Load frequency stabilization of four area hydro thermal system using Superconducting Magnetic Energy Storage system

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Abstract— Automatic generation control in electric power system design is a major concern nowadays due to its rising size, varying structure, integration of renewable-energy sources and distributed generators to meet the growing demand. In this paper, automatic generation control of an interconnected four area hydro thermal system examined. Each area equipped with reheat turbine for thermal system and hydro turbine with electric governor for hydro system. Load frequency stabilization gained by including Superconducting Magnetic Energy Storage system (SMES) in all areas. A comparative analysis made between Proportional and Integral (PI) controller with Fuzzy Logic controller with and without including SMES in the four area power system. The designed Fuzzy Logic Controller can generate best dynamic performance for step load perturbations given in all areas. The system simulation realized by using MATLAB software.

Keyword- Automatic Generation Control, Frequency deviation, Fuzzy Logic Controller, Proportional Integral Controller, Superconducting Magnetic Energy Storage system.

I. INTRODUCTION

Major variations introduced into the structure of a power system currently due to its rising size, promising renewable-energy resources, environmental constraints and complexity in the power system. Each control area of interconnected power system must meet its own demand and its scheduled power interchange to maintain the power balance between the generation and the demand. If the power balance does not exist, then the difference would enter or exit from kinetic energy storage. As the kinetic energy depends on generator speed, a power imbalance will thus turn into a speed and frequency deviation. This system frequency deviation will cause unnecessary disturbances in the power system and the frequency-dependent loads like electric clocks and CNC machines do not work [1]. The frequency change will also cause vibrations in turbine blades, which will harm the turbine. This load frequency change managed by under frequency relays or by load shedding. If these load frequency changes not properly managed, then the power system will lead to blackout [2].

Automatic Generation Control (AGC) will correct the load frequency change in the generating plant itself, before the frequency relays acts. Therefore, the unnecessary action of relays ignored for small changes in frequency [3], [4]. The goals of AGC in a power system is to minimize the area control error, to decrease the magnitude of unscheduled tie lie power flow among adjacent control areas, to get good tracking of load demand and to preserve the acceptable overshoot and settling time with zero steady state error in the frequency and the tie line power deviations.

Mostly the big generators in the power system equipped with two control loops which are Automatic Generation Control (AGC) loop and the Automatic Voltage Regulator (AVR) loop. Automatic Generation Control is the key focus of this paper which preserves the system frequency and tie line power interchange within the scheduled limits. AGC itself has two control loops, namely the primary control loop and secondary control loop. Primary control loop is responsible for regulating the control valve via the speed governor when the system frequency deviates from its nominal value. Secondary control is responsible for the fine adjustment of frequency and it preserves the megawatt interchange with other interconnected areas using the reset action.

Conventional PI, PD, PID controllers used for Secondary control. By tuning the proportional, integral and derivative gains, the desired dynamic response for the power system has achieved [4]-[9]. But the Area Control Error cannot reach at a minimal value. During the last few decades, various control strategies carried out with intelligent controllers to achieve minimal Area Control Error [10-17]. Fuzzy Logic Controller will give not only the desired dynamic performance but the Area Control Error to a minimum value [10], [11]. Fuzzy logic PI controllers used to damp oscillations resulted from load perturbations [12]. The AGC system performance evaluated using a neural network controller to get enhanced system dynamic response [13]. Genetic algorithm used for load frequency control for two area interconnected power system [14]-[16]. Evolutionary algorithm based controller for load frequency problem has also examined [17]. When comparing all these intelligent technique's fuzzy logic control has less processing time. In addition, FLC has imposed easily in practical systems. Literature survey shows that, the automatic generation control always tested with single source in each control area using different intelligent controllers. Even these techniques have satisfied results in the interconnected power system but the number of areas have restricted to two or three [10-16]. In realistic situations, each control area may have various types of generation such as hydro, thermal, nuclear and gas, etc. But the major contribution for power generation is, firstly from thermal and secondly from hydro sources. This paper is an attempt to study the AGC of a four area system using thermal and hydro power generation in each control area.

Even in the existence of supplementary controllers, the governor not able to correct the frequency variations quickly. In contrast, electromechanical oscillations in a power system can effectively damped by energy storage devices, because the energy storage capacity have used as a supplement to the kinetic energy in the rotating mass of the generator rotor. The energy storage device shares the sudden load change within the power system. Thus, the imbalances between the generation and demand have reduced by the active power sources with a fast response such as Battery energy storage units and Superconducting magnetic energy storage units. Superconducting magnetic energy storage can control active and reactive power simultaneously, and it has expected as one of the most effective and significant stabilizer for power system oscillations [18]-[21]. The outstanding features of SMES units such as low discharge rate, fast acting, the larger time requirements for power flow reversal and maintenance have led to its application as a load frequency stabilizer. Due to these features of SMES, it included in each area of the four area hydro thermal power system to get a fast response. Under the occurrence of load disturbances, the frequency oscillations in each area has effectively suppressed by SMES.

II. MODELING OF THERMAL UNIT, HYDRO UNIT AND SMES

A. Modeling of a thermal power plant

Turbine acts as the prime mover for the generator which has rotated by the steam from the boiler unit. The steam input controlled by using the speed governor, when there is an imbalance occurs between the generation and demand. This imbalance sensed by the governor with change in frequency (Δf). Based on the change in frequency, the speed governor controls the position of the control valve, and increases or decreases the steam injection to the turbine blades [1]-[4]. The steam input has controlled using the reference power setting (ΔP_{ref}) of the governor. The speed governor output (ΔP_g) given by equation (1).

$$\Delta P_g = \Delta P_{ref} - \Delta f \frac{1}{R} \tag{1}$$

$$\Delta P_g(S) = \Delta P_{ref}(S) - \Delta F(S) \frac{1}{R} \tag{2}$$

The governor has a time constant of T_g then the governor output equation is

$$\Delta P_v(S) = \frac{1}{1+sT_g} \Delta P_g(S) \tag{3}$$

The turbine has a time constant of T_t then the turbine output equation is

$$\Delta P_t(S) = \frac{1}{1+sT_t} \Delta P_v(S) \tag{4}$$

The model for thermal power plant used in the four area hydro thermal system shown in figure 1. The reheat turbine considered in this paper, whose output (ΔP_T) has furnished in equation (5)

$$\Delta P_T(S) = \frac{1+K_r T_r s}{1+sT_t} \Delta P_t(S) \tag{5}$$

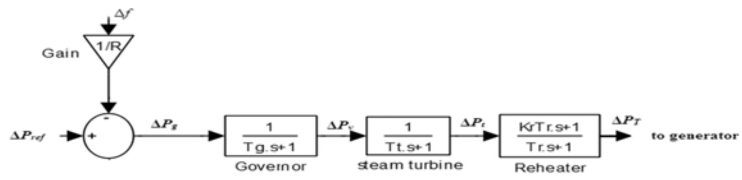

Fig.1. Model of thermal power plant.

B. Modeling of Hydro power plant

In hydro plants, water is the source for producing mechanical energy to drive the turbine. The Electro-Hydraulic Governing System for hydro power plant has chosen in this study. The Electro-Hydraulic Governing System operation is similar to that of mechanical hydraulic governors. Sensing of Speed, droop compensation, and computing are carried out electrically. The output signal drives an electro-mechanical transducer, which runs a pilot valve and a servomotor. The turbine rotor speed has measured electronically with high accuracy. Figure 2 shows the model for hydro power plant used in the four area hydro thermal system. The output of hydraulic Turbine (ΔP_{HT}) given as

$$\Delta P_{HT}(S)=\frac{1-sT_W}{1+0.5sT_W}\Delta P_{HV}(S) \tag{6}$$

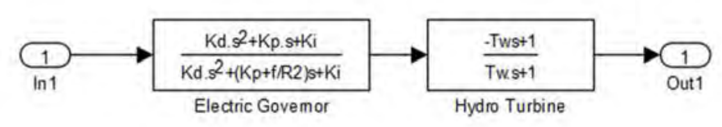

Fig.2. Model of hydro power plant.

C. Modeling of Superconducting magnetic energy storage unit

Superconducting magnetic energy storage unit acts as an energy storage device in the power system. SMES can control the active and reactive power simultaneously and it has expected as significant stabilizers of power system oscillations. The system load disturbance occurs SMES effectively suppresses the load frequency oscillations by discharging its stored magnetic energy. On the whole, the active power has controlled effectively by the SMES in the respective areas for short duration until the governor, and its secondary controller takes its action. This is possible only because of the fast-acting nature of SMES. The mathematical model of SMES based frequency stabilizer shown in Figure 3.

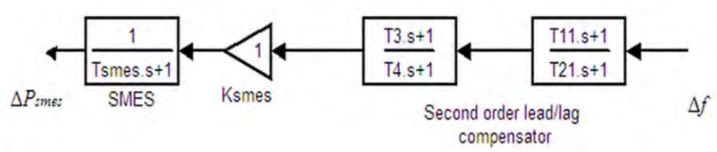

Fig.3. Structure of SMES as frequency stabilizer.

III. POWER SYSTEM MODEL FOR INVESTIGATION

The power system with four control areas interconnected by tie line has considered. Each area equipped with thermal and hydro power plant as shown in figure 4. Each area supplies its user pool, and the tie line allows electric power to flow between areas. Therefore, the load distribution in one of the areas affects the frequencies of other areas, as well as the power flows on the tie line. Due to this, a control system has needed for each area to bring the system frequency to its steady-state value.

The area control error of all the four hydro thermal areas given by

$$ACE_1 = P_{tie,12} + \beta_1 \Delta f_1 \tag{7}$$

$$ACE_2 = P_{tie,23} + \beta_2 \Delta f_2 \tag{8}$$

$$ACE_3 = P_{tie,34} + \beta_3 \Delta f_3 \tag{9}$$

$$ACE_4 = P_{tie,41} + \beta_4 \Delta f_4 \tag{10}$$

A step load disturbance given in all the four areas, and the performance of conventional PI and fuzzy controller studied. Then, SMES unit has included for each area, and the same step load disturbance is given in all the areas, and the performance of conventional PI and fuzzy controller has studied.

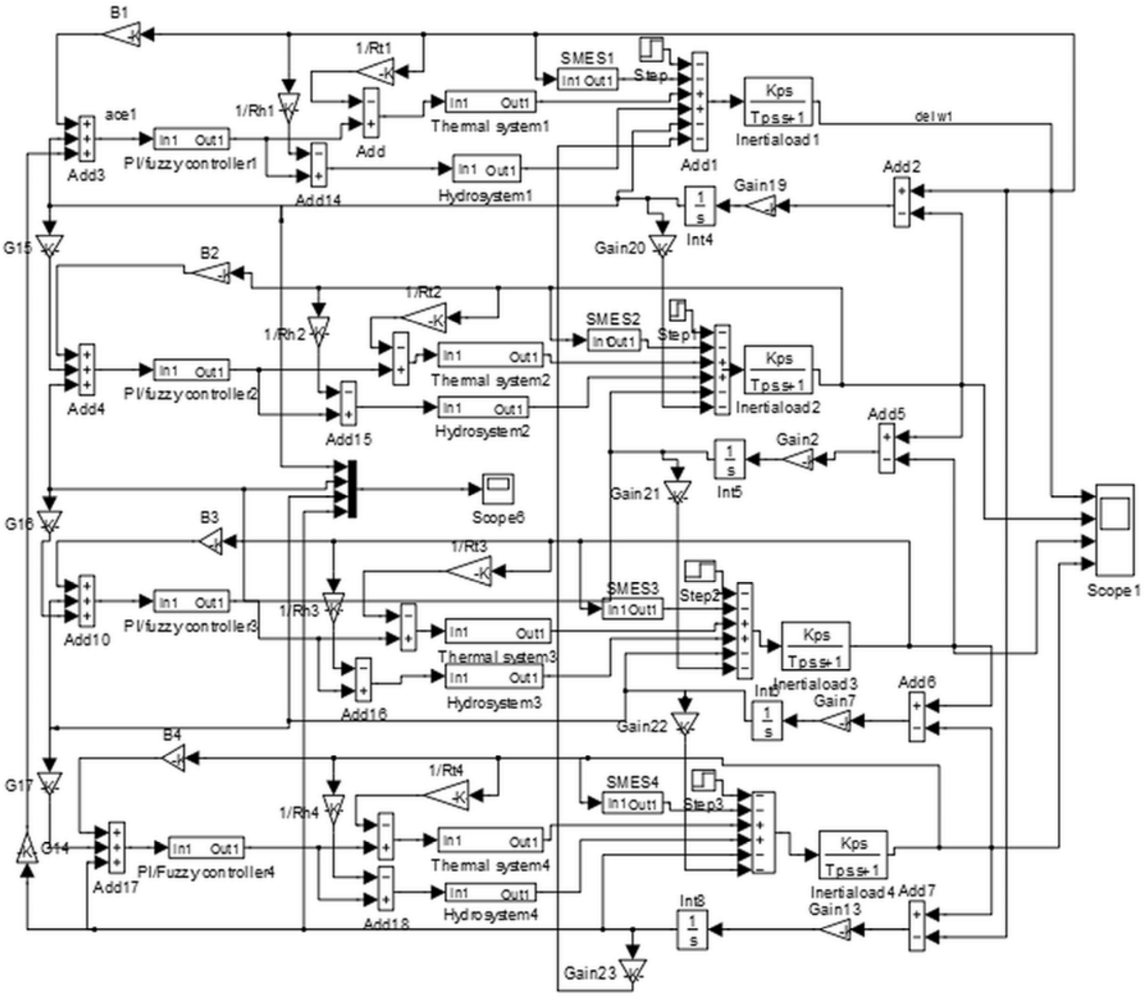

Fig.4. Simulink model for four area hydro thermal system.

IV. PI CONTROLLED FOUR AREA HYDRO THERMAL SYSTEM

Proportional - Integral controller acts as a feedback controller which drives the plant with a weighted sum of error and the integral of that value. The relative simplicity of this controller is a successful approach towards zero steady-state error. The ‘PI’ controller helps to improve the transient performance and reduces the steady-state error. When the proportional term combined with the integral controller, it speeds up the movement of the process towards set-point and reduces the steady-state error to zero. The mathematical expression of PI controller gained for the four area hydro thermal system is

$$U1 = -K_{p1}\, ACE_1 \;\; -K_{i1}\int ACE_1 dt \tag{11}$$

$$U2 = -K_{p2}\, ACE_2 \;\; -K_{i2}\int ACE_2 dt \tag{12}$$

$$U3 = -K_{p3}\, ACE_3 \;\; -K_{i3}\int ACE_3 dt \tag{13}$$

$$U4 = -K_{p4}\, ACE_4 \;\; -K_{i4}\int ACE_4 dt \tag{14}$$

The optimum values for proportional and integral gain K_p and K_i has obtained by Ziegler Nichols’ (ZN) tuning method. In this method, the process kept under closed-loop P control. The gain of the P controller at which the loop start oscillates with constant amplitude has referred as the ultimate gain (K_{cu}). Ultimate period (T_u) is the period of these sustained oscillations. The higher the ultimate gain, it is easier to control the process loop. K_p and K_i values tuned using ZN method which has earned as 1 and 0.01.

V. FUZZY CONTROLLED FOUR AREA HYDRO THERMAL SYSTEM

In order to improve the dynamic performance of the four area hydro thermal system the PI controller has replaced with fuzzy logic controller.

A. Fuzzification

Fuzzification is the process of transforming real valued variable into a fuzzy set value. The real input values for the Fuzzy Logic Controller are Area Control Error and rate of change of Area Control Error. The triangular membership function with seven linguistic variables and Mamdani type Fuzzy Inference System is used in this study. The linguistic variables are NL (Negative Large), NM (Negative medium), NS (Negative Small), Z (Zero Error), PS (Positive Small), PM (Positive medium) and PL (Positive Large). The structure of the proposed fuzzy logic controller shown in figure 5.

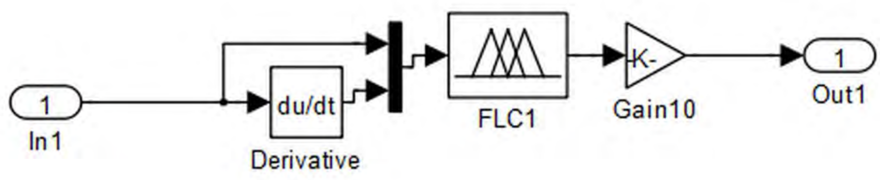

Fig.5. Structure of fuzzy logic controller.

B. Knowledge Base

The heart of the fuzzy system is a knowledge base consisting of fuzzy if-then rules. The rule base consists of a set of fuzzy rules. The database contains the membership function of fuzzy subsets. A Fuzzy rule may contain fuzzy variables and fuzzy subsets characterized by membership function. For example, if the value of Area Control Error (ACE) is NL and the rate of change of Area Control Error is [d (ace) / dt] NL, then the output control signal is NL. With these fuzzy variables and membership functions, a set of 49 rules is formed. The rule base is given in the Table 1.

TABLE 1
Rule base for fuzzy controller

ACE	**Rate of change of ACE**						
	NL	**NM**	**NS**	**Z**	**PS**	**PM**	**PL**
NL	NL	NL	NL	NM	NM	NS	Z
NM	NL	NL	NM	NM	NS	Z	PS
NS	NL	NM	NS	NS	Z	PS	PM
Z	NM	NM	NS	Z	PS	PM	PM
PS	NM	NS	Z	PS	PS	PM	PL
PM	NS	Z	PS	PM	PM	PL	PL
PL	Z	PS	PM	PM	PL	PL	PL

C. Defuzzification

The objective of defuzzification is to convert the output fuzzy variable to a crisp value, so it can be used for real time control. The centroid method of defuzzification employed here. The membership function, knowledge base and method of defuzzification combinally determine the controller performance.

VI. SIMULATION RESULTS

Frequency deviation of the proposed PI controlled and fuzzy controlled four area hydro thermal system with and without including SMES, following a step load disturbance in all the areas is shown in figure 6 and figure 7 respectively. Tie line power deviations in area 12, area 23, area 34 and area 41 in PI controlled four area hydro thermal system with and without SMES is shown in figure 8 and figure 9 respectively. Tie line power deviations in area 12, area 23, area 34 and area 41 with fuzzy controlled four area hydro thermal system with and without SMES is shown in figure 10 and figure 11 respectively. The peak overshoot values and settling time values on the frequency deviation curves of the proposed four area hydro thermal system following a step load disturbance given in all areas is shown in table2.

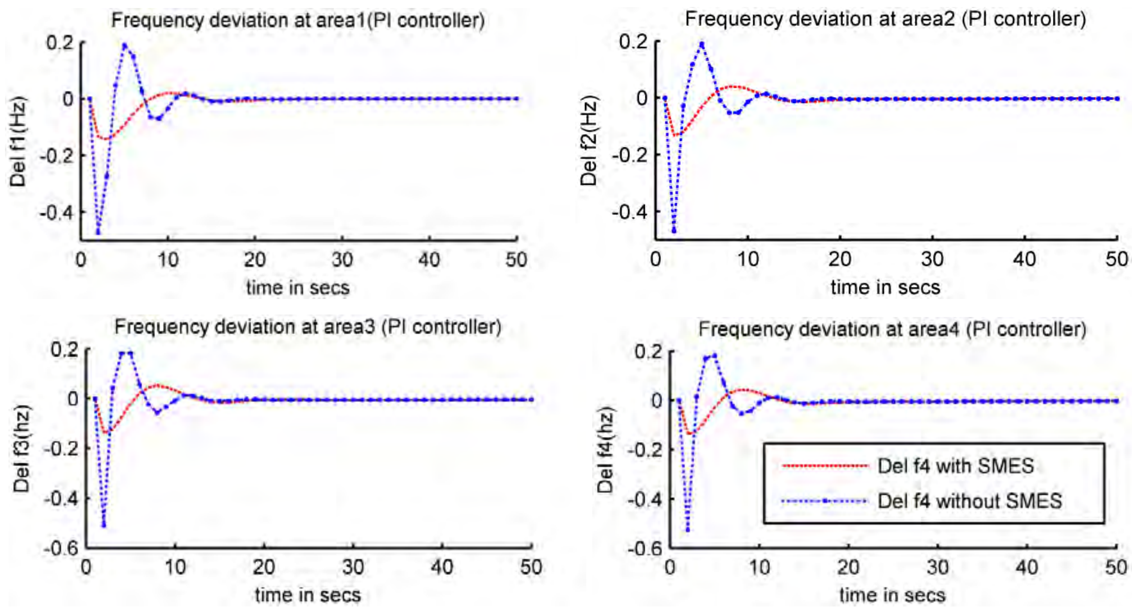

Fig6: Frequency deviation of PI controlled four area hydro thermal system with 1% step disturbance at all areas.

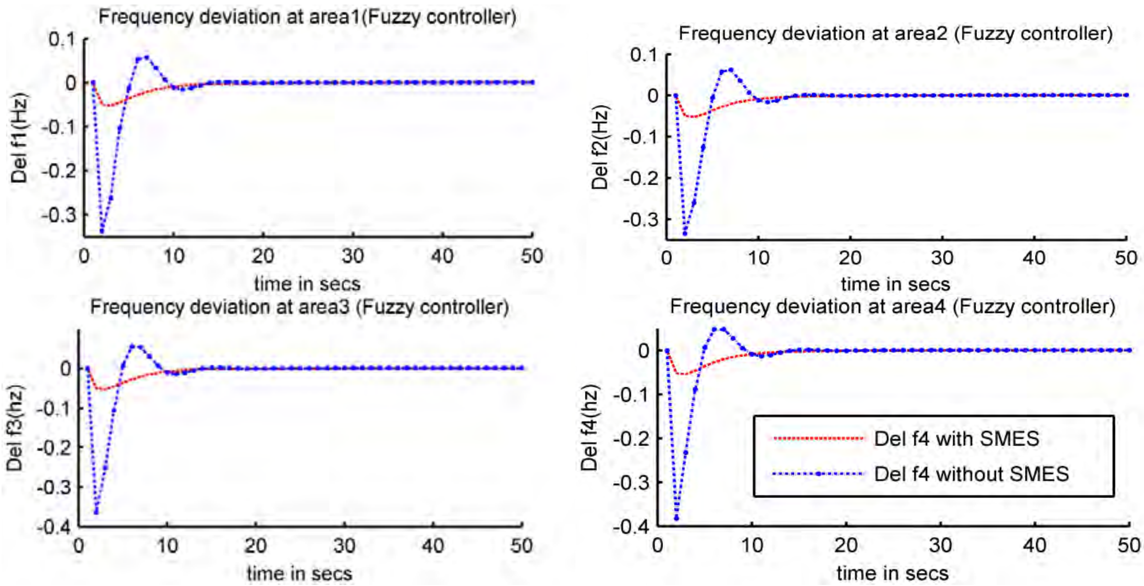

Fig7: Frequency deviation of fuzzy controlled four area hydro thermal system with 1% step disturbance at all areas.

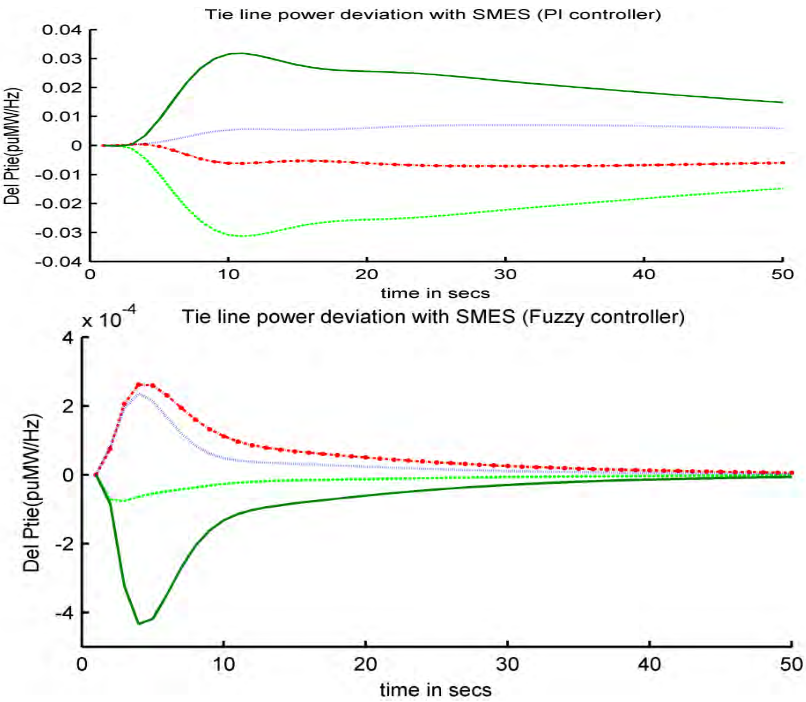

Fig8: Tie line Power deviation of PI and fuzzy controlled four area hydro thermal system with 1% step disturbance at all areas including SMES.

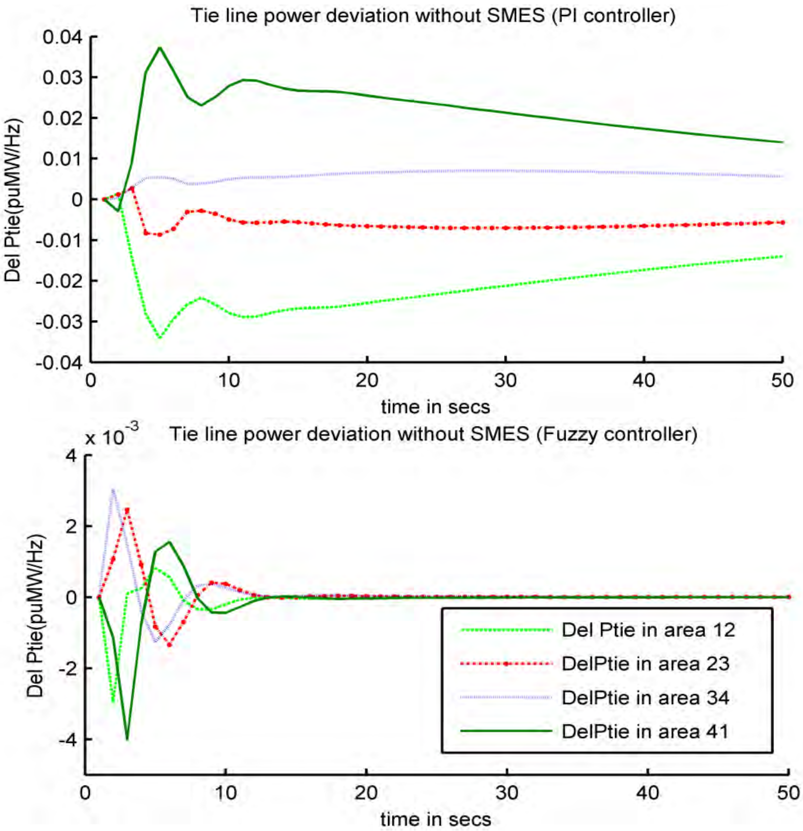

Fig9: Tie line Power deviation of PI and fuzzy controlled four area hydro thermal system with 1% step disturbance at all areas without including SMES.

TABLE 2
Simulation Results

		PI controlled four area hydro thermal system		Fuzzy controlled four area hydro thermal system	
		With SMES	Without SMES	With SMES	Without SMES
Frequency deviation of area1	Peak Overshoot(Hz)	0.021	0.201	0.033	0.160
	Settling Time(sec)	17	19	12	19
Frequency deviation of area 2	Peak Overshoot(Hz)	0.040	0.213	0.033	0.155
	Settling Time(sec)	20	25	12	15
Frequency deviation of area 3	Peak Overshoot(Hz)	0.052	0.197	0.032	0.150
	Settling Time(sec)	21	22	13	15
Frequency deviation of area 4	Peak Overshoot(Hz)	0.426	0.201	0.030	0.144
	Settling Time(sec)	22.5	27.2	12	16

VII. CONCLUSION

In this study, Automatic Generation Control of four area system with thermal and hydro sources of power generation in each area is employed. The dynamic performance of PI controlled system with and without including SMES and also Fuzzy Logic Controlled system with and without including SMES shown in the simulation results. It is observable the Fuzzy Logic Controlled four area hydro thermal system with SMES has less settling time and less peak over shoot for frequency deviation as compared to conventional PI controlled four area hydro thermal system including SMES. Here the generator rate constraints and governor non linearity's has not taken for simplicity.

APPENDIX

Parameter	Description	Value
B1, B2	Tie line frequency bias	0.425 pu MW/HZ.
R_{th}, R_{hy}	Regulations of governors in thermal and hydro areas respectively.	2.4HZ/PuMW, 2.4 HZ/PuMW.
Tg	Governor time constants for thermal areas.	0.2s, 0.1s, 0.1s & 0.2s for area1, area2, area3, area4.
Tt	Turbine time constants for thermal areas	0.3s, 0.3s, 0.5s & 0.5s for area1, area2, area3, area4.
K_r, T_r	Steam turbine reheater gain and time constant respectively.	0.5, 10s for all four areas.
K_d, K_p, K_i	Electric governor derivative, proportional, and integral gains, respectively	4, 1, 5 for all four areas.
T_w	Water starting time constant	1s for all four areas.
K_{smes}, T_{smes}	SMES gain and time constant	2, 0.03s.
T_{11},T_{21}, T_3 & T_4	Second order frequency stabilizer constants	0.7087s, 0.2481s, 0.2333s & 0.016s.
K_{ps}, T_{ps}	Power system gain and time constants	120 Hz/PuMw, 20s for all four areas.

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