A Fuzzy Logic-Controlled Superconducting Magnetic Energy Storage for Transient Stability Augmentation

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***Abstract*—This paper presents a fuzzy logic-controlled superconducting magnetic energy storage (SMES) to improve the transient stability of an electric power system. In order to see how effective the proposed fuzzy controlled SMES in improving the transient stability is, its performance is compared to that of a conventional proportional–integral (PI) controlled SMES. Furthermore, a comparative study between the fuzzy controlled SMES and fuzzy controlled braking resistor (BR) is carried out. Simulation results show that the performance of fuzzy controlled SMES is better than that of PI controlled SMES. Again, the performance of SMES is better than that of BR. Finally, it can be concluded that the proposed fuzzy controlled SMES provides a very simple and effective means of transient stability enhancement of electric power systems.**

***Index Terms*—Balanced and unbalanced faults, braking resistor (BR), electro-magnetic transients program (EMTP), fuzzy logic controller (FLC), proportional–integral (PI) controller, superconductive magnetic energy storage (SMES), transient stability augmentation.**

I. Introduction

INTENSIVE progress in power electronics and superconductivity has provided power transmission and distribution industry with superconductive magnetic energy storage (SMES) units. Since the successful commissioning test of the BPA 30-MJ unit [1], SMES systems have received much attention in power system applications, such as, diurnal load demand leveling, frequency control, automatic generation control, uninterruptible power supplies, etc. The real power can be absorbed or released from the low loss superconducting magnetic inductor according to system power requirements. The amount of energy to be supplied or received by the SMES unit can be controlled by the firing angle of the converters of the SMES unit. By using high-speed electronic switches, the technology offers many chances for stability enhancement of power systems. The thyristor controlled SMES unit is also such a device. A number of articles [2]–[6] have been reported demonstrating the use of SMES unit for power system transient stability enhancement. However, in all of these works, SMES is controlled through conventional controllers. The effectiveness of SMES on power system stabilization depends on its proper control strategy. Therefore, although the strategies [2]–[6] for SMES control have been proposed in the literature, the real problem has been and still is the determination of the best or optimal switching strategies. So, continuous attempts to explore new and effective control options are ongoing.

Fuzzy logic is a powerful problem-solving methodology with a myriad of applications in embedded control and information processing. Fuzzy logic resembles human decision making with its ability to work from approximate data and find precise solutions. The control method of modeling human language has many advantages, such as simple calculation, high robustness, lack of a need to find the transfer function of the system, suitability for nonlinear systems, etc. Therefore, considering these views, this paper presents a fuzzy logic switching of the thyristor controlled SMES to improve the transient stability of an electric power system.

In order to see how effective the fuzzy controlled SMES unit in improving the transient stability is, its performance is compared to that of a conventional proportional-integral (PI) controlled SMES scheme. Again, in [2]–[6], the effectiveness of SMES for transient stability enhancement has been demonstrated only for a balanced fault in the power system. With a view to carrying out a detail study, in this work the effectiveness of SMES in enhancing the transient stability is demonstrated considering both balanced and unbalanced faults in the system.

Again, the braking resistor (BR) is known to be a very effective device for transient stability control. It can be viewed as a fast load injection to absorb excess transient energy of an area that arises due to severe system disturbances. In [7] and [8] the effectiveness of fuzzy logic-controlled BR in improving the transient stability of electric power systems has been demonstrated. While both SMES and BR are effective devices for transient stability control, this paper makes a comparative study between fuzzy logic-controlled SMES and fuzzy logic-controlled BR.

As a whole, the distinguishing features of this paper compared to [2]–[6] are as follows: 1) the use of fuzzy logic concept for SMES control; 2) the performance comparison between the fuzzy controlled SMES and the PI controlled SMES; 3) the effectiveness demonstration of SMES in case of both balanced and unbalanced faults; and 4) the performance comparison between the fuzzy controlled SMES and the fuzzy controlled BR.

II. Model System

For the simulation of transient stability, the model system [8], as shown in Fig. 1, has been used in this paper. The model

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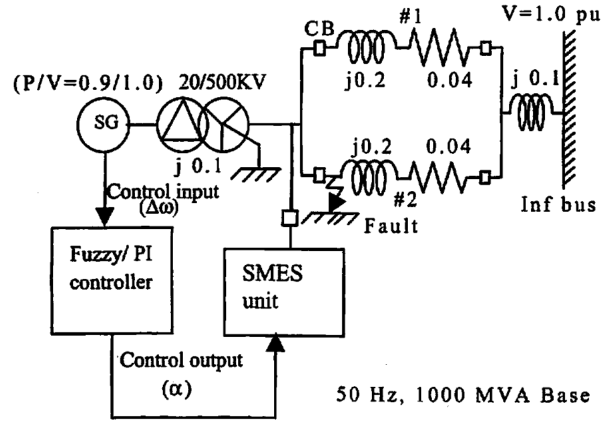


Fig. 1. Power system model.

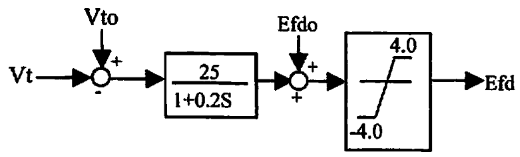


Fig. 2. AVR model.

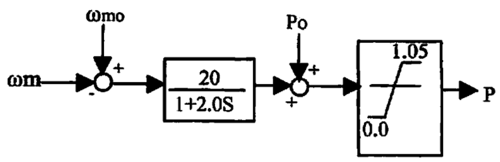


Fig. 3. GOV model.

TABLE I
GENERATOR PARAMETERS

MVA	1000
r_a [pu]	0.003
x_a [pu]	0.13
X_d [pu]	1.79
X_q [pu]	1.71
X'_d [pu]	0.169
X'_q [pu]	0.228
X''_d [pu]	0.135
X''_q [pu]	0.20
X_0 [pu]	0.13
T'do [sec]	4.30
T'qo [sec]	0.85
T''do [sec]	0.032
T''qo [sec]	0.05
H [sec]	2.894

system consists of a synchronous generator (SG) feeding an infinite bus through a transformer and double circuit transmission line. CB in the figure represents a circuit breaker. In order to effectively control the power balance of the synchronous generator during a dynamic period, the SMES unit is located at the generator terminal bus. The automatic voltage regulator (AVR) and governor (GOV) control system models, as shown in Figs. 2 and 3, respectively, have been included in the present simulation. Moreover, various parameters of the generator used for the simulation are shown in Table I.

III. MODELING OF SMES

Fig. 4 shows the proposed SMES unit which consists of a Wye-Delta 500 KayV/5 KayV transformer, an ac/dc thyristor controlled bridge converter, and a superconducting coil or inductor of 0.5 H. The converter impresses positive or negative voltage on the superconducting coil. Charge and discharge are easily controlled by simply changing the delay angle α that controls the sequential firing of the thyristors. If α is less than 90°, the converter operates in the rectifier mode (charging). If α is greater than 90°, the converter operates in the inverter mode (discharging). As a result, power can be absorbed from or released to the power system according to the requirement. At steady state, SMES should not consume any real or reactive power.

For initial charging of the SMES unit, the bridge voltage V_{sm} is held constant at a suitable positive value. 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 constant by lowering the voltage across the inductor to zero. The SMES unit is then ready to be coupled to the power system for stabilization. It is desirable to set the rated inductor current I_{sm0} such that the maximum allowable energy absorption equals the maximum allowable energy discharge.

The voltage V_{sm} of the dc side of the converter is expressed by

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

where V_{sm0} is the ideal no-load maximum dc voltage of the bridge. 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 P_{sm} absorbed or delivered by the SMES can be given by

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

since the bridge current I_{sm} is not reversible, the bridge output power P_{sm} is uniquely a function of α, which can be positive or negative depending on V_{sm}. If V_{sm} is positive, power is transferred from the power system to the SMES unit. While if V_{sm} is negative, power is released from the SMES unit. The energy stored in the superconducting inductor is

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

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

The assumptions given as follows are considered in modeling of the present SMES unit:

1) superconducting coil has a large inductance so that the effect of the ripple of the direct current is ignored;
2) resistance of the superconducting coil is zero;
3) voltage drop in the converter thyristor is ignored;
4) harmonic power generated by the converter is neglected.

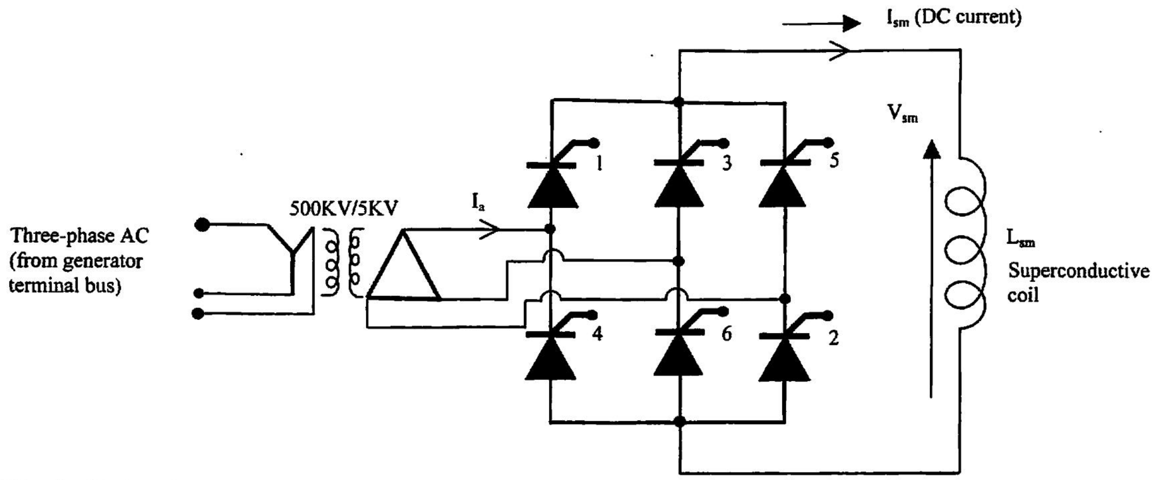


Fig. 4. SMES unit with six-pulse bridge ac/dc thyristor controlled converter.

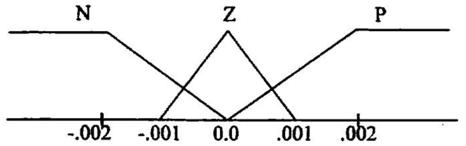


Fig. 5. Membership functions of $\Delta\omega$ (pu) for SMES.

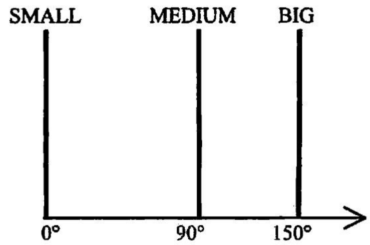


Fig. 6. Membership functions of α (degree) for SMES.

TABLE II
FUZZY RULE TABLE FOR SMES

Δω (pu)	α (degree)
N	BIG
Z	MEDIUM
P	SMALL

IV. Design of Fuzzy Logic and PI Controllers

The fuzzy logic, unlike the crispy logic in the Boolean theory that uses only two logic levels (0 to 1), is a branch of logic that admits infinite logic levels (from 0 to 1), to solve a problem that has uncertainties or imprecise situations. Again, a fuzzy control is a process control that is based on fuzzy logic and is normally characterized by "IF-THEN" rules. The design of the proposed fuzzy logic controller (FLC) is described in the following.

A. Fuzzification

The fuzzification procedure consists of finding appropriate membership functions to describe crisp data. For the design of the proposed FLC, deviation of speed of synchronous generator, $\Delta\omega$, and firing angle of thyristor, α, are selected as the input and output, respectively. Triangular membership functions for $\Delta\omega$ are shown in Fig. 5, in which the linguistic variables N, Z, and P stand for negative, zero, and positive, respectively. The membership functions have been determined by the trial and error approach in order to obtain the best system performance. The equation of the triangular membership function used to determine the grade of membership values is as follows [9]:

$$\mu_{Ai}(x) = \frac{1}{b}(b - 2|x - a|) \tag{5}$$

where $\mu_{Ai}(x)$ is the value of grade of membership, "b" is the width, "a" is the coordinate of the point at which the grade of membership is 1 and "x" is the value of the input variable.

B. Fuzzy Rule Base

The rule base is the heart of a fuzzy controller, since the control strategy used to control the closed-loop system is stored as a collection of control rules. The specific feature of the proposed fuzzy controller is its very simple design having only one input variable and one output variable. The use of the single-input, single-output (SISO) variable makes the fuzzy controller very straightforward [7], [8]. Fig. 6 shows the membership functions for the output variable α consisting of three singleton fuzzy sets SMALL, MEDIUM, and BIG. The control rules of the proposed controller are determined from the viewpoint of practical system operation and by trial and error and are shown in Table II.

C. Fuzzy Inference

The basic operation of the inference engine is that it infers, i.e., it deduces (from evidence or data) a logical conclusion. Actually, the inference engine is a program which uses the rule base and the input data of the controller to draw the conclusion. The conclusion of the inference engine is the fuzzy output of the controller, which subsequently becomes the input to the defuzzification interface. For the inference mechanism of the proposed FLC, Mamdani's method [10] has been utilized. A fuzzy rule typically has an IF-THEN format as follows:

$$\text{IF } (X_1 \text{ IS } A_i \text{ And } X_2 \text{ IS } B_i) \text{ THEN}$$
$$Z_1 = C_i, \qquad i = 1, 2, \ldots, r$$

where X_1 and X_2 are fuzzy input variables, Z_1 is the fuzzy output variable, i is the rule number, r is the total number of rules, A_i, B_i and C_i are fuzzy subsets in the universe of

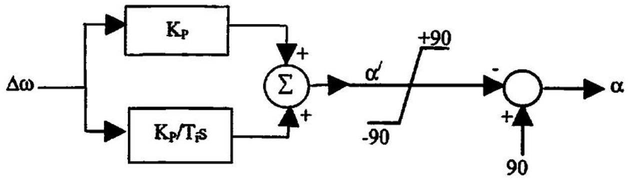


Fig. 7. Block diagram of PI controller.

TABLE III
PARAMETERS OF PI CONTROLLER

K_P	T_i
180.0	0.2

discourses X, Y, and Z, respectively. Therefore, according to Mamdani, the degree of conformity W_i, of each fuzzy rule is as follows:

$$W_i = \mu_{A_i}(X_1) \times \mu_{B_i}(X_2) \tag{6}$$

where $\mu_{A_i}(X_1)$ and $\mu_{B_i}(X_2)$ are the values of the grade of membership.

D. Defuzzification

In this last operation, the fuzzy conclusion of the inference engine is defuzzified, i.e., it is converted into a crisp signal. This last signal is the final product of the FLC which is, of course, the crisp control signal to the process. The center-of-area method is the most well-known and rather simple defuzzification method [9] which is implemented to determine the output crispy value. This is given by the following expression:

$$Z = \frac{\Sigma W_i C_i}{\Sigma W_i} \tag{7}$$

where Z is the crispy output function and C_i is already defined in the previous section.

In order to see how effective the fuzzy controlled SMES unit in improving the transient stability is, its performance is compared to that of a conventional PI controlled SMES scheme. Fig. 7 shows the block diagram of the PI-controller. The PI controller parameters, as shown in Table III, are determined by trial and error in order to obtain good system performance.

V. SIMULATION RESULTS AND DISCUSSIONS

The simulation is implemented by using the electro-magnetic transients program (EMTP) [11]. Simulations are performed considering both balanced (3LG: three-phase-to-ground) and unbalanced (1LG: single-line-to ground) faults near the generator at line #2 as shown in the system model. It is also considered that the fault occurs at 0.1 s, circuit breakers on the faulted line are opened at 0.2 s, and closed again at 1.2 s. Time step and simulation time have been chosen as 0.00005 and 5.0 s, respectively.

A. Transient Stability Enhancement by Fuzzy Controlled SMES

For the evaluation of transient stability, in this paper, we have used the stability index W_c [7], given by

$$W_c(\text{sec}) = \int_0^T \left|\frac{d}{dt}W\right| \frac{dt}{\text{system base power}} \tag{8}$$

TABLE IV
VALUES OF Wc

Fault type	With fuzzy controlled SMES	With PI controlled SMES	With fuzzy controlled BR	Without controller
3LG	0.4147	0.7037	0.4953	1.0639
1LG	0.2761	0.3055	0.2971	0.4453

where T is the simulation time selected to 5.0 s, W is the kinetic energy in joules that can be calculated easily by knowing the rotor speed of the generator and is given by:

$$W = \frac{1}{2} J\omega_m^2(J). \tag{9}$$

In (9), J denotes the moment of inertia in Kg·m^2 and ω_m rotor angular velocity in mechanical radians per second.

The smaller the value of W_c, the better the system's performance. Table IV shows the values of Wc for both 3LG and 1LG faults. It is shown that both fuzzy controlled SMES and PI controlled SMES are effective in enhancing the transient stability in case of both balanced and unbalanced faults. However, the performance of fuzzy controlled SMES is better than that of PI controlled SMES.

Fig. 8 shows the load angle responses for both 3LG fault and 1LG fault. It is clear from these responses that both fuzzy and PI controlled SMES effectively enhance the transient stability, however, the performance of fuzzy controlled SMES is better than that of PI controlled SMES.

B. Performance Comparison Between Fuzzy Controlled SMES and Fuzzy Controlled BR

It is already shown in Section V-A that the fuzzy controlled SMES is a very effective device for transient stability control. It is well known that the fuzzy controlled BR is also an effective device for transient stability control. While both SMES and BR are effective devices for transient stability control, this paper makes a comparative study between fuzzy controlled SMES and fuzzy controlled BR. The power system model, AVR model, GOV model, various parameters of the generator used for the BR method are the same as those used for the SMES method. In order to effectively control the power balance of the synchronous generator during the dynamic period, the BR unit is located at the generator terminal bus through the thyristor switching circuit as shown in Fig. 9. The conductance value of BR is considered to be 1.0 pu. For the design of the fuzzy logic controller for BR, deviation of speed of synchronous generator $\Delta\omega$ and conductance value of BR G_{SBR} are selected as the input and output, respectively. The firing-angle α, for the thyristor switching circuit is calculated from the output of the fuzzy controller, i.e., from the conductance value of BR. The modeling of BR is described in detail in [8]. The membership functions for $\Delta\omega$ and G_{SBR} are shown in Figs. 10 and 11, respectively. Again, the fuzzy rule table used for the BR in this work is shown in Table V.

Fig. 12 shows the load angle responses for both SMES and BR methods in case of both 3LG fault and 1LG fault. It is shown that the settling time of SMES is a bit worse than that of BR.

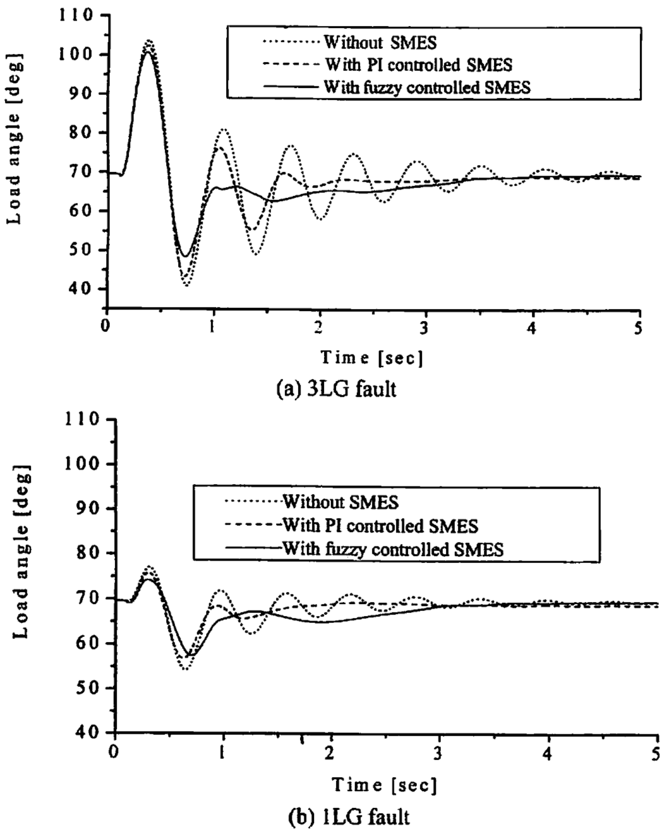


Fig. 8. Load angle responses.

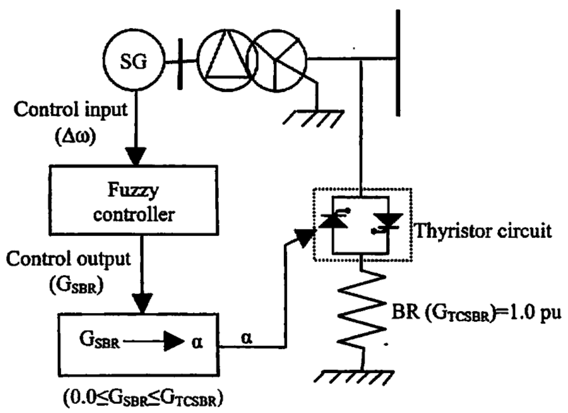


Fig. 9. BR with thyristor switching circuit.

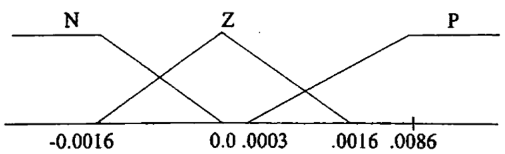


Fig. 10. Membership functions of $\Delta\omega$ (pu) for BR.

However, from the viewpoint of faster operation, the performance of SMES is better than that of BR.

Moreover, from Table IV it is easily shown that the values of W_c with fuzzy controlled SMES are smaller than those with fuzzy controlled BR in the case of both 3LG fault and 1LG fault. This fact indicates that the performance of SMES is better than that of BR.

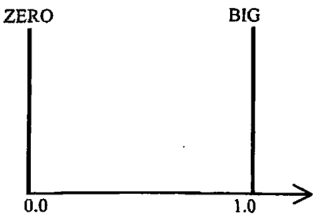


Fig. 11. Membership functions of G_{SBR} (pu) for BR.

TABLE V
FUZZY RULE TABLE FOR BR

Δω (pu)	G_{SBR} (pu)
N	ZERO
Z	ZERO
P	BIG

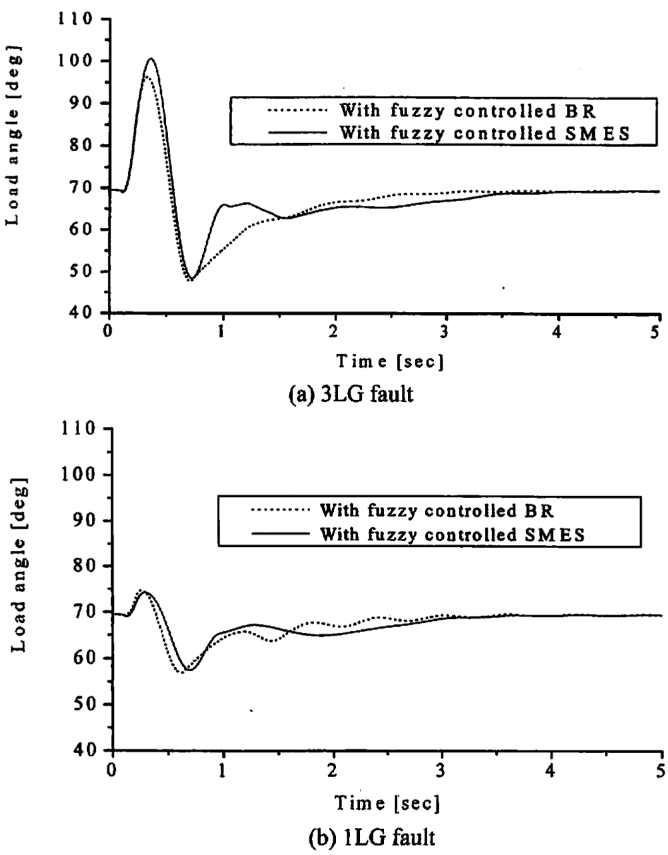
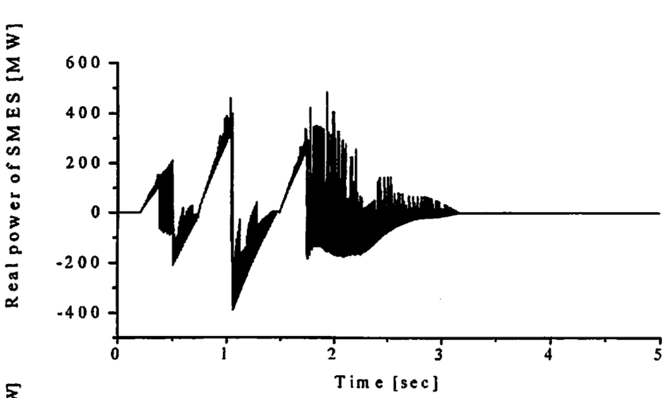
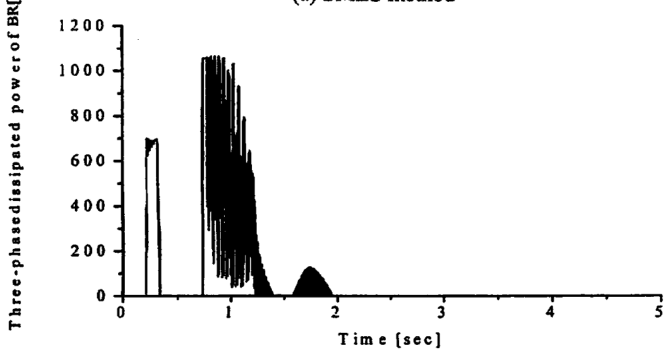


Fig. 12. Performance comparison between SMES and BR.

Figs. 13 and 14 show the responses for real power of SMES and three-phase dissipated power of BR in case of 3LG fault and 1LG fault, respectively. It is shown that the real power absorbed by BR is higher than that by SMES in order to have a good stabilizing effect in case of both balanced and unbalanced faults. This fact indicates that the performance of fuzzy controlled SMES is better than that of fuzzy controlled BR. The main reason of the better performance of SMES is its ability to control both acceleration and deceleration of the generator by consuming and supplying real power. On the other hand, BR is only able to consume the accelerative power and is not able to supply the power.

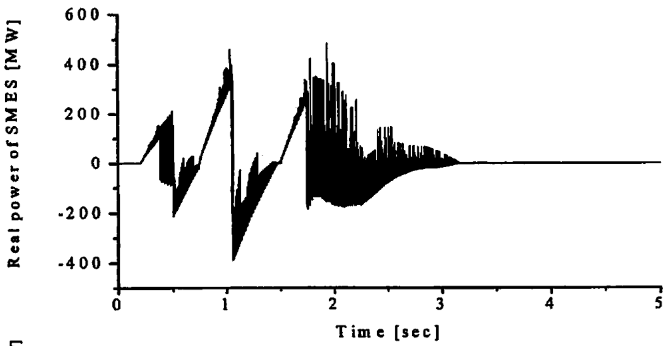


(a) SMES method

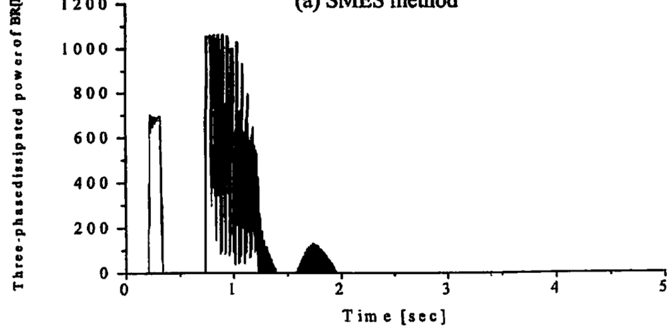


(b) BR method

Fig. 13. Real power responses of SMES and BR for 3LG fault.



(a) SMES method



(b) BR method

Fig. 14. Real power responses of SMES and BR for 1LG fault.

It is important to note here that although SMES is better than BR in damping, BR is more effective than SMES in reducing the first transient swing as can be shown from Fig. 12(a). Moreover, the major components of the BR system are a linear resistance and a thyristor switching unit. On the other hand, the major components of the SMES system are a transformer, a converter with thyristor switches (6 pulse/12 pulse bridge), a large superconducting coil cooled by liquid helium, and a refrigerator that maintains the temperature of the helium coolant. Therefore, the number of necessary components of the SMES system is bigger than that of the BR system. So, although the actual costs of SMES and BR are not investigated in this paper, it may be conjectured that the total installation and maintenance cost of SMES may be higher than that of BR.

However, although the cost of the SMES method may be higher than that of the BR method, BR is only able to consume the real power. Therefore, up to now, BR finds few applications, namely, transient stability enhancement of electric power systems, damping shaft torsional oscillations of synchronous generators, and dynamic braking control of induction motors. On the other hand, SMES is able to both consume and supply real power as well as reactive power. Therefore, up to now, it finds a variety of applications, such as increased transmission capacity through enhanced line stability, spinning reserve, energy storage (including load leveling and renewable sources), automatic generation control, voltage control, frequency control, uninterruptible power supply, tie line control, sub-synchronous resonance damping, black start, etc. [12]. As a whole, the salient properties such as real power as well as reactive power absorption from, and injection into the power system, faster operation, etc., prove the superiority as well as excellency of the SMES method over the BR method. Thus, it can be concluded that the proposed fuzzy controlled SMES strategy provides a very simple and effective means of transient stability enhancement of an electric power system.

VI. Conclusion

A fuzzy logic switching of the thyristor controlled SMES to improve the transient stability of the electric power system is proposed in this paper. Simulation results of both balanced 3LG and unbalanced 1LG faults clearly indicate the effectiveness and validity of the proposed method in improving the transient stability. Moreover, the performance of fuzzy controlled SMES is found to be better than that of PI controlled SMES. Again, it is found that the performance of SMES is better than that of BR from the viewpoint of a faster operation. However, in reducing the first transient swing, BR is more effective than SMES. The total installation and maintenance cost of SMES may be higher than that of BR. Finally, it can be concluded that the proposed fuzzy logic-controlled SMES strategy is superior to the fuzzy logic-controlled BR strategy, and provides a very simple and effective means of transient stability enhancement of an electric power system.

Future research will focus on the use of insulated gate bipolar transistor (IGBT)-based converter bridge under a pulse width modulation (PWM) scheme instead of a thyristor-based converter bridge for SMES control. Moreover, in our future study, in addition to Mamdani-type fuzzy system used in this work, the Takagi-Sugeno (TS) fuzzy control method will be tested.

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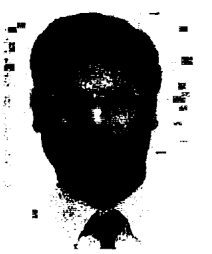

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