

# Minimization of shaft oscillations by fuzzy controlled SMES considering time delay

Mohd Hasan Ali<sup>a,\*</sup>, Bin Wu<sup>b</sup>, Junji Tamura<sup>c</sup>, Roger A. Dougal<sup>a</sup>

<sup>a</sup> Department of Electrical Engineering, University of South Carolina, 301 South Main Street, Columbia, SC 29208, USA

<sup>b</sup> Department of Electrical and Computer Engineering, Ryerson University, George Vari Engineering & Computing Center, 245 Church Street, Toronto, Ontario M5B 1Z2, Canada

<sup>c</sup> Department of Electrical and Electronic Engineering, Kitami Institute of Technology, 165 Koen cho, Kitami, Hokkaido 090-8507, Japan

## ARTICLE INFO

### Article history:

Received 24 June 2009

Received in revised form 3 December 2009

Accepted 4 December 2009

Available online 23 December 2009

### Keywords:

Fuzzy controller

Global positioning system (GPS)

Minimizing shaft torsional oscillations

Superconductive magnetic energy storage (SMES)

Time delay

Total kinetic energy deviation (TKED)

## ABSTRACT

This paper analyzes the effect of fuzzy logic-controlled superconductive magnetic energy storage (SMES) on minimizing shaft torsional oscillations of synchronous generators in a multi-machine power system. The proposed fuzzy logic controller has been designed in a very simple way considering only one input variable and one output variable. The time derivative of the total kinetic energy deviation (TKED) of the synchronous generators is used as the global input to the fuzzy controller for SMES switching. The influence of time delay associated with the global input calculation of the fuzzy controller on minimizing shaft torsional oscillations is investigated. Global positioning system (GPS) is proposed for the practical implementation of the calculation of the global input to the fuzzy controller. Simulation results of a balanced fault at different points in a multi-machine power system show that the proposed SMES can minimize the shaft torsional oscillations of synchronous generators well. Moreover, the time delay has an influence on the performance of fuzzy controlled SMES to minimize shaft torsional oscillations. However, even though the performance of fuzzy controlled SMES is somewhat effected by the communication delay, it is clear from the simulation responses that the fuzzy logic-controlled SMES considering typical communication delays can minimize the shaft torsional oscillations of synchronous generators well.

Published by Elsevier B.V.

## 1. Introduction

Usually in the analysis of power system dynamic performance, the rotor of a turbine-generator is assumed to be made of a single mass. However, in reality, a turbine-generator rotor has a very complex mechanical structure consisting of several predominant masses (such as rotors of turbine sections, generator rotor, couplings, and exciter rotor) connected by shafts of finite stiffness. Therefore, when the generator is perturbed, torsional oscillations result between different sections of the turbine-generator rotor. The torsional oscillations in the subsynchronous range could, under certain conditions, interact with the electrical system in an adverse manner [1]. Conversely, certain electrical system disturbances can impose torque oscillations on the shaft and reduce the life expectancy of turbine shafts. Therefore, sufficient damping is needed to reduce turbine shaft torsional oscillations.

Intensive progress in power electronics and superconductivity has provided the power transmission and distribution industry with superconducting magnetic energy storage (SMES) units. SMES is a large superconducting coil capable of storing electric energy in

the magnetic field generated by DC current flowing through it. The real power as well as the reactive power can be absorbed (charging) by or released (discharging) from the SMES coil according to system power requirements. Since the successful commissioning test of the BPA 30 MJ unit [2], SMES systems have received much attention in power system applications, such as, diurnal load demand leveling, frequency control, automatic generation control, uninterruptible power supplies. SMES can also be used to damp torsional oscillations of synchronous generator shafts [3–8]. However, in all of the results [3–8], the analysis of damping shaft torsional oscillations by SMES was carried out in the case of a single machine power system only.

This paper analyzes the effect of the SMES on minimizing shaft torsional oscillations of synchronous generators in a large multi-machine power system. The control scheme of SMES is based on fuzzy logic. It is important to note here that the fuzzy logic system [9,10] for the SMES control is used only based on the fact that it can be designed more easily in comparison to other alternative systems. The time derivative of the total kinetic energy deviation (TKED) of the synchronous generators is used as the input to the fuzzy controller for SMES switching in this work. In real systems, a time delay is introduced in online calculation of the total kinetic energy as well as the time derivative of TKED, which may fatally affect the control system, and consequently the torsional oscillations of

\* Corresponding author. Tel.: +1 803 777 8475; fax: +1 803 777 8045.

E-mail address: [hasan@cec.sc.edu](mailto:hasan@cec.sc.edu) (M.H. Ali).

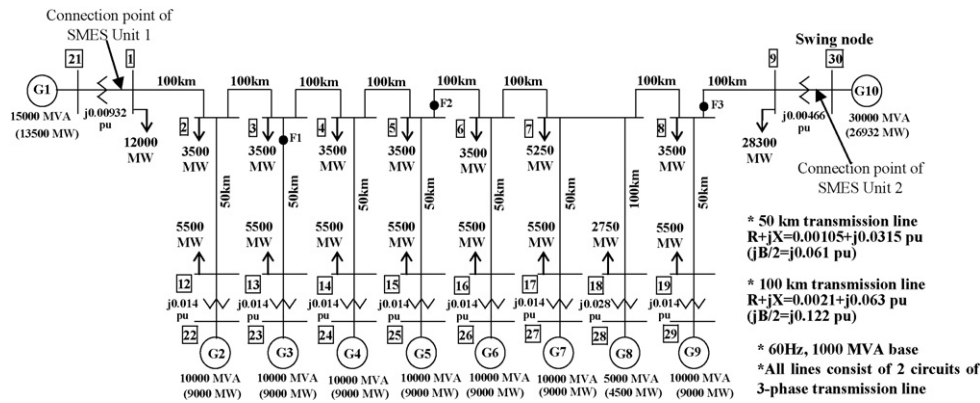


Fig. 1. IEEJ West 10-machine model system.

**Table 1**  
Generator parameters.

$X_d$ [pu]	1.70	$T''_d$ [s]	0.03
$X_q$ [pu]	1.70	$T'_q$ [s]	0.03
$X'_d$ [pu]	0.35	$T_a$ [s]	0.40
$X''_d$ [pu]	0.25	$X_i$ [pu]	0.225
$X'_q$ [pu]	0.25	$H$ [s]	7.00
$T'_d$ [s]	1.00		

generator shafts. So, the time delay phenomenon associated with the online calculation of the total kinetic energy as well as the time derivative of TKED should be considered for the actual analysis of shaft oscillations minimization. In [3–8] such time delays are not considered.

The most important and the novel feature of this work is that it analyzes the effect of time delays introduced in online calculation of the global input variable of the fuzzy controller for SMES switching on the shaft torsional oscillations minimization of synchronous generators in a multi-machine power system. Global positioning system (GPS) [11–16] is proposed for the practical implementation of the calculation of the input of the SMES controller and the total kinetic energy of the generators.

The organization of this paper is as follows: Section 2 describes the model system for the proposed study. Section 3 describes the control scheme of SMES. Section 4 explains the online calculation method of the total kinetic energy as well as the time derivative of TKED using GPS. Section 5 describes the simulation results. Finally, Section 6 provides some conclusions regarding this work.

## 2. Model system

For the simulation analysis of reducing shaft torsional oscillations, the IEEJ West 10-machine model system [17] as shown in Fig. 1 has been used. The “West 10-machine system” model as shown in Fig. 1 is a 10-machine tandem model that is a prototype of the Japanese 60 Hz systems. It presents the long time oscillation characteristics of a tandem system. The model system has 10 generators, G1–G10. Generator G10 is considered as the swing generator in the system. In the figure, the double circuit transmission line parameters are numerically shown in the forms  $R + jX (jB/2)$ , where  $R$ ,  $X$  and  $B$  represent resistance, reactance and susceptance, respectively, per phase with two lines. All lines represent two circuits of three-phase transmission line. The system base is 60 Hz, 1000 MVA. The automatic voltage regulator (AVR) and governor (GOV) control system models for the IEEJ West 10-machine model system [17] have been included in this work. Table 1 shows the various parameters of the generators [17] used for the simulation. The generator parameters in Table 1 are based on the machine ratings.

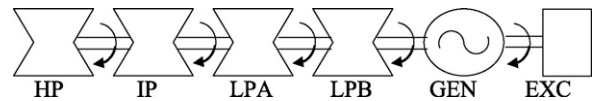


Fig. 2. Turbine-generator shaft model.

It is considered that each turbine-generator shaft model has 6 (six) masses, namely high-pressure (HP) turbine, an intermediate-pressure (IP) turbine, two low-pressure turbines (LPA, LPB), the generator (GEN) and exciter (EXC) as shown in Fig. 2. Rotor spring mass constants as shown in Table 2 are described in [18].

## 3. Control scheme of SMES

### 3.1. Brief overview of SMES system

An SMES device is a DC current device that stores energy in the magnetic field. The DC current flowing through a superconducting wire in a large magnet creates the magnetic field. During SMES operation, the magnet coils have to remain in the superconducting status. A refrigerator in the cryogenic system maintains the required temperature for proper superconducting operation.

In order to effectively control the power balance of the synchronous generators during dynamic period, two SMES units, namely SMES Unit1 and SMES Unit2 are used at the terminal buses of generators G1 and G10, respectively, in the power system model of Fig. 1. Fig. 3 shows the basic configuration of one of the proposed SMES units, which consists of a Wye-Delta 500 kV/5 kV transformer, an AC/DC thyristor controlled bridge converter, and a superconducting coil or inductor. The ratings of the proposed SMES units are shown in Table 3.

**Table 2**  
Rotor spring mass parameters.

Mass	Shaft	Inertia, $H$ (s)	Spring constant	
			$K$ (pu)	pu torque/rad
HP	HP–IP	0.225	7277	19.303
IP	IP–LPA	0.376	13,168	34.929
LPA	LPA–LPB	2.077	19,618	52.038
LPB	LPB–GEN	2.139	26,713	70.858
GEN	GEN–EXC	2.101	1064	2.822
EXC		0.082		

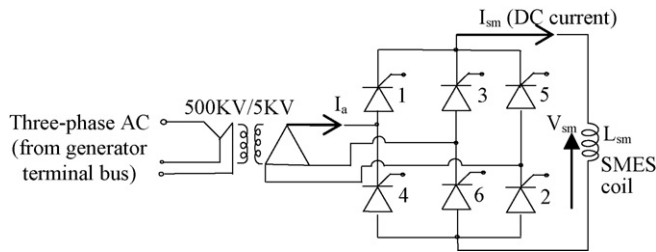


Fig. 3. SMES unit with 6-pulse bridge AC/DC thyristor controlled converter.

The converter impresses positive or negative voltage on the superconducting coil. Charge and discharge are easily controlled by simply changing the delay angle  $\alpha$  that controls the sequential firing of the thyristors. If  $\alpha$  is less than  $90^\circ$ , the converter operates in the rectifier mode (charging). If  $\alpha$  is greater than  $90^\circ$ , the converter operates in the inverter mode (discharging). As a result, power can be absorbed from or released to the power system according to requirement. At the steady state, SMES should not consume any real or reactive power.

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

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

where  $V_{sm0}$  is the ideal no-load maximum DC voltage of the bridge. The current and voltage of superconducting inductor are related as

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

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

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

Since the bridge current  $I_{sm}$  is not reversible, the bridge output power  $P_{sm}$  is uniquely a function of  $\alpha$ , 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

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

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

### 3.2. Design of fuzzy logic controller

The design of the proposed fuzzy logic controller is described in the following section.

#### 3.2.1. Fuzzification

For the design of the proposed fuzzy logic controller, time derivative of TKED of the generators,  $TKED'$ , and firing angle,  $\alpha$ , are selected as the input and output, respectively. In this work, the difference between the total kinetic energy ( $W_{total}$ ) of the generators at transient state and that at steady state is defined as total kinetic energy deviation, TKED, i.e.  $TKED = (W_{total} \text{ at transient state}) - (W_{total} \text{ at steady state})$ . The triangular membership functions for  $TKED'$  are shown in Fig. 4 in which the linguistic variables N, Z, and P stand for negative, zero, and positive, respectively. It is important to note that the membership functions are the same for each fuzzy controller. The equation of the triangular membership function used to determine the grade of membership values is as follows [9]:

$$\mu_A(TKED') = \frac{1}{b} (b - 2|TKED' - a|) \quad (5)$$

where  $\mu_A(TKED')$  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 'TKED'' is the value of the input variable.

#### 3.2.2. Fuzzy rule table

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 single input and single output variable makes the fuzzy controller very straightforward [17]. The proposed control strategy has only three control rules for each controller as shown in Table 4, where the values of  $\alpha$  in terms of linguistic variables represent the output of the fuzzy controller.

#### 3.2.3. Fuzzy inference

For the inference mechanism of the fuzzy controller design, Mamdani's method [9] is used. According to Mamdani, the degree of conformity,  $W_i$ , of each fuzzy rule is as follows:

$$W_i = \mu_A(TKED') \quad (6)$$

where  $\mu_A(TKED')$  is the value of grade of membership and  $i$  is rule number.

#### 3.2.4. Defuzzification

The center-of-area method is the most well-known and rather simple defuzzification method [9] which is implemented to determine the output crisp value (i.e. the firing angle,  $\alpha$ ). This is given by the following expression:

$$\alpha = \frac{\sum W_i C_i}{\sum W_i} \quad (7)$$

where  $C_i$  is the value of  $\alpha$  in the fuzzy rule table.

One important point to note here is that usually two input variables (error and its time derivative) are used for fuzzy logic controller design. In this work, at first two input variables (TKED and its time derivative) were used. However, the performance of using two input variables were almost the same as that of using single input variable. Moreover, the use of two input variables increases the number of fuzzy rules and membership functions. Therefore, in

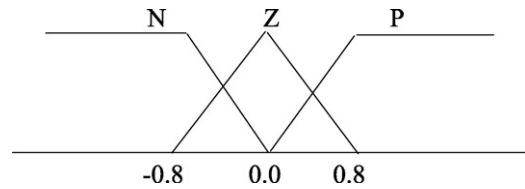


Fig. 4. Membership functions of  $TKED'$  (pu/s).

Table 3  
Ratings of SMES.

	SMES Unit1	SMES Unit2
Power	500 MW	400 MW
Energy	0.05 MWh	0.04 MWh
Coil inductance	0.4 H	0.2 H

Table 4  
Fuzzy rule table.

TKED' (pu/s)	$\alpha$ (firing angle)
N	Big
Z	Medium
P	Small

order to make the controller simple, only one input, i.e. the time derivative of TKED is used in this work.

#### 4. Online calculation of the time derivative of TKED using GPS

As already explained, in this work the time derivative of TKED is used as the fuzzy controller input for SMES switching. TKED is defined in Section 3.2. In order to calculate TKED,  $W_{total}$  is needed, which can be determined easily by knowing the rotor speed of each generator and is given by:

$$W_{total} = \sum_{i=1}^N W_i(j) \quad (8)$$

$$\text{where } W_i = \frac{1}{2} J_i \omega_{mi}^2 (J) \quad (9)$$

denotes kinetic energy in joule for a generator,  $W_{total}$  is the total kinetic energy in joule,  $i$  is the generator number and  $N$  is the total number of generators. Again, in (9)  $J_i = (H \times \text{MVA rating}) / \{5.48 \times 10^{-9} \times (N_s)^2\}$  denotes moment of inertia in  $\text{kg m}^2$ , where  $N_s$  and  $H$  are synchronous angular speed in rpm and inertia constant, respectively, and  $\omega_{mi} = 2 \times \pi \times (N/60)$  rotor angular velocity in mechanical rad/s, where  $N$  is rotor speed in rpm.

##### 4.1. GPS method for the online calculation of the time derivative of TKED

The online calculation of the time derivative of TKED using the speed signal of each generator, and then again using the signal of the time derivative of TKED as the input to each fuzzy controller can be accomplished by using GPS [11–16] which provides time synchronization of signals. GPS is a US Department of Defense radio-navigation system consisting of 24 satellites placed into orbit and arrayed to provide at least 4 satellites visibility at all times. Each satellite transmits a navigation signal from which a receiver can decode time synchronized to within  $0.2 \mu\text{s}$  of Coordinated Universal Time (UTC), the world Standard. The inherent availability, redundancy, reliability, and accuracy make it a system well suited for synchronized phasor measurement systems [11]. It has recently been recognized that synchronized measurement of power system quantities is feasible using the GPS, since GPS can easily and precisely provide a time signal, with a  $1 \mu\text{s}$  accuracy, at any location on the power network [12].

Fig. 5 shows a closed loop control system including the GPS function. It is noteworthy that the delay includes both the upstream and downstream link. As shown in Fig. 5, the speed equivalent signal of each generator is passed through a filter and an A/D converter. Then the digitalized speed equivalent signals of the generators are sent to a central control office where a GPS receiver synchronizes the signals in a common timing reference. By using the synchronized signals,  $W_{total}$  as well as the time derivative of TKED is calculated. Data output, i.e. the signal of time derivative of TKED is then sent to each fuzzy controller input. In this case, signals may be transmitted and received through microwave or optical fibre.

##### 4.2. Time delays

During online calculation of the time derivative of TKED, time delays are introduced mainly due to signal transmission through optical fibre or microwave, A/D conversion, calculation of  $W_{total}$  as well as time derivative of TKED, and time synchronization of signals by GPS. The time delays may affect the control logic, and consequently the minimization of the shaft torsional oscillations may be affected. So, such time delays should be considered

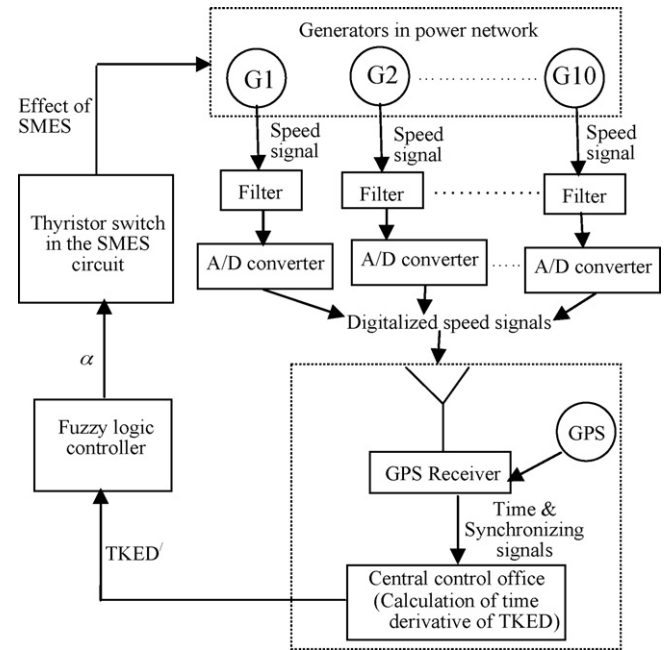


Fig. 5. Closed loop control system including GPS function.

for the actual analysis of shaft torsional oscillations minimization.

Usually, time delays may range from several microseconds to few hundred milliseconds [13–15,19–25]. In this work, extensive simulations are carried out considering various typical values of time delays. Some of the simulation cases corresponding to a typical time delay value of 200 ms are described in Section 5.2.

##### 4.3. Implementation of time delay in the control system

In this work, simulations are carried out by using Electro-Magnetic Transients Program (EMTP), a special transient simulation program which can predict variables of interest in electric power networks as functions of time, typically following some disturbances such as the switching of a circuit breaker, or a fault [26]. During the simulations, various values of time delays are applied to the fuzzy controller input signal through the EMTP TACS (Transient Analysis of Control Systems) code no. 53, i.e. the transport delay code of EMTP. This can be represented by the block diagram shown in Fig. 6. According to the EMTP transport delay code 53, at any time “ $t$ ”, for a value of total delay =  $t_d$  s,  $\text{OUTPUT}(t) = \text{INPUT}(t - t_d)$  [26].

#### 5. Simulation results and discussions

In order to show the effectiveness of the proposed method, simulations have been carried out considering a balanced (3LG: three-phase-to-ground) fault at points F1, F2, and F3 on the transmission lines as shown in Fig. 1. In all of the cases, the fault occurs at 0.1 s, the circuit breakers on the faulted lines are opened at 0.17 s and closed again at 1.003 s. It is assumed that the circuit breaker clears the line when the current through it crosses the zero level. The time step and the simulation time have been chosen as  $50 \mu\text{s}$  and 20.0 s, respectively.

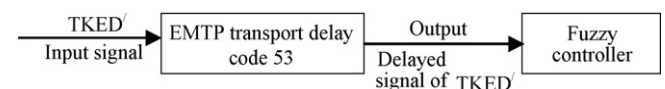


Fig. 6. Application of time delays to fuzzy controller.



**Table 5**

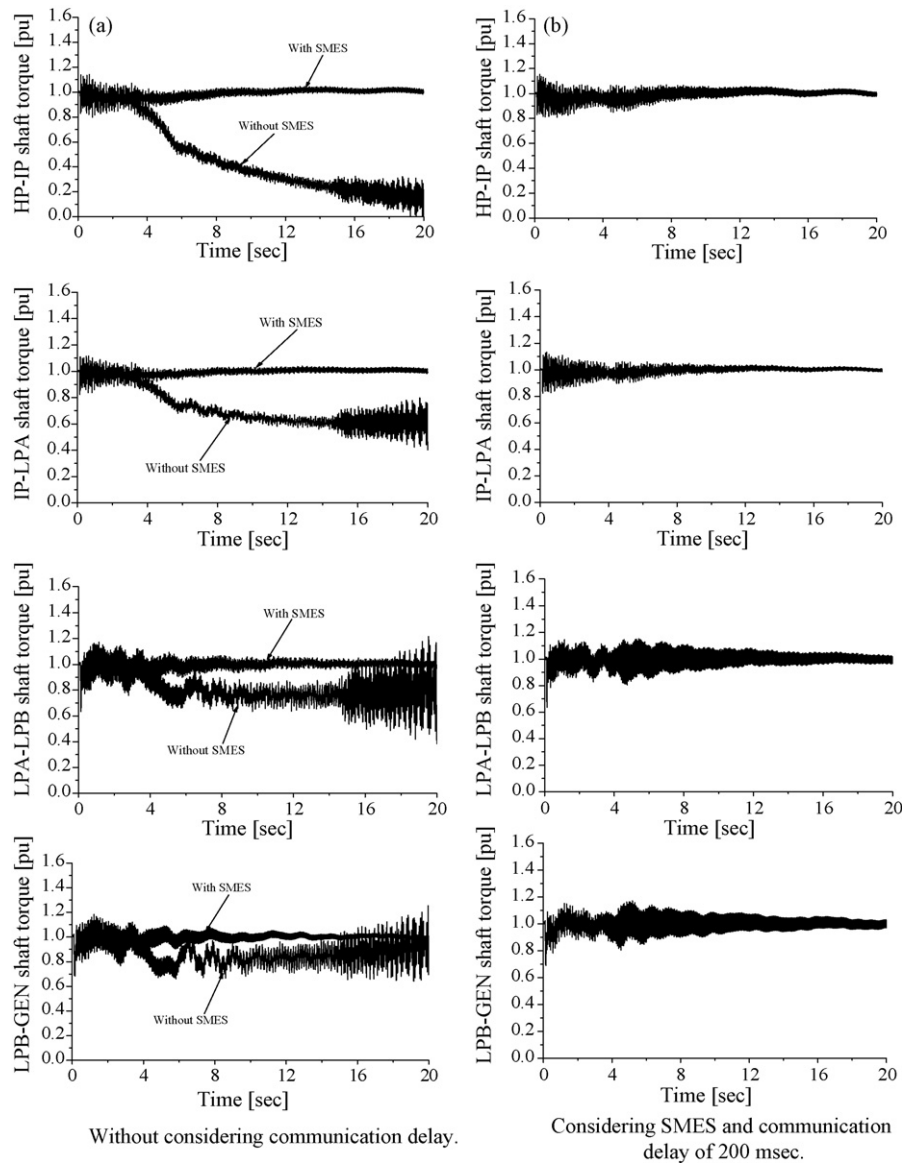
Values of TOR of generator G1 without considering time delay.

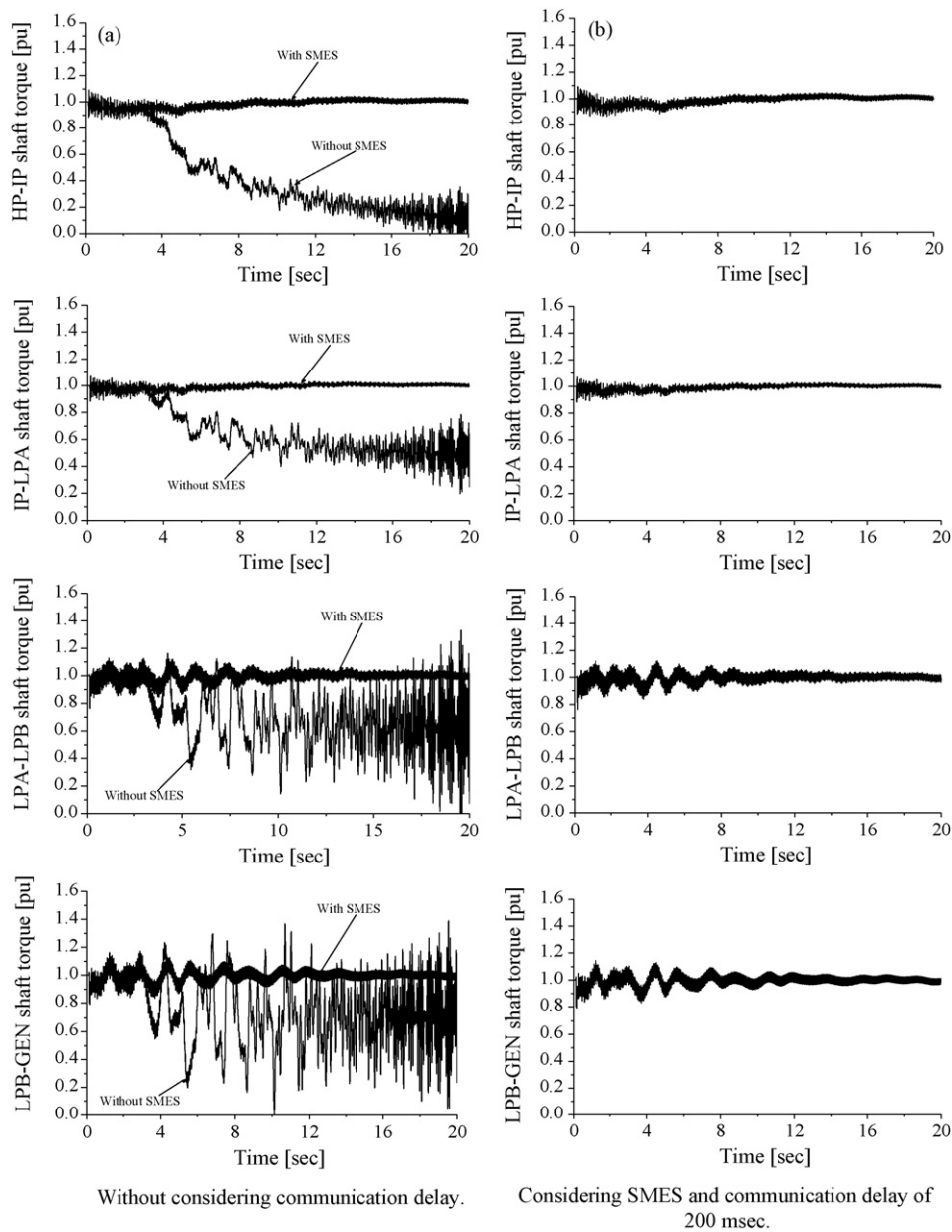
Fault point	TOR (pu s) with SMES				TOR (pu s) without SMES			
	HP-IP shaft	IP-LPA shaft	LPA-LPB shaft	LPG-GEN shaft	HP-IP shaft	IP-LPA shaft	LPA-LPB shaft	LPG-GEN shaft
F1	0.54	0.38	0.56	0.54	10.69	5.66	3.88	2.87
F2	0.67	0.37	0.35	0.36	7.13	3.89	2.87	2.32
F3	0.54	0.30	0.36	0.38	9.26	4.93	3.40	2.53

**Table 6**

Values of TOR of generator G5 without considering time delay.

Fault point	TOR (pu s) with SMES				TOR (pu s) without SMES			
	HP-IP shaft	IP-LPA shaft	LPA-LPB shaft	LPG-GEN shaft	HP-IP shaft	IP-LPA shaft	LPA-LPB shaft	LPG-GEN shaft
F1	0.50	0.32	0.57	0.63	11.40	6.93	5.93	5.63
F2	1.49	1.11	1.94	2.06	9.21	5.42	5.00	5.35
F3	0.52	0.30	0.28	0.28	10.08	6.26	5.64	5.39

**Fig. 7.** Shaft torsional torque responses of generator G1 for 3LG fault at point F1. (a) Without considering communication delay. (b) Considering SMES and communication delay of 200 ms.



**Fig. 8.** Shaft torsional torque responses of generator G5 for 3LG fault at point F1. (a) Without considering communication delay. (b) Considering SMES and communication delay of 200 ms.

### 5.1. Effect of SMES on minimizing shaft torsional oscillations (without considering time delay)

For the evaluation of the performance of minimizing shaft torsional oscillations by SMES, we have considered the index,  $TOR$  (pu s), given by the following expression:

$$TOR \text{ (pu s)} = \int_0^T |\Delta Torque| dt \quad (10)$$

where  $\Delta Torque$  denotes the deviation of torque in different shaft sections (HP–IP, IP–LPA, LPA–LPB, LPB–GEN, etc., as shown in Fig. 2), and  $T$  is the simulation time selected to 20.0 s. The lower the value of  $TOR$ , the better the system's performance.

Tables 5 and 6 show the values of  $TOR$  for different shaft sections of generators G1 and G5, respectively, with and without SMES in case of a 3LG fault at points F1, F2 and F3. From the responses of Tables 5 and 6, it is clear that the fuzzy controlled SMES can min-

imize the shaft torsional oscillations of synchronous generators in a multi-machine power system.

Figs. 7(a) and 8(a) show the effects of the fuzzy controlled SMES on minimizing shaft torsional oscillations of generators G1 and G5, respectively, in case of a 3LG fault at point F1 without considering a communication delay. From the responses of Figs. 7(a) and 8(a) it is clear that the fuzzy controlled SMES can minimize the shaft torsional oscillations well.

### 5.2. Effect of time delay on minimizing shaft torsional oscillations

In this work, extensive simulations are carried out considering various typical values of time delays. Tables 7 and 8 show the values of  $TOR$  for different shaft sections of generators G1 and G5, respectively, with SMES considering a typical time delay value of 200 ms. From the responses of Tables 7 and 8, it is seen that the fuzzy controlled SMES can minimize the shaft torsional oscillations. However, the oscillations minimizing performance by SMES considering

**Table 7**

Values of TOR of generator G1 considering a time delay of 200 ms.

Fault point	TOR (pu s) with SMES			
	HP–IP shaft	IP–LPA shaft	LPA–LPB shaft	LPG–GEN shaft
F1	0.61	0.41	0.79	0.83
F2	0.74	0.39	0.38	0.38
F3	0.70	0.40	0.55	0.56

**Table 8**

Values of TOR of generator G5 considering a time delay of 200 ms.

Fault point	TOR (pu s) with SMES			
	HP–IP shaft	IP–LPA shaft	LPA–LPB shaft	LPG–GEN shaft
F1	0.57	0.39	0.65	0.71
F2	1.57	1.20	2.05	2.14
F3	0.66	0.38	0.42	0.50

a time delay as demonstrated in Tables 7 and 8 is worse than that without considering a time delay as demonstrated in Tables 5 and 6. This fact indicates that the time delay has an effect on minimizing shaft torsional oscillations by SMES.

Figs. 7(b) and 8(b) show the responses of shaft torsional oscillations of generators G1 and G5, respectively, in case of a 3LG fault at point F1 considering the fuzzy controlled SMES and a communication delay of 200 ms. In comparison with the shaft torsional torque responses with SMES as shown in Figs. 7(a) and 8(a), the responses as shown in Figs. 7(b) and 8(b) are somewhat worse owing to the effect of communication delay.

In general, the delay in action with any control system would degrade the performance of the system. Therefore, the control objective should be to check whether a designed control system including standard delays is effective for a system, and also to know what the maximum acceptable delay is for the system. For the present system, the maximum acceptable delay is 300 ms. But this delay value is much bigger than the typical delay values of 150–200 ms which are actually encountered in practice [24,25]. Moreover, even though the performance of fuzzy controlled SMES is somewhat effected by the communication delay, it is clear from the responses of Figs. 7(b) and 8(b) that the fuzzy logic-controlled SMES considering typical communication delay can minimize the shaft torsional oscillations well.

As a whole, the proposed fuzzy logic-controlled SMES can be considered a very effective means of minimization of shaft torsional oscillations of synchronous generators in a multi-machine power system.

### 5.3. Cost-effectiveness of SMES

Although the SMES is an expensive device, due to its salient properties such as very fast response, high efficiency, capability of control of real power and reactive power, etc., SMES system is getting increasing interest in the field of power systems [27–36]. It is hoped that its potential advantages and environmental benefits will make SMES units a viable alternative for energy storage and management devices in the future [37,38]. And although at present the cost of a SMES unit appears somewhat high, continued research and development is likely to bring the price down and make the technology appear even more attractive.

## 6. Conclusion

This paper analyzes the influence of time delays associated with the online calculation of the global input of the fuzzy logic controller for SMES switching on minimizing shaft torsional oscillations of synchronous generators in a multi-machine power system. From

the simulation results of a balanced fault at different points in the system, the following conclusions can be drawn.

- The fuzzy logic-controlled SMES is effective in minimizing shaft torsional oscillations of synchronous generators in a multi-machine power system.
- The time delay associated with the online calculation of the global input of the fuzzy logic controller for SMES switching has an influence on minimizing shaft torsional oscillations of synchronous generators.
- Even though the performance of fuzzy controlled SMES is somewhat effected by the communication delay, it is clear from the simulation responses that the fuzzy logic-controlled SMES considering typical communication delays can minimize the shaft torsional oscillations well.

As a whole, it can be concluded that the proposed fuzzy logic-controlled SMES is a very effective means of minimization of shaft torsional oscillations of synchronous generators in a multi-machine power system.

## References

- [1] P. Kundur, Power System Stability and Control, McGraw-Hill, Inc., 1994.
- [2] H.J. Boenig, J.F. Hauer, Commissioning tests of the Bonneville power administration 30 MJ superconducting magnetic energy storage unit, IEEE Transactions on Power Apparatus and Systems 104 (2) (1985) 302–309.
- [3] L. Wang, S.M. Lee, C.L. Huang, Damping subsynchronous resonance using superconducting magnetic energy storage unit, IEEE Transactions on Energy Conversion 9 (4) (1994) 770–777.
- [4] Y.-S. Lee, C.-J. Wu, Application of superconducting magnetic energy storage unit on damping of turbogenerator subsynchronous oscillation, IEE Proceedings-C Generation Transmission and Distribution 138 (5) (1991) 419–426.
- [5] C.-J. Wu, C.-F. Lu, Damping torsional oscillations by a superconducting magnetic energy storage unit, Electric Machines and Power Systems 22 (1) (1994) 1–15.
- [6] C.-J. Wu, Y.-S. Lee, Application of simultaneous active and reactive power modulation of superconducting magnetic energy storage unit to damp turbine-generator subsynchronous oscillations, IEEE Transaction on Energy Conversion 8 (1) (1993) 63–70.
- [7] A.H.M.A. Rahim, A.M. Mohammad, M.R. Khan, Control of subsynchronous resonant modes in a series compensated system through superconducting magnetic energy storage units, IEEE Transaction on Energy Conversion 11 (1) (1996) 175–180.
- [8] M.H. Ali, T. Murata, J. Tamura, A fuzzy logic-controlled SMES for damping shaft torsional oscillations of synchronous generator, IEEE Transaction on Electrical and Electronic Engineering 1 (2006) 116–120.
- [9] D. Driankov, H. Hellendoorn, M. Reinfrank, An Introduction to Fuzzy Control, Springer-Verlag, Berlin-Heidelberg, NY, 1993.
- [10] H. Ying, Fuzzy Control and Modeling, Analytical Foundations and Applications, IEEE Press, New York, 2000.
- [11] Working Group H-8 of the Relay Communications Subcommittee of the IEEE Power System Relaying Committee: 'IEEE standard for synchrophasors for power systems', IEEE Transactions on Power Delivery, 13 (1) (1998) 73–77.
- [12] H.Y. Li, E.P. Southern, P.A. Crossley, S. Potts, S.D.A. Pickering, B.R.J. Caunce, G.C. Weller, A new type of differential feeder protection relay using the global positioning system for data synchronization, IEEE Transaction on Power Delivery 12 (3) (1997) 73–77.
- [13] R.E. Wilson, Methods and uses of precise time in power systems, IEEE Transaction on Power Delivery 7 (1) (1992) 126–131.
- [14] R.E. Wilson, An investigation of time transfer accuracies over a utility microwave communications channel, IEEE Transaction on Power Delivery 8 (3) (1993) 993–999.
- [15] Working Group H-7 of the Relaying Channels Subcommittee of the IEEE Power System Relaying Committee: 'Synchronized sampling and phasor measurements for relaying and control', IEEE Transactions on Power Delivery, 9 (1) (1994) 442–452.
- [16] R.O. Burnett Jr., M.M. Butts, T.W. Cease, V. Centeno, G. Michel, R.J. Murphy, A.G. Phadke, Synchronized phasor measurements of a power system event, IEEE Transaction on Power Systems 9 (3) (1994) 1643–1650.
- [17] M.H. Ali, T. Murata, J. Tamura, The effect of temperature rise of the fuzzy logic-controlled braking resistors on transient stability, IEEE Transaction on Power Systems 19 (2) (2004) 1085–1095.
- [18] IEEE Subsynchronous Resonance Task Force of the Dynamic System Performance Working Group Power System Engineering Committee: 'First benchmark model for computer simulation of subsynchronous resonance', IEEE Transactions on Power Apparatus and Systems, 96 (5) (1977) 1565–1572.
- [19] B. Chaudhuri, R. Majumder, B.C. Pal, Wide-area measurement-based stabilizing control of power system considering signal transmission delay, IEEE Transaction on Power Systems 19 (4) (2004) 1971–1979.

- [20] C.W. Taylor, D.C. Erickson, K.E. Martin, R.E. Wilson, V. Venkatasubramanian, WACS—wide-area stability and voltage control system: R&D and online demonstration, *Proceedings of the IEEE* 93 (5) (2005) 892–906.
- [21] C.W. Taylor, D.C. Erickson, R.E. Wilson, Reducing blackout risk by a wide-area control system (WACS): adding a new layer of defense, in: 15th PSCC Power Systems Computation Conference, Liege, Belgium, 2005, pp. 1–7.
- [22] X. Xie, J. Xiao, C. Lu, Y. Han, Wide-area stability control for damping inter-area oscillations of interconnected power systems, *IEEE Proceedings-Generation Transmission and Distribution* 153 (5) (2006) 507–514.
- [23] F. Okou, L.-A. Dessaint, Q. Akhrif, Power systems stability enhancement using a wide-area signals based hierarchical controller, *IEEE Transactions on Power Systems* 20 (3) (2005) 1465–1477.
- [24] H. Ota, Y. Kitayama, H. Ito, N. Fukushima, K. Omata, K. Morita, Y. Kokai, Development of transient stability control system (TSC system) based on on-line stability calculation, *IEEE Transactions on Power Systems* 11 (3) (1996) 1463–1472.
- [25] M. Koaizawa, M. Nakane, K. Omata, Y. Kokai, Actual operating experience of on-line transient stability control systems (TSC systems), in: *IEEE PES Winter Meeting*, vol. 1, 2000, pp. 84–89.
- [26] EMTP Theory Book, Japan EMTP Committee, 1994.
- [27] M.H. Ali, T. Murata, J. Tamura, A fuzzy logic-controlled superconducting magnetic energy storage (SMES) for transient stability augmentation, *IEEE Transactions on Control Systems Technology* 15 (1) (2007) 144–150.
- [28] R.J. Abraham, D. Das, A. Patra, Automatic generation control of an interconnected hydrothermal power system considering superconducting magnetic energy storage, *International Journal of Electrical Power & Energy Systems* 29 (8) (2007) 571–579.
- [29] A. Taguchi, T. Imayoshi, T. Nagafuchi, T. Akine, N. Yamada, H. Hayashi, A study of SMES control logic for power system stabilization, *IEEE Transactions on Applied Superconductivity* 17 (part 2 (2)) (2007) 2343–2346.
- [30] M.G. Molina, P.E. Mercado, E.H. Watanabe, Static synchronous compensator with superconducting magnetic energy storage for high power utility applications, *Energy Conversion and Management* 48 (8) (2007) 2316–2331.
- [31] J. Shi, Y.J. Tang, L. Ren, J.D. Li, S.J. Chen, Application of SMES in wind farm to improve voltage stability, *Journal of Physica C: Superconductivity* 468 (15–20) (2008) 2100–2103.
- [32] M.H. Ali, T. Murata, J. Tamura, Transient stability enhancement by fuzzy logic-controlled SMES considering coordination with optimal reclosing of circuit breakers, *IEEE Transactions on Power Systems* 23 (2) (2008) 631–640.
- [33] S. Pothiya, I. Ngamroo, Optimal fuzzy logic-based PID controller for load–frequency control including superconducting magnetic energy storage units, *Energy Conversion and Management* 49 (10) (2008) 2833–2838.
- [34] I. Ngamroo, A.N. Cuk Supriyadi, S. Dechanupaprittha, Y. Mitani, Power oscillation suppression by robust SMES in power system with large wind power penetration, *Journal of Physica C: Superconductivity* 469 (1) (2009) 44–51.
- [35] H.-Y. Jung, A.-R. Kim, J.-H. Kim, M. Park, I.-K. Yu, S.-H. Kim, K. Sim, H.-J. Kim, K.-C. Seong, T. Asao, J. Tamura, A study on the operating characteristics of SMES for the dispersed power generation system, *IEEE Transactions on Applied Superconductivity* 19 (3) (2009) 2028–2031.
- [36] L. Wang, S.-S. Chen, W.-J. Lee, Z. Chen, Dynamic stability enhancement and power flow control of a hybrid wind and marine-current farm using SMES, *IEEE Transactions on Energy Conversion* 24 (3) (2009) 626–639.
- [37] Y.-S. Lee, Decentralized suboptimal control of power systems with superconducting magnetic energy storage units, *International Journal of Power and Energy Systems* 21 (2) (2001) 87–96.
- [38] P.D. Baumann, Energy conservation and environmental benefits that may be realized from superconducting magnetic energy storage, *IEEE Transactions on Energy Conversion* 7 (2) (1992) 253–259.