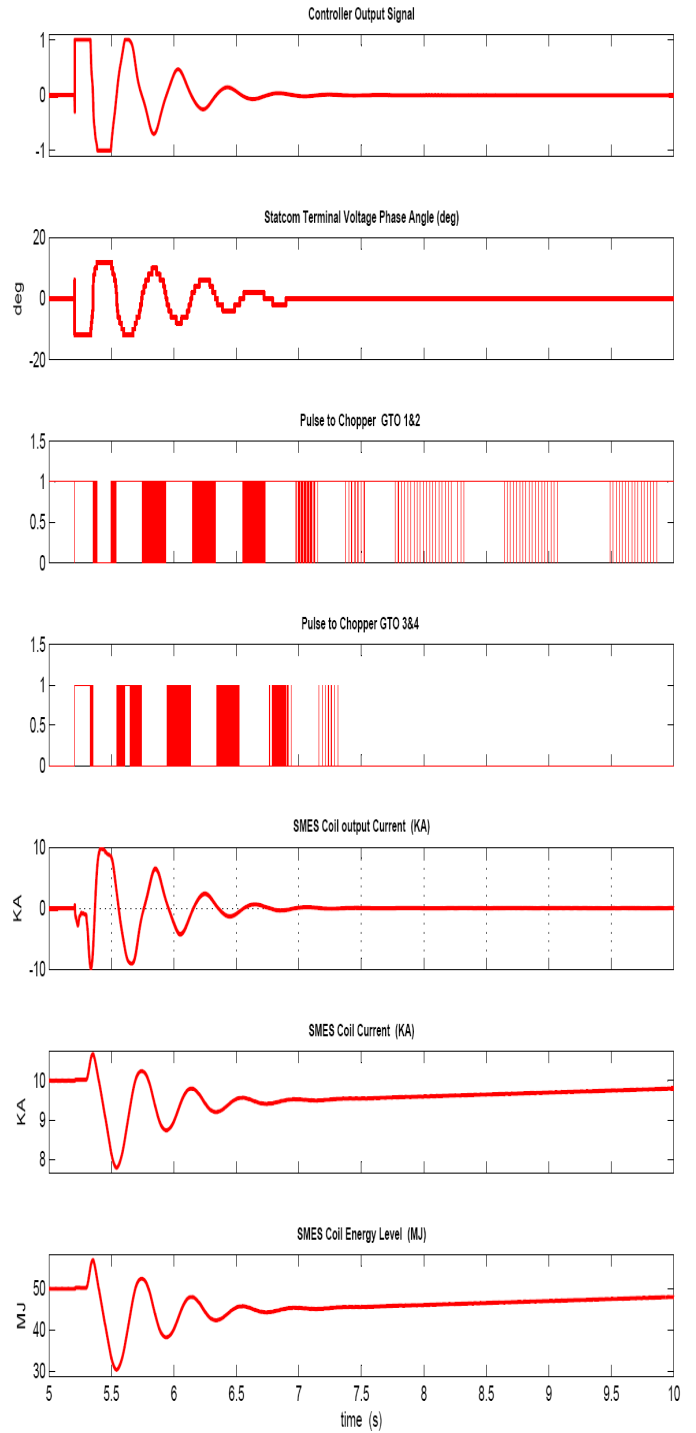


Fig. 13. Controller output signal, phase angle of STATCOM terminal voltage, control pulse to chopper GTO,s, output current of SMES coil, circulating current in SMES coil, stored energy in SMES coil with ANN controlled STATCOM-SMES.

Table 1 Comparison of settling time (2 % tolerance) of rotor speed of generator of SMIB system connected with STATCOM-SMES using different controllers

Controller \ Machine	Without compensation (seconds)	With PI controller (seconds)	With ANN controller (seconds)
Generator	0.6	0.3	0.2

Table 2 Comparison of peak overshoot of rotor speed of generator of SMIB system connected with STATCOM-SMES using different controllers

Controller \ Machine	Without compensation (%)	With PI controller (%)	With ANN controller (%)
Generator	2.2	1.8	1.8

Table 3 Comparison of settling time (5 % tolerance) of rotor angle of generator of SMIB system connected with STATCOM-SMES using different controllers

Controller \ Machine	Without compensation (seconds)	With PI controller (seconds)	With ANN controller (seconds)
Generator	2.4	1.2	0.5

Table 4 Comparison of peak overshoot of rotor angle of generator of SMIB system connected with STATCOM-SMES using different controllers

Controller \ Machine	Without compensation (%)	With PI controller (%)	With ANN controller (%)
Generator	25	22	11

Table 5 Comparison of settling time (5 % tolerance) of active power of generator of SMIB system connected with STATCOM-SMES using different controllers

Controller \ Machine	Without compensation (seconds)	With PI controller (seconds)	With ANN controller (seconds)
Generator	3.5	2.0	1.6

Table 6 Comparison of peak overshoot of active power of generator of SMIB power system connected with STATCOM-SMES using different controllers

Controller \ Machine	Without compensation (%)	With PI controller (%)	With ANN controller (%)
Generator	154	137	135

6. Conclusion

The paper presents ANN controlled STATCOM-SMES system connected to SMIB system. A detailed

model of controlled STATCOM-SMES and test power system has been developed using SimPowerSystems of MATLAB. The proposed control algorithm and ANN controller have been developed using “nntool” of MATLAB. The performance of ANN controller for STATCOM-SMES connected to SMIB has been evaluated for single line to ground faults. It was observed from the analysis of simulation results that ANN controller ensures fast controllability of the STATCOM-SMES system, which effectively improves the dynamic performance of the power system. The analysis of simulation results presented, verifies the effectiveness of the control strategy and the model of STATCOM-SMES using ANN controller. The performance of ANN controlled STATCOM-SMES is found to be better as compared to that of PI controlled STATCOM-SMES. The terminal voltage at PCC also has been restored rapidly and maintained within permission limits. Moreover, the ANN controlled STATCOM-SMES improves the overall dynamic performance and stability of power system more rapidly.

Appendix: Test system data

Table 8. Transformer data

S (MVA)	R (p.u.)	L (p.u.)	R_m (p.u.)	L_m (p.u.)	N_p/N_s (kV/kV)
500	0.002	0.08	500	500	400/11

Table 9. Generator data

S_N (MVA)	V_N (kV)	V_s (p.u.)	H (MW/MJ)	R_s (p.u.)	X_l (p.u.)
500	11	1.02	3.7	0.003	0.18

Table 10. Generator data Cont.

X_d (p.u.)	X_a (p.u.)	X'_d (p.u.)	X_q (p.u.)	$T'_{do}(s)$ (p.u.)	T_{do} (p.u.)	$T_{q0}(s)$
1.305	0.474	0.296	0.243	4.490	0.0681	1.5

Table 11. Line data

L1 (km)	L2 (km)	R (Ohm/Km)	L (mH/Km)	C (μ F/Km)
150	70	0.012	0.933	12.740

Table 12. STATCOM-SMES data

Q_{\max} (Mvar)	$E_{SC \max}$ (MJ)	V_d (kV)	C_1, C_2 (mF)	L (H)
± 200	100	19.3	3	1

References

- Chen, Tjing J., lie T., and Vilathgamuwa D.M.: *Damping of Power System oscillations using SSSC in real-time implementation*. In: Electrical power and Energy systems, XXVI, 2004, p. 357-364.
- Indulkar C.S. and Kothari D.P.: *Power System Transients: A Statistical Approach*. Prentice Hall of India, New Delhi (Fourth Reprint 2003).
- Arabic S. and Kundur P.: *A Versatile FACTS device model for power flow and stability simulation*. In: IEEE Trans. on Power systems, I, Issue 4, 1996, p. 1944-1950.
- Ali M. H., Bin W., Dougal R. A.: *An overview of SMES Application in Power and Energy Systems*. In: IEEE Trans. on Sustainable Energy, I, 2010, p. 38 – 47.
- Ribeiro P. F., Aysen Arsoy and Yilu Liu.: *Transmission Power Quality benefits realized by a SMES-FACTS controller*. In: Proc. of International Conference on Harmonics and Quality of Power, 2000, vol. I, p. 307-312.
- Xue X. D., Cheng K.W.E. and Sutanto D.: *Power system applications of superconducting magnetic energy storage systems*. In: Industry Applications Conference 2005, IAS Annual Meeting. Conference Record of 14th 2005, I, p. 1524 – 1529.
- Dagle J. E., Eckroad S. W., Trudnowski D. J., DeStees J. G.: *A Case Study of Transmission Stability Enhancement Using Superconducting Magnetic Energy Storage (SMES)*. In: FACTS Applications, IEEE PES Publication no. 96TP116-0, 1996, p. 8.82-8.87.
- Anil Dahiya.: *Eenergy function approach for transient stability enhancement of power system incorporating the effect of SMES*. In: National Conference on Power Electronics and Intelligent Control 2007, 2007, India, p. 201-204.
- Rao P., Crow M. L. and Young Z.: *STATCOM control for power system voltage control applications*. In: IEEE Trans. on Power Delivery, XV, No. 4, 2000. p. 1311-1317.
- Arsoy A. B., Liu Y., Rebeiro P. F. and Wang F.: *STATCOM-SMES*. In: Industry Applications Magazine, IEEE, IX, Issue 2, 2003, p. 21-28.
- Molina M. G., Mercado P. E. and Watanabe E. H.: *Dynamic Performance of a Static Synchronous Compensator with Superconducting Magnetic Energy Storage*. In: IEEE 36th Conference on Power Electronics Specialists Conference 2005, pp. 224–230.
- Mohaddes, A. M. Gole and McLaren P. G.: *A Neural Network controlled optimal pulse-width Modulated STATCOM*. In: IEEE Trans. Power delivery. XIV, No. 2, April 1999, p. 481-488.
- Changaroon B., Srivastava S. C., Thukaram D. and Chirarattananon S.: *Artificial Neural Network based Power System Damping controller for SVC*. In: IEE Proc. of Generation Transmission and distribution, vol. 146, Issue: 4. 1999, p. 370-376.