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FUZZY PID CONTROLLER BASE ON LFC IN THE DEREGULATED POWER SYSTEM INCLUDING SMES

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Abstract- This paper presents a fuzzy PID control including SMES for the solution Load Frequency Control (LFC) problem in a deregulated power system that operate under deregulation based on the bilateral policy scheme. The SMES units and fuzzy PID controller are expected to compensate for the sudden load change, as the most effective contermeasure. In order to overcome difficulty of accuracy constructing the rule base in the fuzzy controller, the parameters of the proposed controller is tuned by Genetic Algorithm (GA). The aim is to reduce fuzzy system effort, find a better fuzzy system control and take large parametric uncertainties into account. This newly developed control strategy combines the advantage of SMES and fuzzy system control techniques and leads to a flexible controller with simple structure that is easy to implement. The proposed GA based FPID controller is tested on a three-area deregulated power system in the presence of an SMES unit in one area of the power system. Analysis reveals that the proposed control strategy with considering SMES unit improves significantly the dynamical performances of system such as settling time and overshoot against parametric uncertainties for a wide range of area load demands and disturbances in either of the areas even in the presence of system nonlinearities.

Keywords: LFC, SMES, Fuzzy PID Controller, Deregulated, GA.

I. INTRODUCTION

Global analysis of the power system markets shows that the frequency control is one of the most profitable ancillary services at these systems. This service is related to the short-term balance of energy and frequency of the power systems. The most common methods used to accomplish frequency control are generator governor response (primary frequency regulation) and Load Frequency Control (LFC). The goal of 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 [5]. 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. Efforts have been made to design load frequency controllers with better performance to cope with parameter changes, using various adaptive neural networks and robust methods [6-10]. The proposed methods show good dynamical responses, but robustness in the presence of model dynamical uncertainties and system nonlinearities were not considered. Also, some of them suggest complex state feedback or high order dynamical controllers, which are not practical for industry practices.

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] an improved control strategy based on fuzzy theory and Genetic Algorithm (GA) technique have been proposed. 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 rule bases. Because, it is a computationally expensive combinatorial optimization and also extraction of an appropriate set of rule bases from the expert may be tedious, time consuming and process specific. Thus, to reduce fuzzy system effort cost, in Ref. [14] the GA technique have been presented. It was shown that, the global optimal point is guaranteed and the speed of algorithms convergence is extremely improved.

Literature survey shows that, in most of the works concerned with LFC problem [2-15] 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 [16]. 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 [17-21] 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 FPID 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, GA technique is used for finding rule base of the proposed FPID controller.

The designed GA based FPID (GAFPID) controller with consideration SMES unit is tested on a three-area deregulated power system under different operating conditions in comparison with the designed GAFPID controller without consideration SMES [13] through some performance indices. The performance indices are chosen as the Integrated Square Error (ISE) 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. 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 Transactionsformer is mounted on each side of the converter unit to convert the high voltage and low current of the AC system to the low Volumetage 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 Volumetage 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 [17-22] 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.

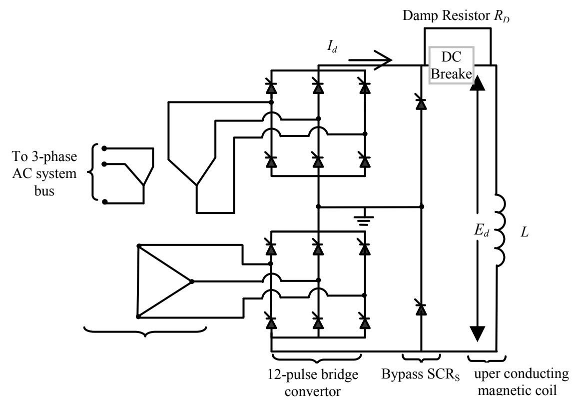

Figure 1. SMES circuit diagram

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 [21]:

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

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^o, 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 [17-22], 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:

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

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

In this study, as in recent literature, the input signal to the SMES control logic is considered the ACE_i of the same area in power system [16]. 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 transactions from AC grid to DC. Figure 2 shows block diagram of SMES unit.

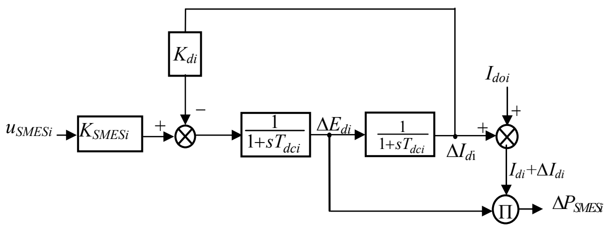

Figure 2. The block diagram of SMES unit

III. DESCRIPTION OF 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 [23], 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,

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

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

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 deregulated system is shown in Figure 3 with 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 shows the modified LFC scheme for control area i in a deregulated system. It can be seen from this figure that four input disturbance channels, d_i, η, ζ_i and ρ_i are considered for decentralized LFC design. They are defined as bellow:

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

$$\eta_i = \sum_{j=1, j\neq i}^{N} T_{ij} \Delta f_j \quad (8)$$

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

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

$$\Delta P_{tie,i-error} = \Delta P_{tie,i-actual} - \zeta_i \quad (11)$$

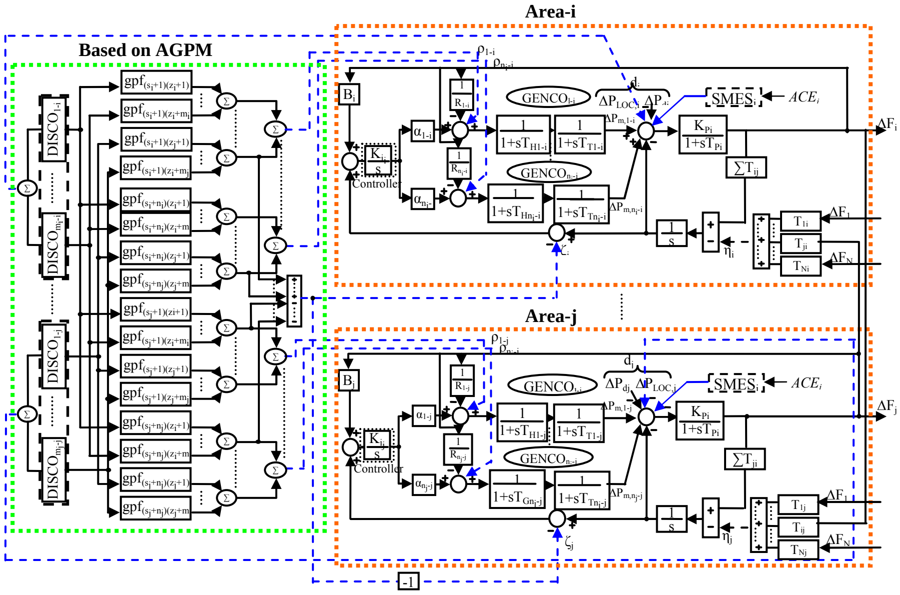

Figure 3. The generalized LFC scheme in the deregulated system

$$\rho_i = [\rho_{1i} \cdots \rho_{ki} \cdots \rho_{n_i i}]^T$$

$$\rho_{ki} = \sum_{j=1}^{N} [\sum_{t=1}^{m_j} gpf_{(s_i+k)(z_j+t)} \Delta P_{Lt-j}] \quad (12)$$

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

$\Delta P_{m,ki}$ 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 considering one SMES unit in areas 2, 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.

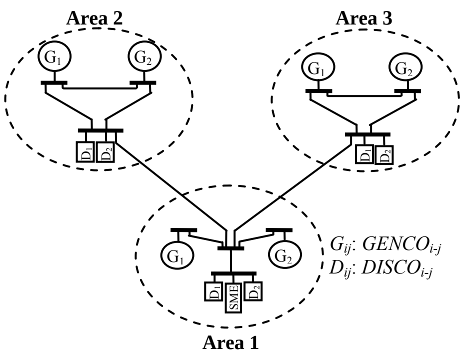

Figure 4. A three-area deregulated power system

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$_{base}$ (1000 MW) 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. GA BASED FPID CONTROLLER SCHEME

Fuzzy set theory and fuzzy logic establish the rules of a nonlinear mapping. The use of fuzzy sets provides a basis for a systematic way for the application of uncertain and indefinite models. Fuzzy control is based on a logical system called fuzzy logic is much closer in spirit to human thinking and natural language than classical logical systems. Nowadays fuzzy logic is used in almost all sectors of industry and science. One of them is power system control. Because of the complexity and multi-variable conditions of the power system, 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 in the power systems. In general, the application of fuzzy logic to PID control design can be classified in two major categories according to the way of their construction [12]:

1. A typical LFC is constructed as a set of heuristic control rules, and the control signal is directly deduced from the knowledge base.
2. The gains of the conventional PID controller are tuned on-line in terms of the knowledge based and fuzzy inference, and then, the conventional PID controller generates the control signal.

Figure 5 shows the block diagram of fuzzy type controller to solve the A problem for each control area (Figure 3).

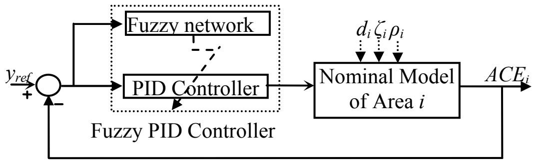

Figure 5. The proposed FPID controller design problem

In the design of fuzzy logic controller, there are five parts of the fuzzy inference process:
1. Fuzzification of the input variables;
2. Application of the fuzzy operator (AND or OR) in the antecedent;
3. Implication from the antecedent to the consequent;
4. Aggregation of the consequents across the rules;
5. Defuzzification.

According to the control methodology as given in Ref. [11] a fuzzy PID controller for each of three areas is designed. The proposed controller is a two-level controller. The first level is fuzzy network and the second level is PID controller. The structure of the classical FPID controller is shown in Figure 6.which in the PID controller gains is tuned online for each of the control areas.

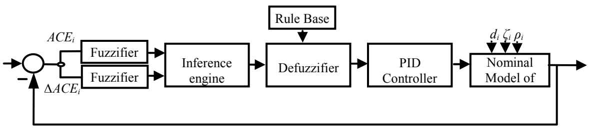

Figure 6. The scheme of Fuzzy Network

The controller block is formed by fuzzification of Area Control Error (ACE_i), the interface mechanism and defuzzification. There for U_i is a control signal that applies to governor set point in each area. By taking ACE_i as the system output, the control vector for a conventional PID controller is given by:

$$u_i = K_{Pi} ACE_i(t) + K_{Ii}\int_0^t ACE_i(t)dt + K_{di} A\dot{C}E(t) \qquad (14)$$

In this strategy, the conventional controller for LFC scheme (Figure 3) is replaced by a fuzzy PID type controller. The gains K_{Pi}, K_{Ii} and K_{di} in Equation (14) are tuned on-line in terms of the knowledge base and fuzzy inference, and then, the conventional PID controller generates the control signal. The motivation of using the fuzzy logic for tuning gains of PID controllers is to take large parametric uncertainties, system nonlinearities and minimizing of area load disturbances.

Fuzzy logic shows experience and preference through its membership functions. These functions have different shapes depending on the system expert’s experience. The membership function sets for ACE_i, ΔACE_i, K_{Ii}, K_{di} and K_{pi} are shown in Figure 7.

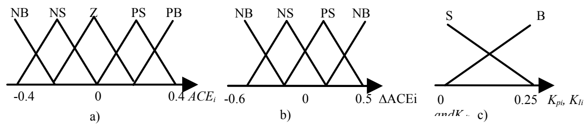

Figure 7. (a) Membership for ACE_i (b) Membership for ΔACE_i (c) Membership for K_{Ii}, K_{Pi} and K_{di}

A major problem plaguing the effective use of this method is the difficulty of accurately constructing the rule bases. Because, it is a computationally expensive combinatorial optimization and also extraction of an appropriate set of rule bases from the expert may be tedious, time consuming and process specific. Thus, to reduce fuzzy system effort cost, in [15] a GA have been proposed. It was shown that, the global optimal point is guaranteed and the speed of algorithms convergence is extremely improved, too. GA’s are search algorithms based on the mechanism of natural selection and natural genetics. They can be considered as a general-purpose optimization method and have been successfully applied to search and optimization [14].

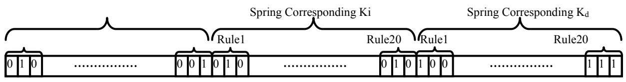

Figure 8. Encoding for fuzzy rule table

In the GA just like natural genetics a chromosomes (a string) will contain some genes. These binary bits are suitably decoded to represent the character of the string. A population size is chosen consisting of several parent strings. The strings are then subjected to evaluation of fitness function. The strings with more fitness function will only survive for the next generation, in the process of the selection and copying, the string with less fitness function will die. The former strings now produce new off-springs by crossover and some off-springs undergo mutation operation depending upend mutation probability to avoid premature convergence to suboptimal condition. In this way, a new population different from the old one is formed in each genetic iteration cycle. The whole process is repeated for several iteration cycles until the fitness function of an offspring is reach to the maximum value. Thus, that string is the required optimal solution. For our optimization problem, the new following fitness function is proposed:

$$f = \frac{1}{1 + MSE(PerformanceIndex)} \qquad (15)$$

$$MSE(PerformanceIndex) = (\sqrt{\sum_{i=1}^{3} 100\int_0^t t\left|ACE_i\right|dt})/3$$

A string of 180 binary bits reprints gains of PID controller in three areas (Figure 8), population size and maximum generation are 20 and 100, respectively. The least MSE is the better string. The better string survives in the next population. Based on the roulette wheel, some strings are selected to make the next population. After the selection and copying the usual mutual crossover of the string (crossover probability is chosen 97%) and mutation of some of the string (mutation probability is chosen 8%)

are performed. In this way, new offspring of rule sets are produced in the total population then system performance characteristics and corresponding fitness value are recomputed for each string. Thus, the sequential process of fitness function, selection, crossover, mutation evaluation completes genetic iteration cycle.

In the GAs rule base optimization we assume that the fuzzy sets C_i and D_i are characterized by the membership functions shown in Figure 9.

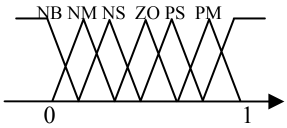

Figure 9. Membership function for K_{Ii}, K_{Pi} and K_d

The proposed method was applied to the LFC task in the deregulated power system. The plot of obtained fitness function value is shown in Figure 10. It can be seen that the fitness value increases monotonically from 0.1521 to 0.2769 in 97 generations. The fuzzy rule base is listed in Tables 4, 5 and 6.

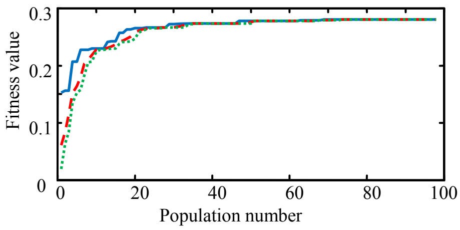

Figure 10. Convergence procedure of GA to obtain fuzzy rule table Solid (Max. value), Dashed (Mean Value) and Dated (Min. value)

Table 4. Rule Table for K_{Ii}

		ΔACE_i NB	NS	PS	PB
ACE_i	NB	NM	NB	NB	NB
	NS	NM	NB	NB	NM
	Z	NB	PB	PB	NM
	PS	PM	PB	PB	PB
	PB	PS	NM	NM	PM

NB=Negative Big, NS= Negative Small, Z=Zero, PS=Positive Small, PB= Positive Big

Table 5. Rule Table for K_{Pi}

		ΔACE_i NB	NS	PS	PB
ACE_i	NB	NS	PS	NB	NB
	NS	PB	NM	ZO	NM
	Z	NB	PB	NS	PM
	PS	PB	PM	NB	PB
	PB	NB	NS	NB	NM

NB=Negative Big, NS= Negative Small, Z=Zero, PS=Positive Small, PB= Positive Big

Table 6. Rule Table for K_{di}

		ΔACE_i NB	NS	PS	PB
ACE_i	NB	NS	PS	NB	NB
	NS	PB	NM	ZO	NM
	Z	NB	PB	NS	PM
	PS	PB	PM	NB	PB
	PB	NB	NS	NB	NM

NB=Negative Big, NS= Negative Small, Z=Zero, PS=Positive Small, PB=Positive Big

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 11 (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 [22] 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 [25]. Also, from the point view of economy SMES unit is considered only one of three areas in the power system [21]. Thus affirmative effect of SMES on LFC is also taken into account in this study. Therefore, 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.

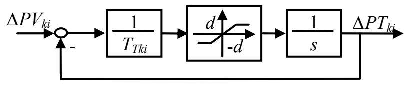

Figure 11. Nonlinear turbine model with GRC

The designed GAFPID controller including a SMES unit in one area is applied for each control area of the deregulated 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 GAFPID controller is compared with designed GAFPID controller without considering SMES unit in power systems.

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. 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 flow with 25% increase in all parameters K_{Pi}, T_{Pi}, B_i and T_{ij} are depicted in Figure 12. Using the FPID controller designed with 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, Eq. (10), over tie-line are zero.

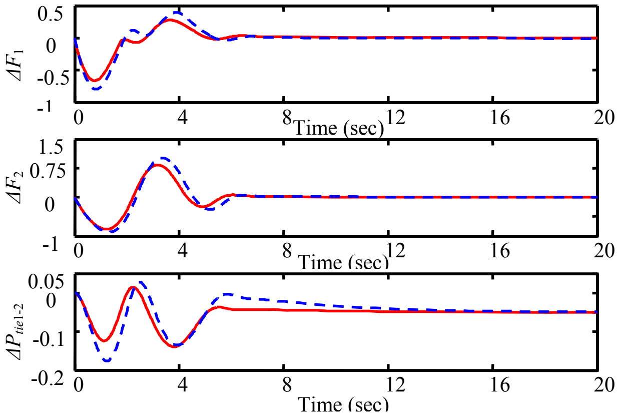

Figure 12. Deviation of frequency and tie-lines power flows using GAFPID controller; Solid (designed with considering SMES) and Dashed (without SMES)

B. Scenario 2: 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. It is assume that a large step load 0.1 pu MW is demanded by each DISCOs in all areas. Moreover, it is assumed that 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

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

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 systems responses with 25% decrease in uncertain parameters K_{Pi}, T_{Pi}, B_i and T_{ij} are depicted are shown in Figures 13 and 14. Using the GAFPID controller designed with 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 14), i.e.; $\Delta P_{tie12,sch}$=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. 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 improvement of the oscillation of frequency due to any load demands and disturbances.

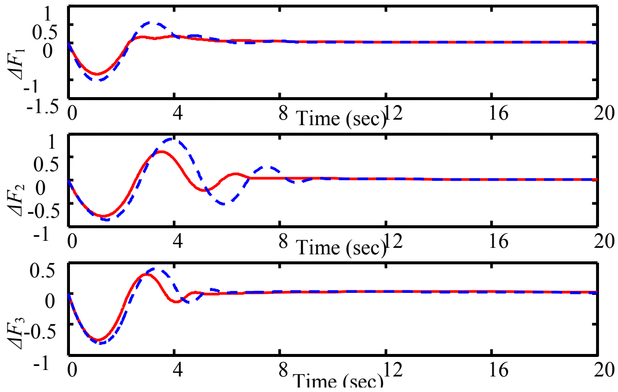

Figure 13. Deviation of frequency sing GAFPID controller; Solid (designed with considering SMES) and Dashed (without SMES)

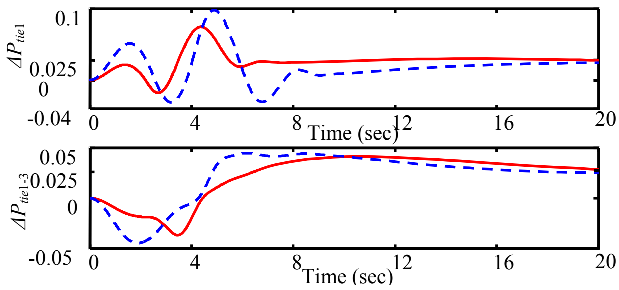

Figure 14. Deviation of tie lines power flows using GAFPID controller; Solid (designed with considering SMES) and Dashed (without SMES)

To demonstrate performance robustness of the proposed method, the ISE, ITAE and FD indices based on system performance characteristics are being used as:

$$ISE = 1000\int_0^{20}\sum_{i=1}^{3} ACE_i(t)^2 dt \qquad (16)$$

$$ITAE = 100\int_0^{20} t\sum_{i=1}^{3}\left|ACE_1(t)\right| dt \qquad (17)$$

$$FD = (OS\times 14)^2 + (US\times 7)^2 + (T_s\times 1)^2 \qquad (18)$$

where, Overshoot (OS), Undershoot (US) and settling time (T_s) (for 5% band of the total load demand in area 1) of frequency deviation area 1 is considered for evaluation of the FD. The value of ISE, ITAE and FD is calculated for scenarios 1 and 2 whereas the system parameters are varied from -25% to 25% of the nominal values and shown in Figures 15, 16 and 17. It can be seen that the GAFPID controller designed with considering small capacity SMES has robust performance against system parametric uncertainties and possible contract scenarios even in the presence of GRC and the system dynamic performances is significantly improved.

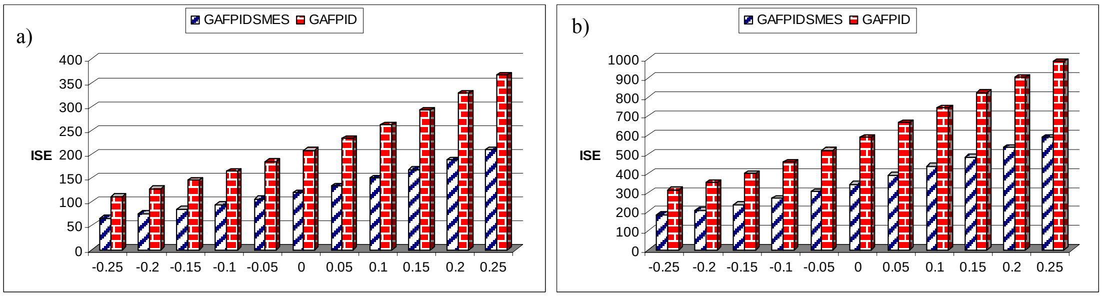

Figure 15. Value of ISE for system parameters variation: (a) Scenario 1, (b) Scenario 2

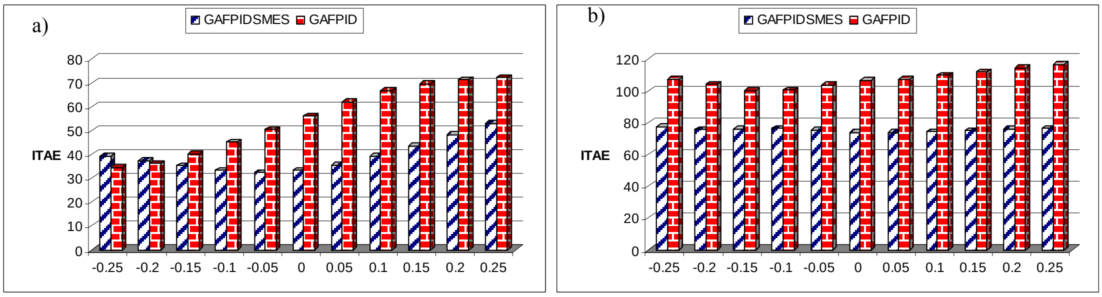

Figure 16. Value of ITAE for system parameters variation: (a) Scenario 1, (b) Scenario 2

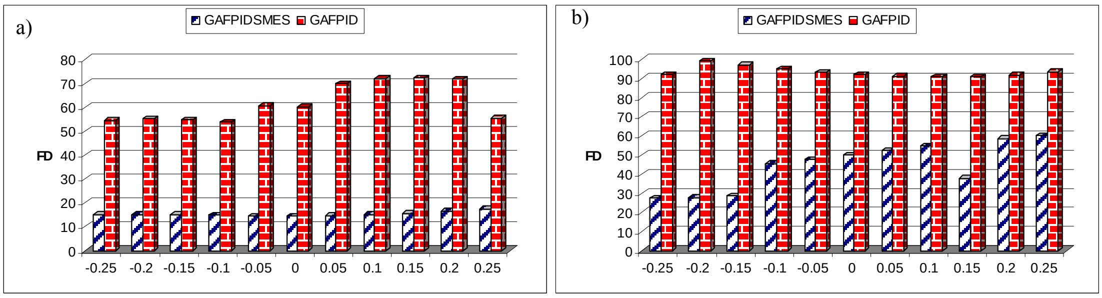

Figure 17. Value of FD for system parameters variation: (a) Scenario 1, (b) Scenario 2

VI. CONCLUSIONS

In this paper a Genetic Algorithm based fuzzy PID (GAFPID) type controller is proposed for solving the Load Frequency Control (LFC) problem including Super conducting Magnetic Energy Storage (SMES) in a deregulated power system that operate under deregulation based on the bilateral policy scheme. This control strategy was chosen because of increasing the complexity and changing structure of power systems. In order to reduce design effort and find better fuzzy system control, a GA with a strong ability to find the most optimistic results algorithm has been used to fuzzy controller rule bases. The aim is to reduce fuzzy system effort, find a better fuzzy system control and take large parametric uncertainties into account.

The effectiveness of the proposed method is tested on a three-area deregulated power system for a wide range of load demands and disturbances under different operating conditions. The simulation results show that with the use of a small capacity SMES in some 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. The system performance characteristics in terms of *ISE*, *ITAE* and *FD* indices reveal that the designed GAFPID controller with considering SMES unit is a promising control scheme for the solution of LFC problem and therefore it is recommended to generate good quality and reliable electric energy in the deregulated power systems.

NOMENCLATURES

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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