Dual Mode Two-Layer Fuzzy Logic based Load-Frequency Controller for a Two-Area Interconnected Power System with Super Capacitor Energy Storage Units

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ABSTRACT

The Load Frequency Control (LFC) is of great importance in power system operation and control for providing sufficient and reliable electric power with good quality. Even though the simple Proportional- Integral (PI) controllers are still popular in power industry for frequency regulation it does not eliminate the conflict between the static and dynamic accuracy. This conflict may be resolved by employing the principle of Dual Mode control. The Dual Mode controller operates by switching between proportional controller mode and Integral controller mode depending upon the magnitude of the Area Control Error (ACE). The Artificial Bee Colony (ABC) algorithm is used to optimize the cost function of the two area interconnected power system along with the PI controller. In this paper proposes Dual Mode two layered fuzzy logic controller, each mode consists of two layer fuzzy logic controllers. The first layer is called pre-compensator, which is used to generate and update the reference value of Area Control Error (ACE). The second layer called feedback fuzzy logic controllers namely Proportional (P) like fuzzy logic controller, or Integral (I) like fuzzy logic controller. In addition to leveling load, the Super Capacitor Energy Storage Unit (SCES) is found to be advantageous for secondary control in the power system and maintains the power quality with the distributed power resource. To ensure the system stability due to sudden load disturbances, the power modulation control offered by SCES is enhanced to suppress the peak value of the transient frequency deviation. Simulation results show that the proposed Dual Mode two layered fuzzy logic controller is not only effective in damping out the frequency oscillations, but also capable of alleviating the transient frequency swing caused by large load disturbance and moreover the proposed Dual Mode two layered fuzzy load frequency controller provides very good transient and steady state response compared to and Dual Mode PI controllers.

Keywords

Load-Frequency Control, Area Control Error, Integral Squared Error criterion, Dual Mode Two Layered Fuzzy Logic Controller, Super Capacitor Energy Storage Unit.

1. INTRODUCTION

Large scale Power Systems are normally composed of control areas or regions representing coherent group of generators. Power System operation has to ensure whether adequate power is being delivered to the consumers reliably and economically or not. The analysis and design of Automatic Generation Control (AGC) system of individual generator eventually controlling large interconnections between different control areas plays a vital role in automation of power system. The primary objectives of AGC are to regulate frequency to the specified nominal value and to maintain the interchange of power between control areas at the scheduled values by adjusting the output of the selected generators. This function is commonly defined as Load Frequency Control (LFC). Load Frequency Control (LFC) is a very important issue in power system due to the increasing load demand and results to more complicated environment which requires adequate and efficient control. Therefore the objective of LFC of a power system is to maintain the frequency of each area and tie-line power flow (among the interconnected system) within specified tolerance by adjusting the new outputs of LFC generators so as to accommodate the fluctuating load demand. A number of control schemes have been employed for the design of load frequency controllers [1] in order to achieve better dynamic performance. Among the various types of load frequency controllers the most widely conventional types used are the tie-line biased control and flat frequency control to achieve the above goals of LFC, both schemes are based on the classic controls which work on the same function made up of the frequency and tie-line power deviations. The conventional approach using proportional plus integral controllers results in relatively large over shoots in transient frequency deviations [2]. Further, the settling time of the system frequency deviations is also relatively long. It is well known that, if the control law employs integral control, the system has no steady state error. However, it increases the order of the system by one. Therefore, the response with the integral control is slow during the transient period. In the absence of integral control, the gain of the closed loop system can be increased significantly thereby improving the transient response [3]. The proportional plus integral control does not eliminate between the static and dynamic accuracy. This conflict may be resolved by employing the dual mode control [4, 5].

The Artificial Bee Colony (ABC) algorithm, a new swarm intelligent algorithm, was proposed by Karaboga [6] in Erciyes University of Turkey in 2005. Since ABC algorithm is simple in concept, easy to implement, and has fewer control parameters. ABC algorithm has applied successfully to unconstrained numerical optimization problems [7]. The extended version of the ABC algorithm is also developed for solving optimization problems in 2007 [8]. ABC algorithms are highly robust yet remarkably simple to implement. Thus, it is quite pertinent to apply the ABC, with more new modifications, to achieve better optimization and handle the load-frequency problems more efficiently. In this study, an ABC algorithm is used to optimizing the proportional and integral controller gains for load frequency control of a two area thermal power system. Nevertheless these conventional control systems have been successful to some extent only [9]. This suggests the necessity of more advanced control strategies that has to be incorporated for a better control. In this aspect a better power quality intelligent controllers [9-15] be adopted replacing the conventional controllers because of their ability in ensuring fast and good dynamic response for the load frequency control problems. Fuzzy logic controllers have received considerable interest in recent years. Fuzzy based methods are found to be very useful in the places where the solution to the mathematical formulations is complicated. Moreover, fuzzy logic controller often yields superior results to conventional control approaches [9-14]. The fuzzy logic based intelligent controllers are designed to facilitate the operation smooth and less oscillatory when system is subjected to load disturbances.

The conventional load-frequency controller may no longer be able to attenuate the large frequency oscillation due to the slow response of the governor. A fast-acting energy storage system in addition to the kinetic energy of the generator rotors provides adequate control to damp out the frequency oscillations. The problems like low discharge rate, increased time required for power flow reversal and maintenance requirements have led to the evolution of Super Capacitor Energy Storage (SCES) or Ultra Capacitor Energy Storage (UCES) devices for their applications also load frequency stabilizers. Super capacitors are electrochemical type capacitor which offer large capacitances in the order of thousands of farads at a low voltage rating of about 2.5V [16, 17]and are used to store electrical energy during surplus generation and deliver high power within a short duration of time especially during the peak-load demand period [18, 19].The energy density of Super Capacitor(SC) is 100 times larger than the conventional electrolytic capacitor and their power density is 10 times larger than the lead-acid battery. Ultra capacitors possess a number of attractive properties like fast charge-discharge capability, longer life, no-maintenance and environmental friendliness. The effective specific energy for a prescribed load can be satisfied using various SC bank configurations. The SCES will, in addition to load leveling, a function conventionally assigned to them, have a wide range of applications such as power quality maintenance for decentralized power supplies. The SCES are excellent for short-time overload output and the response characteristics possessed in the particular. The effect of generation control and the absorption of power fluctuation needed for power quality maintenance are expected. However, it will be difficult to locate the placement of SCES alone in every possible area in the interconnected system due to the economical reasons. In this paper SCES unit is located in area 1 of the two-area interconnected reheat thermal power system.

In this paper, the control scheme consists of dual mode two layers viz fuzzy pre-compensator and fuzzy like P and Fuzzy like I controller. The purpose of the fuzzy pre-compensator is to modify the command signals to compensate for the overshoots and improve the steady state error. Fuzzy rules from the overall fuzzy rule vectors are used at the first layer, linear combination of independent fuzzy rules are used at the second layer. The two layer fuzzy system has less number of fuzzy rules as compared with the fuzzy logic system. The proposed dual mode two layered fuzzy logic controllers give better simulation results which is compared with the simulation results obtained using the dual mode PI controllers. Thus the Dual mode two layered fuzzy PI controller enhances an efficient way of coping even with imperfect information, offers flexibility in decision making processes

2. PROBLEM FORMULATION

The state variable equation of the minimum realization model of ‘ N ’ area interconnected power system [19] may be expressed as

$$\begin{aligned} \dot{x} &= Ax + Bu + \Gamma d \\ y &= Cx \end{aligned} \quad (1)$$

Where $x = [x_1^T, \Delta p_{ei} \ldots x_{(N-1)}^T, \Delta p_{e(N-1)} \ldots x_N^T]^T$,

n - state vector

$$n = \sum_{i=1}^{N} n_i + (N-1)$$

$u = [u_1, .. u_N]^T = [\Delta P_{C1} .. P_{CN}]^T$, N - Control input vector

$d = [d_1, .. d_N]^T = [\Delta P_{D1} .. P_{DN}]^T$, N - Disturbance input vector

$y = [y_1 .. y_N]^T$, $2N$ - Measurable output vector

where A is system matrix, B is the input distribution matrix, Γ is the disturbance distribution matrix, C is the control output distribution matrix, x is the state vector, u is the control vector and d is the disturbance vector consisting of load changes. The objective of LFC is to re-establish primary frequency regulation, restore the frequency to its nominal value as quickly as possible and minimize tie-line power flow oscillations between neighboring control areas. In order to satisfy the above requirement, gain values of the proportional controller (K_{p1}, K_{p2}) and gain values of (K_{i1}, K_{i2}) the integral controller in LFC loop are to be optimized to have minimum undershoot (US), overshoot (OS) and settling time (ts) in area frequencies and power exchange over tie-line. Fig. 1 represent the block diagram of two area reheat thermal interconnected power system. The area control error (ACE) of each area is fed to the corresponding controller and the accurate control signal is generated for the ACE at that particular load change. A performance index given by Eqn (2) has been considered. In the present work, an Integral Square Error (ISE) criterion is used to minimize the objective function defined as follows

$$J = \int_0^t \left((\beta_1 \Delta F_1)^2 + (\beta_2 \Delta F_2)^2 + \Delta P_{tie}^2 \right) dt \quad (2)$$

The optimum gain values of Proportional (Kp) and Integral (Ki) were found using Artificial Bee Colony (ABC) algorithm

3. PROPOSED CONTROL SCHEME

3.1 Dual mode scheme

The fixed gain controllers are designed at nominal operating conditions and fail to provide best control performance over a wide range of operating conditions. The well designed integral controller can bring the steady state error to zero but the speed of the response of the system becomes slow resulting high over/ under shoot and settling time. The over/under shoot is reduced and speed of the response improves by using only proportional controller. It is obvious that the presence of the proportional controller is highly required at transient to make system response faster thus reducing the over/under shoot. But incorporating the proportional controller alone fails to bring the steady state error to zero. So there is need to present both proportional and integral controller. The proportional plus integral control does not eliminate the conflict between the static and dynamic accuracy. This conflict may be resolved by employing the principle of Dual Mode control.

The control law employed during the transient period is switched between Eqn (3) and Eqn (4) depending on the magnitude of error signal i.e., ACE (t). For | ACE (t)| > E the output of the controller

$$\Delta P_c(t) = -K_p \,.\, ACE(t) \tag{3}$$

Where $\Delta P_c(t)$ output signal of the controller and E is constant indicating the specified limit of error signal

$$\Delta P_c(t) = -K_i \,.\int ACE(t)\,dt \tag{4}$$

Based upon the above mentioned facts, the dual mode concept is introduced here in the following way. The proportional controller will act during the transient period when the error (ACE) is sufficiently larger, whereas the integral controller would be the better option when the error is small. The proposed control dual mode control scheme for two area interconnected reheat thermal power system is shown in Fig 1. For the proposed control scheme, the control law is taken as follows

$$\Delta P_{c1}(t) = -K_{p1}\,(ACE(t)), \qquad for|ACE_1| > E_1 \tag{5}$$

$$\Delta P_{c1}(t) = -K_{i1}\,(ACE(t)\,dt), \qquad for|ACE_1| \le E_1 \tag{6}$$

$$\Delta P_{c2}(t) = -K_{p2}\,(ACE(t)), \qquad for|ACE_2| > E_2 \tag{7}$$

$$\Delta P_{c2}(t) = -K_{i2}\,(ACE(t)\,dt), \qquad for|ACE_2| \le E_2 \tag{8}$$

When the error signal remains within the specified limit, i.e, |ACE (t)| < E, the system will operate in integral control strategy.

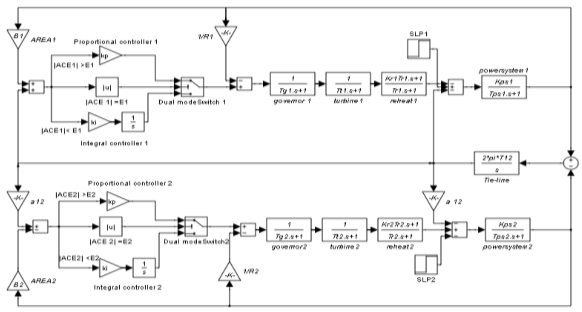

Fig.1 Linearized model of Dual mode PI Controller based two- area interconnected reheat thermal Power system

3.4 Application of the ABC algorithm for the Load Frequency Control problem

The Artificial Bee Colony (ABC) algorithm was introduced by Karaboga [6]. The algorithm mimics the food foraging behavior of swarms of honey bees. Honey bees use several mechanisms like waggle dance to optimally locate food sources and to search new ones. This makes them a good candidate for developing new intelligent search algorithms. It is very simple, robust and population based stochastic optimization algorithm. In ABC algorithm, the colony of artificial bees consists of three groups of bees: Employed bees (E_b), Onlookers (O_b) and Scout bees (S_b). Some of the bee of the colony consists of the employed artificial bees and the some includes the onlookers. For every food source, there is only one employed bee. In other words the number of employed bees is equal to the number of food sources around the hive. The employed bee who's the food sources has been abandoned by the bees becomes a scout. In ABC algorithm the position of the food sources determines the solution and the amount of nectar represents to fitness of this respective solution. The foraging strategy is governed by three process namely initialization, Reproduction and Replacement of bee and selection.

a) Initialization

A randomly distributed initial populations solutions *[X_i=1, 2, 3…D]* is being dispread over the *D* dimensional problem space

b) Reproduction

An artificial onlooker bee choose a food source depending on the probability value associated with that food source, *Pi*, calculated by the following expression,

$$Pi = \frac{f_i * t_i}{\sum_{n=1}^{N} f_i * t_i} \tag{9}$$

Where the fitness values of the solution *i* which is proportional to the nectar amount of the food source in the position *i* and *N* is the number of food sources which is equal to the number of employed bees. In order to produce a candidate food position from the old one in memory, the ABC uses the following expression.

$$V_{ij} = x_{ij} + \varphi_{ij}\left(x_{ij} - x_{kj}\right) \tag{10}$$

Where *k = (1,2,3….D*) and *j =(1,2,3...N)* are randomly chosen indexes φ_{ij} is a random number between [-1,1].

c) Replacement of Bee selection

In ABC, providing that a position cannot be improved further through a predetermined number of cycles, then that food source is assumed to be abandoned. The value of pre determined number of cycles is an important control parameter of the ABC algorithm, which is called "limit" for abandonment. Assume that the abandoned source is X_i and *J=(1,2,3,..N)*, then the scout discovers a new food source to be replaced with X_i. This operation can be defined as

$$X_i^j = X_{\min}^j + rand(0,1) * \left(X_{\max}^j - X_{\min}^j\right) \tag{11}$$

After each candidate source position V_{ij} , is produced and then evaluated by the artificial bee ,its performance is compared with that of its old one. If the new food has equal or better nectar than the old source, it replaces the old one in the memory. Otherwise, the old one is retained in the memory.

The following ABC algorithm is adopted for the proposed control solution to the LFC problem.

1. Initialize the food source position x_i (solutions population) where $i=1, 2 \ldots D$

2. Calculate the nectar amount of the population by means of their fitness values using:

$$f_i * t_i = 1/(1+obj.fun._i\ J)$$

Where *obj. fun.*$_i$ represents of equation at solution ***i*** Eq (2)

3. Produce neighbour solution V_{ij} for the employed bees by using Eq (10) and evaluate them as indicated in step 2.

4. Apply the greedy selection process for the employed bees.

5. If all onlooker bees are distributed, Go to step 9 otherwise, Go to the next step.

6. Calculate the probability values P_i for the solution X_i using by Eq (9).

7. Produce the neighbour solution V_i for the onlookers bee from the solution X_i selected depending on P_i and evaluate them.

8. Apply the greedy selection process for the onlooker bees.

9. Determine the abandoned solution for the scout bees, if it exists, and replace it with a completely new solution X_i^j using Eq (11) and evaluate them as indicated in step2.

10. Memorize the best solution attained so for.

11 If cycle = Maximum Cycle Number (MCN). Stop and print result, otherwise go to Step 3.

The employed and Onlooker bees select new food sources in the neighborhood of the previous one in their memory depending on visual information. Visual information is based on the comparison of food –source positions. On the other hand, Scout bees, without any guidance while looking for a food-source position, explore a completely new food-source position. Therefore Scouts bees are characterized based on their behavior by low search costs and a low average in food-source quality. Occasionally, the Scouts bee can be fortunate to discover rich, entirely unknown food sources. In the case of artificial bee, the artificial Scouts bee could have the fast discovery of the group of feasible solutions as the task. [6-8]. Parameter tuning in meta-heuristic optimization algorithms influences the performances of the algorithm significantly. Divergences, becoming trapped in local extreme and time consumption are such consequences of setting the parameter improperly. The ABC algorithm as an advantage has a few controlled parameters, since initializing populations "randomly" with a feasible region is sometimes cumbersome. The ABC algorithm does not depend on the initial population to be in a feasible region. Instead, its performance directs the population to the feasible region sufficiently. The flow chart of ABC algorithm is shown in Fig. 2.

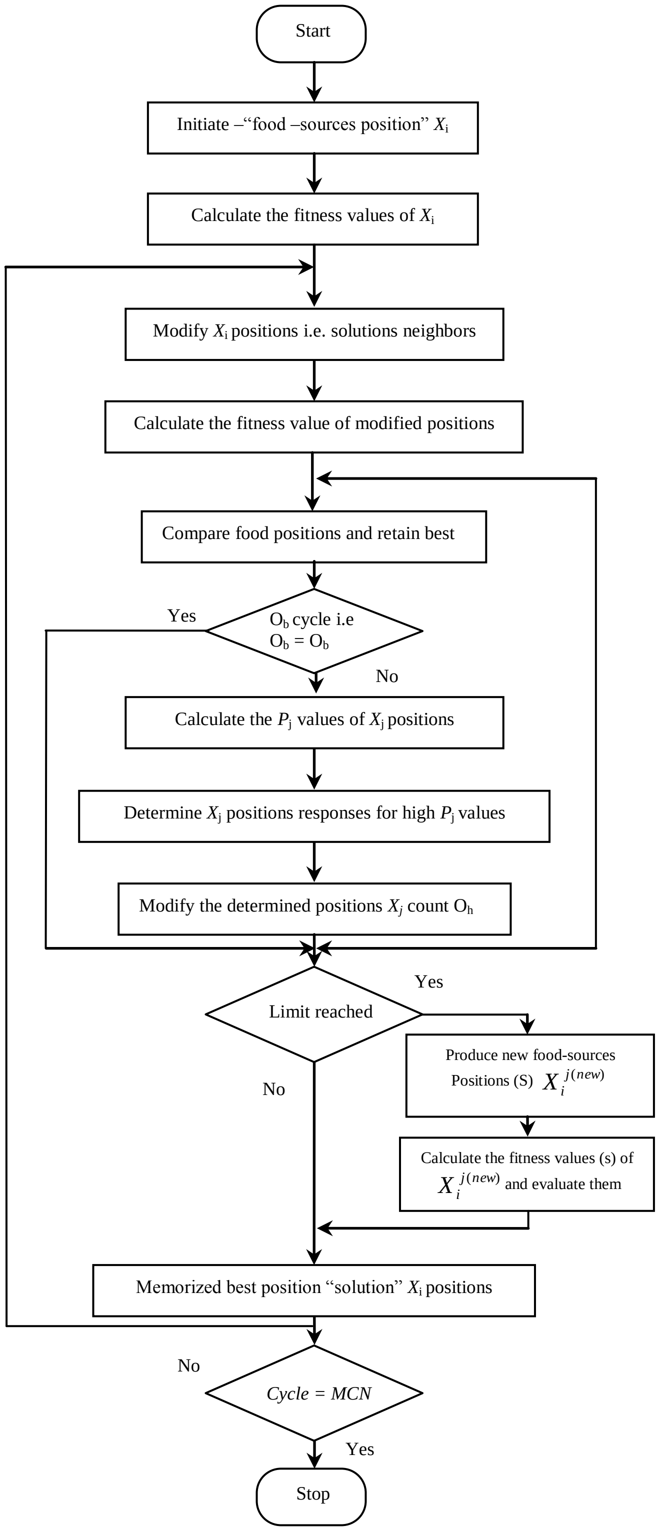

Fig 2 Flow chart for ABC algorithm

4. DESIGN OF FUZZY LOGIC SYSTEM

Fuzzy logic systems belong to the category of computational intelligence technique. One advantage of the fuzzy logic over the other forms of knowledge-based controllers lies in the interpolative nature of the fuzzy control rules. The overlapping fuzzy antecedents to the control rules provide transitions between the control actions of different rules. Because of this interpolative quality, fuzzy controllers usually require far fewer rules than other knowledge-based controllers [10, 11].

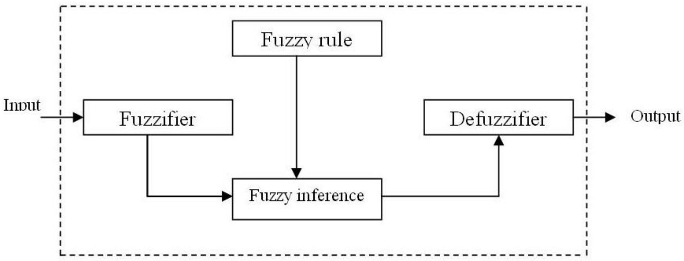

Fig. 3 Block diagram of fuzzy logic controller

A fuzzy system knowledge base consists of a fuzzy if then rules and membership functions characterizing the fuzzy sets. The block diagram and architecture of fuzzy logic controller is shown in Fig 3. Membership Function (MF) specifies the degree to which a given input belongs to a set. Here triangular membership function have been used to explore best dynamic responses namely negative big (NB), negative small (NS) , zero(ZE), positive small (PS), positive big(PB). Fuzzy rules are conditional statement that specifies the relationship among fuzzy variables. These rules help to describe the control action in quantitative terms and have been obtained by examining the output response to the corresponding inputs to the fuzzy controllers. Defuzzification, to obtain crisp value of FLC output is done by centre of area method. The fuzzy rules are designed as shown in table 1.

Table 1. Fuzzy Logic Rules for LFC

ACE / $\dot{ACE}$	**NB**	**NS**	**Z**	**PS**	**PB**
NB	NB	NB	NS	NS	ZE
NS	NB	NB	NS	ZE	ZE
Z	NS	NS	ZE	PS	PS
PS	ZE	NS	PS	PS	PB
PB	ZE	ZE	PS	PB	PB

4.1 Two Layered Fuzzy Logic Controller

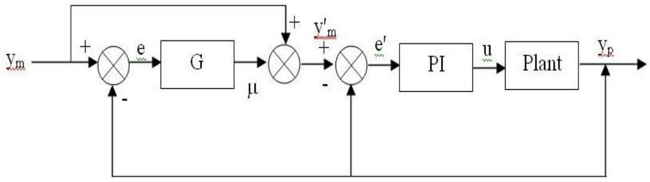

Fig 4. Basic structure of fuzzy pre-compensated PI controller

The aim of introducing two layered fuzzy logic controller [15] is to eliminate the steady state error and improve the performance of the output response of the system under study. The proposed control scheme is shown in Fig. 4. The controller consists of two "layers": a fuzzy pre-compensator and a usual fuzzy PI controller. The error e(k) and change of error Δe(k) are the inputs to the pre compensator. The output of the pre-compensator is μ(k). The PI Controller is usually implemented as follows:

$$u(k) = k_p e(k) + TK_i \sum_{n=0}^{k} e(n) \qquad (12)$$

Where $e(k) = y(k) - y_r(k)$ and Δ e(K) = e (k) - e(k-1)

The controller output, process output and the set point are denoted as u, y and y_r respectively. Experience-based tuning method - Ziegler-Nichols method which widely adopted [16] requires a close attention since the process has to be operated near instability to measure the ultimate gain and period. This tuning technique may fail to tune the process with relatively large dead time [16]. In order to improve the performance of P and I tuning a number of attempts have been made which can be categorized into two groups: Set point modification and gain modification. The set point modification introduces new error terms

$$e_p = y_r(k) F_p(e, \Delta e) - y(k) \qquad (13)$$

$$e_i = y_r(k) F_i(e, \Delta e) - y(k) \qquad (14)$$

The corresponding control law is given by, Where F_p , F_i are non-linear functions of e and Δe.

$$u(k) = k_p e_p(k) + TK_i \sum_{n=0}^{k} e_i(n) \qquad (15)$$

As a special case, the set point is being modified only in proportional terms which implies F_p = β; F_i =1 set point weight.

$$\therefore \text{U (k)} = K_p\{\beta y_r(k) - y(k)\} + TK_i \sum_{n=0}^{k} e(n) \qquad (16)$$

$$U(k) = K_p e'(k) + TK_i \sum_{n=0}^{k} e'(n)$$

The pre-compensation scheme [22, 23] is easy to implement in practice, since the existing PI control can be used without modification in conjunction with the fuzzy pre-compensator as shown in Fig. 5. The procedure of rule generation consists of two parts (i) learning of initial rules which determines the linguistic values of the consequent variables. (ii) Fine tuning adjusts the membership function of the rules obtained by the previous step. The structure of the pre-compensation rule is written as If e is L_e, and Δe is LΔe then C is L_c where L_e, ΔL_e and L_c are linguistic values of e, Δe, c respectively. Each fuzzy variable is assumed to take 5 linguistic values Le, LΔe, or L_c = {NB, NS, ZE, PS, and PB} this leads to fuzzy rules, if the rule base is complete.

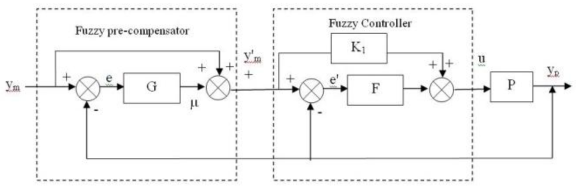

Fig. 5. Proposed two layered fuzzy logic controller

The dynamics of overall system is than described by following equations

$$e(k) = ym(k) - yp(k) \qquad (17)$$

$$\Delta e(k) = e(k) - e(k-1) \qquad (18)$$

$$\mu(k) = G[e(k), \Delta e(k)] \qquad (19)$$

Where μ(k) is a compensating term which is generated using a fuzzy logic scheme

$$y'_m(k) = y_m(k) + \mu(k) \qquad (20)$$

$$e'(k) = y'_m(k) + y_p(k) \qquad (21)$$

$$\Delta e'(k) = e'(k) - e'(k-1) \qquad (22)$$

The proposed two layered FLC compensate these defects and gives fast responses with less overshoot and/or undershoot. Moreover the steady state error reduces to zero. The first layer fuzzy pre-compensator is used to update and modify the reference value of the output signals to damp out the oscillations. The fuzzy states of the input and output all are chosen to be equal in number and use the same linguistic descriptors as N = Negative, Z = Zero, P = Positive to design the new fuzzy rules. The fuzzy logic rules for pre-compensator are presented in Table-2.

Table 2. Fuzzy Logic Rules for Pre compensator

$\dot{ACE}$ \ ACE	N	Z	P
N	N	N	N
Z	Z	Z	Z
P	Z	P	P

The second layer which is known as feedback fuzzy logic control reduces the steady state error to zero. The output of the FLC is given by

$$u(k) = K_1 y'_m(k) + F[e'(k), \Delta e'(k)] \qquad (23)$$

5 APPLICATION OF THE MATHEMATICAL MODEL OF SUPER CAPACITOR ENERGY STORAGE UNIT FOR A TWO- AREA THERMAL REHEAT INTERCONNECTED POWER SYSTEM

5. 1 Super Capacitor Energy Storage Units

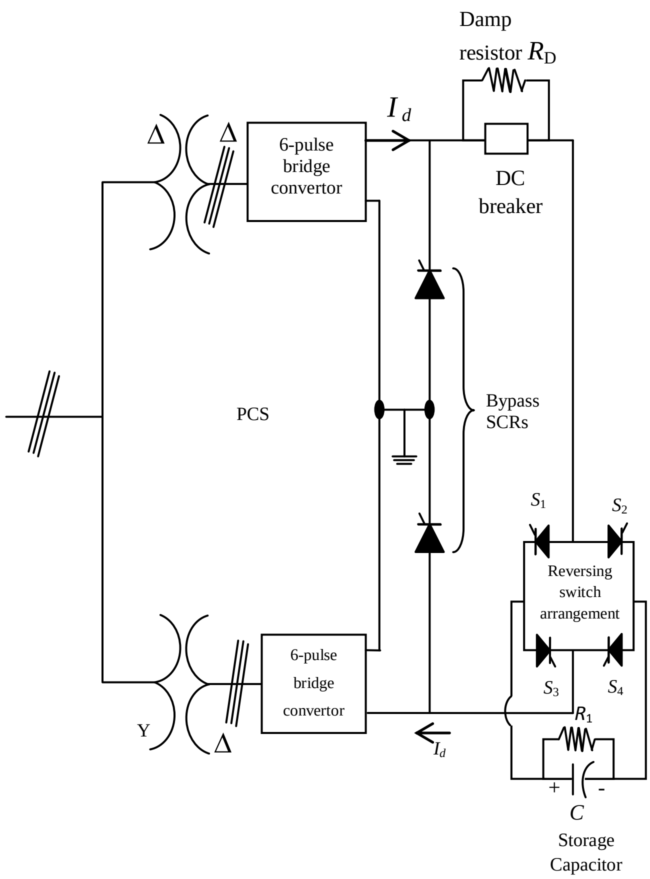

Fig. 6 Super Capacitive Energy Storage Unit

A Super Capacitive Energy Storage (SCES) consists of a super capacitor or a Cryogenic Hyper Capacitor (CHC), a Power Conversion System (PCS) and the associated protective circuitry as shown in Fig.6. The CHCs differ from the conventional capacitors in that they are multilayer ceramic capacitors with a dielectric that has its peak dielectric constant at 77 K, the temperature of liquid nitrogen. The dimensions of the capacitor are determined by the energy storage capacity required. The storage capacitor C may consists of many discrete capacitance units connected in parallel. The resistor R_1 connected in parallel across the capacitor is the lumped equivalent resistance representing the dielectric and leakage losses of the capacitor bank. The PCS, consisting of an ac-to dc rectifier and a dc-to-ac inverter, form the electrical interface between the capacitor and the power system. Two bridges are preferred so that harmonics produced on the ac bus and in the output voltage to the capacitor are reduced. The bypass thyristors provide a path for current I_d in the event of a converter failure. The dc breaker allows current I_d to be diverted into the energy dump resistor R_D if the converter fails. Assuming the losses to be negligible, the bridge voltage E_d is given by [16]

$$E_d = 2E_{d0}\cos\alpha - 2I_dR_D \qquad (24)$$

By changing the relative phase angle α of this pulse through a range from 0° to 180° voltage across the capacitor, E_d can be made to vary from its maximum positive value to the maximum negative value. The voltage pulses from the firing circuits are timed to cause each SCR to begin conduction at a prescribed time. The sequence maintains a constant average voltage across the capacitor. The exact timing of the firing pulses relative to the phase of 50 Hz AC voltage determines the average dc voltage across the capacitor. Since the bridges always maintain unidirectional current and E_d is uniquely defined by α for positive and negative values, the power flow P_d in the capacitor is uniquely determined by α in both magnitude and direction. Thus, without any switching operation, reversibility as well as magnitude control of the power flow is achieved by continuously controlling the firing angle α. The firing angle of the converter is controlled by an algorithm determined by utility needs, but basically the control circuit responds to a demand signal for a certain power level, either positive or negative. Then based on the voltage across the capacitor, a firing angle is calculated and transmitted to the firing circuit. The response time of the control and firing circuits to a new demand signal are so short that a new firing angle may be chosen for the very next SCR to be pulsed, say within a few milliseconds. This rapid response to power demands that may vary by hundreds of megawatts is a unique capability of SCES relative to other energy storage systems such as pumped hydro, compressed air, flywheels etc. This ability to respond quickly allows the SCES unit to function not only as an energy storage unit but also as a spinning reserve and to provide stability in case of disturbances on the utility system. The reversing switch arrangement provided accommodates the change of direction of the current in the capacitor during charging (rated load period) and discharging (during peak load period), since the direction of the current through the bridge converter (rectifier/inverter) cannot change. During the charging mode, switches S_1 and S_4 are on and S_2 and S_3 are off. In the discharging mode, S_2 and S_3 are on and S_1 and S_4 are off.[19]

5.2 Block diagram representation of SCES unit

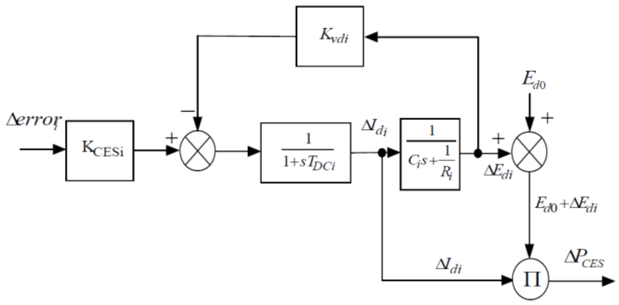

Fig.7 block diagram with capacitor voltage deviation feedback

The normal operating point of the capacitor can be such that the maximum allowable energy absorption equals the maximum allowable energy discharge. This will make the SCES unit very effective in damping the oscillations created by sudden increase or decrease in load. If E_{d0} denotes the set value of voltage and Ed_{max} and Ed_{min} denote the maximum and minimum limits of voltage respectively, then,

$$\frac{1}{2}CE_{d\max}^2 - \frac{1}{2}CE_{d0}^2 = \frac{1}{2}CE_{d0}^2 - \frac{1}{2}CE_{d\min}^2 \qquad (25)$$

$$E_{do} = \frac{[E_{d\max}^2 + E_{d\min}^2]^{1/2}}{2} \qquad (26)$$

The capacitor voltage should not be allowed to deviate beyond certain lower and upper limits. During a sudden system disturbance, if the capacitor voltage goes too low and if another disturbance occurs before the voltage returns to its normal value, more energy will be withdrawn from the capacitor which may cause discontinuous control. To overcome this problem, a lower limit is imposed for the capacitor voltage and in the present study; it is taken as 30% of the rated value. Initially, the capacitor is charged to its set value of voltage E_{d0} (less than the full charge value) from the utility grid during its normal operation. To charge the capacitor at the maximum rate, E_d is set at its maximum value by setting α = 0°. At any time during the charging period, the stored energy in Joules is proportional to the square of the voltage as described.

Once the voltage reaches its rated value, it is kept floating at this value by a continuous supply from PCS which is sufficient to overcome the resistive drop. Since this E_{d0} is very small, the firing angle α will be nearly 90°. The SCES is now ready to be put into service. When there is a sudden rise in load demand, the stored energy is almost immediately released through the PCS to the grid. As the governor and other control mechanisms start working to set the power system to an equilibrium condition, the capacitor charges to its initial value of voltage E_{d0}. The action during sudden releases of load is similar that the capacitor immediately gets charged instantaneously 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 capacitor voltage attains its normal value. The power flow into the capacitor at any instant is

$$P_d = E_d\, I_d \quad (27)$$

And, the initial power flow into the capacitor is

$$P_{d0} = E_{d0}.I_{d0} \quad (28)$$

Where E_{d0} and I_{d0} are the magnitudes of voltage and current prior to the load disturbance. When a load disturbance occurs, the power flow into the coil is

$$P_{d0} + \Delta P_d = (E_{d0} + \Delta E_d)(I_{d0} + \Delta I_d) \quad (29)$$

so that the incremental power change in the capacitor is

$$\Delta P_d = (I_{d0}\Delta E_d + \Delta E_d\, \Delta I_d) \quad (30)$$

The term $E_{d0}.I_{d0}$ is neglected since $E_{d0} = 0$ in the storage mode to hold the rated voltage at constant value.

5.3 Mathematical Model of SCES unit

Either frequency deviation or Area Control Error (ACE) can be used as the control signal to the CES unit ($\Delta error_i = \Delta f_i$ or ACE_i). E_{di} is then continuously controlled in accordance with this control signal. For the i^{th} area, if the frequency deviation Δf_i (i.e., $\Delta error_i = \Delta f_i$). of the power system is used as the control signal to CES, then the deviation in the current, ΔI_{di} is given by

$$\Delta_{di} = \left[\frac{1}{1+sT_{DCi}}\right]\left[K_{CESi}.\Delta f_i - K_{vdi}.\Delta E_{di}\right] \quad (31)$$

If the tie-line power flow deviations can be sensed, then the Area Control Error (ACE) can be fed to the CES as the control signal (i.e., $\Delta error_i = ACE_i$). Being a function of tie-line power deviations, ACE as the control signal to CES, may further improve the tie-power oscillations. Thus, ACE of the two areas are given by

$$ACE_i = B_i \Delta f_i + \Delta P_{tie\ ij} \quad ; i, j = 1, 2 \quad (32)$$

Where $\Delta Ptie_{ij}$ is the change in tie-line power flow out of area i to j.

Thus, if ACE_i is the control signal to the CES, then the deviation in the current ΔI_{di} would be

$$\Delta_{di} = \left[\frac{1}{1+sT_{DCi}}\right]\left[K_{CESi}.\Delta ACE_i - K_{vdi}.\Delta E_{di}\right]; i, j = 1,2 \quad (33)$$

The control actions of Super Capacitor Energy Storage units are found to be superior to the action of the governor system in terms of the response speed against, the frequency fluctuations. The SCES units are tuned to suppress the peak value of frequency deviations quickly against the sudden load change, subsequently the governor system are actuated for compensating the steady state error of the frequency deviations. Fig 8 shows the linearized reduction model for the control design of two area interconnected power system with SCES units. The SCES unit is modeled as an active power source to area 1 with a time constant T_{SCES}, and gain constant K_{SCES}. Assuming the time constants T_{SCES} is regarded as 0 sec for the control design. Then the state equation of the system represented by Fig. 8 becomes.

$$\begin{bmatrix} \Delta\dot{F}_1 \\ \Delta\dot{P}_{T12} \\ \Delta\dot{F}_2 \end{bmatrix} = \begin{bmatrix} -\frac{1}{T_{p1}} & -\frac{k_{p1}}{T_{p1}} & 0 \\ 2\pi T_{12} & 0 & -2\pi T_{12} \\ 0 & \frac{a_{12}\, k_{p2}}{T_{p2}} & -\frac{1}{T_{p2}} \end{bmatrix} \begin{bmatrix} \Delta F_1 \\ \Delta P_{T12} \\ \Delta F_2 \end{bmatrix} + \begin{bmatrix} \frac{k_{p1}}{T_{p1}} \\ 0 \\ 0 \end{bmatrix} \begin{bmatrix} \Delta P_{SCES} \end{bmatrix} \quad (34)$$

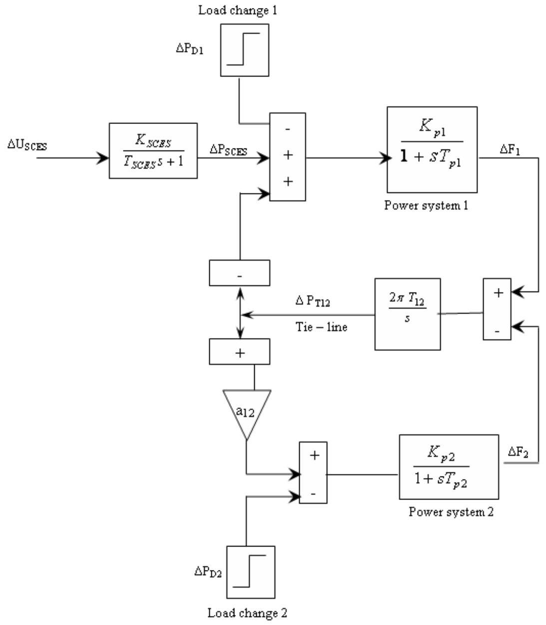

Fig. 8 Linearized reduction model for the control design

5.4 Control design of Super Capacitor Energy Storage unit

The design process starts from the reduction of two area system into one area which represents the Inertia centre mode of the overall system. The controller of SCES is designed for the equivalent one area system to reduce the frequency deviation of inertia centre. The equivalent system is derived by assuming the synchronizing coefficient T_{12} to be large. From the state equation of $\Delta\dot{P}_{T12}$ in Eq (34)

$$\frac{\Delta\dot{P}_{T12}}{2\pi T_{12}} = \Delta F_1 - \Delta F_2 \quad (35)$$

Setting the value of T_{12} in Eq (35) to be infinity yields $\Delta F_1 = \Delta F_2$. Next, by multiplying state equation of $\Delta\dot{F}_1$ *and* $\Delta\dot{F}_2$ in Eq (34) by $\frac{T_{p1}}{k_{p1}}$ and $\frac{T_{p2}}{a_{12}\, k_{p2}}$ respectively, then

$$\frac{T_{p1}}{k_{p1}}\Delta\dot{F}_1 = -\frac{1}{k_{p1}}\Delta F_1 - \Delta P_{T12} + \Delta P_{SCES} \quad (36)$$

$$\frac{T_{p2}}{a_{12}\,k_{p2}}\Delta\dot{F}_2 = \frac{-1}{k_{p2}\,a_{12}}\Delta F_2 + \Delta P_{T12} \qquad (37)$$

By summing Eq (36) and Eq (37) and using the above relation $\Delta F_1 = \Delta F_2 = \Delta F$

$$\Delta\dot{F} = \frac{\left(-\frac{1}{k_{p1}} - \frac{1}{k_{p2}a_{12}}\right)}{\left(\frac{T_{p1}}{k_{p1}} + \frac{T_{p2}}{k_{p2}a_{12}}\right)}\Delta F + \frac{1}{\left(\frac{T_{p1}}{k_{p1}} + \frac{T_{p2}}{k_{p2}a_{12}}\right)}\Delta P_{SCES} + C\Delta P_D \qquad (38)$$

Where the load change in this system ΔP_D is additionally considered, here the control $\Delta P_{SCES} = -K_{SCES}\ \Delta F$ is applied then.

$$\Delta F = \frac{C}{s + A + K_{SCES}\ B}\Delta P_D \qquad (39)$$

Where

$$A = \left(-\frac{1}{k_{p1}} - \frac{1}{k_{p2}a_{12}}\right) \Bigg/ \left(\frac{T_{p1}}{k_{p1}} + \frac{T_{p2}}{k_{p2}a_{12}}\right)$$

$$B = \frac{1}{\left[\frac{T_{p1}}{K_{p1}} + \frac{T_{p2}}{K_{p2}a_{12}}\right]}$$

Where C is the proportionality constant between change in frequency and change in load demand. Since the control action of SCES unit is to suppress the deviation of ΔF quickly against the sudden change of ΔP_D, the percent reduction of the final value after applying a step change ΔP_D can be given as a control specification. In Eq (39) the final values with $K_{SCES} = 0$ and with $K_{SCES} \neq 0$ are C/A and $C/(A+K_{SCES}\ B)$ respectively therefore the percentage reduction is represented by

$$C/(A + K_{SCES}\ B) \big/ (C/A) = R/100 \qquad (40)$$

For a given R, the control gain of SCES is calculated as

$$K_{SCES} = \frac{A}{BR}(100 - R) \qquad (41)$$

5.5 Application of Dual Mode Two Layered Fuzzy Logic controller for the two- area interconnected Power System with SCES units

The Linearized model of two- area reheats thermal interconnected power system with SCES unit as shown in Fig 9.

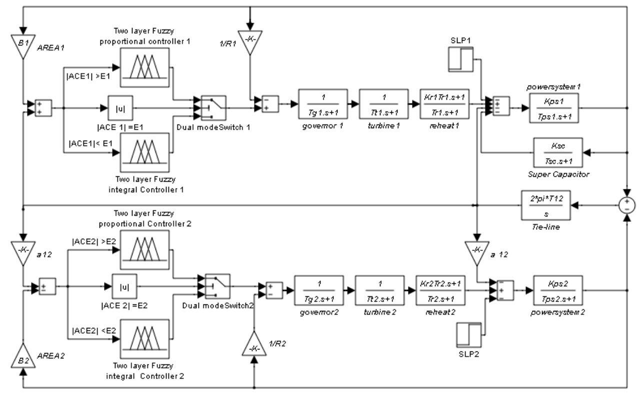

Fig.9 Linearized model of Dual mode Two Layered Fuzzy Logic Controller based two- area interconnected reheat thermal power system with SCES units

6. SIMULATION RESULTS AND OBSERVATIONS

The optimal gains of the conventional dual mode PI controller are determined using ABC algorithm.. These controllers are implemented in a two- area interconnected reheat thermal power system for 1% step load disturbance in area 1. The nominal parameters are given in Appendix. The gain values of SCES (K_{SCES}) are calculated using Eq (41) for the given value of speed regulation coefficient (R). The gain value is of the super capacitor is found to be $K_{SCES} = 0.67$. The conventional optimum gain values of the PI controllers are found to be $K_{P1} = K_{P2} = 0.8$ with $K_{I1} = K_{I2} = 0.26$ using MATLAB 7.01 software. Moreover dual mode two layered fuzzy logic controller are designed and implemented in the interconnected two area power system without and with SCES unit for 1% step load disturbance in area 1. The fuzzy rules are designed according to ACE is shown in Table 1 and 2. The comparative transient response from Fig 10 and 11, it can be observed that the oscillations in area frequencies, tie-line power deviation and control input requirements have decreases to a considerable extent for the system with use of dual mode Two layered fuzzy logic control as compared to that of the system using dual mode PI controller. Moreover the Super Capacitor Energy Storage unit is located in area 1 which is made to ensure the coordinated control action along with the governor unit to enable more improvement in the inertia mode oscillations as shown in Fig10. It is also evident that the settling time and peak over/under shoot of the frequency deviations in each area and tie-line power deviations decreases considerable amount with use of SCES unit. In Fig 11, it should be noted that SCES coordinated with governor unit requires lesser control effort. Fig 12 shows the generation responses for the three case studies as the load disturbances have occurred in area1, at steady state, the powers generated by generating units in both areas are in proportion to the area participation factors. From the Table-3 it can be observed that the controller design using dual mode Two layered fuzzy logic controller for two area thermal reheat power system with SCES unit have not only reduces the cost function but also ensure better stability, as they possesses less over/under shoot and faster settling time. Thus SCES unit coordinated with governor unit improves not only inertia mode but also the inter area mode oscillations effectively.

Table 3. Comparison of the system performance for the three case studies

wo area interconnected power system	Setting time(τ_s)in (s)			Peak over / under shoot		
	ΔF_1	ΔF_2	ΔP_{tie}	ΔF_1 (Hz)	ΔF_2 (Hz)	ΔP_{tie} (p.u.MW)
Case:1 Dual mode PI controller	29.29	28.91	26.12	0.0218	0.0198	0.0054
Case:2 Dual mode Two layer fuzzy controller	6.347	5.572	6.634	0.0096	0.0078	0.0021
Case:3 Dual mode Two layer fuzzy controller with SCES unit	4.012	4.884	4.719	0.0047	0.0037	0.0011

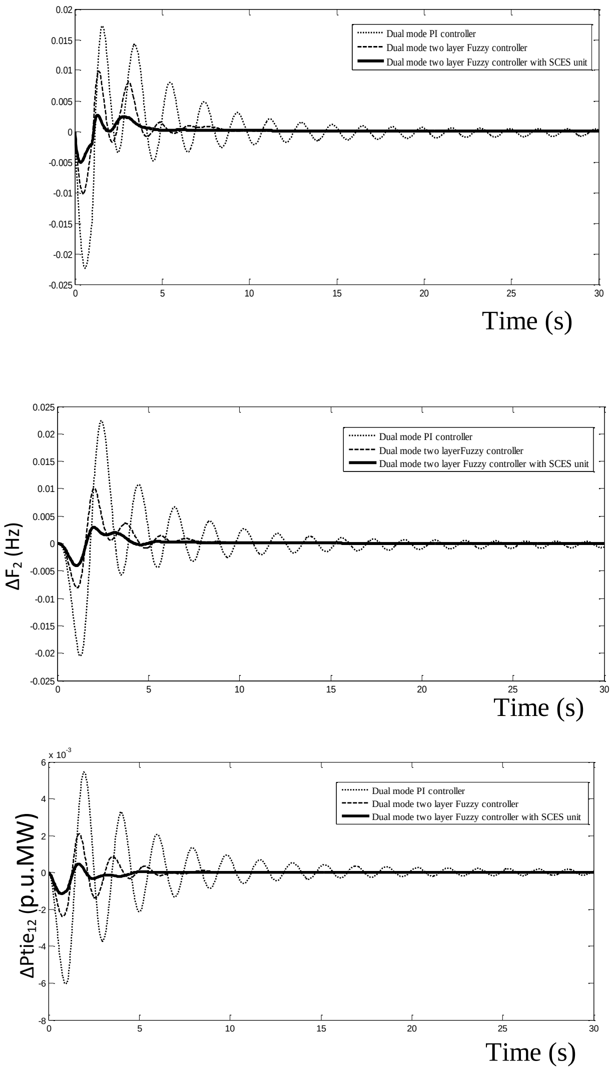

Fig.10 Dynamic responses of the frequency deviations and tie line power deviation of a two-are thermal reheat interconnected Power System considering a step load disturbance of 0.01p.u.MW in area 1

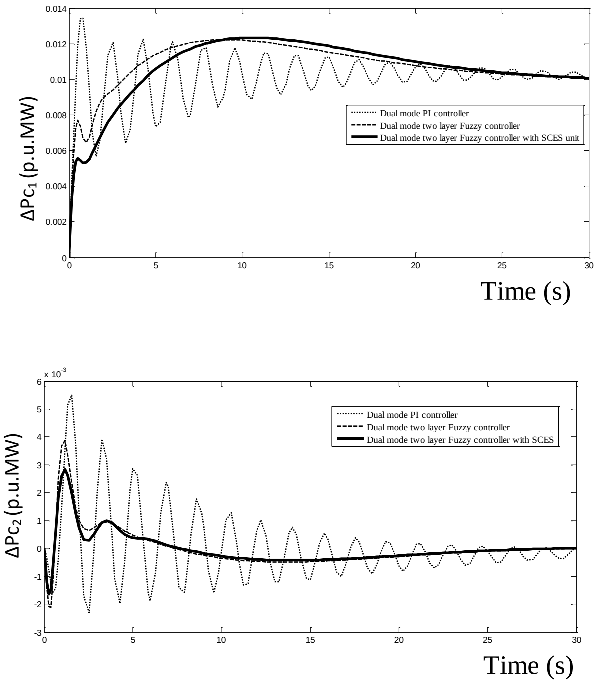

Fig. 11 Dynamic responses of the Control input deviations of a two-area thermal reheat interconnected Power System considering a step load disturbance of 0.01p.u.MW in area 1

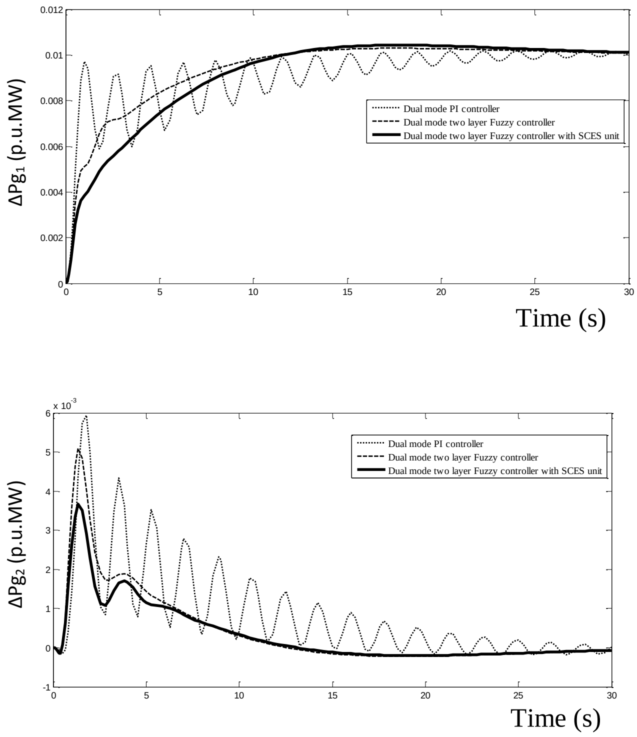

Fig 12 Dynamic responses of the required additional mechanical power generation for two-area thermal reheat interconnected Power System considering a step load disturbance of 0.01 p.u.MW in area 1

7. CONCLUSION

A Dual mode Two Layered Fuzzy logic controllers were designed and implemented in a two area thermal reheat interconnected power system coordinated with super capacitor energy storage devices. This control scheme consists of two layers viz fuzzy pre-compensator and fuzzy like P and fuzzy like I controller. Fuzzy rules from the overall fuzzy rule vectors are used at the first layer, linear combination of independent fuzzy rules are used at the second layer. The two layer fuzzy system has less number of fuzzy rules as compared with the fuzzy logic system. Simulation result ensures that the Dual mode two layered fuzzy logic controllers give better simulation results when compared with the simulation results obtained using the Dual mode PI controllers for the system without super capacitor energy storage unit.

The advantages of the expected SCES over existing power system in the LFC applications were examined. For an overload condition for a short time period because of nature of SCES, extremely faster response is obtained with use of SCES unit. From this it is evident that SCES contributes a lot in promoting the efficiency of overall generation control through the effect of the use in load leveling and the assurance of LFC capacity after overload characteristic and quick responsiveness. It should be noted that the design concept accounts for damping out the inertia mode and inter-area mode oscillations in an effective manner by suppressing the frequency deviation of two area system simultaneously. It may be concluded that, Super Capacitor Energy Storage devices with a sufficient margin of LFC capacity absorbs the speed governor capability in excess of falling short of the frequency bias value. It may be expected to be utilized as a new ancillary service for stabilization of the tie-line power oscillations even under congestion management environment of the power transfer.

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Appendix:

(i) Data for Thermal Power System with Reheat Turbines [10].

f^0 = 60 Hz, $PR_1 = PR_2$ = 2000 MW, $K_{p1}=K_{p2}$= 120 Hz / pu.MW, $T_{pS1} = T_{pS2}$ = 20 sec, $T_{t1} = T_{t2}$ = 0.3 sec, $T_{g1}=T_{g2}$= 0.08 sec, $K_{r1}=K_{r2}$= 0.5, $T_{r1} = T_{r2}$ = 10 sec, R1 = R2 = 2.4 Hz/p.u MW, $\beta_1=\beta_2$ = 0.425 pu.MW/Hz, ΔP_{D1} = 0.01 p.u MW, T = 2 sec (Normal sampling rate), T_{12}=0.545 pu.MW/Hz

(ii) Data for Super Capacitor Energy Storage unit [26]

K_{vd} = 0.1 kV/kA, K_O = 70 kV/Hz , C = 1 F, R = 100Ω
K_{SCES}=0.7 Hz/pu Mw, T_{SCES} =0.01 sec

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