Eng Int Syst (1999) 3: 131–136

Engineering
Intelligent Systems

An ANN based controller for SMES units in power systems

M G Rabbani, J B X Devotta and S Elangovan

Department of Electrical Engineering, National University of Singapore, Singapore 119260. Email: rabbini@ee.nus.sg

A neural network based controller is designed for the Superconducting Magnetic Energy Storage Unit (SMES) to improve the transient stability of synchronous generators. The power modulation capability of the SMES is used to improve the dynamic performance of the system. The neural network is trained by learning linguistic rules. Normalized values of generator speed deviation and acceleration are used to train the network. The gain of the ANN controller is adapted on-line depending on the operating conditions. This allows the SMES unit to provide appropriate compensation required by the system following a disturbance. The control system is tested both for single and multi-machine systems. The simulation results show that the substantial improvement in stability is achieved when equipped with this type of control.

Keywords: SMES, ANN controller, Power system stability

1. INTRODUCTION

Fast acting energy storage devices, such as SMES or battery energy storage can effectively damp out system frequency oscillations caused by small or large disturbance [1–4]. Though expensive, these hold premise as potential devices for improving dynamic performance of the power system. They provide storage capacity in addition to the kinetic energy of the generator rotor, which can share the sudden change in power requirement. These storage devices, in conjunction with back-to-back dc link, have been proposed [5] to facilitate effective and economical control of power flow between interconnected systems. A detailed description of the SMES and its configuration in the power system can be found in [1 ,2, 4]. To make the SMES unit economically viable, its control system has to be carefully designed. Because the efficient control of the SMES unit not only improves the system performance but also reduces its own cost.

Most of the SMES controllers [2–4] are designed using a linearized model of a power system around a given operating point. Therefore, when the network configuration or operating conditions changes widely, it becomes less effective because of the power system nonlinearities. This is becoming a very important problem in large-scale modern power systems. In reference [4], a PI controller has been designed for the SMES unit based on assigned eigenvalues and the performance of the controller has been shown for different operating conditions. The case studies shown are for a single machine-infinite bus system. To obtain maximum benefit, the SMES controller has to be designed such that it can cope with any operating condition and can be used with any power system configuration. The gain of the controller must be decided based on the present operating condition of the power system and the rating of the SMES unit. That will realize the efficient control performance.

A nonlinear adaptive controller can meet the above requirements. In this paper, a new controller is designed for SMES unit based on Artificial Neural Network (ANN). The parameters of the proposed controller are adapted according to the system requirements. The ANN controller is basically nonlinear. The concept of ANN has already been applied successfully to various control problems especially for power system stabilization [6–8]. The proposed ANN controller is trained for 81 linguistic rules. A backpropogation training function for feed forward networks, using momentum and adaptive learning rate techniques is used for the training purpose. Since the inputs and output are all normalized values, the same trained network can be used to control different SMES units of different ratings. The controller gain is decided on-line depending on the disturbance type and the rating of the SMES unit. The other controller parameters are adapted on-line depending on the type of the power system and the operating conditions. The proposed ANN controller is applied for a particular SMES unit and is tested both for single and multimachine systems.

2. SYSTEM DESCRIPTION

In this section, the generator and SMES models are presented. The details of the generator excitation and governing system are the same as used in the reference [4]. Specifically, the generator is modeled based on two axis theory [9], where the armature transient voltage of direct axis and quadrature axis are described by

$$\dot{E}'_d = [-E'_d - (X_q - X'_d) I_q] \;/\; T'_{q0} \tag{2.1}$$

$$E'_d = [E_{FD} - E'_q + (X_q - X'_d) I_d] \;/\; T'_{d0} \tag{2.2}$$

E_{FD} is the field excitation voltage, and T'_{do} and T'_{qo} represent d-axis and q-axis transient time constants respectively. The swing and the rotor angle equations can be written as

$$\dot{\omega} = (P_m - D_{g\omega} - P_e - P_{sm}) / M_g \tag{2.3}$$

$$\dot{\delta} = \omega_0 (\omega - 1) \tag{2.4}$$

where P_m, D_g and M_g are the output power of the reheat steam turbine, damping coefficient, and moment constant respectively. P_e is the electromagnetic power in the air gap. Psm is the stored power in the SMES.

Figure 1 shows the basic configuration of SMES unit in the power system. The SMES unit contains a Y-Δ / Y-Y connected transformer, a 12-pulse converter and a DC superconducting inductor. The converter unit is force commutated and α is the firing angle of SCR. If α < 90°, the converter works as a rectifier (charging mode). If α < 90°, the converter works as an inverter (discharging mode). Real power can be absorbed from or delivered to the power system by controlling the sequential firing angles of thyristors [10]. In order to effectively control the power balance of the synchronous generator during dynamic period, the SMES unit is located at the generator bus. The current and

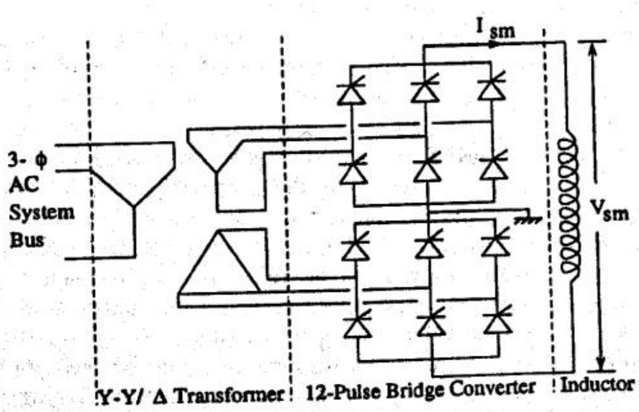

Figure 1 Schematic diagram of the SMES unit

voltage of superconducting inductor are related as:

$$I_{sm} = \frac{1}{L_{sm}} \int_{t_o}^{t} V_{sm}\, d\tau + I_{sm0} \tag{2.5}$$

where I_{sm0} is the initial current of the inductor. The real power absorbed or delivered by the SMES unit is

$$P_{sm} = V_{sm} I_{sm} \tag{2.6}$$

If P_{sm} is positive, power is transferred from the power system to the SMES unit. While if the P_{sm} is negative, power is released from the SMES unit. The energy stored in the superconducting inductor is

$$W_{sm} = w_{sm0} + \int_{t_0}^{t} P_{sm}\, d\tau \tag{2.7}$$

where

$$W_{sm} = w_{sm0} + \frac{1}{2} L_{sm} I_{sm}^2$$

is the initial energy in the inductor. Because of constraints of hardware implementation, both the voltage and currents have upper and lower limits [4]. For the SMES unit modeled, the limits are:

$$-0.438 \text{ p.u.} \le V_{sm} \le 0.438 \text{ p.u.}$$
$$0.31\, I_{sm0} \le I_{sm} \le 1.38\, I_{sm0}$$

Therefore, at any instant, for the particular SMES unit, the power P_{sm} has the following limits:

$$-0.438\, I_{sm} \text{ p.u.} \le P_{sm} \le 0.438\, I_{sm} \text{ p.u.}$$

3. PROPOSED ANN CONTROLLER DESIGN STEPS

Let the pair e and ė are the error and its derivative of an input variable and are defined as

$$e(k) = r(k) - c(k) \tag{3.1}$$

$$\dot{e}(k) = \frac{e(k) - e(k-1)}{h} \tag{3.2}$$

where: $e(k)$ = error of the input variable
$\dot{e}(k)$ error derivative
$r(k)$ = reference signal
$c(k)$ = input variable
k = sample number
h = sampling interval

The set of linguistic rules for ANN compensation is given in Table 1. A typical rule has the following structure:

If *e* is small negative (SN) and *e* small positive (SP) THEN u is zero (Z).

where **u** is the output of the ANN controller. The rule base is developed by heuristics from the viewpoint of practical system operation and contains only normalized values of input and output variables. In the normalized form, the input variables can be expressed as:

$$e = e(k)/e_{b1} \qquad (3.3)$$
$$\dot{e} = \dot{e}(k)/e_{b2} \qquad (3.4)$$

where e_{b1} and e_{b2} are the respective bases of input variables and are generated on-line depending on the present operating conditions. The input variables chosen in the present study are the generator speeds deviation (e) and acceleration ($\dot{e}$).

Thus, the input variables of the ANN controller are normalized between −1 to 1 with respect to their generated bases for a particular system and operating condition. The ANN output, U_{sm}, is also a normalized quantity. The required SMES power P'_{sm} can be determined from U_{sm} as:

$$P'_{sm} = \frac{K_{nn}}{1+ST_{dc}} U_{sm} \qquad (3.5)$$

where T_{dc} is the delay time. The SMES voltage V_{sm} is then calculated from P'_{sm} and the sensed current I_{sm}. If the magnitude of V_{sm} lies beyond $V_{sm,max}$ in the rectifier mode or in the inverter mode, the actual V_{sm} is set equal to the corresponding limiting value. The active power requirement of the SMES system is thus computed using the available values of V_{sm} and I_{sm} signals.

To determine the ANN controller gain K_{nn}, the SMES rating is needed in addition to the power system parameters. The steps to design ANN controller parameters are described below:

1. Simulate a disturbance of substantial magnitude for the single machine infinite bus system until the system is on the verge of instability. Obtain the maximum deviations $e_{b,\max}$ and the maximum derivative $\dot{e}_{b,\max}$ in the presence of SMES unit.
2. Obtain the value of a constant K_b as

$$K_b = \frac{e_{b,\max}}{\dot{e}b,\max} \qquad (3.6)$$

3. Get the value of e_{b2} on-line for a particular operating condition.
4. Determine e_{b1} using the following relation

$$e_{b1} = K_b\, e_{b2} \qquad (3.7)$$

Table 1 Rule base for the ANN controller

Error / d(error)/dt	NVB	NB	NM	NS	Z	PS	PM	PB	PVB
NVB	NVB	NVB	NVB	NVB	NVB	NB	NM	NS	Z
NB	NVB	NVB	NVB	NVB	NB	NM	NS	Z	PS
NM	NVB	NVB	NVB	NB	NM	NS	Z	PS	PM
NS	NVB	NVB	NB	NM	NS	Z	PS	PM	PB
Z	NVB	NB	NM	NS	Z	PS	PM	PB	PM
PS	NB	NM	NS	Z	PS	PM	PB	PM	PVB
PM	NM	NS	Z	PS	PM	PB	PM	PVB	PVB
PB	NS	Z	PS	PM	PB	PM	PVB	PVB	PVB
PVB	Z	PS	PM	PB	PM	PVB	PVB	PVB	PVB

(PVB = 1, PB = 0.75, PM = 0.5, PS = 0.25, Z = 0, NS = -0.25, NM = -0.5, NB = -0.75 and NVB = -1)

5. Determine the gain of the ANN controller as follows:

$$K_{nn} = -\frac{e_{b2}}{e_{b,\,max}} V_{sm,max}\, I_{sm,max} \qquad (3.8)$$

where V_{sm} and I_{sm} are SMES voltage and current, respectively.

In the present analysis, the value of the constant K_b is found to be 0.03. The free responses of the system to a transient disturbance may converge to steady state through mixed modes of behavior, i.e. damped and undamped. Hence, there is the necessity of parameter e_{b2} to be updated dynamically. Once the system enters into a consistent damped mode e_{b2} becomes fixed.

The structure of the neural network is chosen by trial and error. It consists of an input layer with two nodes, one hidden layer with fifteen nodes, and an output layer with one node. The learning rate and momentum constant are changed automatically in the training process. Once trained satisfactorily for all linguistic rules, the weight and bias matrices are saved and the neural network is ready to be used as a controller for the SMES unit. Such a structure is shown in Figure 2. The block diagram representation of the ANN controller is shown in Figure 3.

4. NUMERICAL SIMULATION

In this section, simulations illustrate the controller response to several disturbances. The scenarios are intended to assess the performance of the controller rather than to represent any specific system scenario. Two systems are used for the simulations. A single machine connected to an infinite bus, adapted from [4], was used in the design phase and this controller was used for studies of a multimachine system, adapted from [11]. The same trained neural network is used in both single and multimachine transient stability analysis.

4.1 Single machine system

The single machine connected to an infinite bus shown in Figure 4 has the following parameters [4]:

Generator: 160 MVA, 15 kV, 0.85 p.f., M_g = 4.74 s, X'_d = 0.245 p.u, R_a = 0.001096 p.u, D_g = 1.70 p.u, X_q = 1.64 p.u, T'_{q0} = 0.075 s, T'_{do} = 5.9 s, P_{m0} = 1.0 p.u.

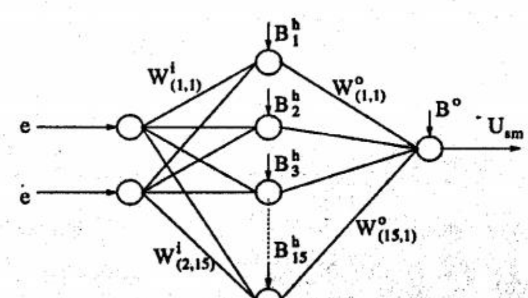

Figure 2 A multilayered feedforward neural network.

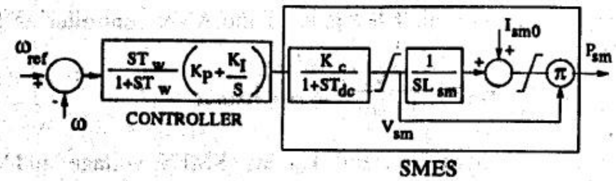

Figure 3 (a) SMES controllers. PI controller for the SMES unit

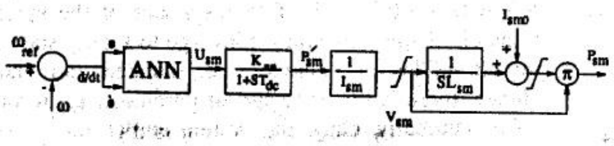

Figure 3 (b) SMES controllers. ANN controller for the SMES unit

Voltage regulator: $K_A = 400$, $T_A = 0.05$ s, $K_F = 0.025$ s, $T_F = 1.0$ s, $|E_{FD}| \leq 7.5$ p.u.

Network: $R_e = 0.02$ p.u, X_e 0.4 p.u.

SMES Unit: $I_{sm0} = 0.6495$ p.u, $V_{sm0} = 0$ p.u, $L_{sm} = 0.5$ H, $W_{sm0} = 4.0$ MJ, $T_{dc} = 0.026$ s

P I Controller: $K_P = 45.99$, $K_I = 376.4$.

The ANN data is given in the appendix.

Case 1

The disturbance considered is a three phase symmetrical fault near the infinite bus cleared after 0.1 sec. with the post fault transfer impedance increased by 50%. It reflects a reduction in power transfer capability due to isolation of part of transmission circuitry. The results of the studies are shown in Figure 5. For comparison purposes, the performance of the traditional PI controller is also shown in the diagram.

4.2 Multimachine system

A system with two machines connected to an infinite bus is shown in Figure 6. Two SMES units of same rating are connected in the respective generator bus terminals. The system has the following parameters (all values are in p.u.):

Network: line 1–2 R=0.018, X=.11, B=0.226; each line 2–3 R=0.008, X=0.05, B=.098; line 1–3 R=0.007, X=.04, B=0.082; $Y_{L1} = 0.3\text{-}j0.15$; $Y_{L2} = 0.4\text{-}j0.2$.

Mechanical Power: $P_{m1} = 1.2$, $P_{m2} = 1.0$

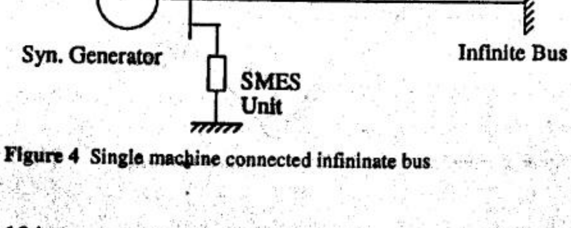

Figure 4 Single machine connected infininate bus

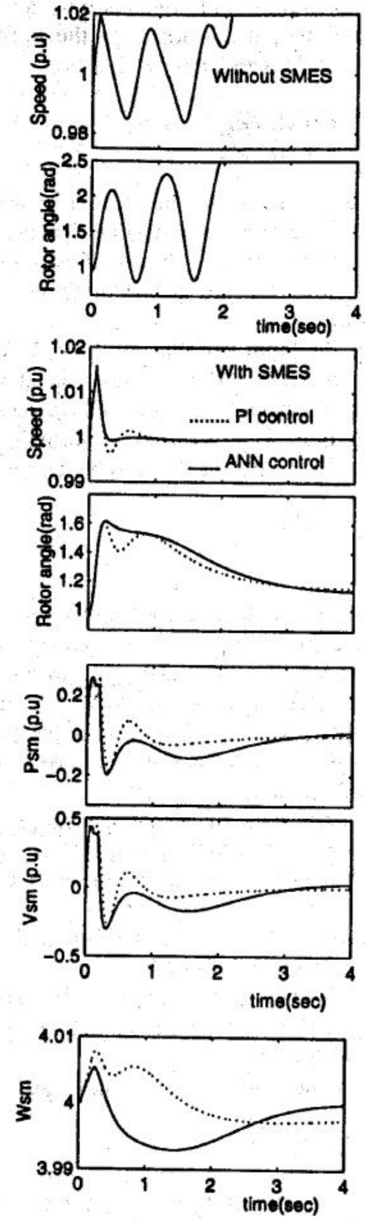

Figure 5 3-phase fault for the single machine (case 1): $t_c = 0.1$ sec

Generator parameters are the same as in the single machine case. One scenario is presented here:

Case 2

A Three phase to ground fault at A. (Fault is 10% of the distance along line 1–3). The line returns to service with a clearing time $t_c = 0.12$ sec. Plot shows response of the system with and without SMES units (Figure 7a and 7b).

5. PERFORMANCE ANALYSIS

In the following discussion the PI controller is used only as a benchmark to evaluate the performance of the ANN controller. The performances of both controllers are shown in Figure 5 for the system disturbance (Case 1). It is seen that the system is unstable without the SMES unit. Appli-

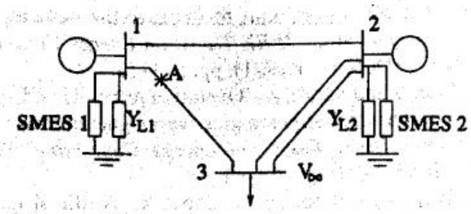

Figure 6 Two machine- three bus system

cation of the SMES unit not only makes the system stable but also the settling time is reduced substantially. With the ANN controller, the rotor speed and the rotor angle settle down in a less oscillatory manner. These two system states are the main parameters of interest. The voltage and the power of the SMES (V_{sm} and P_{sm}) plots show some difference in the manner they settle down their steady state values. However, these parameters are of secondary importance. The important requirement is that W_{sm} (energy of the SMES unit) is restored to the predisturbance value as quickly as possible. The plot of SMES energy shows that this is achieved within 4 seconds. Since the disturbance is of severe magnitude, during the initial correction stages, both the PI and ANN controllers force the SMES unit to reach the upper limit of V_{sm}. This ensures that the SMES unit is being charged at its maximum possible rate. The maximum and minimum power exercised by the ANN controller is the same as that of PI controller. However, due to efficient harnessing of P_{sm}, overall improvement is achieved.

For the multimachine case, the results shown are for the ANN controller (Figures 7a and 7b). The three phase fault near the bus 1 causes heavy fluctuations in the rotor speed of machine 1. Due to interaction through the transmission system, machine 2 is also affected. Unlike machine 1, the rotor speed oscillations of machine 2 show a marked unidirectional shift. Even after 6 secs, the speed does not reach the steady value. It was observed in the present analysis that the rotor speeds of machine 1 and machine 2 reach to their respective steady state values only after 18 secs. The application of the SMES units not only reduces the settling time but also reduces the fluctuation in the speed. As can be seen from the transient responses of both the machines, the efficacy of the SMES unit in damping out the superimposed high frequency oscillations is directly proportional to the magnitude of the transient overshoot. This effect is clearly delineated in Figure 7(b) where, for machine 1, small amount of oscillations still persist during the immediate post-fault period. However, for machine 2, the oscillations are almost eliminated. It was found in the present analysis that the settling time for the rotor speeds are around 7 and 8 secs respectively for machine 1 and machine 2 when SMES units are used for power compensation purposes.

The base parameters 'e_{eb2}' of equation 3.4 are updated continuously throughout the dynamic process. This is the reason for the marked improvement in the dynamic performance of the system. Since this operation is carried out on-line, it performs effectively for all types of system disturbances whether they are small or large. Several types of disturbances were studied, but the results are not shown for the sake of brevity. The system responses show that with SMES units rated at only 4 MJ, with the proposed ANN based control, significant improvement in stability is feasible, for system containing generators of 160 MVA rating.

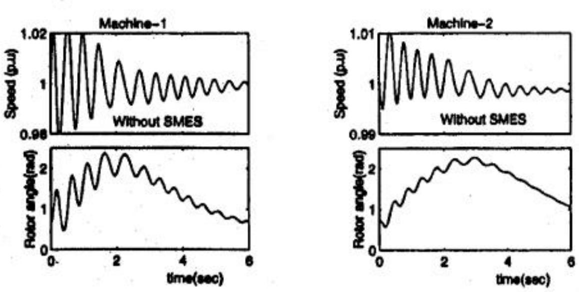

Figure 7 (a) System performance for the multi machine case: $t_c = 0.12$ s

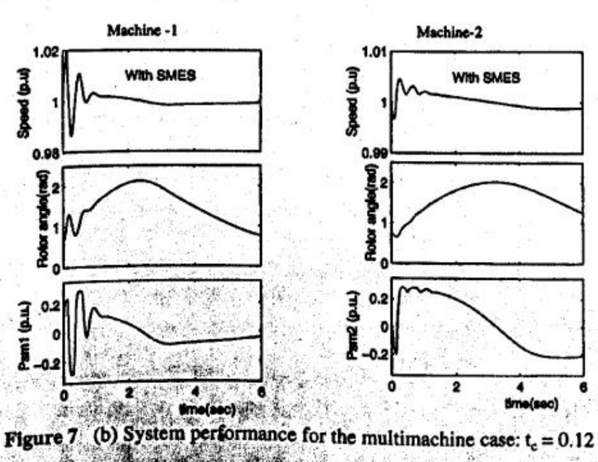

Figure 7 (b) System performance for the multimachine case: $t_c = 0.12$ s

6. CONCLUSION

This paper proposes a general structure of artificial neural network based controller for the Superconducting Magnetic Energy Storage Unit. Controller design requires the calculation of the maximum ranges for rotor speed and rotor speed deviation during a specified disturbance. The main advantage is that it is insensitive to the precise dynamics of the system. On-line adaptation of the control parameters makes it suitable to any power system. Simulation of the response to disturbances has demonstrated the effectiveness of this design technique. Single machine and multimachine transient stability analysis using the same neural network give sufficient evidence of the robustness of the controller. The design structure is simple can be implemented without much complexity.

APPENDIX

ANN model

W^i = [3.6582 2.9070; 2.4240 2.6276; 1.7910 3.0197; -6.1553 1.6125; -5.9398 1.5524; -7.6268 -0/0425; 2.4517 -2.9435; -7.4552 -0.4943; 7.5911 0.2348; -5.9761 1.6978; -5.4971 -2.0633; 7.1895 -1.0519; -4.6871 2.2092; 7.6014 -0.2319; -0.7129 -3.2255];
W^o = [1.0592 1.5297 0.1351 -0.0418 0.0702 0.2282

0.0691 0.0501 0.2441 -0.0601 0.0760 -0.0175 -0.2253 0.0948 -0.3021];

B^h = [-0.9725 0.8692 -1.8423 0.0008 1.6389 4.8418 2.1748 1.5116 -4.8357 -0.3873 2.3450 -4.0191 2.0036 -4.5733 2.3539]/;

B^o = 0.1876;

REFERENCES

1. Peterson, H A, Mohan, N and Boom, R W. 'Superconductive energy storage inductor-converter units for power systems', *IEEE Trans. Power Apparatus and Systems*, Vol. PAS–94, No. 4 (July/August 1975), pp. 1337–48.
2. Banerjee, S, Chatterjee, J K and Tripathy, 'S C Application of magnetic energy storage unit as load-frequency stabilizer', *IEEE Trans. on Energy Conversion*, Vol. 5, No. 1 (March 1990), pp. 46–51.
3. Tripathy, C, Balasubramanian, R and Chandramohanan Nai., 'P S Effect of superconducting magnetic energy storage on automatic generation control considering governor deadband and boiler dynamics', *IEEE Trans. on Power Systems*, Vol. 7, No. 3 (August 1992), pp. 1266–72.
4. Wu, J and Lee, Y S. 'Application of superconducting magnetic energy storage unit to improve the damping of synchronous generator', *IEEE Trans. on Energy Conversion*, Vol. 6, No. 4 (December 1991), pp. 573–78.
5. Tam, S and Yarali, A. 'Operation principle and applications of multiterminal superconductive magnetic energy storage systems', *IEEE Trans. on Energy Conversion*, Vol. 8, No. 1 (March 1992), pp. 54–61.
6. Guan, L, Cheng, S and Zhou, R. 'Artificial neural network power system stabilizer trained with an improved BP algorithm', *IEE Proc.: Generation, Transmission. & Distribution*, Vol. 143, No. 2 (March 1996), pp. 135–41.
7. Park, M, Hun, S H and Lee, J H. 'Power system stabilizer based on inverse dynamics using an artificial neural network, Electrical Power and Energy System', Vol. 18, No. 5 (1996), pp. 297–305.
8. Roger, E and Lie, Y. *Parallel processing in a control system environment*, Prentice Hall (1993).
9. Anderson, P.M and Fouad, A A. *Power System Control and Stability*, IEEE press, 1994.
10. Walker, H. 'Force-commutated reactive power compensation', *IEEE Trans. on Industry Applications*, Vol. 1A–22, No. 6 (1 986), pp. 1091–04.
11. Hoang, P and Tomsovic, K. 'Design and analysis of an adaptive fuzzy power system stabilizer', *IEEE Trans. on Energy Conversion*, Vol. 11, No. 2 (June 1996), pp. 455–61.