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ANN CONTROLLED SMES UNIT TO IMPROVE DAMPING OF LOCAL AREA OSCILLATIONS IN POWER SYSTEM

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ABSTRACT

This paper presents a novel strategy to improve the damping of synchronous generator through control of compensating power of superconducting magnetic energy storage (SMES) unit. The control strategy of SMES is based on artificial neural network (ANN). The neural network is trained off-line for a set of inputs and outputs. The gain of the controller is generated on-line depending on the operating conditions and the type of the disturbance. Computer simulations are performed using the non-linear system model for small as well as large disturbances. It has been found that the SMES unit with ANN controller can greatly improve the damping of the system by providing appropriate power compensation to the system.

INTRODUCTION

The stability problem is concerned with the behavior of the synchronous machines after they have been perturbed. The transients following the perturbation are oscillatory in nature. If the system is stable, these oscillations will be damped towards a new operating point. The perturbation could be a major disturbance such as the loss of generation or system fault or combination of such events (Anderson and Fouad, 1994). Many countermeasures are suggested in the literature to increase the damping such as the use of power system stabilizer (PSS) (see Larsen and Swann, 1981; DeMello and Concordia, 1969; and Lee et al., 1981), governor and turbine system (Tripathy et al., 1984), static var compensator (SVC) (O'Briem and Ledwich, 1987), and static phase shifter (Stemmeler and Guth, 1982).

Fast acting energy storage devices, such as SMES or battery energy storage can effectively damp out power, frequency and voltage oscillations caused by small load perturbances. They provide storage capacity in addition to the kinetic energy of the generator rotor, which can share the sudden change in power requirement. However, the effective use of SMES unit greatly depends on its control strategy.

Different types of controllers for the SMES unit have been proposed in the literature (Banerjee et al., 1990; and Wu and Lee, 1991). The gain settings of SMES controllers are usually fixed at values which are determined based on nominal operating point. These fixed gain controllers are always a compromise between the best setting for light and heavy load conditions. It is impossible for the SMES unit with these fixed gain controllers to maintain the best damping performance for the wide range of operating condition. To solve these problems, Wu and Lee (1991) proposed a PI controller for the SMES unit, in which, based on the assigned eigenvalues, the controller parameters were determined.

This paper presents a new approach to control the SMES unit by using ANN for the improvement of power system dynamic performance. The concept of ANN has already been applied successfully to various control problems including that from power system stabilization (Guan et al., 1996; and Park et al., 1996). Two reasons are put forward for using artificial neural networks. First, since an ANN is based upon parallel processing, it can provide extremely fast processing facilities. The second reason for the high level of interest is the ability of ANN to develop a non-linear model of a system (Rogers, 1993). The ANN adopted for this paper is trained for 81 linguististic rules. A back propagation 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 scaled values, the same trained network can be used for different input and output pairs. To verify this, the same ANN controller for the SMES unit is tested for different operating conditions. A control strategy is developed and the simulation results are compared and discussed.

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-Y/Δ 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) are used to design such type of

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converter. The converter dc output current I_{sm} being unidirectional, the control for the direction and magnitude of the inductor power flow P_{sm}, is achieved by continuously regulating the converter's firing angle α.

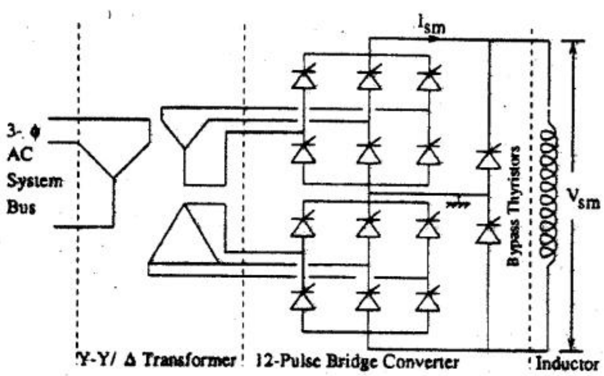


Fig 1 The schematic diagram of the SMES unit.

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 electromechanical mode of oscillation stabilization.

Sudden application or rejection of load causes the generator speed do fluctuate. When the system load increases, the speed falls at the first instant. 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 increases above the reference speed. The converter then works as a rectifier ($0° < \alpha < 90°$) and the power P_{sm} becomes positive (Mitani et al., 1988).

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

$$V_{sm} = 2V_{sm0} \cos \alpha \tag{1}$$

where V_{sm0} is the ideal no-load maximum voltage of the six-pulse bridges.

The current and voltage of superconducting inductor are related as

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

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

$$P_{sm} = V_{sm} I_{sm} \tag{3}$$

The energy stored in the superconducting inductor is

$$W_{sm} = W_{sm0} + \int_{t_0}^{t} P_{sm}\, d\tau \tag{4}$$

where

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

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} (Wu and Lee, 1991). 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 inductor current limit is chosen at $0.3I_{sm0}$, the upper inductor current limit based on the equal energy absorption/discharge criterion is set at $1.38I_{sm0}$. When the inductor current reaches either of these limits, the dependence of P_{sm} on speed deviation is discontinued till the speed deviation swings to the other side.

Because of constraints of hardware implementation due to voltage and current ratings of GTO thyristor, the voltage V_{sm} and the current I_{sm} have their upper and lower limits (Wu and Lee, 1991). For the SMES unit modeled, the limits for V_{sm} are:

$$-0.438 \text{ p.u.} \le V_{sm} \le 0.438 \text{ p.u.}$$

Therefore, at any instant, for the particular SMES unit, the power P_{sm} has the following limits:
$-0.1314\ I_{sm0}$ p.u. $\le P_{sm} \le 0.6044\ I_{sm0}$ p.u.

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

THE PROPOSED CONTROL SCHEME FOR SMES UNIT

ANN Controller

The basic structure of the proposed ANN controller used in this study is shown in Fig 2. The development of neural network approach 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 fifteen nodes, and an output layer with one node. The learning rate and momentum constant are

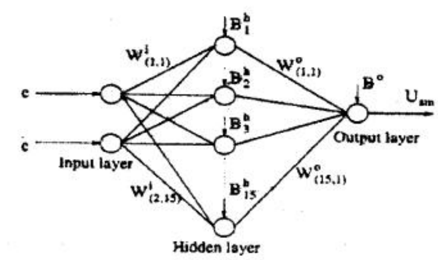
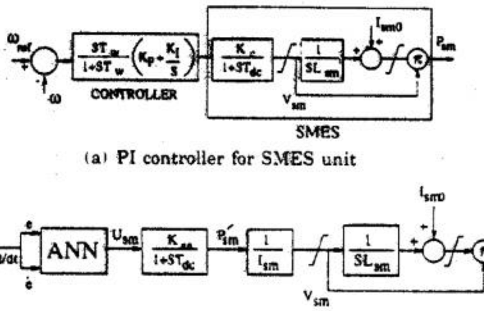


Fig 2 A multi-layered feedforward neural network.

changed automatically in the training process. Once trained (off-line) 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.



(a) PI controller for SMES unit

(b) ANN controller for SMES unit

Fig 3 SMES controllers.

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

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

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

where

$e(k)$ = speed deviation
$\dot{e}(k)$ = acceleration
$r(k)$ = reference speed
$c(k)$ = actual speed
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:

Table 1 Rule base for the ANN controllers.

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

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

IF e is small negative (NS) and $\dot{e}$ is small positive (PS) 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:

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

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

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

$$e_{b1} = K_b e_{b2} \tag{9}$$

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. Free responses of the system to a transient disturbance may converge to steady state through mixed modes of behavior, 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 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:

$$P'_{sm} = \frac{K_{nn}}{1 + ST_{dc}} U_{sm} \tag{10}$$

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. 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.

Design Steps

The steps to determine 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 subjecting it to a significantly large

1. disturbance. Determine the maximum deviation $e_{b,max}$ and maximum derivative $\dot{e}_{b,max}$ in the presence of the SMES unit.

2. Obtain the value of K_b as

$$K_b = \frac{e_{b,max}}{\dot{e}_{b,max}} \tag{11}$$

In the present example, the value of 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} 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 the Eqn. (9).

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

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

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.

DESCRIPTION OF THE SYSTEM MODEL

Fig. 4 shows the studied system with a synchronous generator connected to the infinite bus through a transmission line and a superconducting magnetic energy storage (SMES) unit. Although the example system is a simple one, it is sufficient to demonstrate the damping effect of SMES (Mitani et al., 1988). The unit with thyristor controller is located at the generator bus terminal. The non-linear dynamic behavior of the synchronous generator is described by the two axis model (Anderson and Fouad, 1994). The generator is equipped with a static excitation system and a governor systems (Wu and Lee, 1991). The swing and rotor angle equations can be written as

$$\dot{\omega} = \frac{(P_m - D_g\omega - P_e - P_{sm})}{M_g} \tag{13}$$

$$\dot{\delta} = \omega - 1 \tag{14}$$

where P_m, D_g and M_g are the output power of the reheat steam turbine, damping coefficient, and inertia constant respectively. P_e is the electromagnetic power transfer in the air gap and P_{sm} is the stored power in the SMES. δ is the rotor angle of the synchronous generator. At the initial operating condition, the system eigenvalues are given in Table 2.

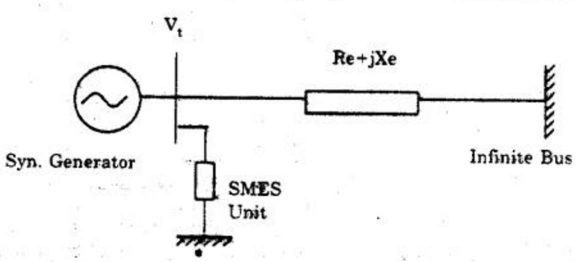


Fig 4 The power system with SMES unit.

Table 2 System eigen values at P_0 = 1.0 p.u., P.F. = 0.85.

Without SMES unit
−217.8
−41.9
−19.95
−10.23
−0.073 ± j9.35*
−1.966
−1.742
−4.885
−0.1249

* Electromechanical mode

COMPUTER SIMULATION AND PERFORMANÇE EVALUATION

In order to demonstrate the beneficial damping effect of the proposed ANN controller, computer simulations based on non-linear differential equations are carried out for small and large disturbances in the system. The differential equations are solved by using the 4th order Runge-Kutta method under the MATLAB environment. All the non-linearities such as the exciter ceiling voltage, SMES voltage limits, inductor current limits have been included. Two different initial conditions are chosen in the present study. They are: (i) initial power P_0 at the air gap is 0.8 p.u., and (ii) P_0 = 1.2 p.u. The disturbances considered include there of a load change and than of (A) a three phase symmetrical fault at the middle of the transmission line cleared after 100 ms with the post fault transfer impedance same as in the prefault case; (B) the same as in (A) but with the post fault transfer impedance increased by 50%. Case B reflects a reduction in power transfer capability due to the isolation of part of the transmission circuitry. The results of the studies are shown in Figs 5 through 7. For the comparison purposes, the performance of the traditional PI controller is also shown in each diagram.

Fig 5 shows the system responses when there is a 0.012 p.u. 100 ms load change. This is a small disturbance, and so the speed oscillation plots certify the damping characteristics of the electromechanical mode as given in Table 2.

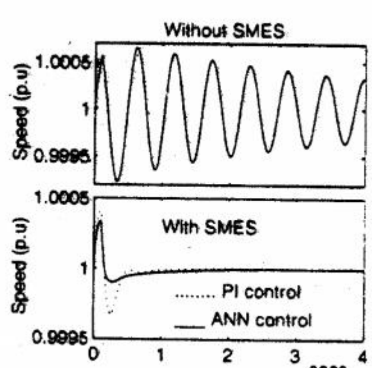


Fig 5 System responses for small disturbance.

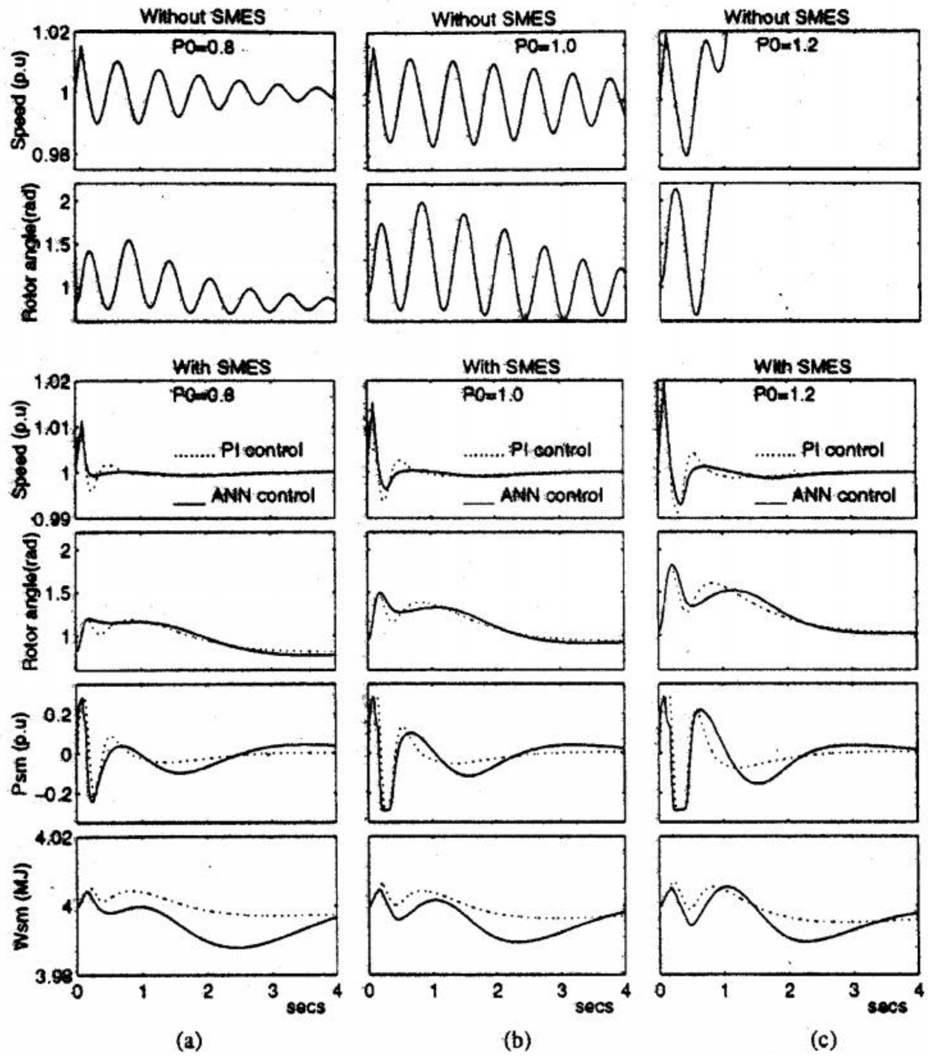


Fig 6 System responses with and without SMES unit for case A_1

Fig 6(a) shows the system performance with and without the SMES unit for case A when $P_0 = 0.8$ p.u. The damping of the system is not satisfactory without the SMES unit. With the addition of SMES, the damping is improved significantly. At the initial period, the speed deviation with PI and ANN controller are almost same. It is due to the delay time T_{dc} which accounts for the SMES power transfer to the system. However, subsequently the ANN controller shows a clear edge over the PI controller. Though both the controllers make use of nearly the same maximum SMES power, due to the efficient harnessing of the SMES power by ANN control, a better performance is obtained. It is evident from Fig 6(a) that the second and third peaks of the generator speed are almost eliminated with the proposed mode of control. This eventually reduces the settling time of the speed which in turn brings the SMES unit in more advantageous position for subsequent use.

For the initial operating condition $P_0 = 1.0$ p.u., the generator speed is oscillatory without the SMES unit (Fig 6(b)). The application of SMES unit removes such oscillations and the system stabilizes within 1.5 secs. Although initial performance of the controllers is similar, again the ANN controller has proved its supremacy over the PI controller subsequently. A careful observation of the first cycle of P_{sm} of Fig 6(b) shows that the ANN controller is more sensitive to the system error and its changes, because P_{sm} is directly obtained from these errors unlike the PI controller where V_{sm} is the corresponding output.

Fig 6(c) shows that the system becomes unstable in the absence of the SMES unit. The presence of the SMES unit makes the system stable with settling time of about 2 secs. Both the controllers perform well but the ANN controller shows a clear edge over the PI controller.

Fig 7 shows the system performance with and without the SMES unit for case B. It is seen that the system damping is unsatisfactory without the SMES unit when the initial power at the air gap $P_0 = 0.8$ p.u. The system becomes unstable for the other two operating conditions ($P_0 = 1.0$ p.u. and $P_0 = 1.2$ p.u.). The corresponding rotor angle variations are also shown. It is observed that the addition of the SMES unit improves system damping and the settling time decreases substantially. For the heavy load condition the system becomes stable with the SMES unit. However the ANN controller performs better than PI controller in all cases. In Fig 7, it is seen that the second peaks are eliminated for all operating conditions when the neural network controller is used. This eventually reduces the settling time of the

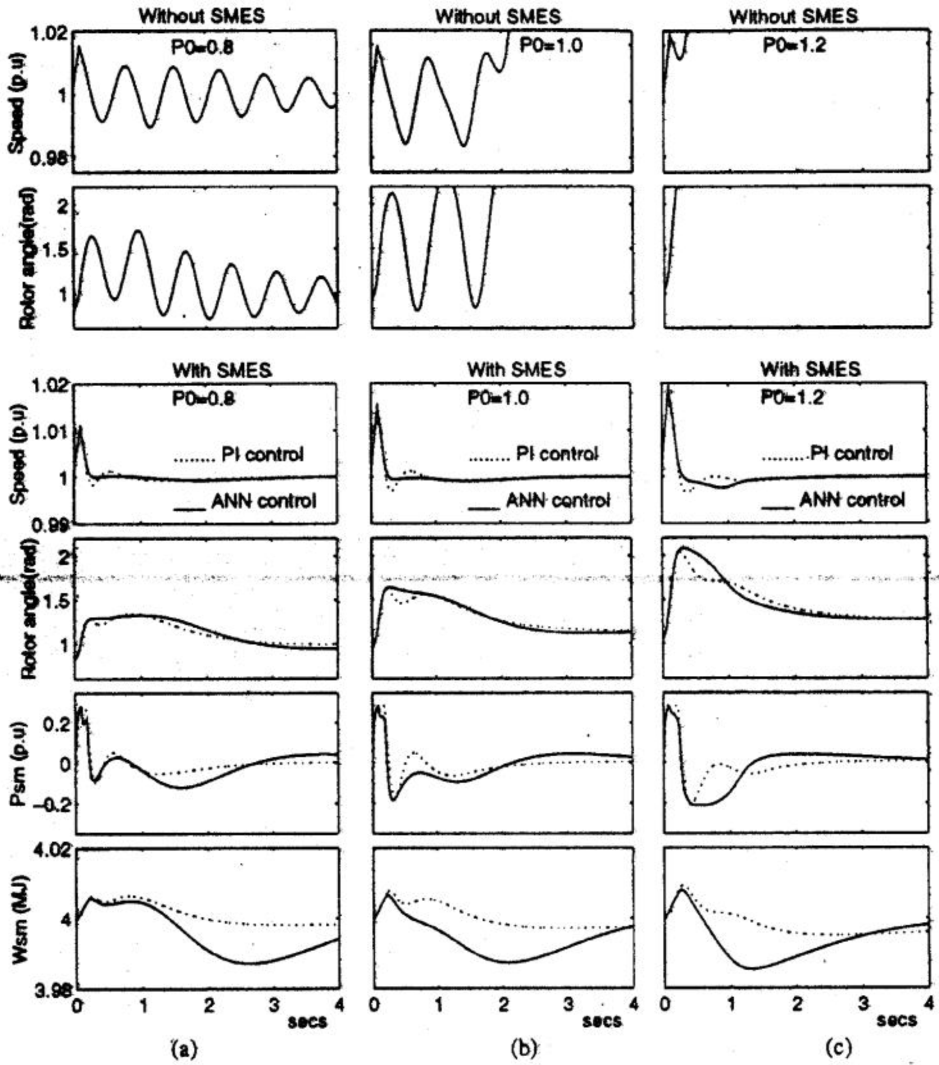


Fig 7 System responses with and without SMES unit for case B.

system. Thus the robustness of the ANN controller is verified. The oscillations in rotor angle are completely removed with the present approach of controlling the SMES. All these results certify the effective use of the SMES power with the proposed mode of control.

The effect of utilizing the reactive power capability of the SMES unit as an additional benefit for stabilization is currently under study. Also the extension of the proposed control strategies to a multi-machine system is under review.

CONCLUSION

A method of improving the damping of synchronous generator 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 the disturbance. The gain of controller is adapted accordingly which makes the SMES system more efficient. The oscillations caused by the disturbance are effectively damped by the appropriate transfer of compensating power from the SMES unit 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 system electromechanical mode of oscillations are removed within a few second for various degree of disturbance. This indicates that the power system can be stabilized reliably if equipped with proper SMES control circuitry.

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APPENDIX

System data and initial conditions (Anderson and Fouad, 1994; Wu and Lee, 1991).

Generator and transmission line

All parameters are expressed in p.u. unless stated otherwise.

Base 160 MVA, 15 kV. Generator 160 MVA, 15 kV, 0.85 p.f. Exciter 375 V, 926 A

$X'_d = 0.245$ $R_a = 0.001096$ $M_g = 4.74$ $D_g = 0$ $X_d = 1.70$

$X_q = 1.64$ $T'_{q0} = 0.075$ s $T'_{d0} = 5.9$ s $R_e = 0.02$ $X_e = 0.4$

SMES Unit

$I_{sm0} = 0.6495$ p.u $V_{sm0} = 0$ p.u. $L_{sm} = 0.5$ H

$W_{sm0} = 4.0$ MJ $T_{dc} = 0.026$ secs

PI Controller (Wu and Lee, 1991)

$K_p = 45.99$, $K_I = 376.4$, $T_w = 0.125$ secs

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;