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AN ADAPTIVE FUZZY CONTROLLED SUPERCONDUCTING MAGNETIC ENERGY STORAGE UNIT FOR POWER SYSTEMS

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Abstract—This paper presents the development of an adaptive fuzzy controller to improve the dynamic stability of an electric power system with a Superconducting Magnetic Energy Storage (SMES) unit. The d.c. voltage applied to the SMES unit is generated from the fuzzy controller. The premise variables chosen for the fuzzy membership functions are speed error and its derivative. The rules in fuzzy cells are adapted according to the performance feedback of the closed loop system. The effectiveness of the proposed controller in restoring energy balance is demonstrated by simulation studies for different types of disturbances. © 1998 Elsevier Science Ltd. All rights reserved.

Energy storage   SMES   Adaptive fuzzy controller   Power system

INTRODUCTION

The stability problem is concerned with the behavior of synchronous machines after they have been perturbed. The transient following the perturbation is oscillatory in nature. If the system is stable, these oscillations will be damped towards a new operating condition. The perturbation could be a major disturbance such as the loss of a line or a fault on the line or combination of such events [1].

Different types of energy storage systems, such as pumped hydro energy storage, compressed air energy storage, battery energy storage and kinetic energy storage, have been proposed in the literature. Except for battery energy storage, all other systems are inherently slow. Since the response of Magnetic Energy Storage (MES) devices is fast, these can effectively damp electromechanical oscillations in a power system. They possess energy storage/absorption capability in addition to the kinetic energy of the generator rotor. Energy can be absorbed by or released from the inductor according to the system requirement. The schematic diagram of an SMES is shown in Fig. 1.

During the past few years considerable research has been devoted to the application of a SMES unit in electrical power systems. Some important works can be found in Refs [2–6]. One of the proposed designs (type-6) of Ref. [6] is used in the present paper. However, for the effective use of the SMES unit, the following two conditions must be satisfied:

(i) The power system should be returned to the steady state condition; the final operating point may be a new one or the predisturbance value.
(ii) The power transfer by the SMES unit should be done in such a way that, when the steady state is reached, the amount of energy storage is equal to its rated value. These will ensure the smooth operation of the SMES unit for subsequent needs.

Most of the controllers designed for the SMES unit deal with a particular operating condition by considering small load disturbances. Only the PI controller proposed in Ref. [3] deals with both small as well as large disturbances. The procedure of calculating parameters K_P and K_I can be described as

- Obtain eigen values of the system for a particular operating point.
- Assign a pair of suitable eigen values for the system.

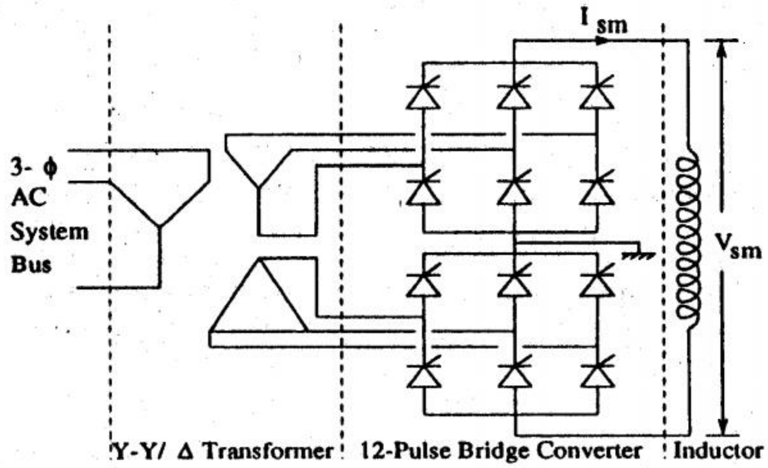

Fig. 1. Schematic diagram of the SMES unit.

- Calculate the parameters K_P and K_I by solving the characteristic equation of the closed loop control system.
- Adjust the eigen values until the parameter values are located in the desirable range.

Because of the absence of a negative feed back signal (either SMES energy or current), the PI controller [3] for the SMES unit cannot give any guarantee of regaining the pre-disturbance energy level. In such a case, its subsequent use will be restricted. The problem becomes more serious when the system runs towards a new steady state operating point. Suppose a synchronous generator is delivering power to an infinite bus through a double circuit transmission line (Fig. 2). If the system runs with only one line after the fault clearance, the application of the SMES unit with the PI controller will definitely improve the stability of the power system, but the SMES unit will be unable to recover its predisturbance energy storage capability. This is because the eigen values have been assigned by considering the double line operation, and not for single line operation. To overcome this defect, a negative feedback of energy or inductor current is employed in the proposed control system.

In the present paper, an Adaptive Fuzzy Controller (AFC) [7] is designed for the SMES unit. Like the PI controller, the inputs considered are the speed error and its derivative. However, the parameters of the AFC are continuously adapted by minimizing the cost function, taking both speed error and its derivative into consideration. The energy feedback signal is added to the output of the AFC. The computer simulation has been performed for different operating conditions, and the effectiveness of the proposed controller has been verified.

DESCRIPTION OF THE SYSTEM

The system consists of a synchronous generator connected to the infinite bus through the parallel transmission line (Fig. 2). A superconducting magnetic energy storage unit is connected at

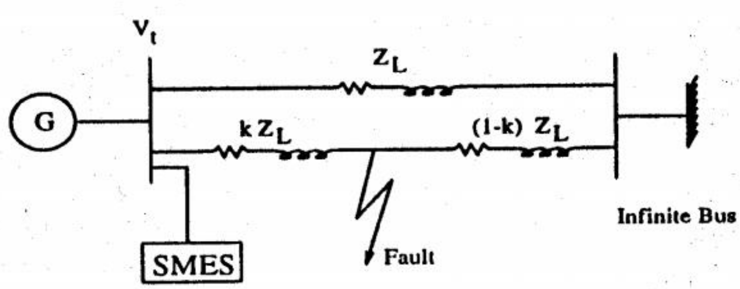

Fig. 2. Study system.

the sending end of the transmission line to improve the stability of the system during dynamic periods. The non-linear dynamic behavior of the generator is described by the two axis model [1]. The generator is equipped with static excitation and governor systems [3].

The swing and rotor angle equations can be written as

$$\dot{\omega} = (P_m - D_g\omega - P_e - P_{sm})/M_g \tag{1}$$

$$\dot{\delta} = \omega_0(\omega - 1) \tag{2}$$

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. P_{sm} is the stored power in the SMES unit and can be expressed as

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

where V_{sm} and I_{sm} are the voltage and current of the superconducting inductor. The energy stored in the inductor is

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

where W_{sm0} is the initial energy in the inductor.

The disturbance considered is the occurrence and subsequent clearance of a 3-phase fault on one of the double circuit lines linking the machine to the infinite bus.

FUZZY MODELING

The purpose of fuzzy modeling is to build a fuzzy model which describes the behavior of the system by using the observed input–output data. The present modeling is based on fuzzy modeling proposed by Sugeno [8], which does not require fuzzy sets defined in the output space but only in the input space. The input space is partitioned into a number of fuzzy cells by the fuzzy sets defined. A linear function of input variables is used in each fuzzy cell to describe the relation of input and output data. The final output of the fuzzy model is given by the weighted average of all local outputs. The final output will be obtained for each set of premise variables of $\Delta\omega$ and $\Delta\dot{\omega}$. Final control to the SMES unit will be obtained after the addition of the energy feedback signal (Fig. 3). A general algorithm using two premise variables in each and every rule can be expressed as follows:

$$\text{if } x_1 \text{ is } A_1, \text{ and } x_2 \text{ is } A_2, \qquad \text{then } y = P_0 + P_1x_1 + P_2x_2 \tag{5}$$

where y: variable of the consequence, the internal function x_i: variables of the premise, i = 1,2

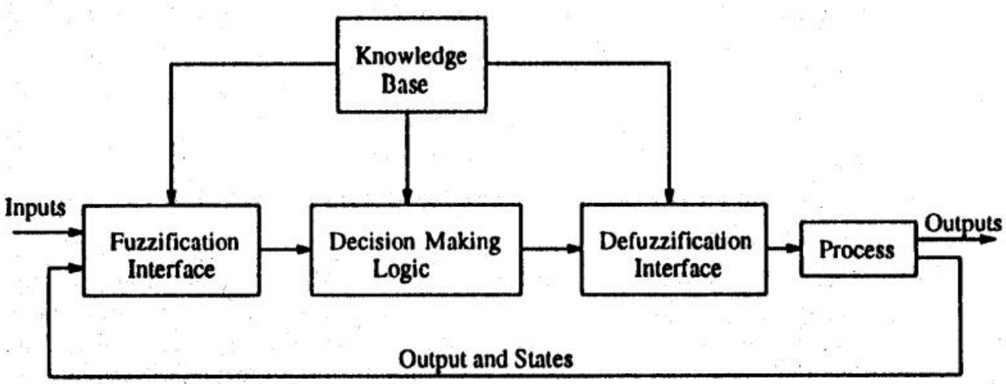

Fig. 3. Basic structure of an adaptive fuzzy controller (AFC).

A_i: reference fuzzy subsets, $i = 1,2$ and P_0, P_1 and P_2 are the parameters of the internal function y and are to be adapted in the iteration process. Let the number of fuzzy subsets in the input spaces of $\Delta\omega$ and $\Delta\dot{\omega}$ be m and n, respectively. Then, the total number rules for the speed will be $m \times n$. Defining $mn = m \times n$, the rules for speed can be expressed as

$$R^1 : \text{ if } x_1 \text{ is } A_1^1 \text{ and } x_2 \text{ is } A_2 \qquad \text{then } y = P_0^1 + P_1^1 x_1 + P_2^1 x_2$$
$$\vdots$$
$$R^{mn} : \text{ if } x_1 \text{ is } A_1^{mn} \text{ and } x_2 \text{ is } A_2^{mn} \qquad \text{then } y = P_0^{mn} + P_1^{mn} x_1 + P_2^{mn} \tag{6}$$

where $x_1 = \Delta\omega$ and $x_2 = \Delta\dot{\omega}$. The final output of the AFC, derived from the speed error and its derivative, can be evaluated by combining the local output in a weighted average manner. It can be described as:

$$P_{\rm sm}^* = \frac{\sum_{i=1}^{mn} (A_1^i(x_1) \wedge A_2^i(x_2)(P_0^i + P_1^i x_1 + P_2^i x_2)}{\sum_{i=1}^{mn} (A_1^i(x_1) \wedge (A_2^i(x_2))} \tag{7}$$

where $x_1 = \omega_{\rm ref} - \omega = e$ and $x_2 = \frac{dx_1}{dt} = \frac{1}{M_s}[P_m - D_g\omega - P_{\rm sm}] = \dot{e}$.

The output of the fuzzy model is $P^*_{\rm sm}$, the desired active power compensation from the SMES unit. The corresponding d.c. voltage $V_{\rm sm}$ applied to its superconducting inductor is calculated as

$$V_{\rm sm} = (P_{\rm sm}^* - k_e \Delta W_{\rm sm})/I_{\rm sm} = P'_{\rm sm}/I_{\rm sm} \tag{8}$$

where k_e is the gain for energy change and $P'_{\rm sm}$ is the actuating signal for the voltage regulator. In practice, there are limits on stored energy $W_{\rm sm}$, active power $P'_{\rm sm}$ and inductor current $I_{\rm sm}$. The voltage $V_{\rm sm}$ also has its upper and lower limits. These limits are expressed as follows:

If $P'_{\rm sm} \geq P_{\rm sm,max}$, then $P_{\rm sm} = P_{\rm sm,max}$
else if $P'_{\rm sm} \leq P_{\rm sm,min}$, then $P_{\rm sm} = P_{\rm sm,min}$ else $P_{\rm sm} = P'_{\rm sm}$.
If $(W_{\rm sm} \geq W_{\rm sm,max})$ or $(W_{\rm sm} \leq W_{\rm sm,min})$, then $P_{\rm sm} = 0$.
If $(I_{\rm sm} \geq I_{\rm sm,max})$ or $(I_{\rm sm} \leq I_{\rm sm,min})$, then $P_{\rm sm} = 0$.

Finally,

if $V_{\rm sm} \geq V_{\rm sm,max}$, then $V_{\rm sm} = V_{\rm sm,max}$
else if $V_{\rm sm} \leq V_{\rm sm,min}$, then $V_{\rm sm} = V_{\rm sm,min}$, else $V_{\rm sm} = P_{\rm sm}/I_{\rm sm}$.

where $I_{\rm sm}$ is the present value of the inductor current.

Since $I_{\rm sm}$ cannot change instantaneously, any change in $P^*_{\rm sm}$ will cause a change in the control signal $V_{\rm sm}$. Initially, $P^*_{\rm sm}$ is the one which determines the control signal because the change in energy storage of the SMES unit is very small. As the speed stabilizes, the determination of $V_{\rm sm}$ is dominated by $\Delta W_{\rm sm}$.

ADAPTIVE FUZZY CONTROLLER (AFC) FOR THE SMES UNIT

Basic structure of the fuzzy controller

Once the structure of the fuzzy model is decided, the parameters of the internal function which determine the performance of the fuzzy model need to be adapted. For each fuzzy cell, a rule is assigned to obtain the local control. The number of fuzzy cells is determined by the number of membership functions. The rules are adapted according to the performance feedback of the closed loop system. By using this adaptive controller, the d.c. voltage across the superconducting inductor of the SMES unit will be continuously controlled (Fig. 4).

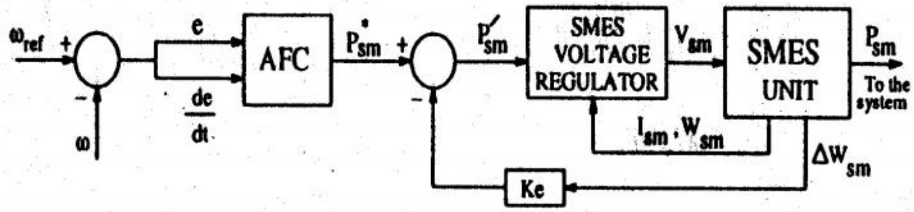

Fig. 4. SMES with AFC.

Algorithm for rule adaptation

The output of the fuzzy model can be expressed as

$$P^*_{sm} = \sum_{i=1}^{n} B^i(t)(P^i_0 + P^i_1 x_1 + P^i_2 x_2) \tag{9}$$

where 'i' is the rule number and

$$B^i(t) = \frac{A^i_1(x_1) \wedge A^i_2(x_2)}{\sum_{s=1}^{n} A^s_1(x_1) \wedge A^s_2(x_2)}.$$

The value of $B^i(t)$ is known in the iteration process. Since ΔW_{sm} is independent of the parameter P therefore, one can write

$$\frac{\partial P_{sm}}{\partial P} = \frac{\partial P'_{sm}}{\partial P} = \frac{\partial P^*_{sm}}{\partial P} \tag{10}$$

Using Equation (9), we can have,

$$\frac{\partial P^*_{sm}}{\partial P_0} = B^i(t), \quad \frac{\partial P^*_{sm}}{\partial P_1} = B^i(t)x_1 \text{ and } \frac{\partial P^*_{sm}}{\partial P_2} = B^i(t)x_2$$

Let us choose a performance index

$$J = \frac{1}{2}\int_0^t (x_1^2 + x_2^2)\mathrm{d}t \tag{11}$$

The adaptive algorithm is derived according to the gradient descent method for all parameters. To determine the parameters P_0, P_1 and P_2 for all the fuzzy cells, the cost function J has to be minimized. The general procedure is

$$P^i_{n,\text{new}} = P^i_{n,\text{old}} - \alpha_n \frac{\delta J}{\partial P^i_n} \quad n = 0, 1, 2 \tag{12}$$

Consider $x_1 = \Delta\omega = e$, we have

$$\frac{\partial J}{\partial P_n} = \sum_{k=1}^{NS}\left[e(k)\frac{\partial e}{\partial P_n} + \dot{e}(k)\frac{\partial \dot{e}}{\partial P_n}\right] \quad n = 0, 1, 2 \tag{13}$$

where NS: no. of data points need to be considered in the performance index.

Using Equations (1) and (10), we can write

$$e = \omega_{\text{ref}} - \int [(P_m - D_g\omega - P_e - P_{sm})/M_g]\mathrm{d}t \tag{14}$$

$$\frac{\partial e}{\partial P_n} = \frac{1}{M_g}\int \frac{\partial P_{sm}^*}{\partial P_n}\,dt \qquad (15)$$

$$\frac{\partial \dot{e}}{\partial P_n} = \frac{1}{M_g}\frac{\partial P_{sm}^*}{\partial P_n} \qquad (16)$$

For the *i*th rule,

$$\frac{\partial J}{\partial P_0^i} = \frac{1}{M_g}\sum_{k=1}^{NS}\left[e(k)\sum_{s=1}^{k}B^i(s) + \dot{e}(k)B^i(k)\right]$$

$$\frac{\partial J}{\partial P_1^i} = \frac{1}{M_g}\sum_{k=1}^{NS}\left[e(k)\sum_{s=1}^{k}B^i(s) + \dot{e}(k)B^i(k)\right]e(k)$$

$$\frac{\partial J}{\partial P_2^i} = \frac{1}{M_g}\sum_{k=1}^{NS}\left[e(k)\sum_{s=1}^{k}B^i(s) + \dot{e}(k)B^i(k)\right]\dot{e}(k) \qquad (17)$$

COMPUTER SIMULATION

To demonstrate the usefulness of the proposed adaptive fuzzy controller, computer simulations were performed using the MATLAB environment under different operating conditions. Three phase faults are considered on one of the double circuit lines (Fig. 2) at positions $k = 0$, $k = 0.25$ and $k = 0.5$, respectively, where k is the distance in p.u. measured from the generator bus. Two case studies were conducted. They are:

Case 1: The faulted line is isolated after 80 ms, allowing the system to run with only one line.

Case 2: The isolated line is re-closed to the normal position. An additional 100 ms after fault clear is allowed before the line is re-closed.

Performances of the controller for both cases are investigated. A comparison of the results for the different assigned eigen values used in designing the PI controller [4] is also presented.

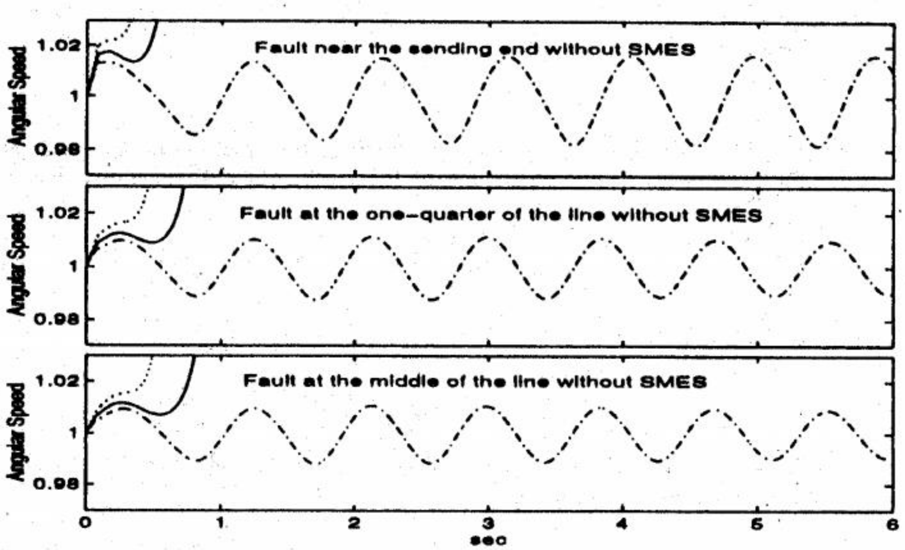

Fig. 5. System performance without SMES (single line operation).

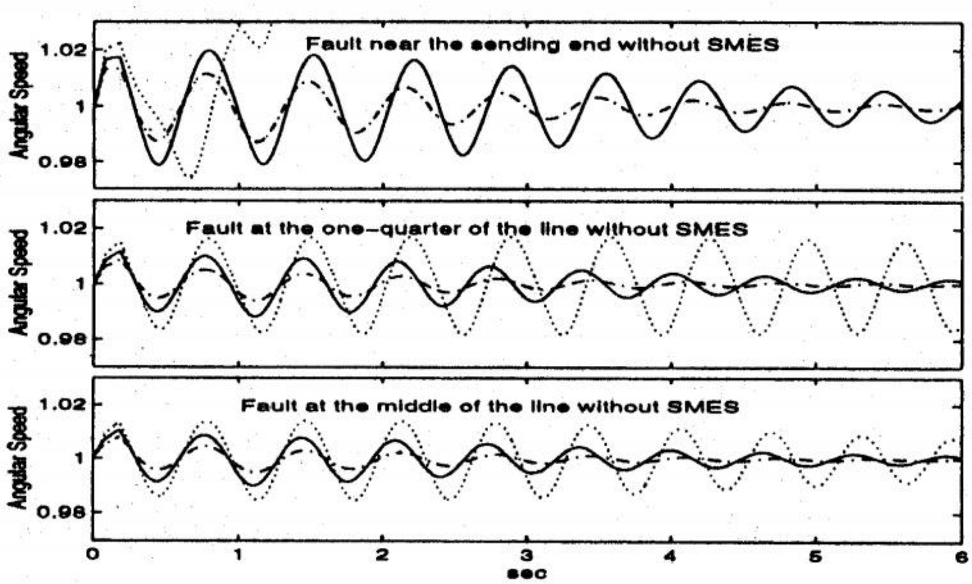

Fig. 6. System performance without SMES (double line operation).

During fuzzy modeling, the number of fuzzy subsets considered for each of the premise variables is 7. So, altogether, 49 rules are obtained. The maximum and minimum values chosen for the premise variable $\Delta\omega$ are 0.01 and −0.005 p.u., respectively, whereas the maximum and minimum values of the premise variable $\Delta\dot{\omega}$ are 0.1 and −0.05 p.u./ s, respectively. All fuzzy sets in each premise variable are equally distant from each other.

Figure 5 and 6 show the system responses without the SMES unit for three-phase faults at different positions of the transmission line. In these figures, the dotted line (······) represents

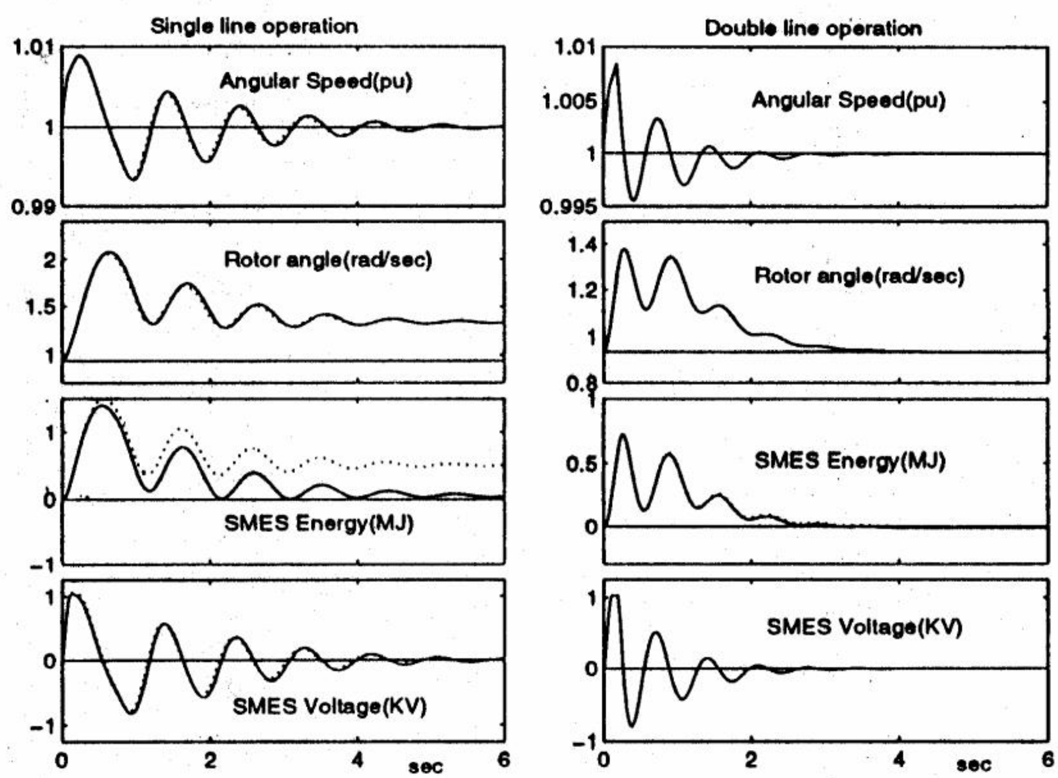

Fig. 7. System responses with SMES and PI (fault at the middle—single and double line operation).

Table 1. System performances for different sets of eigen values

Eigen values	Post fault operation	K_P	K_I	Speed max (p.u.)	Speed min (p.u.)	Settling time (s)	W_{sm} max (MJ)	W_{sm} min (MJ)	V_{sm} max (kV)	V_{sm} min (kV)
$-12\pm j10$	Single line	53.5	407	1.0083	0.9970	6	1.5	0.18	1.2	−0.85
	Double line			1.0080	0.9952	4	0.8	0.02	1.1	−0.85
$-10\pm j10$	Single line	50.5	389	1.0085	0.9970	>6	1.5	0.18	1.2	−0.90
	Double line			1.0080	0.9952	4	0.79	0.02	1.0	−0.80
$-8\pm j10$	Single line	45.5	345	1.0087	0.9930	>6	1.4	0.18	1.0	−0.82
	Double line			1.0085	0.9945	3.8	0.75	0.02	1.0	−0.85
$-12\pm j8$	Single line	52.2	378	1.0087	0.9930	>6	1.4	0.18	1.01	−0.82
	Double line			1.0085	0.9955	3.5	0.75	0.02	1.01	−0.80

initial power $P_0=1.2$ p.u., the solid line (—) represents $P_0=1.0$ p.u. and the dash-dotted line (-·-·-·) represents $P_0=0.8$ p.u.. When the fault occurs at the generator bus end of the transmission line ($k=0$), the most severe one, the system is unstable for $P_0=1.2$ p.u.. Also, for $P_0=1.0$ p.u., there is almost no damping at the initial period. The system damping for $P_0=0.8$ p.u. is very low. The overall system damping is improved as k increases from 0 to 1. However, the damping is not satisfactory.

Figure 7 shows the performances of the SMES unit with the PI controller. The fault is considered at the middle of the transmission line. It is observed that, with negative feedback of the energy change, the SMES energy attains its predisturbance energy level while maintaining almost the same angular speed response obtained without negative feedback of the energy change. However, fluctuations in the angular speed responses are significant which, in turn, causes fluctuations in rotor angle. For double line operation, the angular speed becomes stable after a few oscillations. These results using the PI controller are obtained for the eigen values of $-12\pm j8$. The system performances with negative feedback of the energy change for different sets of eigen values are shown in Table 1.

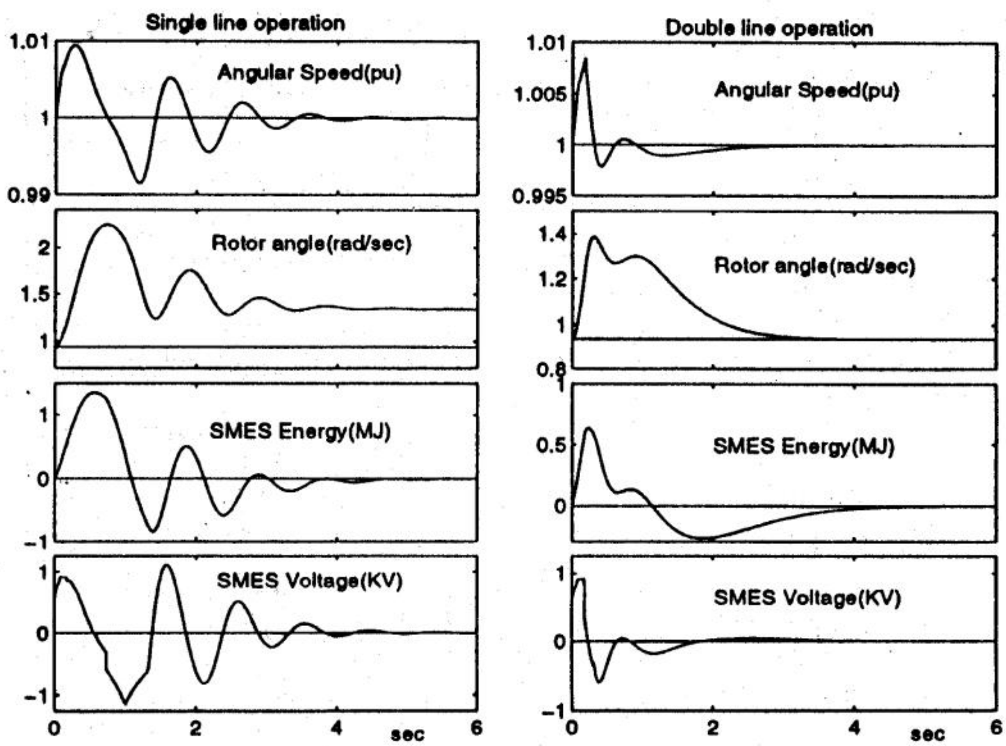

Fig. 8. System responses with SMES and AFC (fault at the middle—single and double line operation).

Table 2. Performance comparison of AFC and PI controlled SMES unit

System behaviors	Post fault system	Without SMES	SMES (PI)	SMES (AFC)
Angular speed deviation	Single line	Unstable		
1st peak (p.u.)			0.00875	0.0093
2nd peak (p.u.)			−0.00671	−0.00812
Settling time (s)			>6	4.8
SMES energy change (MJ)	Single line	—	1.421	1.342
Angular speed deviation	Double line			
1st peak (p.u.)		0.018	0.00859	0.00857
2nd peak (p.u.)		0.020	−0.0045	−0.00214
Settling time (s)		>6	3.5	3.1
W_{sm} *change* (MJ)	Double line	—	0.75	0.66

Table 3. The rule base for P_0 parameters of the fuzzy controller

	MN	SN	Z	SP	MP	BP	VBP
MN	VBN	BN	MN	SN	Z	SP	MP
SN	BN	MN	SN	Z	SP	MP	BP
Z	MN	SN	Z	SP	MP	BP	VBP
SP	SN	Z	SP	MP	BP	VBP	VBP
MP	Z	SP	MP	BP	VBP	VBP	VBP
BP	SP	MP	BP	VBP	VBP	VBP	VBP
VBP	MP	BP	VBP	VBP	VBP	VBP	VBP

Figure 8 shows the performances of the SMES unit with the adaptive fuzzy controller for the same disturbance at the middle of the transmission line. A significant improvement is achieved in both single and double line operations. The SMES energy requirement is less in each case when compared to the PI controller. A large amount of SEMS energy is saved with the AFC while maintaining a response similar to the PI controller. Also, the settling time is less. Table 2 shows a summary of the comparison. The comparative study is performed for $P_0 = 1.0$ p.u. The basic compensations provided by the SMES unit and its base matrix are shown in Table 3. The initial and final parameter values of the rules in the fuzzy model are shown in Tables 4–6 (see Appendix II).

The initial values of all P_1 and P_2 parameters are chosen as 15 and 0.5, respectively, based on the maximum power compensation of the SMES unit. The compensation proportional to the

Table 4. Initial parameters of all 49 fuzzy cells

		Min ≤0.005 p.u.	Speed error $e\rightarrow$				Max ≥0.01 p.u.	
		A1	A2	A3	A4	A5	A6	A7
Min ≤ 0.05 p.u.	B1 P0	−0.096	−0.072	−0.048	−0.024	0	0.024	0.048
	P1	15	15	15	15	15	15	15
	P2	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Speed error	B2 P0	−0.072	−0.048	−0.024	0	0.024	0.048	0.072
	P1	15	15	15	15	15	15	15
	P2	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Derivative	B3 P0	−0.048	−0.024	0	0.024	0.048	0.072	0.096
	P1	15	15	15	15	15	15	15
	P2	0.5	0.5	0.5	0.5	0.5	0.5	0.5
de/dt	B4 P0	−0.024	0	0.024	0.048	0.072	0.096	0.1052
	P1	15	15	15	15	15	15	15
	P2	0.5	0.5	0.5	0.5	0.5	0.5	0.5
↓	B5 P0	0	0.024	0.048	0.072	0.096	0.12	0.144
	P1	15	15	15	15	15	15	15
	P2	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	B6 P0	0.024	0.048	0.072	0.096	0.12	0.144	0.168
	P1	15	15	15	15	15	15	15
	P2	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Max ≥0.1 p.u.	B7 P0	0.048	0.072	0.096	0.12	0.144	0.168	0.192
	P1	15	15	15	15	15	15	15
	P2	0.5	0.5	0.5	0.5	0.5	0.5	0.5

Table 5. AFC parameters adaptation (single line operation)

		Min ≤0.005 p.u.		Speed error $e\rightarrow$			Max ≥0.01 p.u.	
		A1	A2	A3	A4	A5	A6	A7
Min ≤0.05 p.u.	B1 P0	−0.1038	−0.0757	−0.0575	−0.0401	−0.0132	0.0201	0.0475
	P1	15.1921	15.0697	15.1706	15.3581	15.4117	15.1998	15.0364
	P2	0.347	0.4771	0.4665	0.3218	0.0917	0.2210	0.4422
Speed error	B2 P0	−0.1021	0.0763	−0.0728	−0.0341	0.0045	0.0397	0.0697
	P1	15.7789	15.5717	15.9688	15.7448	15.5936	15.6416	15.3890
	P2	−0.4267	0.2714	0.2252	0.1471	−0.1115	−0.4795	−0.1308
Derivative	B3 P0	−0.0564	−0.0268	−0.0018	0.0240	0.0539	0.0790	0.0976
	P1	15.3090	15. 0583	15.0464	15.0228	15.6261	15.8155	15.6243
	P2	−0.2088	0.4420	0.5024	0.4886	0.1323	−0.2023	−0.3563
de/dt	B4 P0	−0.0254	0.0005	0.0252	0.0494	0.0799	0.1107	0.1214
	P1	15.2023	15.0139	15.0273	15.0853	15.6193	16.3640	15.2087
	P2	0.1309	0.4995	0.5389	0.5311	0.2084	−0.4763	0.2670
↓	B5 P0	0.0013	0.0260	0.0498	0.0764	0.1045	0.1211	0.14440
	P1	15.1238	15.0962	15.0846	15.2300	15.4633	15.0651	15
	P2	0.4716	0.6076	0.6007	0.6129	0.6068	0.5029	0.5
	B6 P0	0.0240	0.0480	0.0839	0.1195	0.1286	0.1451	0.1680
	P1	15.0009	15.0013	15.5549	16.1476	15.4598	15.0622	15
	P2	0.5010	0.5015	1.0005	1.2679	0.6264	0.5029	0.5
Max ≥0.1 p.u.	B7 P0	0.0480	0.0720	0.1076	0.1249	0.1440	0.1680	0.1920
	P1	15	15	15.5343	15.2275	15	15	15
	P2	0.5	0.5	1.0324	1.0324	0.5	0.5	0.5

speed error 'e' can be obtained by multiplying the P_1 parameters and their respective membership functions of 'e', and this is considered to be the dominant factor. Similarly, the compensation proportional to 'de/dt' can be obtained by multiplying the P_2 parameters and their respective membership functions of 'de/dt', and this is considered less dominant. A maximum of four rules can be activated for a particular set of 'e' and 'de/dt'.

The acceleration factor α_0 for P_0 is kept very low to keep the basic compensation unchanged. However, the acceleration factors for P_1 and P_2 are kept high to make the controller more sensitive to the changes of 'e' and 'de/dt'. Also, this will help to adapt the parameters according to the system requirement whenever the initial selections are not appropriate.

Figure 9 shows the responses with the SMES unit and AFC when the faults considered are at the generator bus (k = 0 p.u.) and one-quarter of the transmission line (k = 0.25 p.u.).

From Figs 7–9, the following observations are obtained:

Table 6. AFC parameters adaptation (double line operation)

		Min ≤ 0.005 p.u,		Speed error $e\rightarrow$			Max ≥0.01 p.u.	
		A1	A2	A3	A4	A5	A6	A7
Min ≤0.05 p.u.	B1 P0	−0.0960	−0.0729	−0.0528	−0.0284	−0.0044	0.0202	0.0478
	P1	15	15.0027	15.0107	15.0038	15.0028	15.0345	15.0059
	P2	0.5	0.5126	0.5981	0.5987	0.5365	0.2872	0.4629
Speed error	B2 P0	−0.0720	−0.0531	−0.0314	−0.0007	0.0240	0.0480	0.0720
	P1	15	15.011	15.0139	15.0013	15	15	15
	P2	0.5	0.4983	0.5013	0.5002	0.5	0.5	0.5
Derivative	B3 P0	−0.0480	−0.0314	−0.0155	0.0232	0.0530	0.0765	0.9630
	P1	15	15.0149	15.0283	15.0017	15.0017	15.1329	15.0123
	P2	0.5	0.4829	0.4994	0.5004	0.3920	0.3451	0.4560
de/dt	B4 P0	−0.024	−0.0008	0.0230	0.0480	0.0772	0.1048	0.1203
	P1	15	15.0018	15.0022	15.0001	15.1480	15.2911	15.0131
	P2	0.5	0.5009	0.5014	0.5001	0.3590	−0.0036	0.4527
↓	B5 P0	0	0.0240	0.0481	0.0750	0.1027	0.1209	0.1440
	P1	15	15	15.0023	15.0635	15.1509	15.0212	15
	P2	0.5	0.5	0.5059	0.6220	0.7007	0.5166	0.5
	B6 P0	0.024	0.0480	0.0819	0.1153	0.1269	0.1449	0.1680
	P1	15	15	15.1841	15.3836	15.1525	15.0203	15
	P2	0.5	0.5	1.1161	1.5074	0.7227	0.5161	0.5
Max ≥0.1 p.u.	B7 P0	0.048	0.072	0.1057	0.1241	0.1440	0.1680	0.1920
	P1	15	15	15.1766	15.0755	15	15	15
	P2	0.5	0.5	1.1445	0.7546	0.5	0.5	0.5

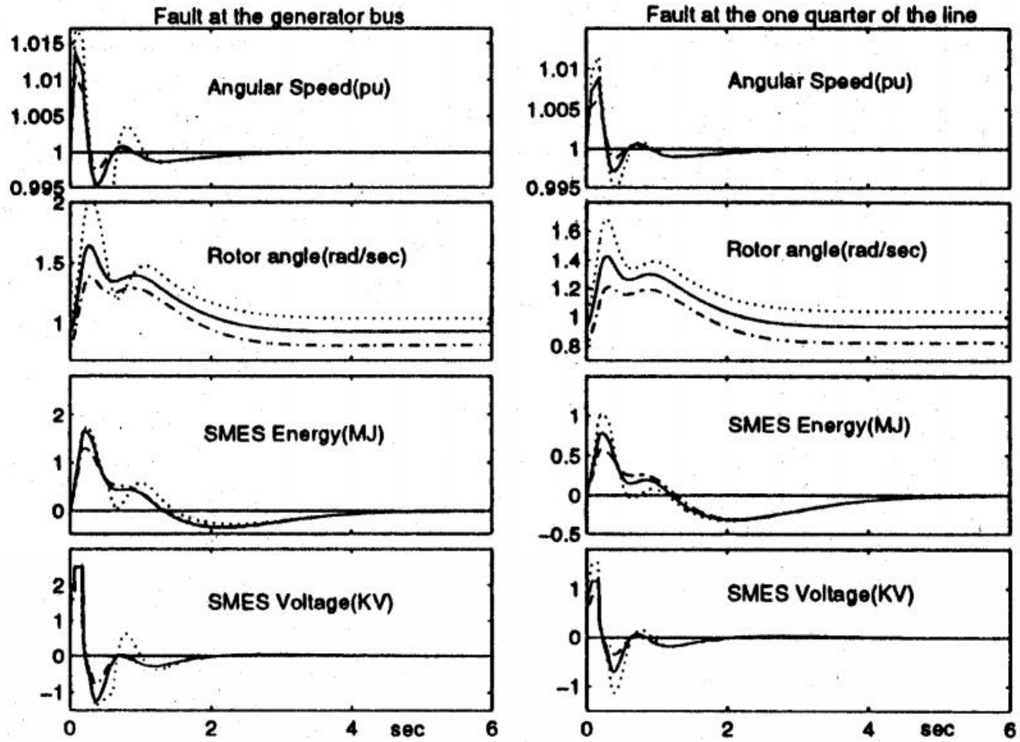

Fig. 9. System responses with SMES and AFC (fault at the generator bus and fault at one-quarter of the line—double line operation).

1. The system damping is greatly improved when the SMES unit is equipped with the adaptive fuzzy controller.
2. The system is restored to the normal condition for different operating conditions with the AFC, and the energy level in the SMES is returned to its prefault position. The SMES unit with the PI controller [3] is unable to regain its prefault energy storage capability.
3. All the other expected advantages of the PI controller are also obtained with the proposed method.

For case 1, an investigation was also done for large values of P_0 (for severe faults close to the generator bus). The results showed that the maximum required energy from the SMES unit exceeded 3 MJ. Practical operating conditions do not allow such a large value for the 6 MJ SMES unit considered [2].

CONCLUSIONS

In this article, a Superconducting Magnetic Energy Storage Unit is proposed to improve the dynamic stability of a power system. A rule based adaptive fuzzy controller is used to generate the d.c. voltage which determines the power flow to or from the SMES unit. The parameters of each of the rules are continuously adapted according to the system performance. A cost function considering speed deviation and its derivative is minimized in the solution process. The changes of parameters are based on the minimization of this cost function. To show the effectiveness of the proposed controller, faults are considered at various positions of the transmission line. Addition of the SMES energy change signal in the feedback control loop restores the energy storage capability of the SMES unit to its prefault position. The system is restored to its steady state operation in an optimal manner. Also, due to the robust nature of the proposed controller, the SMES unit is utilized efficiently.

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APPENDIX I

XXX Opp make line below a d head XXX
System data and initial conditions [1, 5, 6]

Generator And Transmission Line

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

$X'_d = 0.245$ p.u.	$R_a = 0.001096$ p.u.	$M_g = 4.74$ p.u.	$D_g = 0$ p.u.	$X_d = 1.70$ p.u.
$X_q = 1.64$ p.u.‡ I	$T_{q0} = 0.075$ s	$T_{d0} = 5.9$ s	$Z_L = 0.04 + j0.8$ p.u.	

SMES Unit & Fuzzy Model

$I_{sm0} = 4$ kA	$V_{sm0} = 0$ kV	$L_{sm} = 0.5$ H	$W_{sm0} = 6.0$ MJ
$\alpha_0 = 0.05$	$\alpha_1 = 20$	$\alpha_2 = 25$	$k_e = 0.05$