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Multi-mode wide range subsynchronous resonance stabilization using superconducting magnetic energy storage unit

M.G. Rabbani, J.B.X Devotta*, S. Elangovan

Department of Electrical Engineering, National University of Singapore, Singapore 119260

Abstract

This paper presents a novel strategy to stabilize the torsional oscillations due to subsynchronous resonance (SSR) of a capacitor compensated power system through control of firing angles of superconducting magnetic energy storage (SMES) unit. The control strategy of SMES is based on artificial neural network (ANN). The gain of the controller is generated on-line depending on the operating conditions and the type of the disturbance. The proposed method of control of SMES for power system stabilization has been tested on the IEEE first benchmark model for subsynchronous resonance studies. Dynamic simulations are performed using the non-linear system model. It has been found that the SMES unit is very effective to eliminate the slowly growing transients resulting from the unstable modes.

Keywords: SSR; Energy storage; SMES; ANN controller

1. Introduction

The SSR problems usually occur in power systems containing steam-generators and series-capacitor compensated lines. When the degree of series-compensation is increased, an electrical resonance of the generator, transformer, transmission lines and capacitor may develop, usually at the subsynchronous frequency. Series shaft failure and other damage may develop when the electrical resonance becomes complementary to one of the torsional frequencies of the turbine generator of the mechanical system [1]. During the past 20 yr, a good amount of literature has been devoted to the study of SSR. An exhaustive list of references is given by the IEEE Working Group bibliography on SSR [2, 3]. Countermeasures proposed in the literature are excitation control, static var compensators, HVDC, static phase shifter, bypass filter and shunt reactors [1, 4–6].

Superconducting magnetic energy storage systems have the capability of storing energy in their low resistance coils. The energy can be transferred to/from the system according to the system requirements. The amount of energy supplied or received by it can be controlled by controlling the firing angles of the converters in the SMES unit. A number of articles have been reported demonstrating the use of SMES unit for power system transient stability, dynamic stability, load frequency control and stabilizing transmission lines [7–9].

Application of SMES to damp SSR have been reported recently to the IEEE first and second benchmark models [9–11]. These articles used PID controls in the converter firing angle circuits and the parameters of the controllers were obtained by the pole-placement methods. Linear control theory for the controller design were used and simulation tests were done on non-linear system models. Extensive eigenvalue studies for different operating conditions show that the SMES unit is quite effective in dampening the torsional oscillations. In Ref. [12], subsynchronous resonant modes are controlled through the control of currents injected from an SMES unit.

This paper introduces a novel idea for controlling the SMES compensating power using artificial neural network (ANN) for subsynchronous resonance stabilization in power system. The inputs to the ANN controller are speed deviation and its derivative, and output is the compensating power P_{sm}. The parameters of the proposed controller are adapted according to the system requirements. The ANN controller is basically non-linear. The concept of ANN has already been applied successfully to various control problems especially for power system stabilization [13–15]. The ANN is trained for 81 linguistic rules. A back-propagation training function for feed forward networks using momentum and adaptive learning rate techniques is

* Corresponding author.

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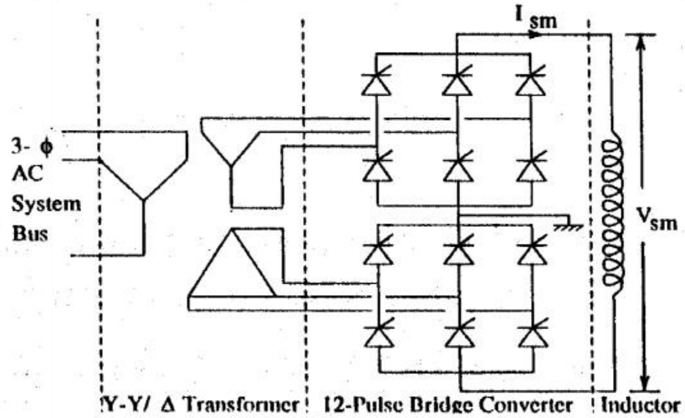

Fig. 1. The schematic diagram of the SMES unit.

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 type of the disturbance 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 required SMES voltage is derived from the power and once the SMES voltage is determined, the corresponding firing angles of the converters can be calculated by using the sensed SMES current. Direct generation of the compensating power from the SMES unit makes the control strategy very effective in controlling the uncontrolled subsynchronous modes.

2. Power modulation of the SMES unit

The SMES inductor-converter unit consists of a dc superconducting inductor, a 12-pulse cascaded bridge type AC/DC converter and a Y–Δ/Y–Y step down transformer (see Fig. 1). Control of the converter firing angle enables the dc voltage V_{sm} appearing across the inductor to be continuously varied between a wide range of positive and negative values. Gate turn off thyristors (GTO) allow us to design such a type of converter. The converter dc output current I_{sm} being unidirectional, the control for the direction of the inductor power flow P_{sm}, is achieved by continuously regulating the firing angle α.

For initial charging of the SMES unit, the bridge voltage V_{sm} is held constant at a suitable positive value depending on the desired charging period. The inductor current I_{sm} rises exponentially and magnetic energy W_{sm} is stored in the inductor. When the inductor current reaches its rated value I_{sm0}, it is maintained by lowering the voltage across the inductor to zero. The SMES unit is then ready to be coupled with the power system for torsional oscillation stabilization.

Due to sudden application or rejection of load, the generator speed fluctuates. When the system load increases, the speed falls at the first instance, but due to the governor action, the speed oscillates around the reference value. The converter works as an inverter ($90° < \alpha < 180°$) when the actual speed is less than the reference speed and energy is withdrawn from the SMES unit (P_{sm} negative). However, the energy is recovered when the speed swings to the other side. The converter then works as a rectifier ($0° < \alpha < 90°$) and the power P_{sm} becomes positive.

According to the circuit analysis of the converter, the voltage V_{sm} of the DC side of the 12-pulse converter is expressed by

$$V_{sm} = 2V_{sm0}\cos\alpha \quad (1)$$

The current and voltage of superconducting inductor are related as

$$I_{sm} = \frac{1}{L_{sm}}\int_{t_0}^{t} V_{sm}\,d\tau + I_{sm0} \quad (2)$$

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

$$P_{sm} = V_{sm}I_{sm} \quad (3)$$

The energy stored in the superconducting inductor is

$$W_{sm} = W_{sm0}\int_{t_0}^{t} P_{sm}\,d\tau \quad (4)$$

where $W_{sm0} = \frac{1}{2}L_{sm}I_{sm}^2$ is the initial energy in the inductor.

In actual practice the inductor current should not be allowed to reach zero to prevent the possibility of discontinuous conduction in the presence of the large disturbances. To avoid such problems, the lower limit of the inductor current is set at 30% of I_{sm0} [10]. It is desirable to set the rated inductor current I_{sm0} such that the maximum allowable energy absorption equals the maximum allowable energy discharge. This makes the SMES unit equally effective in damping swings caused by sudden increase as well as decrease in load. Thus, if the lower current is chosen at $0.3I_{sm0}$, the upper inductor current based on the equal energy absorption/discharge criterion is set at $1.38I_{sm0}$. When the inductor current reaches either of these limits, the depen-

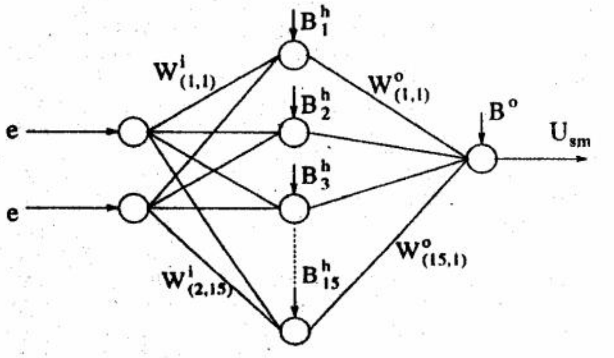

Fig. 2. A multilayered feedforward neural network.

dence of P_{sm} on speed deviation is discontinued till the speed deviation swings to the other side.

Because of constraints of hardware implementation, the voltage V_{sm} has also its upper and lower limit [10]. For the SMES unit modelled, the limits are: -0.2532 p.u. $\leq V_{sm} \leq$ 0.2532 p.u. Therefore, at any instant, for the particular SMES unit, the power P_{sm} has the following limits: $-0.2532 I_{sm}$ p.u. $\leq P_{sm} \leq 0.2532 I_{sm}$ p.u.

In order to control the power balance of the synchronous generator effectively during the dynamic period, the SMES unit is located at the generator bus.

3. The proposed control scheme for the SMES unit

3.1. ANN controller

The basic structure of the proposed ANN controller used in this study is shown in Fig. 2. The approach for the development of the neural network here is limited to the controller structure and design. 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 15 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. The block diagram representation of the ANN controller for SMES unit is shown in Fig. 3b.

Using the knowledge gained from experience, generator speed deviation (e) and acceleration ($\dot{e}$) of the synchronous generator are chosen as the input signals to the ANN controller. The acceleration signals can be derived from the two successive error signals.

Let the pair e and $\dot{e}$ be the error and its derivative of an input variable defined as

$$e(k) = r(k) - c(k) \tag{5}$$

$$\dot{e}(k) = \frac{e(k) - e(k-1)}{h} \tag{6}$$

where $e(k)$ = error of the input variable, $\dot{e}(k)$ = error derivative, $r(k)$ = reference signal, $c(k)$ = input variable, k = sample number, and h = sampling interval. The set of linguistic rules for ANN compensation are given in Table 1. A typical rule has the following structure:

IF e is small negative (SN) and $\dot{e}$ is 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:

$$e = e(k)/e_{b1} \tag{7}$$

$$\dot{e} = \dot{e}(k)/e_{b2} \tag{8}$$

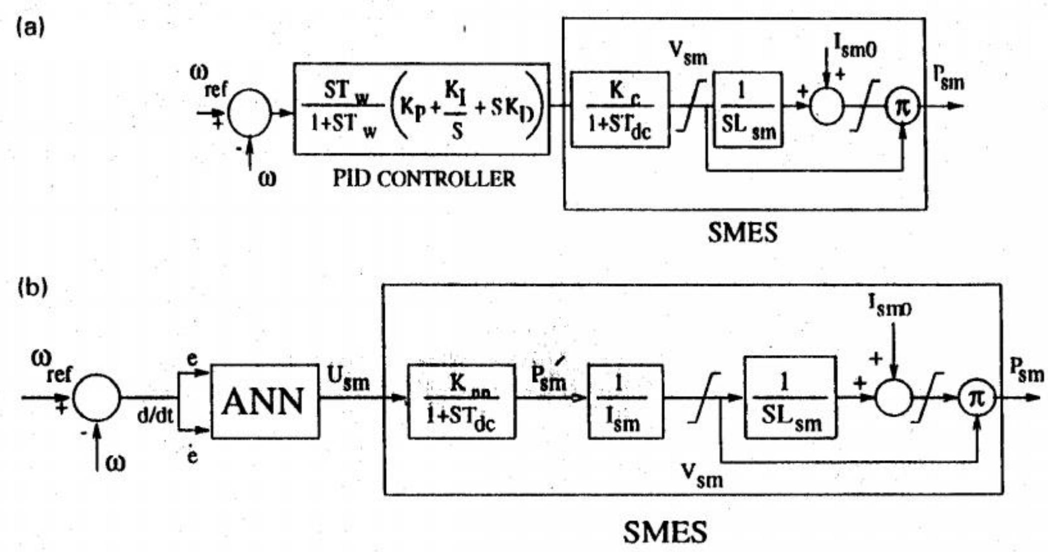

Fig. 3. SMES controllers.

Table 1
Rule base for the ANN controller. 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

d(error)/dt	Error								
	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

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 two bases are related as

$$e_{b1} = K_b e_{b2} \quad (9)$$

where K_b is a constant and has to be determined once off-line. To cope with various types of disturbances the base value e_{b2} for $\dot{e}$ is generated on-line when the system experiences any disturbance from its steady state operating condition. There is a need for parameter e_{b2} to be updated dynamically. Because, the free responses of the system to a transient disturbance may converge to steady state through mixed modes of behaviour, i.e. damped and undamped. Once the system enters into a consistent damped mode e_{b2} becomes fixed.

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

$$P\prime_{sm} = \frac{K_{nn}}{1 + sT_{dc}} U_{sm} \quad (10)$$

where T_{dc} is the delay time. The SMES voltage V_{sm} is then calculated from $P\prime_{sm}$ 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. In such a case, the V_{sm} settling signal along with this sensed I_{sm} signal gives the active power required to flow through the converter.

The ANN controller gain K_{nn}, can be determined using the SMES rating, in addition to the power system parameters.

3.2. 2 Design steps

The steps to design ANN controller parameters are described below:

Step 1: Determination of the constant K_b:

1. Bring the studied power system to the verge of instability by simulating it with a significantly large disturbance. Determine the maximum deviations $e_{b,max}$ and maximum derivative in the presence of SMES unit.
2. Obtain the value of K_b as

$$K_b = \frac{e_{b,max}}{\dot{e}_{b,max}} \quad (11)$$

In the present analysis, the value of the constant K_b is found to be 0.034.

Step 2: Determination of the gain K_{nn}

1. From the first few samples of e, calculate the base e_{b2}

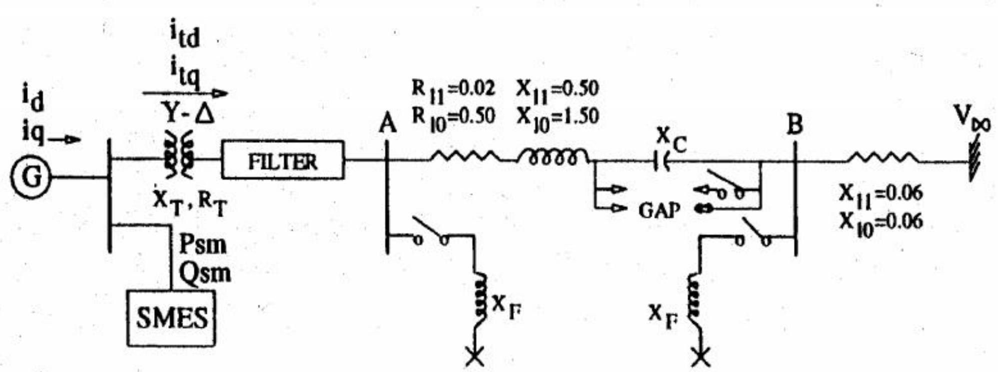

Fig. 4. The IEEE first benchmark model with SMES unit.

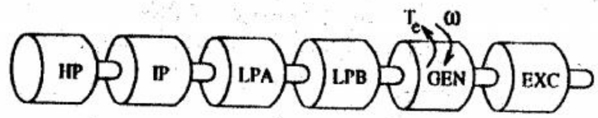

Fig. 5. The generator–turbine system.

on-line for a particular operating condition. Update the value of e_{b2} by the magnitude of $\dot{e}$, if and only if $|\dot{e}| > e_{b2}$.

2. Calculate e_{b1} using the relationship shown in Eq. (9).
3. Determine the gain of the ANN controller as follows:

$$K_{nn} = \frac{e_{b2}}{e_{b,max}} V_{sm,max} I_{sm,max} \quad (12)$$

where $V_{sm,max}$ and $I_{sm,max}$. are the maximum voltage and current limits for a particular SMES unit.

The value of K_{nn} is not fixed but is adapted depending on the operating condition and disturbance. To evaluate the performance of the proposed control strategy, a comparison is made with previous studies [9, 10], where traditional PID controllers have been used.

4. The studied system

In order to study the effect of SMES unit with proposed mode of control, the IEEE first benchmark model shown in Fig. 4 has been considered. The system consists of a synchronous generator feeding an infinite bus over a capacitor compensated transmission line. A superconducting magnetic energy storage (SMES) unit is located at generator bus terminal to increase the damping of the torsional modes.

Combining the mass–spring system, armature and field winding damping windings, excitation system, governor system and the capacitor compensated transmission line, a set of 27 order non-linear differential equations for the system without the SMES unit can be obtained. All the state equations can be found in Ref. [1]. The mass–spring system contains six bodies shown in Fig. 5. The high-pressure turbine (HP), the medium-pressure-turbine (IP), the two low-pressure turbines (LPA and LPB), the generator (GEN), and the exciter (EXC), are all coupled on the same shaft. The static excitation system shown in Fig. 6 supplies the field current to the generator.

5. Computer simulation and performance evaluation

Digital simulations on the non-linear dynamic model of the system are performed under the MATLAB environment in order to highlight the damping effect of the SMES unit with ANN controller. All the nonlinearities such as exciter voltage limit and the current limit of the superconducting inductor are also included. Two types of disturbances are considered under different operating conditions as follows:

Case 1: a 100 ms, 0.15 p.u. step change in torque, $P_0 = 0.9$ p.u., $X_C/X_L = 0.5$.
Case 2: a 100 ms, 0.2 p.u. step change in torque, $P_0 = 1.1$ p.u., $X_C/X_L = 0.8$.

The results of the dynamic responses are shown in Figs. 7 and 8 . For the sake of comparison, the results of the PID controller [9, 10] are also included. In both cases, the system parameters and initial conditions were made to be the same. The parameters of the PID controller have been obtained by pole assignment [9], and these were adopted for study. The relevant data (Fig. 3a) are: $K_P = 4.96$, $K_I = 334$, $K_D = 0.0066$, and $T_W = 0.0085$ s. Table 2 lists the eigenvalues of different modes of torsional oscillations without SMES unit for the operating condition $P_0 = 0.9$ p.u. and $X_C/X_L = 0.5$. It can be observed that in modes 3 and 4, positive real parts of the eigenvalues appear which pose a threat to the stability of the system without SMES unit. This point can be further proved from the dynamic analysis of the system. Fig. 7 and Fig. 8 clearly indicate that the system without the SMES unit is unstable for both the cases mentioned above as expected. However, the addition of the SMES unit has improved the situation. It is worthwhile to mention that the SMES unit with both PID and ANN controller damps out subsynchronous oscillations. In the controlling of the SMES unit, the PID is outputting the SMES voltage V_{sm}. Using the present value of I_{sm}, the compensating power P_{sm} is obtained. Whereas the ANN controller is outputting the compensating power P_{sm} directly and the SMES voltage is obtained from this power. Once V_{sm} is known, the corresponding firing angle of the converter can be calculated.

Fig. 7 shows the system performance with and without the SMES unit following the disturbance in case 1. The system oscillations are growing up and after 5 s, the system becomes unstable. These growing oscillations may lead to a

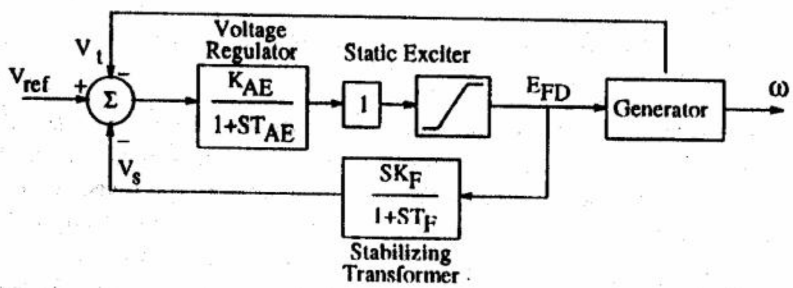

Fig. 6. The static excitation system.

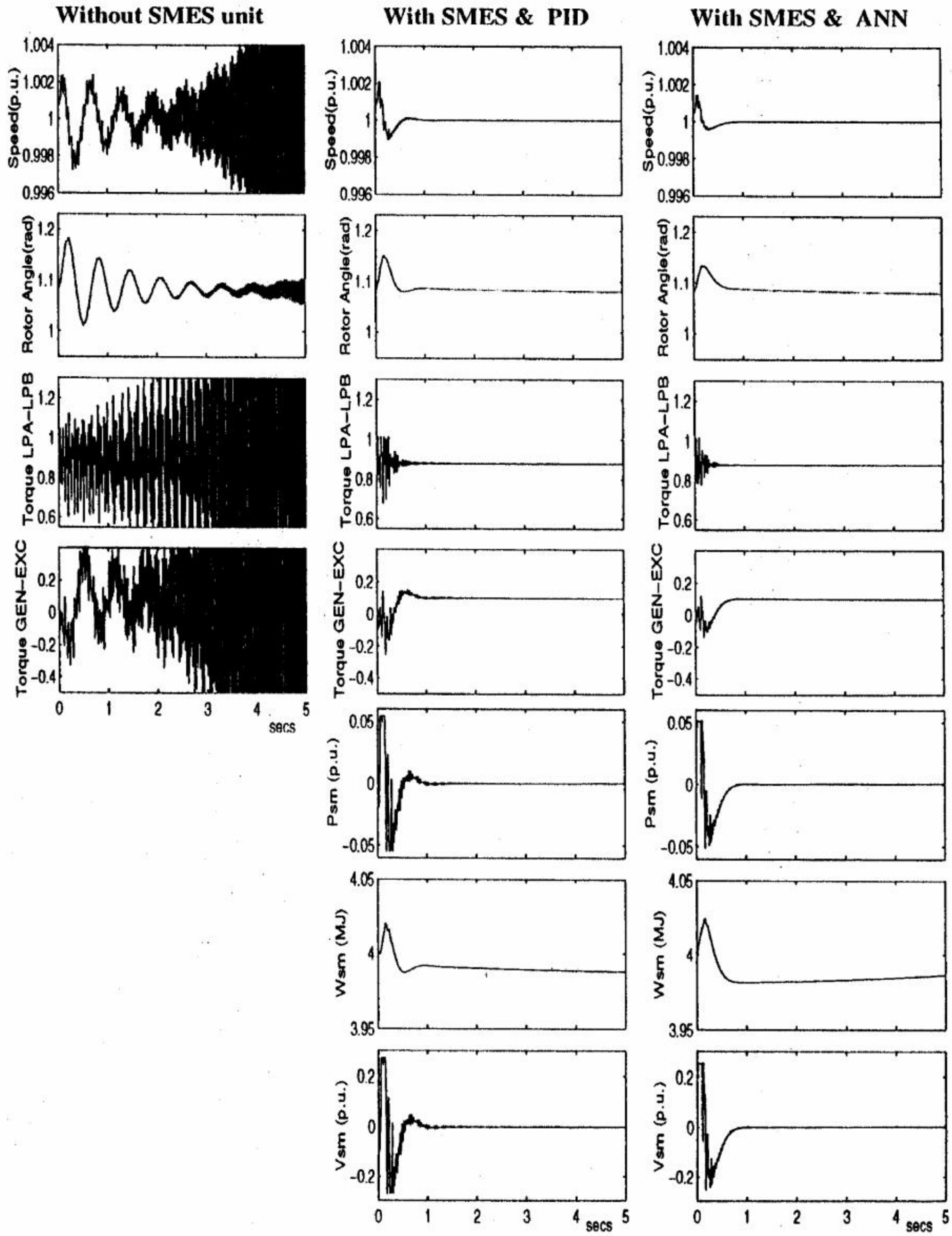

Fig. 7. System performance with and without SMES unit: case 1.

series of shaft failures. A well controlled SMES unit can easily counter these problems. It is observed in the figure that the SMES unit suppresses all such oscillations and the system stabilizes within 0.65 s in the case of the ANN controlled system compared to 1 s in the case of the PID controlled system. The maximum deviation of the speed and rotor angles also decreases with both types of SMES controllers. However, the ANN controlled SMES unit has superior performance over the PID controller, which is evident from the figure as the third peak has almost diminished with the proposed mode of control.

In case 2, a more severe disturbance has been simulated with a diversity of initial conditions. The system responses without the SMES unit reflects the severity of the distur-

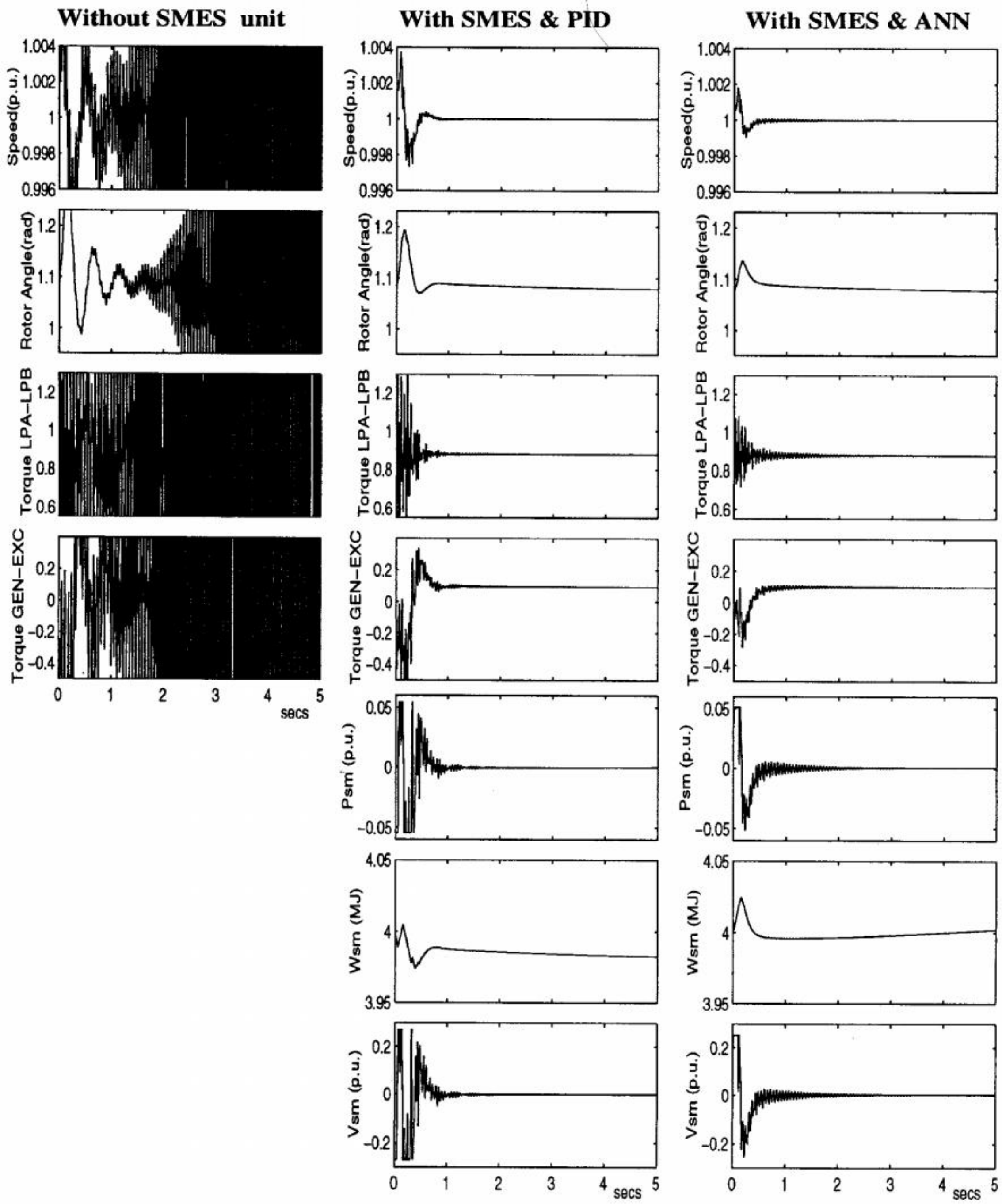

Fig. 8. System performance with and without SMES unit: case 2.

bance. Fig. 8 shows that the system becomes unstable within 2.5 s. The shaft torques are highly oscillatory from the very beginning and it may trigger shaft failure with other damage just after the disturbance. The system regains its stability with the help of the SMES unit. But due to efficient harnessing of the ANN controller, the maximum deviations along with settling time have noticeably improved. From speed deviation to the SMES voltage, each plot shows better performance of the SMES controller. The maximum speed deviation with the ANN controller is around 50% less than that of the PID control response. The rotor angle stabilizes very quickly but steadily with the proposed mode of control. These improved responses are achieved due to the following reasons:

Table 2
The eigenvalues of torsional oscillation modes without SMES unit

Modes	$P_0 = 0.9$, $X_C/X_L = 0.5$
Mode 5	$-0.1817 \pm j298.180$
Mode 4	$0.1705 \pm j202.741$
Mode 3	0.9892 ± 162.175
Mode 2	-0.7240 ± 127.095
Mode 1	$-0.3455 \pm j99.558$
Mode 0	$-0.5670 \pm j9.9980$

1. The compensating power is obtained directly which makes the controller more sensitive to the disturbance.
2. The gain of the controller is adapted according to the grade of the disturbance.

Additional studies were conducted to confirm the advantages of the ANN based controller, especially for effective damping of local area oscillations in power systems. The results have been presented in Ref. [16]. In the present paper, reactive power modulation is not utilised which is an additional benefit for stabilization. This is currently under investigation.

6. Conclusion:

A method of controlling the unstable modes arising from the subsynchronous resonance phenomenon through control of the power of the SMES unit is presented. The control strategy is derived from a simple principle that the SMES unit should receive or deliver power according to the degree of disturbance. The gain of the controller is therefore adapted that makes the controller more effective. The unstable synchronous modes due to series capacitor compensation are cancelled by the appropriate transfer of compensating power as is evidenced in the results. The proposed ANN controller for the SMES unit is equally effective for any degree of disturbance. Transient responses show that the subsynchronous oscillations are removed in less than a second for various degrees of capacitor compensation. This indicates that long transmission links with series capacitor compensation can be reliably operated if equipped with proper SMES control circuitry.

Appendix A

The system data used are as follows [1, 9, 10]

Mass–spring system: $M_H = 0.185794$ $D_H = 0.1$ p.u. $K_{HI} = 19.303$ $M_I = 0.311178$ s $D_I = 0.1$ p.u. $K_{IA} = 34.929$ $M_A = 0.185794$ s $D_A = 0.1$ p.u. $K_{AB} = 19.303$ $M_B = 0.185794$ s $D_B = 0.1$ p.u. $K_{BG} = 19.303$ $M_G = 0.185794$ s $D_G = 0.1$ p.u. $K_{GX} = 19.303$ $M_X = 0.185794$ s $D_X = 0.1$ p.u.

Turbine and governor $F_H = 0.30$ $T_{CH} = 0.3$ s $K_G = 25$ $F_I = 0.26$ $T_{RH} = 7.0$ s $T_{SR} = 0.2$ s $F_A = 0.22$ $T_{CO} = 0.2$ s $F_B = 0.22$ $T_{SM} = 0.3$ s

Transformer and transmission line $R_T = 0.01$ p.u. $R_L = 0.02$ p.u. $X_c/X_L = 0.5$ $X_T = 0.14$ p.u. $X_L = 0.56$ p.u

Synchronous generator (p.u.) $X_d = 1.790$ $X_q = 1.710$ $X_{fd} = 1.700$ $X_{kd} = 1.666$ $X_{fq} = 1.695$ $X_{kq} = 1.825$ $X_{ad} = 1.660$ $X_{aq} = 1.580$ $R_a = 0.0015$ $R_{fd} = 0.001$ $R_{kd} = 0.0037$ $R_{kq} = 0.00182$ $R_{fq} = 0.0053$

Exciter and voltage regulator $K_{AE} = 50$ $T_{AE} = 0.01$ s $K_F = 0.5$ $T_F = 0.5$ s SMES unit
$I_{smo} = 0.2018$ p.u. $V_{smo} = 0.2532$ p.u. $W_{smo} = 4.0$ MJ $L_{sm} = 0.5$ H $T_{dc} = 0.026$ s

The initial operating conditions $P_o = 0.9$ p.u. $V_t = 1.05$ p.u. P.F. = 0.9 lag

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]/;
$B^o = 0.1876$.

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