Dynamic Participation of Gencos in SMES Based Competitive Electricity Market

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Abstract: - A dynamic participation of Gencos in a Superconducting Magnetic Energy Storage (SMES) unit based multi-area Automatic Generation Control scheme is presented. In this paper, SMES units have been used to the power systems to inject or absorb active power. Developed scheme utilizes a proportional, integral and derivative (PID) controller to control the output of the generators. The parameters of PID controller have been tuned according to Genetic Algorithm (GA) based performance indices. The developed Genetic Algorithm based PID (GAPID) controller has been tested on a practical Indian power system network representing 75- bus system. A deregulated electricity market scenario has been assumed in the 75- bus system, which has been divided into four control areas. Mixed transaction (Poolco and bilateral) has been considered in the frequency regulation. The effect of generator rate constraint (GRC) has also been included in developing the multi area AGC model.

Key-Words: - Automatic Generation Control (AGC), Genetic Algorithm, Super-conducting Energy Storage (SMES) unit, Generator Rate Constraints.

1 Introduction

Modern power system consists of number of control areas interconnected together and power is exchanged between control areas over tie-lines by which they are connected. In order to achieve interconnected operation of a power system, an electric energy system must be maintained at a desired operating level characterized by nominal frequency, voltage profile and load flow configuration. This is achieved by close control of real and reactive powers generated through the controllable source of the system. Automatic generation control (AGC) plays a significant role in the power system by maintaining scheduled system frequency and tie line flow during normal operating condition and also during small perturbations. Many investigations in the area of isolated and interconnected power systems have been reported in the past. The concept of conventional AGC is discussed in [1]–[3].

Around the world, the electric power industry has been undergoing reforms from the traditional regulated, vertically integrated utility into a competitive, deregulated market. Market deregulation has caused significant changes not only in the generation sector, but also in the power transmission and distribution sectors and has introduced new challenges for market participants. A detailed discussion on Load Frequency Control issues in power system operation after deregulation is reported in reference [4].

The application of Superconducting Magnetic Energy Storage (SMES) to electric power systems can be grouped into two categories [5]: (1) large scale energy storage like conventional pumped hydro plant storage meant for diurnal load leveling application and (2) low capacity storage to improve the dynamic performance of the power system. In the first case, large sized (hundreds of meters in diameter) high capacity superconducting magnets capable of storing 10^2 MJ are necessary [6]. For the second application, very small sized SMES units with storage capacity of the order of 18 MJ or even less would be sufficient. Several design methods of AGC, which is equipped with SMES, have been successfully proposed in ref. [7-9].

In this work, first a multi-area AGC scheme suitable in a restructured power system has been developed then a Genetic Algorithm based PID (GAPID) controller has been proposed for this multi area AGC scheme. Integral of the square of the area control error (ISACE) have been utilized to select the fitness function for genetic algorithm. The population size 50 has been chosen for genetic algorithm to obtain the optimal values of PID controller.

The proposed GAPID based AGC scheme has been tested on a 75-bus Indian power system divided into four control areas. A deregulated electricity market scenario has been assumed in both systems. The effect of generator rate constraint (GRC) has also been considered in the multi area AGC model. A combination of bilateral transactions and Poolco-based transactions has been considered, and it has been assumed that both the generators and the consumers are participating in the frequency regulation market. The performance studies have been carried out by using the MATLAB SIMULINK for transactions within and across the control area boundaries.

2 Problem Formulation

Introduction of competition in electricity market may cause emergence of several new entities, such as Generating companies (Gencos), Transmission companies (Transcos), and Distribution companies (Discos) and system operator (SO). The system operator is an entity entrusted with the responsibility of ensuring the reliability and security of the power system. It is an independent entity and does not participate in the electricity trading. In order to maintain the system security and reliability, the SO procures various services, such as supply of emergency reserves, frequency regulation and reactive power from the other entities in the system. These services are known as the ‘ancillary services’. In a competitive electricity environment, Poolco as well as bilateral transactions may take place simultaneously.

2.1Pool co Based Transaction

In Poolco based transaction [10], the Discos and Gencos of the same area participate in the frequency regulation through system operator. System operator (SO) accepts bids (volume and price) from power producers (Gencos) who are willing to quickly (with in about 10-15 minutes) increase or decrease their level of production. Consumers (Discos) also can submit bids to SO for increasing or decreasing their level of consumption. In each hour of operation, the SO activates the most favorable bid.

If the frequency is lower than nominal value, up regulation bids are activated by the System Operator in steps and the highest activated bid becomes the regulation price, uniformly paid to all the providers of upward regulation service. If the frequency is higher than nominal, down regulation is activated by the System Operator in steps and the lowest activated bid price becomes the uniform price, to be paid by all the down regulation service providers. Thus, the hourly regulating price is fixed as the price for the most expensive measure (regulating up) or least expensive measure (regulating down) utilized during the hour. At the end of scheduled interval, the net energy balance of each entity is calculated and financial settlements are carried out.

2.2 Bilateral Transaction

In bilateral transaction [11-14], Gencos and Discos negotiate bilateral contracts among each other and submit their contractual agreements to a system operator (SO). The players are responsible for having a communication path to exchange contract data as well as measurements to do load following in real-time. In such an arrangement, a Disco sends a pulse to Genco to follow the predicted load as long as it does not exceed the contracted value. The responsibility of the Disco is to monitor its load continuously and ensure the loads following requirements are met according to the contractual agreement. A detailed discussion on bilateral transactions is given in [14].

In this work, bilateral transactions within the area and across the area have been considered. Disco of one area can contract to the Genco of same area or other area to supply a certain amount of power in a specified time interval. These bilateral contracts can be represented in the matrix form in which the number of rows equal to the number of Gencos and column equal to the number of Discos in the system. The elements of this Contract Participation Matrix (CPM) represent the percentage load demand of one Disco to different Gencos. Let us consider a Contract Matrix as given below:

$$CPM = \begin{bmatrix} 0 & 10 & . & . & . \\ 20 & 10 & . & . & . \\ 10 & . & . & . & . \\ & . & & & . \\ . & & & & \\ . & . & . & . & . \\ . & & & & \\ 0 & 0 & . & . & . \end{bmatrix}$$

For example, the first column of CPM represents the Disco D1 bilateral contract with different Gencos. Element CPM_{21} is 20 which mean 20% of total demand of Disco D1 in the schedule time interval will be supplied by the Genco G2. Sum of the elements of any column represents the percentage of total demand of that Disco which will be supplied by the bilateral contracts. Rest of the demand will be supplied by the Poolco transactions.

In case of Poolco transaction tie-line power between area-i and area-j is settled at zero value. But in case of bilateral transition the tie-line power is not settled at zero value but settled according to the bilateral contract between Gencos of one area and Discos of other area.

2.3 Calculation of Area Control Error (ACE)

In a practical multi area power system, a control area is interconnected to its neighboring areas with tie lines, all forming part of the overall power pool. If P_{ij} is the tie line real power flow from an area-i to another area- j and m is the total number of areas, the net tie line power flow from area-i will be

$$P_{tie-i} = \sum_{\substack{j=1 \\ j \neq i}}^{m} P_{ij} \tag{1}$$

In a conventional AGC formulation, P_{tie-i} is generally maintained at a fixed value. However, in a deregulated electricity market, a Disco may have contracts with the Gencos in the same area as well as with the Gencos in other areas, too. Hence, the scheduled tie-line power of any area may change as the demand of the Disco changes.

Thus, the net change in the scheduled steady-state power flow on the tie line from an area- i can be expressed as

$$P_{tie-new} = \Delta P_{tie-i} + \sum_{\substack{j=1 \\ j \neq i}}^{m} D_{ij} - \sum_{\substack{j=1 \\ j \neq i}}^{m} D_{ji} \tag{2}$$

Where, P_{tie-i} is the change in the scheduled tie-line power due to change in the demand, D_{ij} is the demand of Discos in area-j from Gencos in area-i , and D_{ji} is the demand of Discos in area- i from Gencos in area-j.

Generally, P_{tie-i} =0 (Conventional AGC). During the transient period, at any given time, the tie-line power error is given as:

$$\Delta P_{tie-i-error} = \Delta P_{tie-i-actual} - \Delta P_{tie-i-new} \tag{3}$$

This error signal can be used to generate the Area Control Error (ACE) signal as:

$$ACE_i = B_i \Delta f_i + \Delta P_{tie-i-error} \tag{4}$$

Where, B_i is the frequency bias factor and Δf_i is the frequency deviation in area-i.

2.4 Control System of SMES

When there is sudden rise in power demand in a control area, the stored energy is almost immediately released by the SMES through its power conversion system (PCS). As the governor control mechanism starts working to set the power system to the new equilibrium condition, the SMES coil stores energy back to its nominal level. Similar action happens when there is a sudden decrease in load demand. Basically, the operation speed of governor-turbine system is slow compared with that of the excitation system. As a result, fluctuations in terminal voltage can be corrected by the excitation system very quickly, but fluctuations in generated power or frequency are corrected slowly.

Neglecting the transformer and the converter losses, the DC voltage is given by

$$E_d = 2U_{do} \cos\gamma - 2I_d R_c \tag{5}$$

where E_d is DC voltage applied to the inductor (kV), γ is firing angle (degrees), I_d is current flowing through the inductor (kA), R_c is equivalent commutating resistance (Ω) and U_{do} is maximum circuit bridge voltage (kV). The schematic diagram of SMES unit is shown in Fig.1 [7].

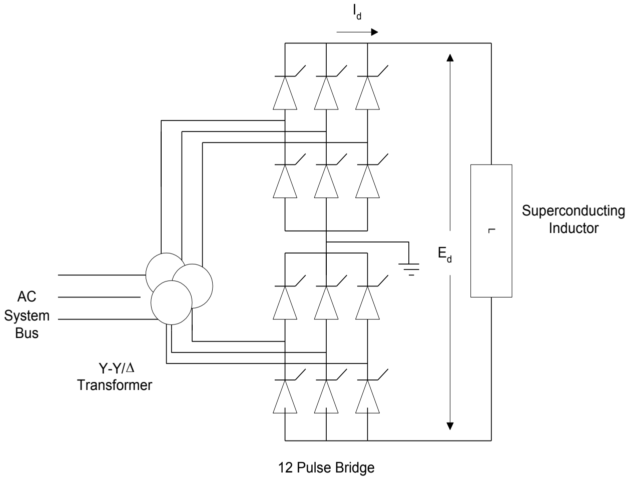

Fig. 1: SMES unit.

Fig. 2 shows the proposed configuration of SMES units in a four-area power system. Areas 1 and 3 have installed SMES1 and SMES3 in order to stabilize frequency oscillations. By controlling the active power injected/absorbed of SMES1 and SMES3, the frequency oscillations in areas 1 and 3 can be effectively damped. In this study, inductor voltage deviation of SMES unit of each area is based on ACE of the same area. The inductor current deviation is used as a negative feedback signal in the SMES control loop. If the load demand changes suddenly, the feedback provides quickly restoration of current.

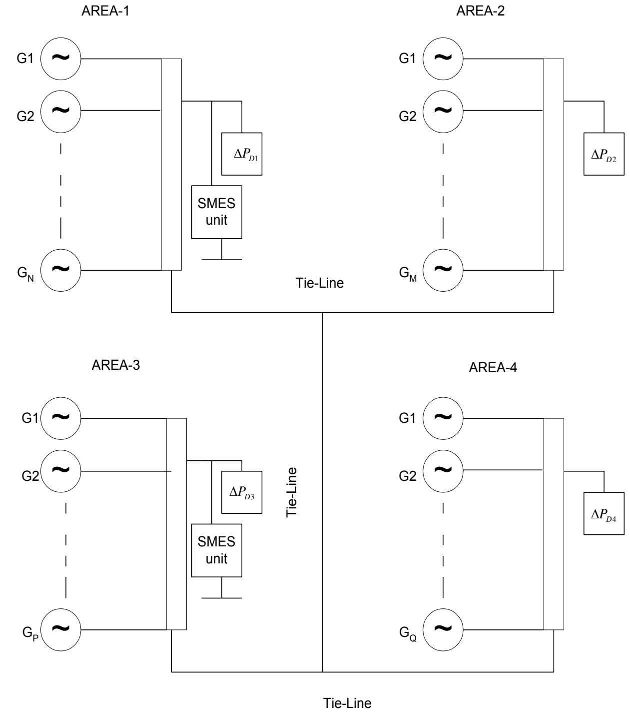

Fig 2: Configuration of four-area system with SMES

The change in voltage across the inductor [8] is expressed as:

$$\Delta E_{di} = \frac{K_{SMES}}{1+sT_{dc}}[(\Delta f_i + \frac{1}{B_i}\Delta P_{tie-i-error}) - K_{id}\Delta I_d] \tag{6}$$

The proposed simple control scheme for SMES, which is incorporated in the two control area to reduce the instantaneous mismatch between the demand power and generation power, as shown in Fig. 3 [8] , Where, ΔI_d is the incremental change in SMES current (kA); T_{dc} is the converter time delay (Sec.); K_{SMES} is the gain of the SMES control loop for ACE signal (kV/unit ACE); K_{id} is the gain of the inductor current deviation feedback loop (kV/kA) L is the inductance of SMES coil, P_{SM} is Power into the inductor at any time respectively.

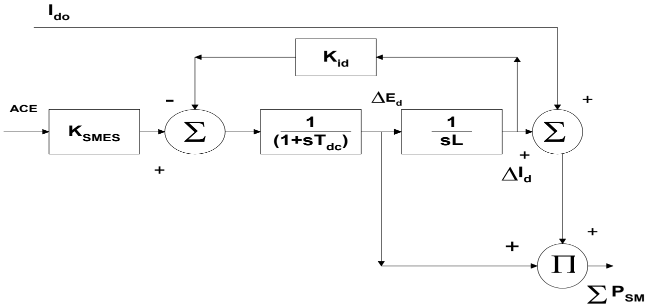

Fig. 3: SMES control scheme

2.5 Generation Rate Constraint (GRC)

In any practical electrical power generating system, due to thermodynamic and mechanical constraints, there is a limit to the rate at which its output power can be changed. This limit is referred to as generator rate constraint (GRC). A Saturation nonlinearity is shown in Fig. 4 is considered for Generation Rate Constraint (GRC). S_{max} is the maximum capacity of the generating plant. S is the slope representing the rate of change of generator output.

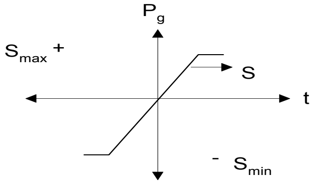

Fig. 4: Saturation non-linearity

There may be a number of Gencos in the i^{th} area. Fig.5 represents the block diagram of the k^{th} Genco in area-i. The pf is the Gencos participation factor as described in the section 2.1 , R_i is the droop, and G_g and G_t represents the transfer function model of Governor and turbine respectively, and are expressed as [1], $G_g = \frac{1}{1+sT_g}$, where T_g is the governor time constant and

$G_t = \dfrac{1}{1+sT_t}$, where T_t is the turbine time constant. $\Delta P_{G1}, \Delta P_{G2}, \ldots\ldots.., \Delta P_{GK}, \ldots\ldots\Delta P_{Gn}$ represents the change in the output of area-*i* Gencos. The net change in area-i generation is $\Delta P_{Gi} = \Delta P_{G1} + \Delta P_{G2} + \ldots\ldots. + \Delta P_{GK} + \ldots.\Delta P_{Gn}$, where n is the total number of Gencos in area-*i*. There may be number of Discos in the i^{th} area. If $\Delta P_{D1}, \Delta P_{D2}, \ldots\ldots\Delta P_{Dp}, \ldots.\Delta P_{DK}$ represents the change in load demand of Discos in the area-*i*.

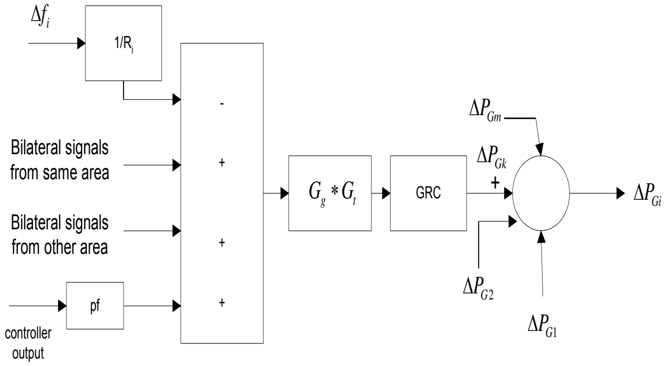

Fig. 5: Block Diagram of Genco-k of area-i.

The overall block diagram of AGC scheme including SMES unit for an ith area of m-area power system is shown in Fig.6.
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Mathematical Equations must be numbered as follows: (1), (2), …, (99) and not (1.1), (1.2),…, (2.1), (2.2),… depending on your various Sections.

3 PID Controller Tuning Using Genetic Algorithm

The form of a PID controller can be expressed as the sum of three terms, proportional, integral, and derivative control. The transfer function of such a PID controller can be expressed as:

$$G_C(s) = K_p + \frac{K_i}{s} + K_d s$$

Where, K_p, K_i, K_d are the proportional, integral and derivative gain constant of the controller. Optimal values of K_p, K_i, K_d can be determined by many ways, one of them, is suggested by the Donde et al [14]. A Genetic Algorithm based minimization approach to determine the values of K_p, K_i, K_d has been developed in this work [15].

Genetic Algorithms are based on Darwin's theory of natural selection and survival of the fittest. It is a heuristic optimization technique for the most optimal solution (fittest individual) from a global perspective but more importantly, it provides a mechanism by which solutions can be found to complex optimization problems fairly quickly and reliably. Following are the important terminology in connection with the genetic algorithm [16]:

Individual - An individual is any point to which objective function can be applied. It is basically the set of values of all the variables for which function is going to be optimized. The value of the objective function for an individual is called its *score*. An individual is sometimes referred to as a *genome* and the vector entries of it as *genes*.

Population – It is an array of individuals. For example, if the size of the population is 100 and the number of variables in the objective function is 3, population can be represented by a 100-by-3 matrix in which each row correspond to an individual.

Generation - at each iteration, the genetic algorithm performs a series of computations on the current population to produce a new population by applying genetic operators. Each successive population is called a new generation.

Parents and children - To create the next generation, the genetic algorithm selects certain individuals in the current population, called parents, and uses them to create individuals in the next generation, called children. Following three genetic operators [20] are applied on parents to form children for next generation:

1. *Reproduction* - Selects the fittest individuals in the current population to be used in generating the next population. The children are called *Elite children.*

2. *Cross-over* - Causes pairs of individuals to exchange genetic information with one another. The children are called *Crossover children.*

3. *Mutation* - Causes individual genetic representations to be changed according to some probabilistic rule. The children in this case are called *Mutation* children.

In GA's the value of fitness represents the performance which is used to rank 0 and the ranking is then used to determine how to allocate reproductive opportunities. This means that individual with a higher fitness value will have a higher opportunity of being selected as a parent. The fitness function is essentially the objective function for the problem. The fitness function taken in the present work, is integral of the square of the area control error (ISACE). By considering m-areas in a system, equation (7) represent the ISACE criterion as follows,

$$ISACE = \int \sum_{i=1}^{m} (ACE_i)^2 dt \tag{7}$$

Subjected to

$$K_{p,i}^{\min} \le K_{p,i} \le K_{p,i}^{\max},\ K_{i,i}^{\min} \le K_{i,i} \le K_{i,i}^{\max},$$
$$K_{d,i}^{\min} \le K_{d,i} \le K_{d,i}^{\max}$$

Where, K_{pi}, K_{ii}, K_{di} are the proportional, integral and derivative gains of the PID controller of i^{th} area, $K_{pi}^{\min}, K_{ii}^{\min}, K_{di}^{\min}$ and $K_{pi}^{\max}, K_{ii}^{\max}, K_{di}^{\max}$ are the lower bounds and upper bounds of the PID controller.

With the above description, the procedure of applied genetic algorithm for the tested system in this work is given below:

a) Generate randomly a population of parameter strings to form parameter vector.Calculate the fitness function as given in the equation (7) for each *Individual* in the population.

b) Create *Parents.*

c) Evaluate the *children* and calculate the fitness function for each *Parent.*

d) If the fitness function of the *Parents* is reached to the maximum value, stop and return; else go to step (c).

Genetic algorithm parameters are taken as given below

The number of population = 50

The number of generation = 100

The probability of crossover is 0.8

The mutation function taken is Gaussian

The fitness scaling function is Rank

In this work, the GA optimization toolbox GAOT in MATLAB proposed by C. R. Houck et al. [17] is used to determine the values of K_p, K_i, K_d .

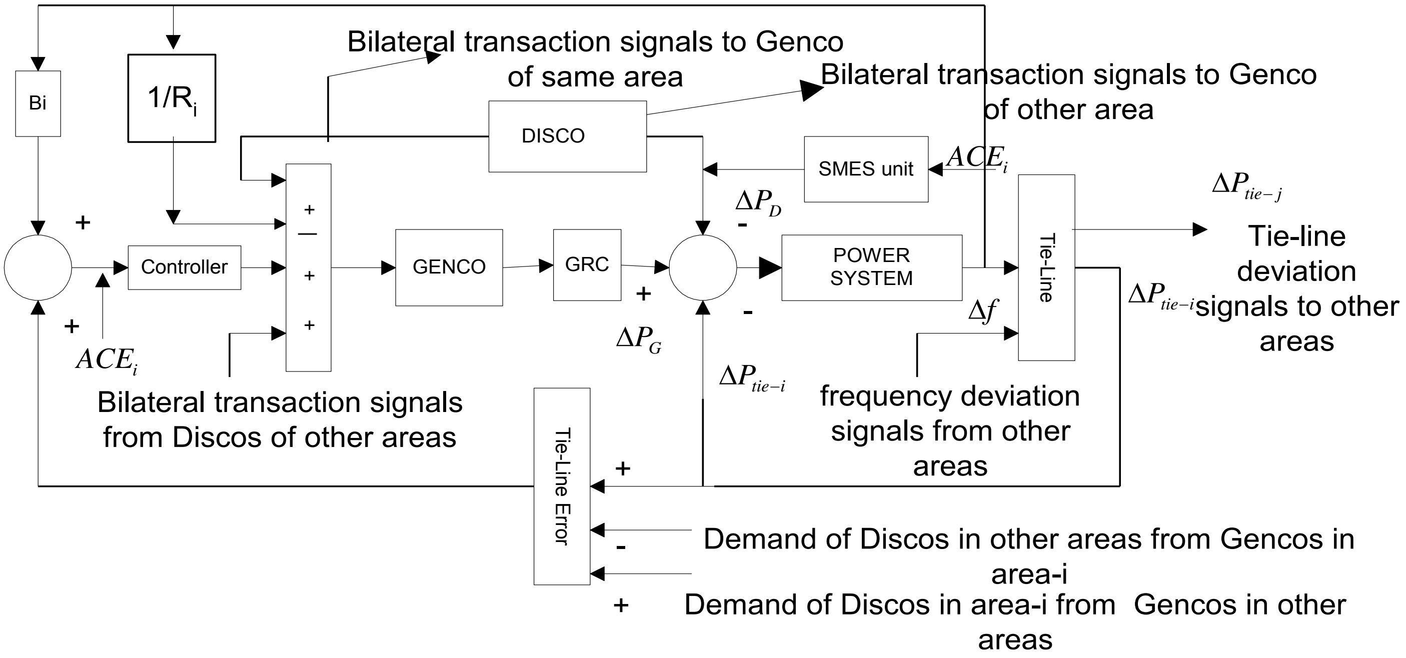


Fig. 6: AGC Block Diagram for Area-i

5 Simulation Results

The proposed GAPID controller for a multi-area power system, described in the previous section, and has been tested on a 75-bus Indian system [18]. The 75-bus system divided into four control areas. The number of Gencos participating in the frequency regulation market in the 75-bus system is given in Table1. A general purpose Governor- Turbine model has been used, which is taken from [19].

TABLE 1: CONTROL AREAS IN 75-BUS INDIAN POWER SYSTEM

Control Area	*Area Rating(MW)*	*Market Participants*
Area-1	460	Genco 1,2,3,
Area-2	994	Genco 4,5,6,7,8
Area-3	400	Genco 9,10
Area-4	4470	Genco11,12,13,14,15

To simulate the 75-bus system, it is assumed that the only generators are participating in the frequency regulation, and the loads are not participating in the market. The Gencos bids for area-2 were assumed as given in Table 2 and 3.

TABLE 2: GENCOS BIDS IN AREA-2

Gencos	*Price(Rs./KWh)*	*Capacity(MW)*
Genco-4	4.1	25.0
Genco-5	4.3	25.0
Genco-6	4.7	25.0
Genco-7	4.6	25.0
Genco-8	4.9	25.0

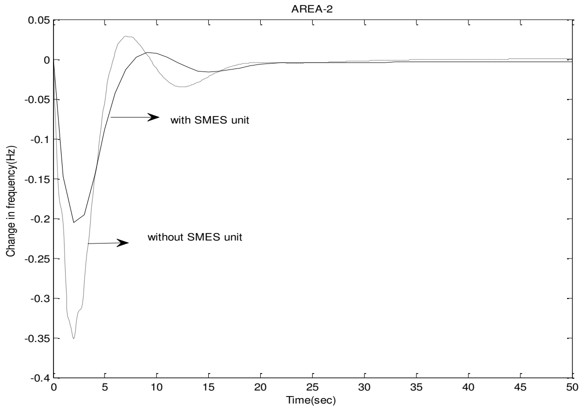
TABLE 3: GENCOS BIDS IN AREA-4

Gencos	*Price(Rs./KWh)*	*Capacity(MW)*
Genco-11	5.6	15.0
Genco-12	4.7	25.0
Genco-13	4.9	25.0
Genco-14	5.6	25.0
Genco-15	4.3	35.0

Assume a step change in load demand of area-1 by 0.1087 p.u (50 MW), area-2 by 0.0503 p.u. (50 MW), area-3 by 0.125 p.u. (50 MW) and area-4 by 0.0224 p.u. (100 MW) at time t=0. The changes in load demand of area-2 and area-4 are met according to their bilateral and Poolco transactions. The Bilateral transactions considered between various Gencos are given below.

- The 10% power demand of area-1 is contracted with Genco-5 of area-2.
- The 10% power demand of area-2 is contracted with Genco-4 itself and 20% power is contracted with Genco-11 of area-4.
- No bilateral transaction is considered in area-3.
- The 10% power demand of area-4 is contracted with Genco-5 of area-2 and 20% power demand is contracted with Genco-12 of area-4.

The results of frequency deviations in area-2 and 4 are shown in Fig.7 (a). The effect of SMES units in the corresponding area suppressed fluctuations in the frequency more quickly as compared to the configuration without SMES unit. Further, presence of SMES improves the frequency response as well.



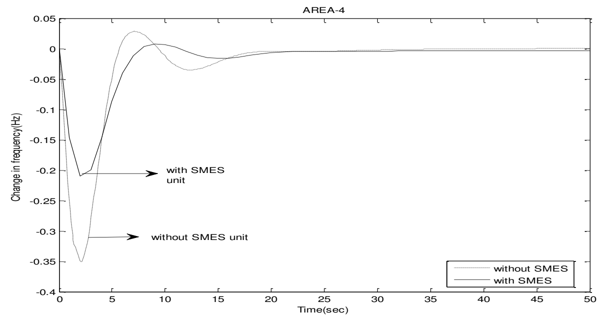
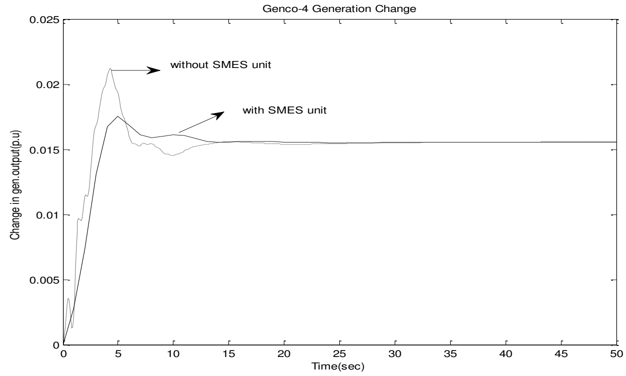
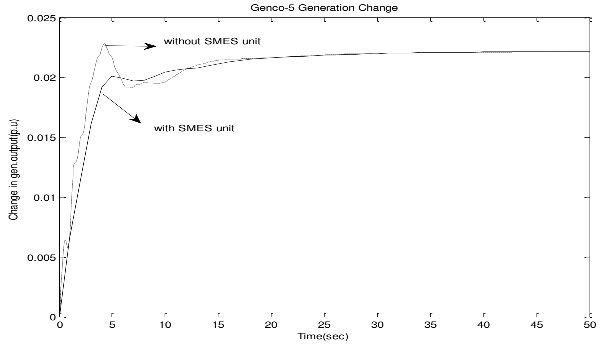
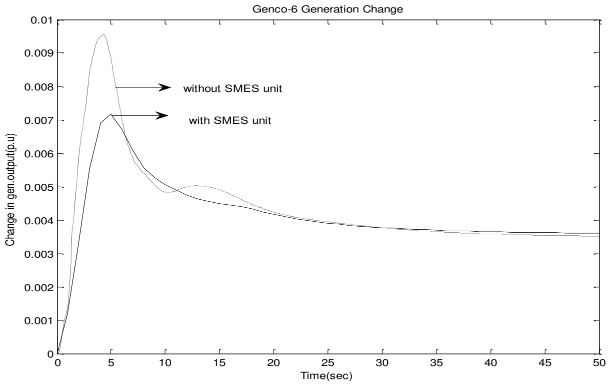


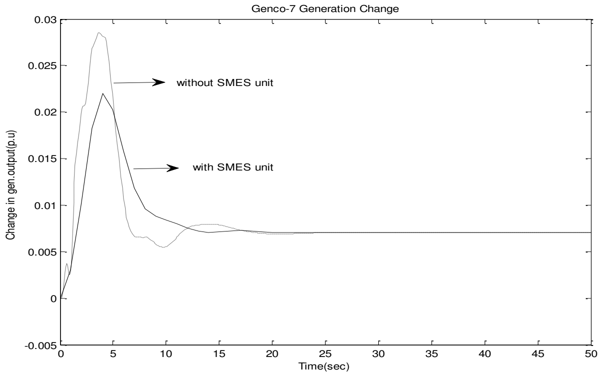
Fig. 7(a): Area-2 and 4 Frequency Deviations in Hz

The change in generation (p.u) in all the gencos of area-2 and 4 are shown in Fig. 7(b) and 7 (c) with and without SMES unit using GAPID controller. Application of SMES unit has been used in the present work to inject active power in an interconnected power system. This function of SMES unit has also been allowed the participated Gencos according to their participation factor (pf). The simulated results supported this statement.









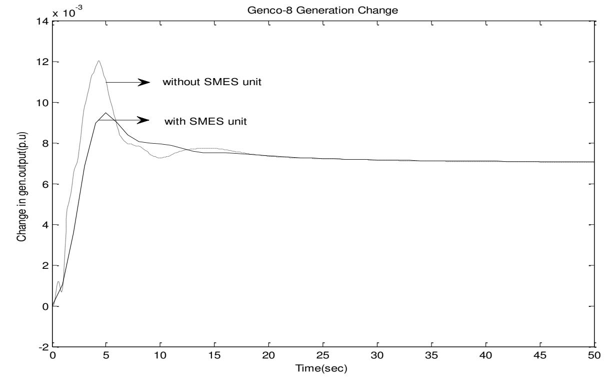
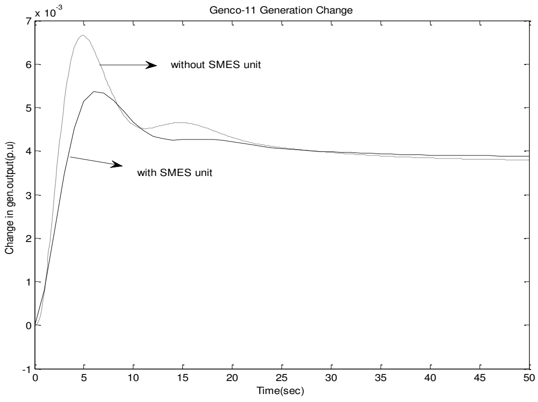


Fig. 7(b): Area-2 Change in generation in p.u.



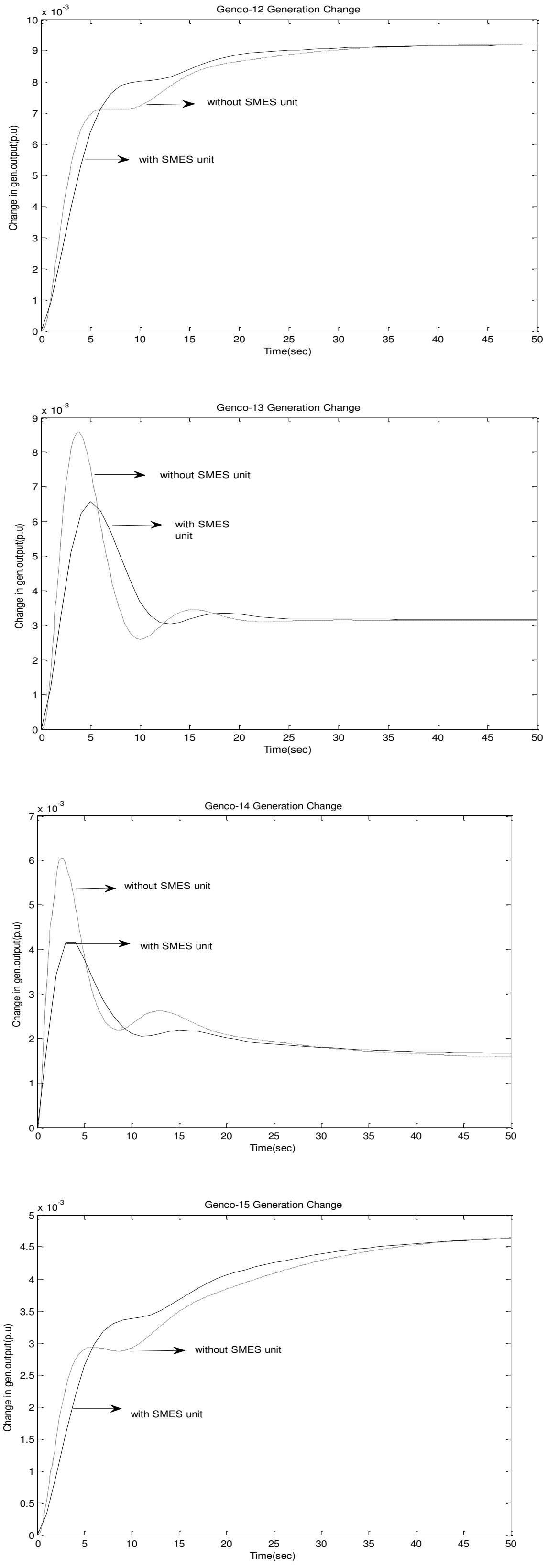


Fig. 7(c): Area-4 Change in generation in p.u.

6 Conclusion

A Genetic Algorithm based PID (GAPID) controller for multi-area AGC, suitable for the restructured competitive electricity market, has been proposed in this paper to meet the Poolco-based as well as mixed (Poolco & bilateral) transactions. The investigation shows that for the mixed transactions, the response is faster and less undershoots with SMES unit compared to without SMES unit. Effort has been made in this paper to reduce the cost incurred by earlier proposed systems by having SMES unit located only in one area to regulate multi-area frequency. Further, it has been shown that the system frequency and tie-line power oscillations can be effectively damped out with the use of a small capacity SMES unit in either of the areas following a step load disturbance. It has also been observed that the use of ACE for the control of SMES unit substantially reduces the peak deviations of frequencies and tie-power responses. Results of the GAPID based controller have been obtained with and without SMES unit. The result shows that the performance of the GAPID controller with SMES unit is better than the performance without SMES unit.

APPENDIX

SMES unit data [8, 9]:

$L = 2.65$ H

$T_{DC} = 0.03$ s

$K_{SMES} = 100$ kV/unit MW

$K_{id} = 0.2$ kV/kA

$I_{d0} = 4.5$ kA

TABLE A.I PARAMETERS OF PID CONTROLLER WITHOUT SMES UNIT

Genetic Algorithm based optimal values of PID			
Control Area	K_p	K_i	K_d
Area-1	-0.7412	-0.4989	0.1859
Area-2	1.4524	-3.0132	0.0028
Area-3	-0.8090	-1.9705	-0.0156
Area-4	0.8975	-0.1773	-0.0206

TABLE A.II PARAMETERS OF PID CONTROLLER WITH SMES UNIT

Genetic Algorithm based optimal values of PID			
Control Area	K_p	K_i	K_d
Area-1	-0.1	- 1.66558	0.12533
Area-2	0.28768	-1.14647	1.19092
Area-3	1.18916	0.03763	0.32729
Area-4	0.17464	-0.18671	0.72579

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