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Regular paper

Performance of SMES unit on Artificial Neural Network based Multi-are AGC scheme

This work investigates the performance of Superconducting Magnetic Energy Storage (SMES) unit on Artificial Neural Network (ANN) based multi-area AGC scheme. SMES units have been used to the power systems to inject or absorb active power. A three layer feed forward neural network (NN) is proposed for controller design and trained with Back propagation algorithm (BPA). The poolco based transaction can be implemented by optimizing the bids (price & capacity) submitted by the generating companies (Gencos) and distribution companies (Discos). The functioning of the proposed ANN based controller has been demonstrated on a two-area System.

Keywords: Automatic Generation Control, artificial neural network, Superconducting Magnetic Energy Storage (SMES).

1. Introduction

The parallel operation of interconnected systems is the today's requirement with the increase of size of electric power system, controlling the frequency of interconnected power system has becoming the challenge for control engineer. The deviation of the frequencies and tie-line power arise because of unpredictable load variations, which occur due to a mismatch between the generated and the demanded power. The main objective of providing an Automatic Generation Control (AGC) has been to maintain the system frequency at nominal value and the power interchange between different areas at their scheduled values. The concepts of the conventional AGC are well discussed in [1-4]. After the deregulation of the electricity sector, there will be many market players, such as generating companies (Gencos), distribution companies (Discos), transmission company (Transco), and system operator (SO). For stable and secure operation of a power system, the SO has to provide a number of ancillary services. One of the ancillary services is the "frequency regulation" based on the concept of the load frequency control. A detailed discussion on Load Frequency Control issues in power system operation after deregulation is reported in [5]. In a practical power system, there may be more than two areas, and each of the areas may have different ratings. Authors in reference [6-10] consider that the SMES units in each area of the two-area system for AGC. With the use of SMES units, frequency deviations in each area are effectively suppressed. However, it may not be economically feasible to use SMES unit in every area of a multi-area interconnected power system. Therefore, it is advantageous if an SMES unit located in an area is available for the control of frequency of other interconnected areas. In the paper, ANN controller is used because the controller provides faster control than the others. The proposed ANN controller uses back propagation-through time algorithm [11]. In the study, neural network technique is considered to control interconnected power system with three areas connected with tie-lines

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to each other to supply different consumers, and it is shown that the NN configuration using back propagation through- time algorithm and applied for AGC at power system gives better dynamic response than conventional integral controller. In this work, a general model for multi-area AGC suitable for a competitive electricity environment has been proposed. A deregulated electricity market scenario has been assumed in four area systems. A feed forward Neural Network has been designed to eliminate the frequency error in the developed model. Area Control Error (ACE) and the load disturbance have been taken as the input to the Neural Network and the output of the ANN is processing the changes required in the governor inputs to eliminate the frequency error. A back propagation Algorithm has been used to train the Artificial Neural Network offline. Effect of SMES unit on the dynamic performances is also studied. The performance studies have been carried out by using the MATLAB SIMULINK for transactions within and across the control area boundaries.

2. Notation

The notation used throughout the paper is stated below.

Constants:

C_{reg}	Cost of regulating power
CPM	Contract Participation Matrix
P_{ij}	Tie line real power flow from an area-i to another area- j
P_{tie-i}	Net tie line power flow from area-i
ACE	Area Control Error
B_i	Frequency Bias factor in area-i
Δf_i	Frequency deviation in area-i.

3. Problem formulation

3.1. Objective function

A competitive electricity market may have following transactions:

i. Poolco based transactions
ii. Bilateral transactions
iii. Mixed (Poolco and Bilateral) transactions

3.1.1 Poolco based transaction

In Poolco based transaction [12], 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. When regulation is needed, the SO activates the most favorable bid.
Let there be n number of power producers and m number of consumers participating in the market. Assume that the bids submitted by the power producers and the consumers, for frequency regulation are (pg(1),pg(2),…….,(pg(n),cg(n)) and (pl(1),cl(1)),(pl(2),cl(2)),………..(pl(m),cl(m)), respectively [13]. Where, pg(i) is the price for regulating power quoted by ith Genco for upward regulation, Cg(i) is the capacity quoted by ith Genco for upward regulation, i=1,2,…..n, pl(j) is the price for regulating power quoted by jth Disco for upward regulation, Cl(j) is the capacity quoted by jth Disco for upward regulation, j=1,2,…..m. If Tdem is the total extra demand that arises in the hour of operation in any area for upward regulation, the participation factor of each Genco and Disco in that area can be calculated by minimizing the cost of regulating power

$$C_{reg} = \sum_{i=1}^{n} pg(i) * gen(i) + \sum_{j=1}^{m} pl(i) * load(j) \tag{1}$$

subject to a set of constraints

$$gen(i) + load(j) = T_{dem}$$

$$gen(i) \le cg(i)$$

$$load(j) \le cl(j)$$

Participation factor of the ith Genco

$$pgf(i) = \frac{gen(i)}{T_{dem}} \tag{2}$$

Participation factor of the jth Disco

$$pfd(j) = \frac{load(j)}{T_{dem}} \tag{3}$$

3.1.2 Bilateral transactions

In bilateral transaction [12-16], 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 [16].

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 CM represents the Disco D1 bilateral contract with different Gencos. Element CM_{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.

3.2 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

$$P_{tie-i} = \sum_{\substack{j=1 \\ j\neq i}}^{m} P_{ij} \tag{4}$$

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

$$P_{tie-new} = \Delta P_{tie-i} + \sum_{\substack{j=1 \\ j\neq i}}^{m} D_{ij} - \sum_{\substack{j=1 \\ j\neq i}}^{m} D_{ji} \tag{5}$$

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

$$\Delta P_{tie-i-error} = \Delta P_{tie-i-actual} - \Delta P_{tie-i-new} \tag{6}$$

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

$$ACE_i = B_i \Delta f_i + \Delta P_{tie-i-error} \tag{7}$$

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

There may be a number of Gencos in the i^{th} area. Fig.1 represents the block diagram of the k^{th} Genco in area-i. The pf is the Gencos participation factor as described in the section II (B) , 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], $G_g = \dfrac{1}{1+sT_g}$, where T_g is the governor time constant and $G_t = \dfrac{1}{1+sT_t}$, where T_t is the turbine time constant. $\Delta P_{G1}, \Delta P_{G2}, \ldots\ldots\ldots, \Delta P_{GK}, \ldots\ldots \Delta P_{Gn}$ 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.

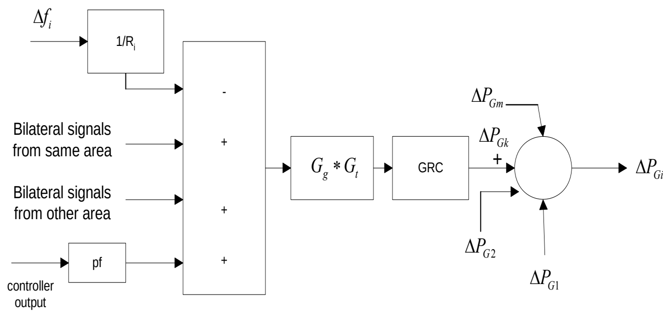


Fig 1. Block Diagram of Genco-k of area-i.

4. Control system of SMES

The schematic diagram in Fig. 2 shows the configuration of a thyristor controlled SMES unit [17]. Control of the converter firing angle provides the DC voltage E_d appearing across the inductor to be continuously varied between a wide range of positive and negative values. The inductor is initially charged to its rated current I_{d0} by applying a low positive voltage. Once the current reaches the rated value, it is maintained constant by reducing the voltage across the inductor to zero since the coil is superconducting [7-10].
Neglecting the transformer and the converter losses, the DC voltage is given by

$$E_d = 2\, U_{do} \cos\gamma - 2\, I_d R_c \qquad (8)$$

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, is equivalent commutating resistance (Ω) and U_{dO} is maximum circuit bridge voltage (kV).

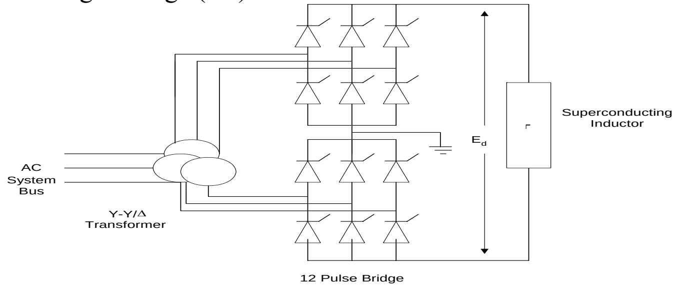


Fig.(2) SMES unit

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. The change in voltage across the inductor [7] is expressed as:

$$\Delta E_{di} = \frac{K_{SMES}}{1+sT_{dc}}[(\Delta f_i + \frac{1}{B_i}\Delta P_{tie-i-error}) - K_{id}\Delta I_d] \quad (9)$$

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 feedgack loop (kV/kA).

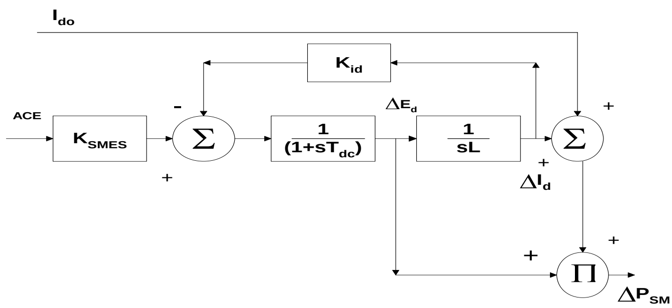


Fig. (3) SMES control scheme [8].

Fig. 4 shows the proposed configuration of SMES units in a two-area power system. Only Areas 1 have installed SMES1 and in order to stabilize frequency oscillations. By controlling the active power injected/absorbed of SMES1, the frequency oscillations in areas 1 and 3 can be effectively damped.

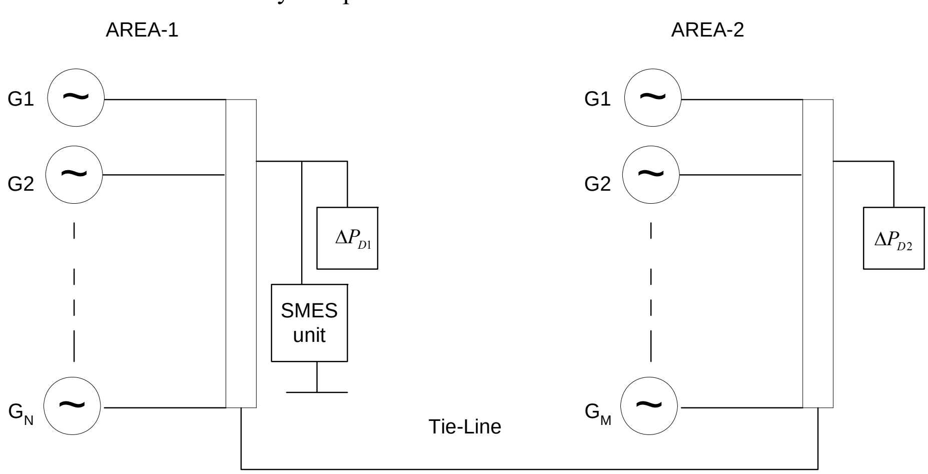


Fig. 4. Configuration of four-area interconnected power system with SMES.

The overall block diagram of AGC scheme including SMES unit for an i[th] area of m-area power system is shown in Fig.5.The power system block represents the power system dynamics given by, $\frac{K_{pi}}{1+sT_{pi}}$,where K_{pi} is the system gain and is equivalent to

$1/D_i$ where D_i is the rate of change of load demand ΔP_D to the change in frequency Δf and is expressed in Hz/pu MW and T_{pi} is the time constant and is equivalent to $2H_i/(f^*D_i)$ where, the parameter H_i is the per –unit inertia constant.

In Fig.4 ΔP_D is the total demand of area-i. The part of area demand is fulfilled by bilateral transactions, and the rest of the demand will be arranged by the system operator through Poolco-based contracts.

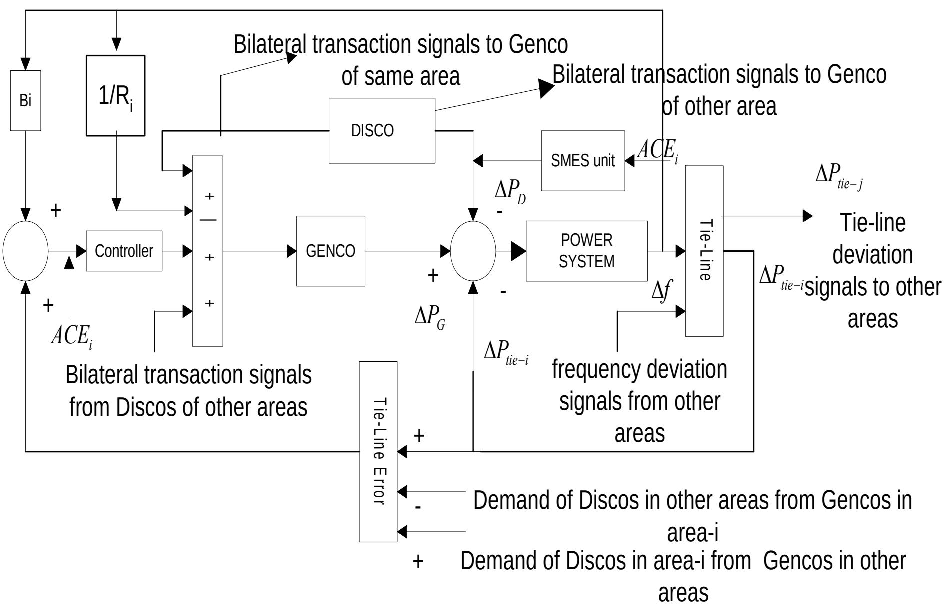


Fig. 5 AGC Block Diagram For Area-i

5. **Controller Design Using Neural Network**

The conventional PID controller is replaced by artificial neural network (ANN) trained controller to improve the dynamic response during the step load change of Discos for multi area AGC scheme. Each area is equipped by a neural controller as shown in figure 5. The best value for controller parameters is obtained by training the ANN off line at different load parameters through Back propagation algorithm (BPA). The inputs to the neural controller are the ACE (Area control error) and a reference load variation.

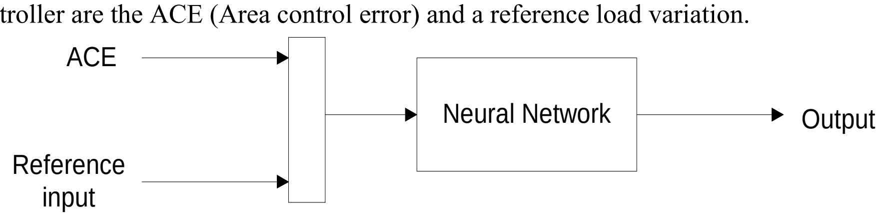


Fig. 6 ANN controller

The output of controller is the signal is settled at a point according to the net Discos demand to the area. The neural network has been designed by taking two input nodes, one hidden layer and one output layer. The transfer function used in hidden layer is Tan-sigmoid and output layer is linear. The basic structure of controller is given in Fig [11] below

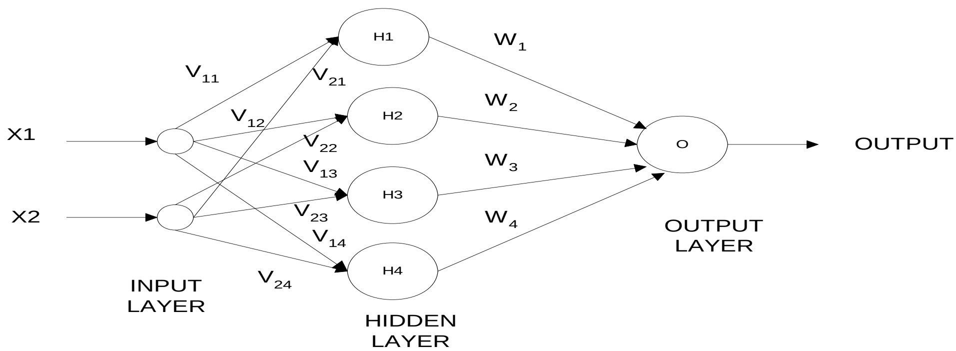


Fig. 7 Structure of Neural Network

The controller has designed by taking four neurons in hidden layer and one neuron in the output layer. The ANN controller is trained by using back propagation algorithm which is well explained in [17-18]. For training purpose more than 10000 sample data samples has been taken. The training data is collected from SIMULINK block diagram by variation of DISCOS demand and participation factor. The neural network is trained for 300 epochs. The best values of weights are obtained by minimizing the error through Gradient Descent optimization technique.

6. Case study

The proposed ANN based controller has been tested on a 39-bus New England Power System [14]. In the present paper, a deregulated market scenario has been assumed in the system. It has been divided into two control areas. The SMES unit is included only in area-1. The number of Gencos and Discos in the 39-bus system is given in Table 1. A general purpose Governor-Turbine model has been used, which is taken from [19].

Table I

CONTROL AREAS IN 39- BUS SYSTEMS

Control Area	Area Rating(MW)	Market Participants
AREA-1	400	Genco 1,2,3,4,5
AREA-2	500	Genco 6,7,8,9,10

To simulate the 39-bus system, it is assumed in the study that Discos are not participating in the frequency regulation; therefore gencos of each area share the load demand of their area as per their participation factors.

Table II

GENCOS AND DISCOS BIDS IN AREA-1 OF 39-BUS SYSTEM

Gencos/Discos	Price(Rs./KWh)	Capacity(MW)
Genco-1	4.0	30.0
Genco-2	5.1	20.0
Genco-3	6.0	20.0
Genco-4	4.9	25.0
Genco-5	5.5	25.0

Table III

GENCOS AND DISCOS BIDS IN AREA-2 OF 39-BUS SYSTEM

Gencos/Discos	Price(Rs./KWh)	Capacity(MW)
Genco-6	4.6	25.0
Genco-7	4.4	30.0
Genco-8	4.9	20.0
Genco-9	6.0	25.0
Genco-10	5.7	25.0

Assume a step change in load demand of area-1 by 0.125 pu (50 MW) and area-2 by 0.1 pu (50 MW) at time t=0. To meet these changes in load demand, Gencos responses were obtained using MATLAB Simulation with Artificial Neural Network based (ANN) controllers for the proposed multi-area AGC scheme. The change in load demand of any area is met by the Gencos in the same area, according to their mixed (poolco based and bilateral) transactions. The Bilateral transactions considered between various Gencos and Discos are given below.

- The 10% power demand of area-1 is contracted with Genco-6 of area-2.
- The 10% power demand of area-2 is contracted with Genco-8 itself.

The results of frequency deviations in area-2 and 4 are shown in Fig.8 (a). The change in generation (p.u) in all the gencos of area-1 and 2 are shown in Fig. 8(b) and 8 (c) with and without SMES unit using ANN controller.

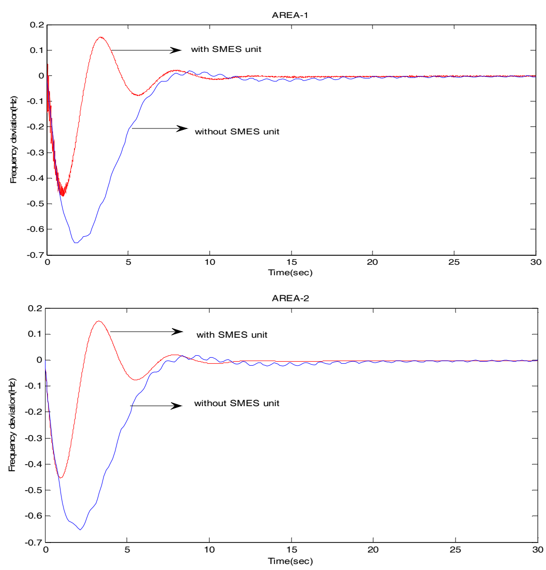
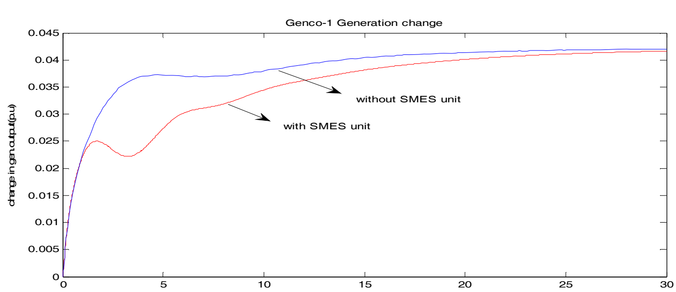


Fig. 8(a) Area-1 and 2 Frequency Deviations in Hz



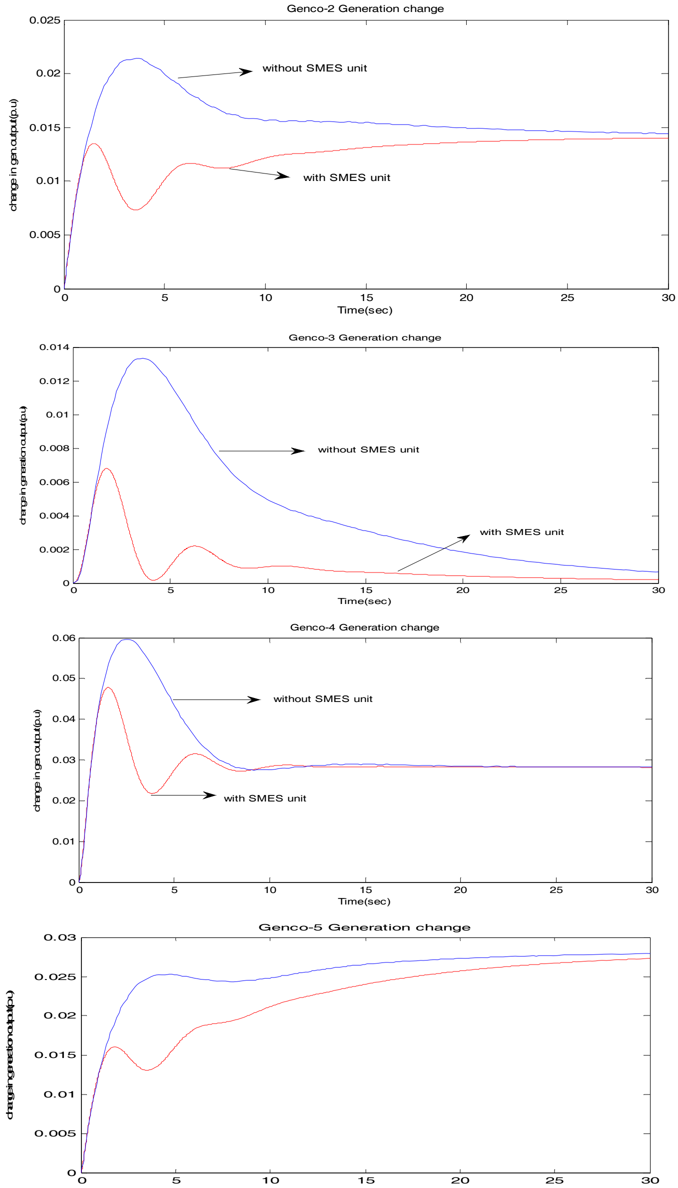
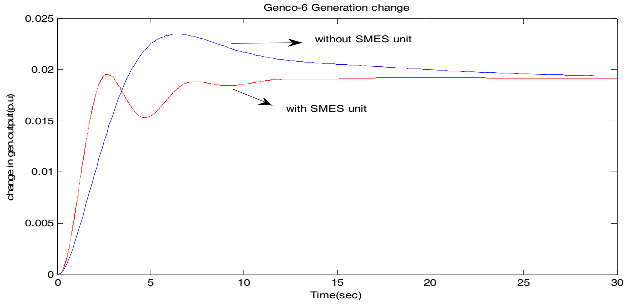
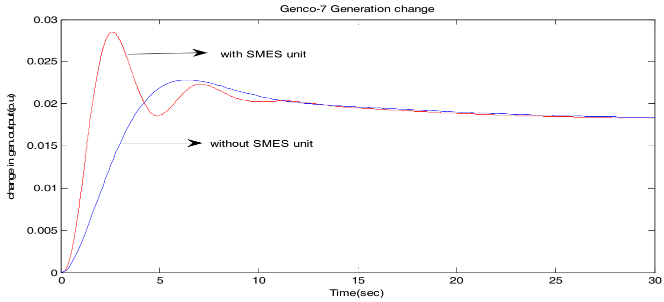
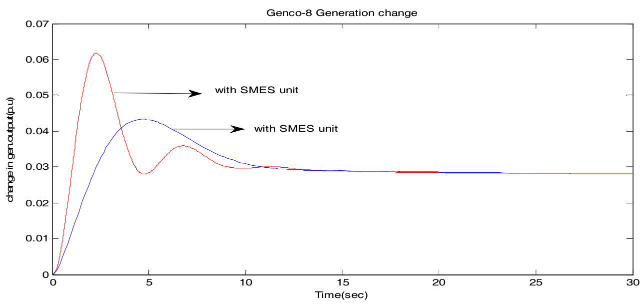
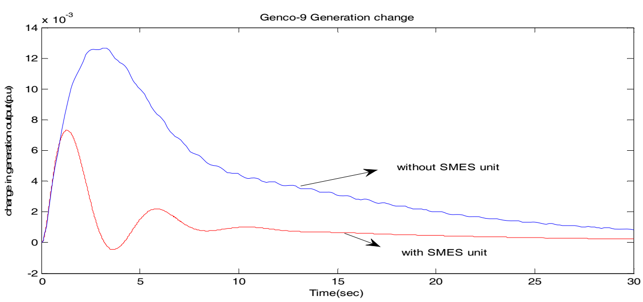


Fig. 8(b) Area-1 Change in generation in pu with and without SMES unit


Genco-6 Generation change
without SMES unit
with SMES unit
change in gen output(p.u)
Time(sec)


Genco-7 Generation change
with SMES unit
without SMES unit
change in gen output(p.u)
Time(sec)


Genco-8 Generation change
with SMES unit
with SMES unit
change in gen output(p.u)
Time(sec)


Genco-9 Generation change
× 10^-3
without SMES unit
with SMES unit
change in generation output(p.u)
Time(sec)

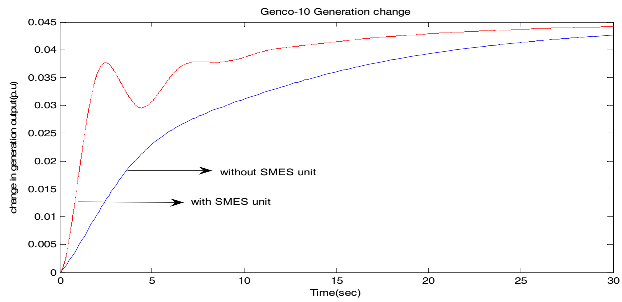


Fig. 8(c) Area-2 Change in generation in pu with and without SMES unit

Comparative results of Tie-line power deviation in area-1 & 2 with and without SMES unit using ANN based controller are shown in Fig. 9. From these results it is clear the performance of ANN based controller with SMES unit is better than without SMES unit, as the response is faster and the deviations settles down more quickly in case of with SMES unit.

The tie-line power deviation, in this case, will be not settles to zero as in the previous case. Due to the bilateral transitions between two different areas, the tie-line power will change. The change in tie-line power can be determined as given below

The tie-line power interchange between area-1 and area-2 is = (Demand of Discos of area-2 to Gencos of area-1) – (Demand of Discos of area-1 to Gencos of area-2) = 0.0126 p.u.

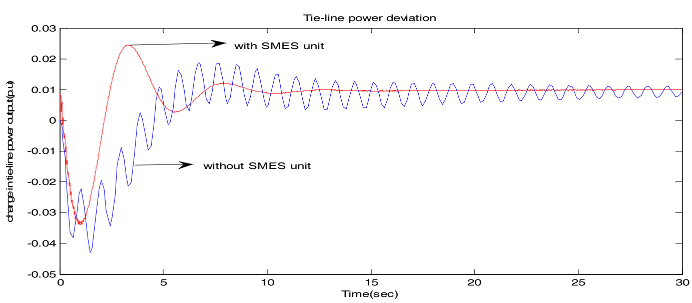


Fig. 9 Tie-Line Power deviation in area-1 and 2.

7. Conclusion

A general-purpose ANN controller for multi area AGC**,** suitable for deregulated electricity market, has been developed with SMES and without SMES unit. 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. The proposed ANN controller has been successfully tested on a 39-bus New England power system for all types of load following contracts. 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 ANN based controller have been obtained with and without SMES unit. The result shows that the performance of the ANN controller with SMES unit is better than the performance without SMES unit.

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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