International Journal on
"Technical and Physical Problems of Engineering"
(IJTPE)
Published by International Organization on TPE (IOTPE)

ISSN 2077-3528
IJTPE Journal
www.iotpe.com
ijtpe@iotpe.com

March 2010 | Issue 2 | Volume 2 | Number 1 | Pages 24-33

APPLICATION OF PSO FOR FUZZY LOAD FREQUENCY DESIGN WITH CONSIDERING SUPERCONDUCTING MAGNETIC ENERGY STORAGE

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Abstract- In this paper, a fuzzy PID type controller with considering Superconducting Magnetic Energy Storage (SMES) is proposed for solution of the Load Frequency Control (LFC) problem. In order for a fuzzy rule based control system to perform well, the fuzzy sets must be carefully designed. A major problem plaguing the effective use of this method is the difficulty of accurately constructing the membership functions. For this reason, in the proposed Multi Stage Fuzzy (MSF) type PID controller, the membership functions are tuned automatically using a Particle Swarm Optimization (PSO) algorithm with a strong ability to find the most optimistic results. This newly developed control strategy combines the advantage of SMES and fuzzy system control technique and leads to a flexible controller with simple stricture that is easy to implement. Analysis on a three-area restructured power system reveals that the proposed control strategy by considering SMES unit improves significantly the dynamical performances of system against parametric uncertainties for a wide range of area load demands and disturbances.

Keywords: LFC, SMES, Multi Stage Fuzzy Controller, Deregulated Power System, PSO.

I. INTRODUCTION

The goal of Load Frequency Control (LFC) is to reestablish primary frequency regulation capacity, return the frequency to its nominal value and minimize unscheduled tie-line power flows between neighboring control areas. From the mechanisms used to manage the provision this service in ancillary markets, the bilateral contracts or competitive offers stand out [1].

During the past decade, several proposed LFC scenarios have been attempted to adapt traditional LFC schemes to the change of environment in the power systems under deregulation [2-4]. In a power system, each control area contains different kinds of uncertainties and various disturbances due to increased complexity, system modeling errors and changing power system structure. As a result, a fixed controller based on classical theory is not certainly suitable for the LFC problem. It is desirable that a flexible controller be developed.

Recently, some authors proposed fuzzy PID methods to improve performance of the LFC problem [11-13]. It should be pointed out that they require a three-dimensional rule base. This problem makes the design process is more difficult. To overcome this drawback, in author's pervious paper [14-15] a improved control strategy based on fuzzy theory and Genetic Algorithm (GA) technique have been proposed. The resulting structure is a Multi Stage Fuzzy (MSF) controller using two dimensional inference engines (rule base) to perform reasonably the task of a three dimensional controller. The proposed method requires fewer resources to operate and its role in the system response is more apparent. In order for a fuzzy rule based control system to perform well, the fuzzy sets must be carefully designed. A major problem plaguing the effective use of this method is the difficulty of accurately constructing the membership functions. Because, it is a computationally expensive combinatorial optimization and also extraction of an appropriate set of membership function from the expert may be tedious, time consuming and process specific. Thus, to reduce fuzzy system effort in our previous paper [16] a Particle Swarm Optimization (PSO) based MSF (PSOMSF) controller have been proposed for tuning membership functions of MSF controller. It was shown that, the global optimal point is guaranteed and the speed of algorithms convergence is extremely improved, too.

Literature survey shows that, in most of the works concerned with LFC problem [2-14, 17] of interconnected power systems the supplementary controllers are designed to regulate the area control errors to zero effectively. However, the power frequency and the tie-line power deviations persist for a long duration. In these situations, the governor system may no longer be able to absorb the frequency fluctuations due to its slow response [18]. Thus, to compensate for the sudden load changes, an active power source with fast response such as a Superconducting Magnetic Energy Storage (SMES) unit is expected to be the most effective countermeasure. The reported works [19-24] further shows that, SMES is located in each area of the power system for LFC problem. With the use of SMES in all areas, frequency deviations in each area are effectively suppressed.

However, it may not be economically feasible to use SMES in every area of a multi-area interconnected power system. Thus, it is advantageous if an SMES located in an area is available for the control of frequency of other interconnected areas. In view of the above, SMES units is used to demonstrate technical and economic feasibility of them in deregulated power system applications. The energy storage requirement to damp the frequency oscillations caused by small load perturbations is much smaller. In such cases, the real power transfer takes place in a very short time. Thus, addition of a SMES unit to the system significantly improves transients of frequency and tie-line power deviations against to small load disturbances. For this reason, a MSF controller is designed including a SMES unit in one area of a deregulated power system for solution of the LFC problem.

In order to improve optimization synthesis and reduce fuzzy system effort, PSO technique is used for tuning membership functions of the proposed MSF controller. PSO is a novel population based metaheuristic, which utilize the swarm intelligence generated by the cooperation and competition between the particle in a swarm and has emerged as a useful tool for engineering optimization. It has also been found to be robust in solving problems featuring non-linearity, non-differentiability and high dimensionality [16, 25-27]. The designed PSOMSF controller with consideration SMES unit is tested on a three-area restructured power system under different operating conditions in comparison with the designed PSOMSF controller without consideration SMES [16] through some performance indices. The performance indices are chosen as the Integral of the Time multiplied Absolute value of the Error (ITAE) and Figure of Demerit (FD). Results evaluation show that the dynamical performances of system such as frequency oscillation and settling time significantly is improved with considering SMES unit for wide range of system parameters and load changes in the presence of system nonlinearities and also it is superior to the designed controller without considering SMES unit.

II. SMES MODEL

The schematic diagram in Figure 1 shows the configuration of a thyristor controlled SMES unit. The nomenclature used is given in Appendix A. In the SMES unit, a DC magnetic coil is connected to the AC grid through a Power Conversion System (PCS) which includes an inverter/rectifier. The superconducting coil is contained in a helium vessel. Heat generated is removed by means of a low-temperature refrigerator. Helium is used as the working fluid in the refrigerator as it is the only substance that can exist as either a liquid or a gas at the operating temperature which is near absolute zero. The current in the superconducting coil will be tens of thousands or hundreds of thousands of amperes. No AC power system normally operates at these current levels and hence a transformer is mounted on each side of the converter unit to convert the high voltage and low current of the AC system to the low voltage and high current required by the coil. The energy exchange between the superconducting coil and the electric power system is controlled by a line commutated converter. To reduce the harmonics produced on the AC bus and in the output voltage to the coil, a 12-pulse converter is preferred. The superconducting coil can be charged to a set value from the grid during normal operation of the power system. Once the superconducting coil gets charged, it conducts current with virtually no losses [19-24] as the coil is maintained at extremely low temperatures. When there is a sudden rise in the load demand, the stored energy is almost released through the PCS to the power system as alternating current.

As the governor and other control mechanisms start working to set the power system to the new equilibrium condition, the coil current changes back to its initial value. Similar action occurs during sudden release of loads. In this case, the coil immediately gets charged towards its full value, thus absorbing some portion of the excess energy in the system and as the system returns to its steady state, the excess energy absorbed is released and the coil current attains its normal value. The control of the converter firing angle provides the DC voltage appearing across the inductor to be continuously varying within a certain range of positive and negative values. The inductor is initially charged to its rated current I_{d0} by applying a small positive voltage. Once the current reaches its rated value, it is maintained constant by reducing the voltage across the inductor to zero since the coil is superconducting. Neglecting the transformer and the converter losses, the DC voltage is given by [24, 28]:

$$E_d = 2V_{d0}\cos\alpha - 2I_d R_C \tag{1}$$

Where, E_d is the DC voltage applied to the inductor in KV, α is the firing angle in degrees, I_d is the current flowing through the inductor in *KA*, R_C is the equivalent commutating resistance in KΩ and V_{d0} is the maximum circuit bridge voltage in KV. Charging and discharging of the SMES unit is controlled through the change of commutation angle *α*. If *α* is less than 90°, converter acts in the converter mode (charging mode) and if α is greater than 90°, the converter acts in the inverter mode (discharging mode).

In LFC operation, the E_d is continuously controlled by the input signal to the SMES control logic. As mentioned in recent literature [19-24], the inductor current must be restored to its nominal value quickly after a system disturbance so that it can respond to the next load disturbances immediately. Thus, in order to improve the current restoration to its steady state value the inductor current deviation is used as a negative feedback signal in the SMES control loop. Based on the above dissuasion, the converter voltage applied to the inductor and inductor current deviations are described as follows:

$$\Delta E_{di}(s) = \frac{K_{SMES}}{1+sT_{dci}}u_{SMESi}(s) - \frac{K_{id}}{1+sT_{dci}}\Delta I_{di}(s) \tag{2}$$

$$\Delta I_{di}(s) = \frac{1}{sL_i}\Delta E_{di}(s) \tag{3}$$

In this study, as in recent literature, input signal to SMES control logic is considered ACE_i of the same area in power system [24]. The ACE_i is defined as follows:

$$ACE_i = B_i \Delta F_i + \Delta P_{tie,i} \quad (4)$$

The deviation in the inductor real power of SMES unit is expressed in time domain as follows:

$$\Delta P_{SMESi} = \Delta E_{di} I_{d0i} + \Delta I_{d0i} \Delta E_{di} \quad (5)$$

This value is assumed positive for transfer from AC grid to DC. Figure 2 shows the block diagram of SMES unit.

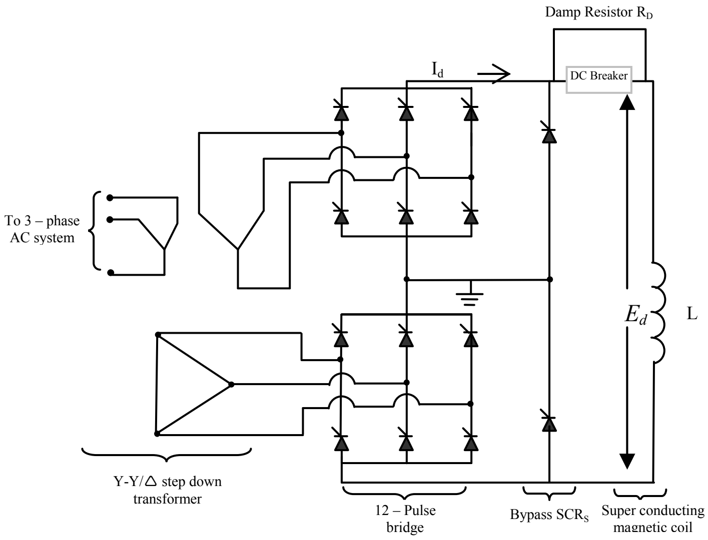

Figure 1. SMES circuit diagram

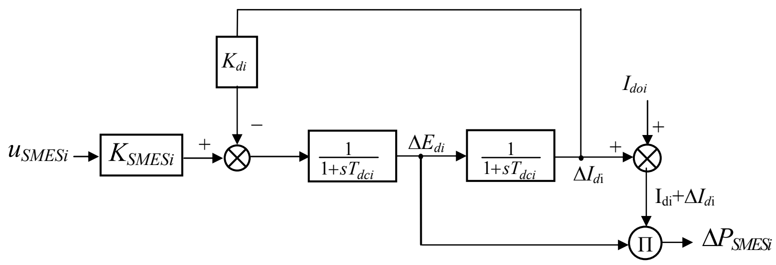

Figure 2. The block diagram of SMES unit

III. DESCRIPTION OF GENERALIZED LFC SCHEME

In the deregulated power systems, the vertically integrated utility no longer exists. However, the common LFC objectives, i.e. restoring the frequency and the net interchanges to their desired values for each control area, still remain. The deregulated power system consists of GENCOs, TRANSCOs and DISCOs with an open access policy. In the new structure, GENCOs may or may not participate in the LFC task and DISCOs have the liberty to contract with any available GENCOs in their own or other areas. Thus various combinations of possible contracted scenarios between DISCOs and GENCOs are possible. All the transactions have to be cleared by the Independent System Operator (ISO) or other responsible organizations. In this new environment, it is desirable that a new model for LFC scheme be developed to account for the effects of possible load following contracts on system dynamics.

Based on the idea presented in [17], the concept of an '*Augmented Generation Participation Matrix*' (AGPM) to express the possible contracts following is presented here. The AGPM shows the participation factor of a GENCO in the load following contract with a DISCO. The rows and columns of AGPM matrix equal the total number of GENCOs and DISCOs in the overall power system, respectively. Consider the number of GENCOs and DISCOs in area i be n_i and m_i in a large scale power system with N control areas. The structure of AGPM is given by:

$$AGPM = \begin{bmatrix} AGPM_{11} & \cdots & AGPM_{1N} \\ \vdots & \ddots & \vdots \\ AGPM_{N1} & \cdots & AGPM_{NN} \end{bmatrix} \quad (6)$$

where,

$$AGPM_{ij} = \begin{bmatrix} gpf_{(s_i+1)(z_j+1)} & \cdots & gpf_{(s_i+1)(z_j+m_j)} \\ \vdots & \ddots & \vdots \\ gpf_{(s_i+n_i)(z_j+1)} & \cdots & gpf_{(s_i+n_i)(z_j+m_j)} \end{bmatrix}$$

For $i, j = 1, \cdots, N$ and

$$s_i = \sum_{k=1}^{i-1} n_i \, , \, z_j = \sum_{k=1}^{j-1} m_j \quad \& \quad s_1 = z_1 = 0$$

In the above, gpf_{ij} refers to '*generation participation factor*' and shows the participation factor of GENCO i in total load following requirement of DISCO j based on the contracted scenario. Sum of all entries in each column of AGPM is unity. The diagonal sub-matrices of AGPM correspond to local demands and off-diagonal sub-matrices correspond to demands of DISCOs in one area on GENCOs in another area.

Block diagram of the generalized LFC scheme in a restructured system is shown in Figure 3 by considering SMES unit. Dashed lines show interfaces between areas and the demand signals based on the possible contracts. These new information signals are absent in the traditional LFC scheme. As there are many GENCOs in each area, ACE signal has to be distributed among them due to their ACE participation factor in the LFC task and $\sum_{j=1}^{n_i}\alpha_{ji}=1$.

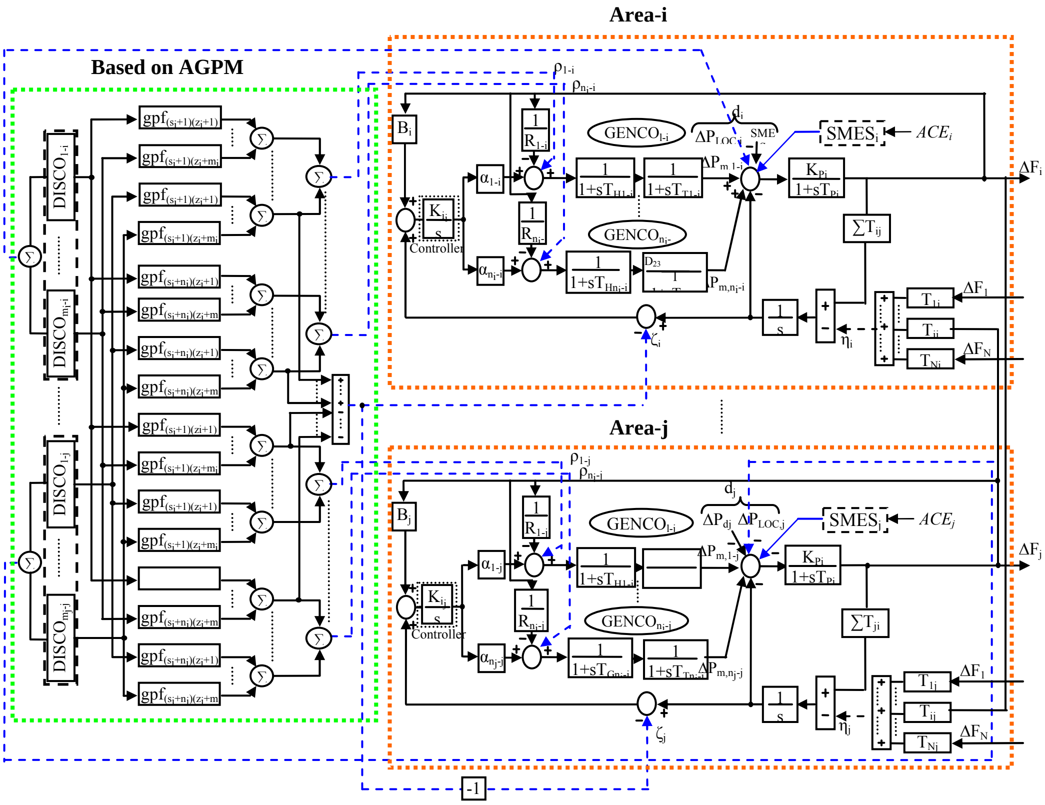

Figure 3. The generalized LFC scheme in the restructured system

It can be seen from this figure that four input disturbance channels, d_i, η_i, ζ_i and ρ_i are considered for LFC design. They are defined as bellow:

$$d_i=\Delta P_{Loc,i}+\Delta P_{di}\,,\quad \Delta P_{Loc,i}=\sum_{j=1}^{m_i}(\Delta P_{Lj}+\Delta P_{ULj}) \tag{7}$$

$$\eta_i=\sum_{\substack{j=1\\ j\neq i}}^{N}T_{ij}\Delta f_j \tag{8}$$

$$\zeta_i=\Delta P_{tie,i,sch}=\sum_{\substack{k=1\\ k\neq i}}^{N}\Delta P_{tie,ik,sch} \tag{9}$$

$$\Delta P_{tie,ik,sch}=\sum_{j=1}^{n_i}\sum_{t=1}^{m_k}apf_{(s_i+j)(z_k+t)}\Delta P_{L(z_k+t)}-\sum_{t=1}^{n_k}\sum_{j=1}^{m_i}apf_{(s_k+t)(z_i+j)}\Delta P_{L(z_i+j)} \tag{10}$$

$$\Delta P_{tie,i-error}=\Delta P_{tie,i-actual}-\zeta_i \tag{11}$$

(12)

$$\Delta P_{m,k-i}=\rho_{ki}+apf_{ki}\sum_{j=1}^{m_i}\Delta P_{ULj-i} \tag{13}$$

$\Delta P_{m,ki}$ is the desired total power generation of a GENCO k in area i and must track the demand of the DISCOs in contract with it in the steady state. A three-area power system including a SMES unit in area 1, shown in Figure 4 is considered as a test system to demonstrate the effectiveness of the proposed control strategy. It is assumed that each control area includes two GENCOs and DISCOs. The power system parameters and SMES are given in Tables 1-3.

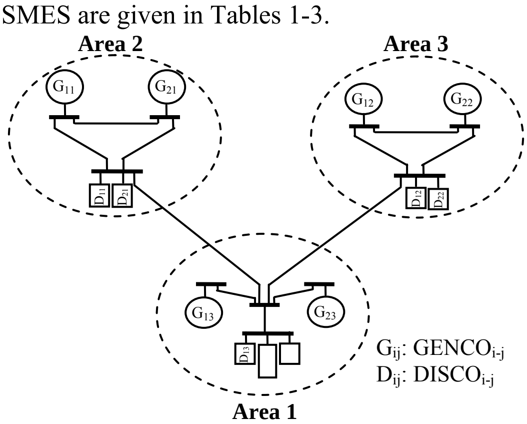

Figure 4. A three-area restructured power system

Table 1. Control area parameters

Parameter	Area -1	Area -2	Area -3
K_P (Hz/pu)	120	72	91
T_P (sec)	20	14.3	10.6
B (pu/Hz)	0.8675	0.785	0.87
T_{ij} (pu/Hz)	$T_{12}=T_{13}=T_{23}=0.545$		

Table 2. GENCOs parameter

MVA_{base} (1000MW) Parameter	GENCOs (*k* in area *i*)					
	1-1	2-1	1-2	2-2	1-3	2-3
Rate (MW)	1000	800	1100	900	1000	1020
T_T (sec)	0.36	0.42	0..44	0.4	0.36	0. 4
T_H (sec)	0.06	0.07	0.06	0.08	0.07	0.08
R (Hz/pu)	2.4	3.3	2.5	2.4	2.4	3.3
α	0.5	0.5	0.5	0.5	0.5	0.5

Table 3. SMES parameter

Parameter	L (H)	T_{dc} (sec)	K_{SMES} (KV/unit MW)	K_{id} (KV/KA)	I_{d0} (KA)
Value	2.65	0.03	100	0.2	4.5

IV. PSO BASED MSF CONTROLLER SCHEME

Because of the complexity and multi-variable conditions of power systems, conventional control methods may not give satisfactory solutions. On the other hand, their robustness and reliability make fuzzy controllers useful for solving a wide range of control problems [25-26]. In this paper, particle swarm optimization based multi stage fuzzy controller including SMES unit is proposed for solution of the LFC problem. The motivation of using the proposed PSOMSF controller is to take large parametric uncertainties, system nonlinearities and minimize of area load disturbances into account. As MSF controller is elaborately explained in author's pervious paper [14], here we points out only the salient features of it briefly. This control strategy combines fuzzy PD controller and integral controller with a fuzzy switch. In order for a fuzzy rule based control system to perform well, the fuzzy sets must be carefully designed.

Because it is computationally expensive combinational optimization problem and also extraction of an appropriate set of membership function from the expert may be tedious, time consuming and process specific. On the other hand, PSO is a population based evolutionary search algorithms characterized as conceptually simple, easy to implement and computationally efficient. As it is reported in [16], this optimization technique can be used to solve many of the same kinds of problems as GA, and does not suffer from some of GA's difficulties. PSO has also been found to be robust problem featuring non-linearity, non-differentiability and high-dimensionality. This new approach features many advantages; it is simple, fast and can be coded in few lines. Also, its storage requirement is minimal. Moreover, this approach is advantageous over evolutionary and genetic algorithms in many ways. First, PSO has memory. That is, ebery particle remembers its best solution (local best) as well as the group best solution (global best). Another advantage of PSO is that the initial population of the PSO is maintained, and so there is no need for applying operators to the population, a process that is time and memory- storage-consuming. In addition, PSO is based on "constructive cooperation" between particles, in contrast with the genetic algorithms, which are based on "the survival of the fittest". Hence, the PSO is more suitable to deal with the problem of lacking experience or knowledge than other searching methods in particular, when the phenomena being analyzed are describable in the terms of rules for action and learning processes.Thus, in order to reduce fuzzy system effort and cost, PSO technique is being used to optimally tune the membership functions in the perposed MSF controller.

Figure 5 shows the structure of the proposed PSOMSF controller for solution of the LFC problem. In this structure, input values are converted to truth-value vectors and applied to their respective rule base. The output truth-value vectors are not defuzzified to crisp value as with a single stage fuzzy logic controller but are passed onto the next stage as a truth value vector input. The darkened lines in Fig. 5 indicate truth value vectors.
In this effort, all membership functions are defined as triangular partitions with seven segments from -1 to 1. Zero (ZO) is the center membership function which is centered at zero. The partitions are also symmetric about the ZO membership function as shown in Figure 6. The remaining parts of the partition are Negative Big (NB), Negative Medium (NM), Negative Small (NS), Positive Small (PS), Positive Medium (PM) and Positive Big (PB).

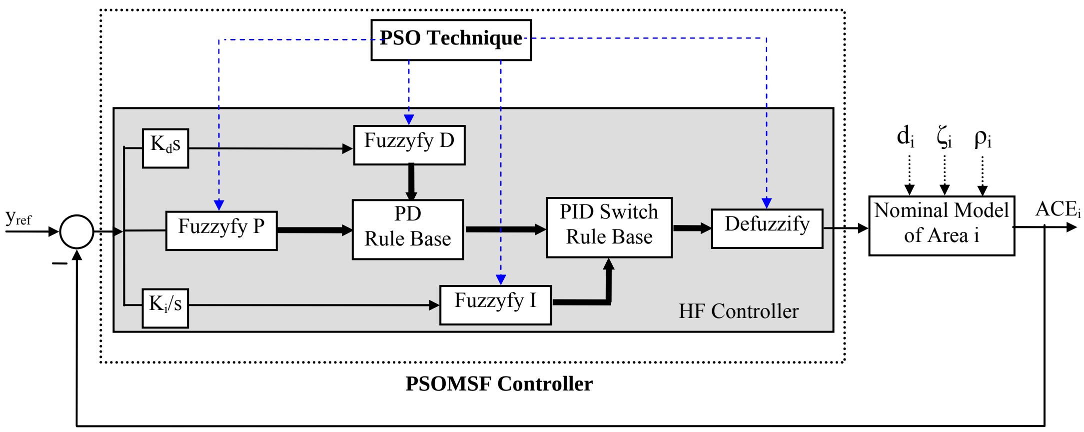

Figure 5. tructure of the proposed PSOMSF control strategy

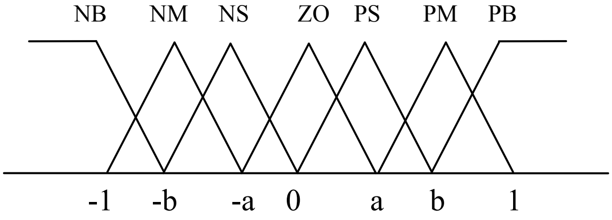

Figure 6. Symmetric fuzzy partition

There are two rule bases used in the MSF controller. The first is called the PD rule bases as it operates on truth vectors form the error (e) and change in error (Δe) inputs. A typical PD rule base for the fuzzy logic controller is given in Table 4. This rule base responds to a negative input from either error (e) or change in error (Δe) with a negative value thus driving the system toward the commanded value. Table 5 shows a PID switch rule base. This rule base is designed to pass through the PD input if the PD input is not in zero fuzzy set. If the PD input is in the zero fuzzy set, then the PID switch rule base passes the integral error values ($\int e$). This rule base operates as the behavior switch, giving control to PD feedback when the system is in motion and reverting to integral feedback to remove steady state error when the system is no longer moving. The operation used to determine the consequence value at the intersection of two input fuzzy value is given as:

$$c_{i,j}=\Pi(a_i*b_j)\ ,\ \ i,j=1,2,\ldots N_m \tag{14}$$

where a_i is the membership value of ith fuzzy set for a given e input, and b_j is likewise for a Δe input. The operator used to determine the membership value of the k^{th} consequence set is:

$$C_k=\sum C_{i,j}\ ,\ \ i,j=1,2,\ldots N_m \tag{15}$$

The defuzzification uses the weighted average method where C_k is the peak point of the kth output fuzzy membership function.

$$d=\sum C_k*c_k/\sum C_k\ \ k=1,\ldots,N.\text{(sets in output point)} \tag{16}$$

In the proposed PSOMSF controller, we must tune the linguistic hedge combinations which are difficult to be contributed according to human experience and knowledge. According to Figure 6 for exact tuning of the membership functions in the proposed method we must find the optimal value for a and b parameters, where $0<a<b<1$. To acquire an optimal combination, this paper employs PSO technique [27] to improve optimization synthesis. It is as the search method to improve the speed of convergence and find the global optimum value of fitness function. In this work, the PSO module works offline and searches the optimal linguistic hedge combination according to the controlled plants. Flowchart of the proposed PSO technique for exact tuning of membership functions is shown in Figure 7.

PSO starts with a population of random solutions ''particles'' in a D-dimension space. The ith particle is represented by $X_i = (x_{i1},x_{i2}, \ldots ,x_{iD})$. Each particle keeps track of its coordinates in hyperspace, which are associated with the fittest solution it has achieved so far. The value of the fitness for particle i (pbest) is also stored as $P_i = (p_{i1}, p_{i2}, \ldots ,p_{iD})$. The global version of PSO keeps track of the overall best value (gbest), and its location, obtained thus far by any particle in the population. PSO consists of changing the velocity of each particle toward its pbest and gbest according to (17) at each step. The velocity of particle i is represented as $V_i=(v_{i1}, v_{i2}, \ldots v_{iD})$. Acceleration is weighted by a random term, with separate random numbers being generated for acceleration toward pbest and gbest.

Table 4. PD rule base

		Δe						
		NB	NM	NS	ZO	PS	PM	PB
e	NB	NB	NB	NB	NB	NM	NS	ZO
	NM	NB	NB	NB	NM	NS	ZO	PS
	NS	NB	NB	NM	NS	ZO	PS	PM
	ZO	NB	NM	NS	ZO	PS	PM	PB
	PS	NM	NS	ZO	PS	PM	PB	PB
	PM	NS	ZO	PS	PM	PB	PB	PB
	PB	ZO	PS	PM	PB	PB	PB	PB

Table 5. PID switch rule base

		PD Values						
		NB	NM	NS	ZO	PS	PM	PB
∫e	NB	NB	NM	NS	NB	PS	PM	PB
	NM	NB	NM	NS	NM	PS	PM	PB
	NS	NB	NM	NS	NS	PS	PM	PB
	ZO	NB	NM	NS	ZO	PS	PM	PB
	PS	NB	NM	NS	PS	PS	PM	PB
	PM	NB	NM	NS	PM	PS	PM	PB
	PB	NB	NM	NS	PB	PS	PM	PB

The position of the ith particle is then updated according to equation (18) [27].

$$v_i^{k+1}=\omega v_i^k+c_1r_1(P_{id}^k-x_{id}^k)+c_2r_2(P_{gd}^k-x_{id}^k) \tag{17}$$

$$x_{id}^{k+1}=x_{id}^k+cv_{id}^{k+1} \tag{18}$$

where, $P_{id} = pbest$ and $P_{gd} = gbest$. Several modifications have been proposed in the literature to improve PSO algorithm speed and convergence toward the global minimum. One modification is to introduce a local-oriented paradigm (lbest) with different neighborhoods. It is concluded that gbest version performs best in terms of median number of iterations to converge. However, lbest version with neighborhoods of two is most resistant to local minima. PSO algorithm is further improved via using a time decreasing inertia weight, which leads to a reduction in the number of iterations [27]. It should be noted that choice properly fitness function is very important in synthesis procedure. Because different fitness functions promote different PSO behaviors, which generate fitness value providing a performance measure of the problem considered [14]. For our optimization problem, the flowing fitness function is introduced:

$$f(ITAE) = \frac{\sqrt{\sum_{i=1}^{3} ITAE_i}}{3} \quad , \quad ITAE_i = \int_0^t t\left|ACE_i\right| dt \tag{19}$$

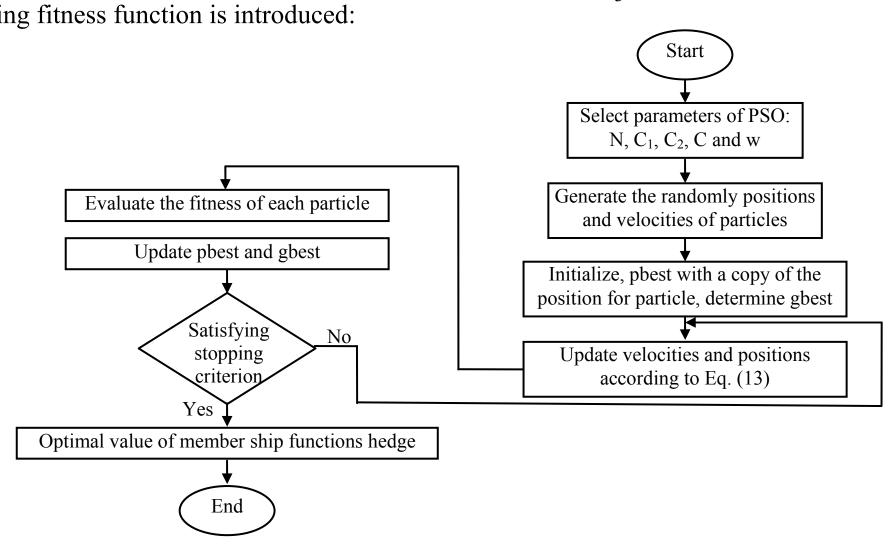

Figure 7. Flowchart of the proposed PSO technique for exact tuning of membership functions

Here, PSO procedure is applied for exact tuning of the membership functions of the proposed MSF controller for the solution of LFC problem. Results of the membership function set values without and with considering SMES unit are listed in Table 6. In order to acquire better performance, number of particle, particle size, number of iteration, c_1, c_2, c is chosen as 20, 500, 2, 2 and 1, respectively. Also, the inertia weight, ω, is linearly decreasing from 0.9 to 0.4.

Table 6. Optimal values of parameters *a* and *b* obtained with PSO

Membership function		ACE_i	ΔACE_i	$\int ACE$	Output
Without SMES	a	0.0563	0.0288	0.0362	0.1232
	b	0.1384	0.4014	0.4091	0.8016
With SMES	a	0.0929	0.6657	0.9319	0.4452
	b	0.0745	0.0184	0.0184	0.1835

V. SIMULATION RESULTS

In the simulation study, the linear model of turbine $\Delta PV_{ki}/\Delta PT_{ki}$ in Figure 3 is replaced by a nonlinear model of Figure 8 (with ±0.05 limit). This is to take GRC into account, i.e. the practical limit on the rate of the change in the generating power of each GENCO. The results in reference [20, 26] indicated that GRC would influence the dynamic responses of the system significantly and lead to larger overshot and longer settling time. Moreover, Simulation results and eigenvalue analysis show that the open loop system performance is affected more significantly by changing in the K_{pi}, T_{pi}, B_i and T_{jj} than changes of other parameters [24]. Thus, to illustrate the capability of the proposed strategy in this example, in the view point of uncertainty our focus will be concentrated on variation of these parameters.

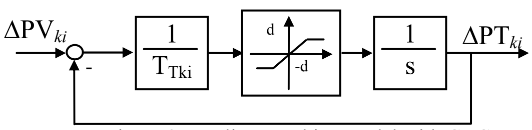

Figure 8. Nonlinear turbine model with GRC

The designed PSOMSF controller including a SMES unit in one area is applied for each control area of the restructured power system as shown in Figure 4. To illustrate robustness of the proposed control strategy against parametric uncertainties and contract variations, simulations are carried out for two scenarios of possible contracts under various operating conditions and large load demands. Performance of the proposed PSOMSF controller is compared with the designed PSOMSF controller without considering SMES unit in the power systems [16].

A. Scenario 1: Poolco Based Transactions

In this scenario, GENCOs participate only in the load following control of their areas. It is assumed that a large step load 0.1 pu is demanded by each DISCOs in areas 1 and 2. Assume that a case of Poolco based contracts between DISCOs and available GENCOs is simulated based on the following AGPM [14]. It is noted that GENCOs of area 3 do not participate in the LFC task.

$$AGPM = \begin{bmatrix} 0.6 & 0.5 & 0 & 0 & 0 & 0 \\ 0.4 & 0.5 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.5 & 0.5 & 0 & 0 \\ 0 & 0 & 0.5 & 0.5 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Also, assume, in addition to the specified contracted loead demands 0.1 pu MW, a step load change as a large uncontracted demand is appears in control area 1 and 2, where, DISCOs of areas 1 and 2 demands 0.1 and 0.06 pu MW of excess power, respectively. This excess power is reflected as a local load of the area and taken up by GENCOs in the same area. Thus, the total local load in 1 and 2 areas is computed as:

$\Delta P_{Loc,1}$=0.1+0.1+0.1=0.3 pu MW

$\Delta P_{Loc,2}$=0.1+0.1+0.06=0.26 pu MW

The frequency deviation of two areas and tie-line power flows with 25% increase in uncertain parameters K_{Pi}, T_{Pi}, B_i and T_{ij} are depicted in Figure 9. Using the MSFPSO controller designed by considering SMES unit, the frequency deviation of all areas and the tie-line power are quickly driven back to zero and has small overshoots. Since there are no contracts between areas, the scheduled steady state power flows, equation (10), over the tie-line are zero.

B. Scenario 2: Combination of Poolco and Bilateral Based Transactions

In this scenario, DISCOs have the freedom to have a contract with any GENCO in their or another areas. Consider that all the DISCOs contract with the available GENCOs for power as per following AGPM. All GENCOs participate in the LFC task.

$$AGPM = \begin{bmatrix} 0.25 & 0 & 0.25 & 0 & 0.5 & 0 \\ 0.5 & 0.25 & 0 & 0.25 & 0 & 0 \\ 0 & 0.5 & 0.25 & 0 & 0 & 0 \\ 0.25 & 0 & 0.5 & 0.75 & 0 & 0 \\ 0 & 0.25 & 0 & 0 & 0.5 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

It is assumed that a large step load 0.1 pu MW is demanded by each DISCOs in all areas. Moreover, DISCOs of areas 1, 2 and 2 demands 0.1, 0.05 and 0.02 pu MW (un-contracted load) of excess power, respectively. The total local load in areas is computed as:

$\Delta P_{Loc,1}$=0.1+0.1+0.1=0.3 pu MW

$\Delta P_{Loc,2}$=0.1+0.1+0.05=0.25 pu MW

$\Delta P_{Loc,3}$=0.1+0.1+0.02=0.22 pu MW

The purpose of this scenario is to test the effectiveness of the proposed controller against uncertainties and large load disturbances in the presence of GRC. Power system responses with 25% decrease in uncertain parameters K_{Pi}, T_{Pi}, B_i and T_{ij} are depicted in Figures 10 and 11. Using the MSFPSO controller designed by considering SMES unit, the frequency deviation of the all areas are quickly driven back to zero and has small settling time. Also, the tie-line power flow properly converges to the specified value, of equation (10), in the steady state case (Figure 10), i.e.; $\Delta P_{tie21,sch}$=0.025 and $\Delta P_{tie13,sch}$=0.025 pu MW. The un-contracted load of DISCOs in all areas is taken up by the GENCOs in these areas according to ACE participation factors in the steady state.

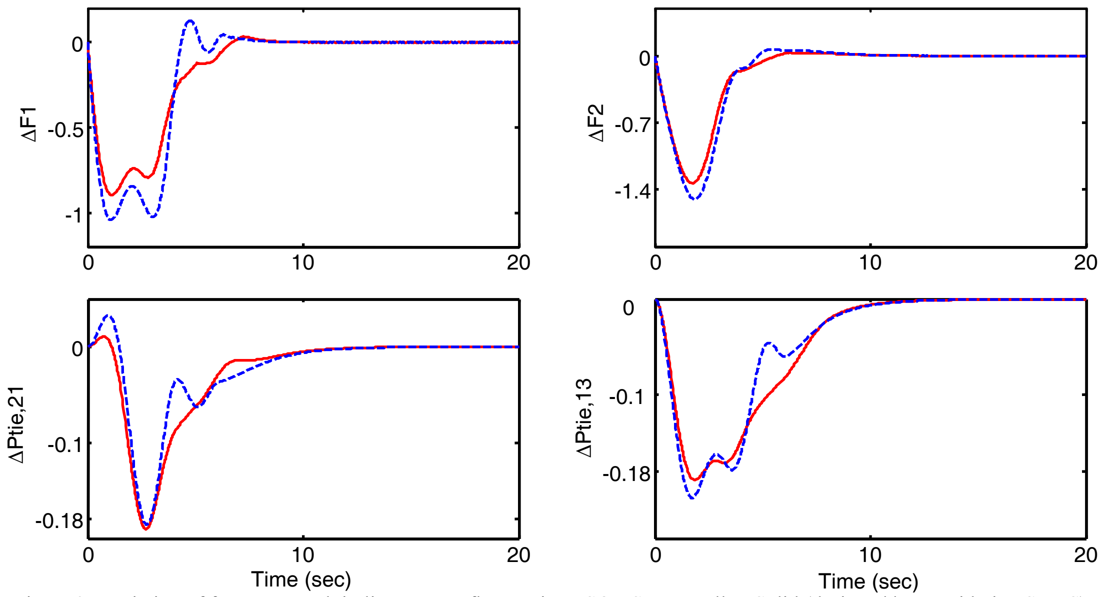

Figure 9. Deviation of frequency and tie-lines power flows using PSOMSF controller; Solid (designed by considering SMES) and Dashed (without SMES)

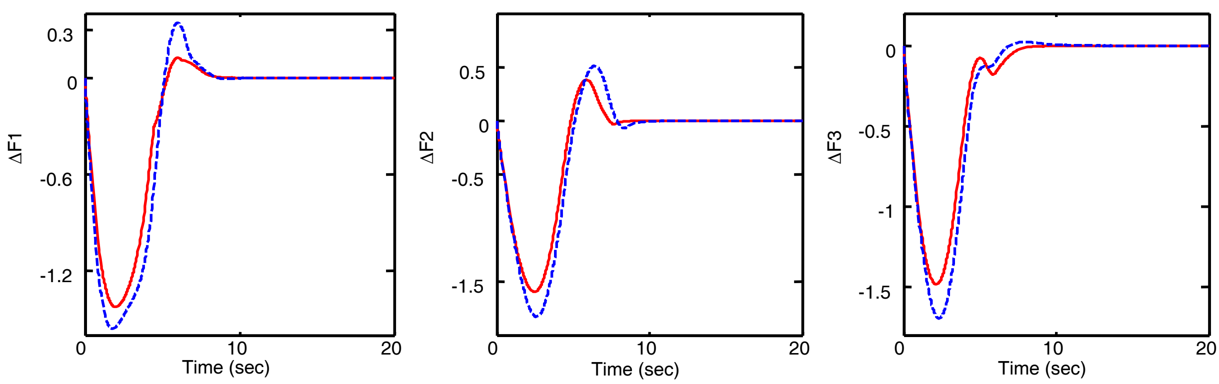

Figure 10. Deviation of frequency using PSOMSF controller; Solid (designed by considering SMES) and Dashed (without SMES)

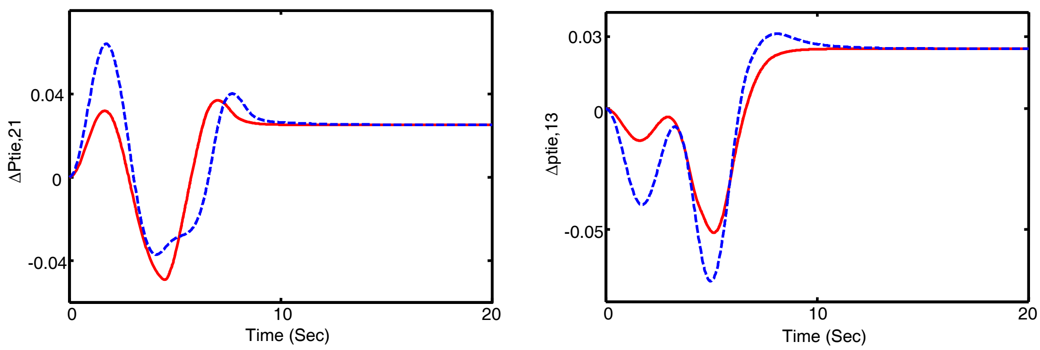

Figure 11. Deviation of tie lines power flows using PSOMSF controller; Solid (designed by considering SMES) and Dashed (without SMES)

The simulation results in the above scenarios indicate that the proposed control strategy can ensure the robust performance such as frequency tracking and disturbance attenuation for possible contracted scenarios under modeling uncertainties and large area load demands in the presence of GRC. Moreover, the simulations represent the positive effect of SMES unit on the improvement of the oscillation of frequency due to any load demands and disturbances.

VI. CONCLUSIONS

In this paper, a fuzzy controller by considering SMES unit is proposed for solution of the LFC problem. It was shown that addition of the SMES units to the system significantly improves transients of frequency and tie-line power deviations against load disturbances. Thus, to demonstrate technical and economic feasibility of them in the deregulated power system applications, a MSF controller is designed including SMES unit in some area of the power systems for solution of the LFC problem. Due to nonlinearity of the proposed fuzzy control structure a PSO based algorithm has been used for tuning of the membership functions automatically in order to reduce design effort and find better fuzzy system control. The simulation results on a three-area restructured power system show that with the use of a small capacity SMES in one area the dynamic performance of system such as frequency regulation, tracking the load changes and disturbances attenuation is significantly improved for a wide range of plant parameter and area load changes.

APPENDICES

Nomenclature

F	area frequency
P_{Tie}	net tie-line power flow turbine power
P_T	turbine power
P_V	governor valve position
P_C	governor set point
ACE	area control error
apf	ACE participation factor
Δ	deviation from nominal value
K_P	subsystem equivalent gain
T_P	subsystem equivalent time constant
T_T	turbine time constant
T_H	governor time constant
R	droop characteristic
B	frequency bias
T_{ij}	tie line synchronizing coefficient between areas i and j
P_d	area load disturbance
P_{Lj-i}	contracted demand of Disco j in area i
P_{ULj-i}	un-contracted demand of Disco j in area i
$P_{m,j-i}$	power generation of GENCO j in area i
P_{Loc}	total local demand
η	area interface
ζ	scheduled power tie line power flow deviation ($\Delta P_{tie,sch.}$)
I_d	inductor current in SMES unit
E_d	converter voltage applied to inductor in SMES unit
K_{SMES}	gain of control loop SMES
K_{id}	the gain for feedback ΔI_d in SMES unit
T_{dc}	converter time constant in SMES unit
u_{SMES}	control signal of SMES unit

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