A Practical Design of Fuzzy SMES Controller based on Synchronized Phasor Measurement for Interconnected Power System

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***Abstract*--Recently, fuzzy logic control has widely received attention in various power system applications, despite difficulties of obtaining its control rules and membership functions. Nowadays, power system consists of multiple areas where load variations with abrupt changes always exist, and proper control rules and membership functions could be hardly achieved. This paper proposes a practical design of fuzzy logic controllers for superconducting magnetic energy storage (SMES) based on wide area synchronized phasor measurement for improving stability of interconnected power system. Moreover, a heuristic method is applied for determining control rules and membership functions. The estimated model is determined via a coupled vibration model for detection and assessment of an approximated inter-area oscillation mode. Finally, some simulation studies based on a two-area four-machine power system are carried out to examine the performance and effectiveness of the designed fuzzy SMES controller.**

***Index Terms*--Fuzzy logic controller, wide area system, synchronized phasor measurement, power system stability, superconducting magnetic energy storage**

I. Introduction

TODAY, the growth and development of modern power system have gradually continued to satisfy both increase of electricity demands and expansions of power industry. Modern power systems consisting of multiple areas and transmission lines are naturally confronted with the presence of complex inter-area oscillation modes. These modes are often poorly damped due to various changes during power system operations. The insufficient damping of such complex modes usually causes unavoidable low frequency oscillations and fluctuations of tie-line power flow when being subjected to unexpected disturbances [1], [2]. In addition, it is challenged to operate and utilize their existing facilities at higher efficiency and effectiveness. Many researchers showed that the SMES applications to the enhancement of power system dynamics and stability could be apparently achieved with proper design of SMES active and reactive power controllers [3]-[6].

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In the past two decades, fuzzy logic control has extensively received attention in various power systems applications [7], [8]. In general, the knowledge and experiences about the power system under consideration are needed in a conventional design of a fuzzy logic controller. Its control rules and membership functions are usually obtained by trial and error based on the experienced designer. However, with complexity of today's power system, it is not easy to realize and comprehensively obtain the necessary input-output signal relationships based on such techniques [9].

Recently, wide area monitoring of power system based on multiple phasor measurements has been put into the spotlight by many engineers and practitioners. Phasor measurement unit (PMU), equipped with the global positioning system (GPS), gives the opportunity of data synchronization at a common time reference. With the GPS, the time stamp is accurate to within 1 microsecond at any location on the earth. Accordingly, observed phasor data measured at multiple locations can be synchronized with high accuracy [10]. Moreover, oscillation modes, especially the inter-area low-frequency mode with poor damping, can be detected from measured data by modeling measured data via a coupled vibration model (CVM) [11].

This paper proposes a practical design of fuzzy SMES controller based on wide area synchronized phasor measurement for improving stability of interconnected power system. The fuzzy SMES controller is designed based on the measured data from multiple PMUs. In particular, the control rules and membership functions are tuned by using a heuristic method, i.e. hybrid tabu search and evolutionary programming (Hybrid TS/EP), toward the desired damping performance. Subsequently, some simulation studies based on a two-are four-machine power system are carried out to examine and investigate the performance and effectiveness of the designed fuzzy SMES controller.

The organization of the paper is as follows. Section II explains the fuzzy SMES controller. Next, Section III provides the controller design methodology. Section IV presents the application to two area power system. Lastly, conclusions are given.

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II. Fuzzy SMES Controller

A. SMES Model and Control Scheme

The SMES model with active and reactive power modulation control scheme, as depicted in Fig. 1, is used in the paper. The SMES unit includes three controllers of $K_P(s)$, $K_Q(s)$ and $K_{IDC}(s)$, where, $K_P(s)$ and $K_Q(s)$ are the SMES active and reactive power controllers, respectively, and $K_{IDC}(s)$ controls the SMES coil current. Moreover, the effect of SMES coil current (I_{DC}) is considered in the SMES model, since the dynamic behavior of I_{DC} affects the overall performance of SMES. In practice, I_{DC} is not allowed to reach zero to prevent the possibility of discontinuous conduction under unexpected disturbances. On the other hand, I_{DC}, which is above the maximum allowable limit, may lead to the loss of superconducting properties. Based on the hardware operational constraints, the lower and upper coil current limits are considered and assigned as $0.30I_{DC0}$ and $1.38I_{DC0}$, respectively [4], where, I_{DC0} is an initial value of I_{DC}.

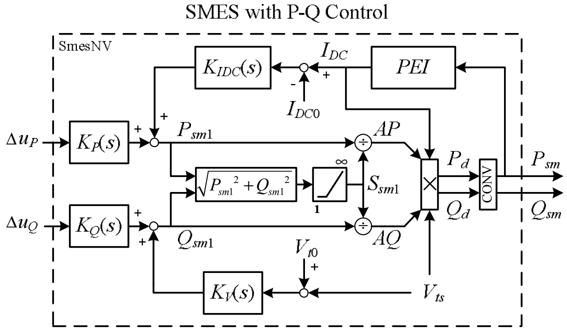

Fig. 1. SMES with P-Q controllers.

The desired SMES output active and reactive power (P_d and Q_d) can be expressed as

$$P_d = V_{ts} I_{DC} AP \,, \tag{1}$$

$$Q_d = V_{ts} I_{DC} AQ \,, \tag{2}$$

where, AP and AQ are the active and reactive power fractions, respectively. For simplicity, V_{ts} is assumed as a terminal bus voltage of SMES unit, (pu). The SMES output active and reactive power, i.e. P_{sm} and Q_{sm} are simply the output of the SMES controlled converter, which is represented by a first order time-lag compensator with a time constant of 0.01s. The *PEI* block in Fig. 1 is used to determine the current I_{DC} based on P_{sm}. In particular, I_{DC} can be calculated by (3) and (4) as follows,

$$E_{out} = \int P_{sm} dt \cdot S_{sm,base} \,, \tag{3}$$

$$I_{DC} = \sqrt{I_{DC0}^2 - \frac{2E_{out}}{L_{sm} \cdot I_{sm,base}^2}} \,, \tag{4}$$

where, L_{sm} is the SMES coil inductance, (H); E_{out} is the SMES energy output, (J); $I_{sm,base}$ is the SMES current base, (A); and $S_{sm,base}$ is the SMES MVAbase, (MVA). Subsequently, the energy stored in the SMES unit (E_{sm}) and the initial E_{sm} (E_{sm0}) can be determined by (5) and (6) as follows,

$$E_{sm} = E_{sm0} - E_{out} \,, \tag{5}$$

$$E_{sm0} = \tfrac{1}{2} L_{sm} I_{DC0}^2 \cdot I_{sm,base}^2 \,. \tag{6}$$

It is assumed that for a nominal condition the SMES unit should not supply/receive active and reactive power to/from the power system. On the other hand, the SMES unit should alleviate power system oscillations following disturbances.

B. Fuzzy Membership Function and Control Rules

For fuzzy SMES controller design, the membership functions in the fuzzification procedure and the fuzzy control rules are primarily considered. In the paper, for simplicity, triangle and trapezoidal shaped membership functions have been selected to describe all of linguistic variables [8]. Fig. 2 shows the fuzzy membership functions for all inputs (A and B) and output (C) variables. The input and output signals are divided into seven linguistic variables using fuzzy set notations, i.e., such as negative big (NB), negative medium (NM), negative small (NS), zero (Z), positive small (PS), positive medium (PM), and positive big (PB).

Subsequently, the fuzzy control rules are constructed so that the output control signal is satisfied. In general, the fuzzy control rules can be obtained from expert's experiences with the choice of input-output membership functions and control rules. However, without expert's knowledge, a simple and practical approach can also be applied by observing the input and output responses of a conventional controller for constructing an initial set of fuzzy control rules [9]. In particular, an initial set of fuzzy control rules as shown in Table I is used in the paper. Za or input A is the feedback input signal, whereas, Zs or input B is the supplementary input signal, which is the integral signal of input A.

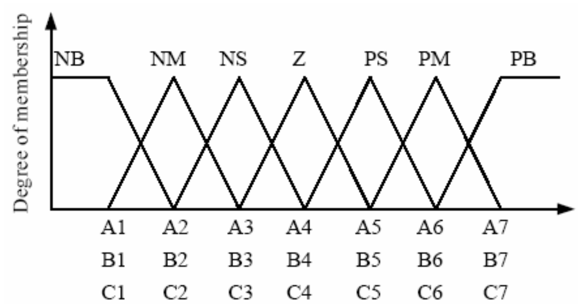

Fig. 2. Membership functions.

TABLE I
Initial Fuzzy Control Rules

Za \ Zs	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NM	NM	NS	Z
NM	NB	NB	NM	NM	NS	Z	PS
NS	NB	NM	NS	NS	Z	PS	PM
Z	NM	NM	NS	Z	PS	PM	PM
PS	NM	NS	Z	PS	PS	PM	PB
PM	NS	Z	PS	PM	PM	PB	PB
PB	Z	PS	PM	PM	PB	PB	PB

Note that the fuzzy SMES controllers of $K_P(s)$ and $K_Q(s)$ are designed simultaneously by using Hybrid TS/EP explained in later section.

III. Controller Design Methodology

A. Modal Analysis with Coupled Vibration Model

In analysis of power system stability, characteristics, i.e., eigenvalues and damping ratios, of a considered power system must be determined and evaluated. The power swing equations of generators in an *n*-machine system can be expressed as follows,

$$\dot{\delta}_i = \omega_r(\omega_i - 1), \tag{7}$$

$$M_i\dot{\omega}_i = -D_i(\omega_i - 1) + P_{mi} - P_{ei}, \tag{8}$$

where, $i = 1, 2, \ldots, n$, δ is the power angle, ω is the generator speed, M is the inertia constant, D is the damping coefficient, P_m is the mechanical power input, P_e is the electric power output and ω_r is the rated system synchronous speed.

In particular, CVM is used for estimating the dominant low-frequency oscillation mode of interest in the considered power system. Two observation sites that significantly participate in the interesting mode are selected. One observation site is set as a reference point. The dynamics of the model can be represented by the polynomial approximation of the phase angle and generator speed as follows,

$$\Delta\dot{\delta}_d = \Delta\omega_d, \tag{9}$$

$$\begin{aligned}\Delta\dot{\omega}_d &= \frac{\omega_r}{M_1}\left(-D_1(\Delta\omega_d - 1) + P_{m1} - P_{e1}\right) \\ &\approx f_\omega(\Delta\delta_d, \Delta\omega_d)\end{aligned}, \tag{10}$$

where, f_ω is assumingly consisting of linear terms; therefore, the system matrix of CVM can be expressed as follow,

$$\begin{bmatrix}\Delta\dot{\delta}_d \\ \Delta\dot{\omega}_d\end{bmatrix} = \begin{bmatrix}0 & 1 \\ b_{21} & b_{22}\end{bmatrix}\begin{bmatrix}\Delta\delta_d \\ \Delta\omega_d\end{bmatrix}, \tag{11}$$

where, $\Delta\delta_d = (\delta_1 - \delta_{1e}) - (\delta_s - \delta_{se})$, and $\Delta\omega_d = \dot{\delta}_1 - \dot{\delta}_s$. Subscripts 1, *s* and *e* denote the observation site number, the reference site and the initial value, respectively.

On the other hand, besides the frequency associated with inter-area low-frequency oscillation mode of interest, the oscillation data of the phase angle observed and obtained by wide area measurement also include other frequency components and noises. Accordingly, the discrete Fourier transform (DFT) filtering technique [8] are employed and applied to select and extract the considered frequency component f_c from the original measured oscillation data as shown in Figs. 3 and 4. Initially, the original measured oscillation data is filtered by DFT filter with the bandwidth of [0.2-0.8] Hz and f_c is evaluated. Subsequently, the original measured oscillation data is filtered by DFT filter with the bandwidth of [f_c ±0.1] Hz to obtain the extracted frequency component. Then, the extracted oscillation data is constructed by applying inverse DFT to the extracted frequency component. Meanwhile, the unwanted frequency components such as local oscillation data and noises with higher frequencies can be eliminated.

Consequently, the coefficients of system (11) can be evaluated by applying the least squares method to time series data set, which includes mostly the considered frequency component. Thus, the estimated system characteristics can be obtained.

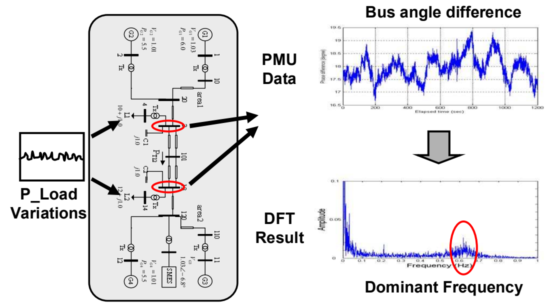

Fig. 3. Dominant mode verification via DFT analysis.

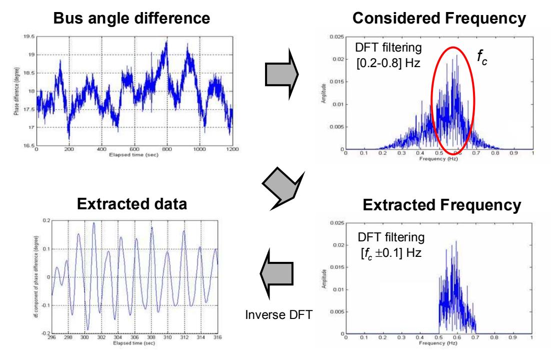

Fig. 4. Extraction of considered frequency component via DFT filtering.

B. Objective Function Formulation

The objective function is formulated as follow.

$$\text{Min } F = \int_{t=0}^{200} |\Delta\omega_d| dt + c.\Delta_D \tag{12}$$

where, Δ_D is the difference between the desired damping ratio and the actual damping ratio. *c* is a scaling coefficient. Equation (12) represents the dynamic stability of the study power system in terms of both time-domain and modal analyses. In the design, only the inter-area oscillation mode is concerned. It is the inter-area mode in which the generators in area 1 oscillate against those in area 2. The other two local modes in which generators within the same area oscillate against each other are not considered. To observe the time-domain dynamic responses of inter-area EMO mode, the generator speed differences between areas ($\Delta\omega_d$) is used to represent the dynamics of the dominant inter-area mode. Note that a damping ratio implies an estimated damping ratio, which is calculated via CVM (11). The value of *c* depends on the designer's experience. The objective function is optimized by using hybrid tabu search and evolutionary programming.

C. Hybrid Tabu Search and Evolutionary Programming

In the paper, the hybrid tabu search and evolutionary programming (Hybrid TS/EP) is employed as the optimization method [12]. The Hybrid TS/EP is an iterative improvement method. For iteration, operations are performed to obtain better solutions with the ability to avoid being trapped in a local optimum. Subsequently, the solution coding scheme, Hybrid TS/EP components and procedure are given.

1) Solution Coding Scheme: Based on a concatenated coding scheme, the actual values of all searched parameters are stacked in series to construct an individual solution as shown in Fig. 5. In addition, all fuzzy control rules (R1-R49) are replaced by integer values to ease the design process. In particular, NB, NM, NS, Z, PS, PM and PB are replaced by 1, 2, 3, 4, 5, 6 and 7, respectively.

2) Hybrid TS/EP Components: Consecutively, each component of Hybrid TS/EP is briefly explained.

A1	…	A7	B1	…	B7	C1	…	C7	R1	…	R49	…
$K_P(s)$												$K_Q(s)$

Fig. 5. Solution coding scheme.

a) Initialization: The set of solution candidates is generated from a given initial solution. For each individual solution, it is a set of searched parameters and its objective function is evaluated to verify the quality of solution.

b) Perturbation Strategies: The Hybrid TS/EP uses two perturbation strategies, i.e. mutation and arithmetic crossover. The mutation operator is used to diversify the search space to increase a chance to meet a better solution. Meanwhile the arithmetic crossover operator is used as an intensification searching strategy towards the optimal solution region.

c) Tabu list restriction: Tabu list (TL) is utilized to keep best individual solutions that have created the best objective values in the past iterations for iterations so that they cannot be used to create new solution candidates. As the iteration proceeds, TL stores a new individual solution and releases the oldest one.

d) Fitness Function Evaluation and Rank Selection with Elitism: The fitness function is evaluated based on a distance away from tabued solutions in TL and an objective function. With the rank selection operator, a half of the highest fitness score individual solutions combined from parent population and its offspring population are selected as parent individual solutions in the next iteration to prevent the premature convergence of solution.

e) Adaptive Parameter Setting Strategies: During the search process, the parameters that control the effective of the search process are determined and adjusted automatically for obtaining better solution candidates. This strategy reduces the search effort towards the optimal solution region.

3) Hybrid TS/EP Procedure: The Hybrid TS/EP procedure can be described as follows:

Step 1: Read the system data, and specify the parameter settings of Hybrid TS/EP.

Step 2: Initialize the initial individuals, X_k; k = 1,…, NP and the design specification. Evaluate the objective function (12), and update tabu list (TL).

Step 3: Initialize the generation counter g to zero.

Step 4: Execute Hybrid TS/EP operators as follows:

Step 4.1: Perform the perturbation strategies.

Step 4.1.1: Initialize the individual counter k to one.

Step 4.1.2: Perform the mutation based on TL restriction until the k-th offspring individual does not satisfy TL restriction.

Step 4.1.3: If $k < N_m$, increase the individual counter k by one and go to *Step 4.1.2*.

Step 4.1.4: Initialize individual counter k to $N_m + 1$.

Step 4.1.5: Perform the arithmetic crossover based on TL restriction until the k-th offspring individual does not satisfy TL restriction.

Step 4.1.6: If $k < NP$, increase the individual counter k by one and go to *Step 4.1.5*.

Step 4.2: Combine the offspring population and parent population into a single population to evaluate the objective value and fitness of each individual.

Step 4.3: Perform the rank selection with elitism mechanism to update the new parent individuals from a combined population of the old parent population and offspring population for the next generation.

Step 4.4: Perform the adaptive parameter setting strategies and update TL.

Step 4.5: If the generation counter g is less than the maximum generation limit g_{max}, increase generation counter g by one and go to *Step 4*.

Step 5: Hybrid TS/EP is terminated and the current best individual is a solution for the controller design.

IV. Application to Two Area Power System

A. Study System

The proposed design method is tested on a two area four machine power system as shown in Fig. 6. Each generator model is represented by a 4-state transient model and is equipped with a simplified exciter. The power system consists of two areas connected by an AC tie-line and exhibits a weak inter-area oscillation mode. The electric power is flowing from areas 1 to 2. Accordingly, bus 120 is the most effective SMES location based on the residue method at the bus [12]. In particular, the active and reactive power flow deviations from bus 120 to bus 13 are used as feedback input signals for the SMES controller for power system stabilization. In the paper, it is assumed that there are load variations in both areas 1 (L1) and 2 (L2). Moreover, two PMUs are assumingly installed at bus 3 and bus 13 for monitoring transmission system. The SMES

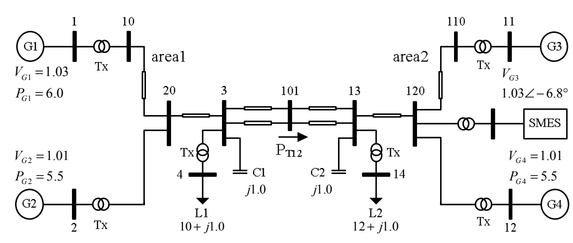

Fig. 6. Two area four machine power system.

has a specification of 80 MJ, 40 kA, 100 MVA [12]. The power system data are given in ref. [2].

B. Simulation Results and Evaluation

Initially, the power system is set at the design operating condition (DOC). To obtain the measured oscillation data, the 200-s random load variations within a range of ±5% are applied in both areas 1 (L1) and 2 (L2). Accordingly, the tie-line power flow is oscillated but, however, the power system still remains under a stable steady-state condition. In the study, the design goal is to gradually increase the damping performance of the power system from 3.3% to 12.5% with a step of 2%. The SMES controller parameters are tuned following the Hybrid TS/EP procedure explained in Section III.C. For Hybrid TS/EP, the population size is set to 50 and the search stops after 20 iterations every a damping step of 2%. The scaling coefficient c is set to 5.

As results, the dominant eigenvalues and damping ratios are improved toward the design specification as shown in Table II. Table III and IV show the optimized membership functions of $K_P(s)$ and $K_Q(s)$, respectively. Moreover, the fuzzy control rules for $K_P(s)$ and $K_Q(s)$ are also optimized. Table V and VI show the optimized fuzzy control rules for $K_P(s)$ and $K_Q(s)$. More specifically, the rule numbers 1, 2, 3, 4, 5, 6 and 7 represent the linguistic rules NB, NM, NS, Z, PS, PM and PB, respectively.

Subsequently, simulation studies are carried out to examine and investigate the performance and effectiveness of the designed fuzzy SMES controller. The simulation studies are done by using Matlab and Dymola with ObjectStab [13]. For comparison purpose, the conventional fuzzy SMES controller is employed. In addition, the membership functions and control rules of the conventional fuzzy SMES controller are obtained by observing the input-output control signal of the conventional SMES controller proposed by [12].

TABLE II
EIGENVALUES AND DAMPING RATIOS

CTLR	Eigenvalue	Damping ratio
Initial	$-0.13\pm j3.80$	3.3%
FSMES(PMU)	$\mathbf{-0.43\pm j3.40}$	**12.4%**

TABLE III
OPTIMIZED MEMBERSHIP FUNCTIONS OF $K_P(S)$

	1	2	3	4	5	6	7
A	-0.160	-0.181	-0.085	0.049	0.058	0.197	0.183
B	-0.214	-0.250	-0.086	0.020	0.147	0.175	0.207
C	-0.365	-0.314	-0.172	0.074	0.096	0.341	0.378

TABLE IV
OPTIMIZED MEMBERSHIP FUNCTIONS OF $K_Q(S)$

	1	2	3	4	5	6	7
A	-0.018	-0.025	-0.006	0.001	0.015	0.017	0.025
B	-0.021	-0.021	-0.010	-0.003	0.012	0.015	0.016
C	-0.025	-0.021	-0.005	0.005	0.008	0.018	0.017

In the paper, two operating conditions other than DOC are additionally employed in the simulation studies as shown in Table VII. For each operating condition, a major system disturbance is applied to investigate the performance and effectiveness of the designed controller by the proposed method. In particular, the three-phase fault-to-ground at Bus101 for 50 ms is applied to operating conditions Cases DOC and 1. For Case 2, the three-phase fault-to-ground on the center of Line3-101 for 50 ms is applied.

Figures 7-9 show the system responses for each case. The generator speed differences $\Delta\omega_d$ are shown to examine the dynamic responses of the inter-area oscillation mode. In addition, the SMES output powers are also given to show that they considerably remain within the limits. From the simulation results, the conventional fuzzy SMES controller can finally damp out the power system oscillations. On the other hand, the power system with the designed fuzzy SMES controller can also suppress the oscillations following disturbances effectively. The designed fuzzy SMES controller apparently shows the improvement of the dynamic responses of the power system after being subjected to major system disturbances. More specifically, by using the proposed design method, the performance and effectiveness of the designed fuzzy SMES controller are properly optimized.

TABLE V
OPTIMIZED CONTROL RULES OF $K_P(S)$

Zp\Zs	**NB**	**NM**	**NS**	**Z**	**PS**	**PM**	**PB**
NB	5	1	7	1	6	6	3
NM	7	2	5	4	7	5	1
NS	6	4	3	3	3	4	2
Z	3	3	4	4	5	4	1
PS	2	3	3	5	5	5	7
PM	6	2	2	7	7	4	5
PB	1	5	6	1	3	5	1

TABLE VI
OPTIMIZED CONTROL RULES OF $K_Q(S)$

Zp\Zs	**NB**	**NM**	**NS**	**Z**	**PS**	**PM**	**PB**
NB	2	7	4	2	6	3	1
NM	7	1	6	1	5	5	3
NS	4	4	3	6	3	4	2
Z	3	5	3	4	5	6	2
PS	4	5	3	2	5	3	3
PM	4	3	7	1	3	6	1
PB	7	1	7	7	3	6	3

TABLE VII
OPERATING CONDITIONS & DISTURBANCES

Case	Tie-line Power (pu)	Disturbance
DOC	1.25	3-ϕ fault at Bus101 for 50 ms
1	2.10	3-ϕ fault at Bus101 for 50 ms
2	2.70	3-ϕ fault on line3-101 for 50 ms

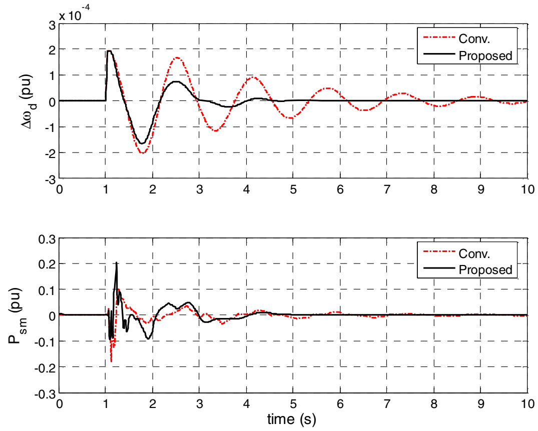

Fig. 7. System responses of DOC.

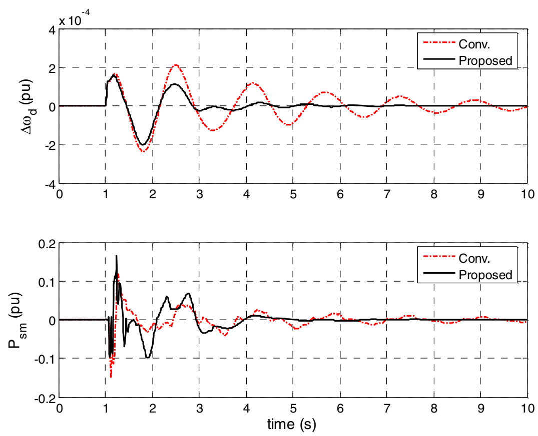

Fig. 8. System responses of 1.

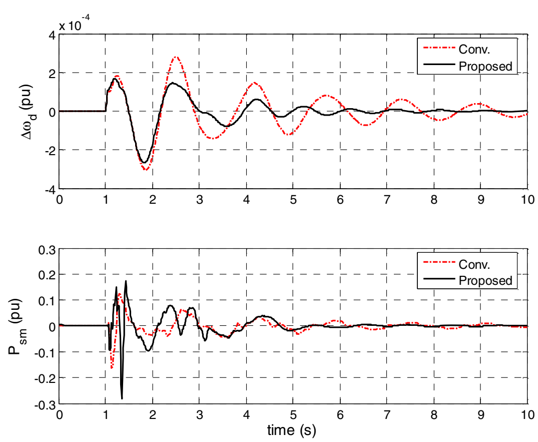

Fig. 9. System responses of 2.

V. Conclusions

A practical design of fuzzy SMES controller based on synchronized phasor measurement for interconnected power system is proposed. The proposed design method takes advantages of wide area measurement system. Moreover, the hybrid tabu search and evolutionary programming is employed for optimizing membership functions and control rules of fuzzy SMES controller. Some merits can be concluded as follows.

- With wide area measurement system, fuzzy SMES controller can be tuned with most recent data toward the desired damping performance.
- Improvement of dynamic stability of an interconnected power system can be achieved with less efforts and system detailed information.
- The effectiveness of the designed controller can be assessed directly from measured system data during the design.

Consequently, the simulation results and evaluation reveal and confirm the applicability and effectiveness of the proposed design method for a practical power system.

VI. References

[1] P. Kundur, *Power System Stability and Control.* New York, McGraw Hill, 1994.

[2] G. Rogers, *Power System Oscillations*. Boston, MA, Kluwer Academic Publishers, 2000.

[3] Y. Mitani, K. Tsuji, and Y. Murakami, “Application of superconducting magnetic energy storage to improve power system dynamic performance,” *IEEE Trans. PS*, vol. 3, no. 4, pp. 1418–1425, 1988.

[4] C. J. Wu, and Y. S. Lee, “Application of superconducting magnetic energy storage unit to improve the damping of synchronous generator”, *IEEE Trans. EC*, vol. 6, no. 4, pp. 573-578, 1991.

[5] M. G. Rabbani, J. B. X. Devotta, and S. Elangovan, “Application of simultaneous active and reactive power modulation of SMES unit under unequal α-mode for power system stabilization”, *IEEE Trans. PS*, vol. 14, no. 2, pp. 547-552, 1999.

[6] J. B. X. Devotta, and M. G. Rabbani, “Application of superconducting magnetic energy storage unit in multimachine power systems”, *Energy Conversion and Management*, vol. 41, no. 5, pp. 493-504, 2000.

[7] T. Hiyama, “Robustness of fuzzy logic power system stabilizers applied to multimachine power system,” *IEEE Trans. EC*, vol. 9, no. 3, pp. 451-459, 1994.

[8] M. E. El-Hawary, *Electric Power Applications of Fuzzy Systems*, New York, Wiley-IEEE Press, 1998.

[9] K. Hongesombut, Y. Mitani, and K. Tsuji, “Fuzzy logic controller based on observed signals and a genetic algorithm application with STATCOM for power system stabilization,” *IEEJ Trans. PE*, vol. 123, no. 5, pp. 589-596, 2003.

[10] N. Kakimoto, M. Sugumi, T. Makino, and K. Tomiyama, “Monitoring of Interarea oscillation mode by synchronized phasor measurement,” *IEEE Trans. PS*, vol. 21, no. 1, pp. 260-268, 2006.

[11] T. Hashiguchi, M. Yoshimoto, Y. Mitani, O. Saeki, K. Tsuji, M. Hojo, H. Ukai, J. Toyoda, and A. Matsushita, “Analysis of oscillation characteristics followed by power system disturbance based on multiple synchronized phasor measurements,” *Proc. Int. Conf. Electrical Engineering 2004*, Jun. 2004.

[12] S. Dechanupaprittha, K. Hongesombut, M. Watanabe, Y. Mitani, and I. Ngamroo, “A heuristic-based design of robust SMES controller taking system uncertainties into consideration,” *IEEJ Trans. Electrical and Electronic Engineering*, vol. 1, no. 3, pp. 255-267, 2006.

[13] M. Larsson, ‘ObjectStab-an educational tool for power system stability studies,” *IEEE Trans. PS*, vol. 19, no. 1, pp. 56-63, 2004.