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Control Performance Standards Criteria Based Load Frequency Control Using Dual Mode Two Layer Fuzzy Logic Controller For An Interconnected Power System With Super Capacitor Unit Considering Nonlinearities

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Abstract

This paper presents Control Performance Standard (CPS) criterion based Dual Mode Two Layer Fuzzy Logic Controller (DMTLFLC) for the Load Frequency Control of a two area interconnected power system considering Governor Dead Band and Generation Rate Constraints nonlinearities. The proposed DMTLFLC consists of two-layer fuzzy logic system. Each layer is designed to target particular objectives, so that design is simpler and reduces the complexity of fuzzy rule design. The first layer is called pre-compensator, which is used to generate and update the reference value of Area Control Error (ACE) according to control area compliance with North American Electric Reliability Council (NERC). The Control Performance Standard (CPS) criterion used as the input of the pre-compensator and rules are designed to reduce the wear and tear of the equipment. The second layer is called fuzzy PI controller with dual mode control i.e., either proportional or integral mode. The concept of dual-mode control in the fuzzy system such that the proportional mode is made active when the rate of change of the new Area Control Error (ACE_N) is sufficiently larger than a specified limit otherwise switched to the integral mode. The simulation results of the proposed controller exhibits superior transient and steady-state performance of the LFC system. Moreover the proposed controller will significantly reduce frequent change in governor set points in order to avoiding unnecessary maneuvering of the generating units. The power modulation control such as Super Capacitor Energy Storage Unit (SCES) has to be adopted to suppress the peak value of the transient frequency deviation and maintains the power quality with the distributed power resource.

Keywords: Dual Mode Two Layered Fuzzy Logic Controller, Super Capacitor Energy Storage, Governor Dead Band, Generation Rate Constraints, Control Performance Standards.

Introduction

Changes in power demand are frequent and unpredictable and they affect the system frequency as well as the inter-area power exchange in an interconnected power system operation. Load Frequency Control (LFC) is a necessary mechanism by which the balance between the power demand and the power generation is maintained with the objectives to keep the frequency at the nominal value and maintain the scheduled inter-area tie-line power flow. For the past several decades lot of work pertaining the design of classical controllers for interconnected power systems [1] has been reported and in most of the cases the mathematical model has been over simplified by ignoring the simultaneous presence of nonlinearities such as Governor Dead Band (GDB) and Generation Rate Constraints(GRC) all governors in the thermal reheat power system have dead bands like mechanical friction, backlash, valve overlaps in hydraulic relays, which are important for speed control even under small disturbances. So, the speed governor dead band has significant effect on the dynamic performance of load-frequency control system. Moreover, the GDB has a destabilizing effect on the transient response of the system [2]. In a power system, another most important constraint on modern large size thermal units is the stringent generation rate constraint *i.e.* the power generation can change only at a specified maximum rate. The GRC of the system is considered as a limiter to the power generating system [3]. In this condition, the response will be with larger overshoots and longer settling times when compared with the system where GRC is not considered. So, if the parameters of the controller are not chosen properly, the system may become unstable. In the simultaneous presence of GDB and GRC, even with small load perturbation, the system becomes highly nonlinear and hence the optimization problem becomes rather complex [4, 5]. So advanced economic, high efficiency and improved control schemes are required to ensure the power system reliability.

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 [6, 7]. 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 approach using proportional plus integral controllers results in relatively large over shoots in transient frequency deviations. 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 [8]. 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 [9].

Fast fluctuations in aggregate load, which can be described as a form of random movements, cannot be matched by load following services. Consequently, resultant mismatches represented as area control error are taken care of by those units providing regulation services [10]. As a response to the LFC requests, the generating units constantly have to move up and down. Too tight control can have big impact on the generating units and the cost related to the wear and tear of the unit and associated maintenance needs to be minimized. At the other side, too loose control can lead to violation of the control standards and inevitable penalization. The Control Performance Standard (CPS) is specifically designed to comply with the performance standards imposed by the North American Electric Reliability Council (NERC) for equitable operation of an interconnected system [11]. Control Performance Standard (CPS1) and Control Performance Standard 2 (CPS2) are derived from rigorous theoretical basis [12]. The control actions are taken only when necessary, when the compliance is low and close to violation of NERC standards. In such a case, the controller will produce a signal to timely adjust the generation and improve area compliance. However, when CPS compliance is satisfied the controller will not produce changes in governor set points, avoiding unnecessary maneuvering of the generating units. In this study the Control Performance Standard criterion is introduced into the fuzzy controller design, thus improves the dynamic quality of system.

The usual fuzzy logic controllers may fail to facilitate the smooth operation and less oscillatory when system is subjected to load disturbances also in presence of nonlinearities. But the design procedures with more skill can overcome the drawback. The fuzzy gain scheduling controller had been used for nonlinear systems by some researcher. In this method, control parameters can be changed very quickly since parameter estimation is not required and thus system outputs are obtained faster with higher quality as compared with conventional controllers. In this same method, the transient response can be unstable because abruptness in system parameters. Also, accurate linear time invariant models cannot be obtained at variable operating point [13]. Fuzzy systems use a method of approximate reasoning, which allows them to make decisions based on vague and incomplete information in a manner which is similar to the way human beings operate. However, the total number of fuzzy rules and adjustable system parameters increases exponentially with the number of input variables in standard fuzzy reasoning processes. This imposes a heavy burden on the system and suffers from poor transient performance and a large steady state error when applied to systems with dead zones. Because of this, classical fuzzy systems cannot perform well even with the fuzzy reasoning. On the other hand, when dealing with complex systems, the single-loop controller may not achieve the control performances and a multilayered controller turns out to be very helpful. The main advantage of the multilevel control lies in the freedom of the design of each layer [14, 15]. The layers are designed to target particular objectives, so that design is simpler and the performance can be very well being improved. Based on the application multilevel control, the proposed fuzzy controller is design with two-layer control architecture to solve the rule explosion problem in multi-input fuzzy logic system. The first layer is constructed from the information that reflects compliance with Control Performance Standard so as called control supervisor or pre-compensator. In second layer is fuzzy PI controller consists of dual-mode control concept such that the proportional mode is made active when the rate of change of the error is sufficiently larger than a specified limit otherwise switches to the integral mode. The proposed DMTLFLC to control two-area reheat thermal interconnected restructured power system with GDB and GRC nonlinearities and it can provide a better dynamic performance and enhances an efficient way of coping even with imperfect information, offers flexibility in decision making processes as compared with conventional PI controllers.

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) devices for their applications as load-frequency stabilizers. The energy density of Super Capacitor (SC) is found to be 100 times larger than the conventional electrolytic capacitor and their power density is 10 times larger than the lead-acid battery [16]. Ultra capacitors possess a number of attractive properties like fast charge-discharge capability, longer life, no-maintenance and environmental friendliness [17]. The effective specific energy for a prescribed load can be satisfied using various SC bank configurations. The SCES will, in addition to load levelling, a function conventionally assigned to them, have a wide range of applications such as power quality maintenance for decentralized power supplies [18, 19]. 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 which are required for the power quality maintenance are met out effectively with the incorporation of SCES.

Problem Formulation

The state variable equation of the minimum realization model of 'N' area interconnected power system [9] may be expressed as

$$\dot{x} = Ax + Bu + \Gamma d \qquad (1)$$
$$y = Cx$$

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

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

$u = [u_1, \ldots u_N]^T = [\Delta P_{C1} \ldots P_{CN}]^T, N$ - Control input vector, $d = [d_1, \ldots d_N]^T = [\Delta P_{D1} \ldots P_{DN}]^T, N$ - Disturbance input vector, $y = [y_1 \ldots y_N]^T$, $2N$ - 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 gain values of the proportional controller (K_{p1}, K_{p2}) and the 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 (ζs) in area frequencies and power exchange over tie-line. Fig. 1 represents the block diagram of two area reheat thermal interconnected power system. In the present work, an Integral Square Error (ISE) criterion is used as a performance index by minimizing the objective function defined as follows

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

Design of Proposed Dual Mode Two-Layer Fuzzy Logic Controller

The design objective is to minimize the adverse effects (ACE and frequency deviation) caused by the load disturbances. In a competitive environment, the LFC providers need not only to comply with the *CPS*1 and *CPS*2 alone, but also to minimize their LFC costs that result from a number of units maneuvering, as well as wear and tear due to reversals. This paper proposed controller to solve the rule explosion problem in the multi-input fuzzy logic system and by adopting double layered fuzzy system. The proposed fuzzy based intelligent controller consists of two “layers”: a fuzzy pre-compensator and a usual feedback fuzzy controller are shown in Fig 1. The main advantage of the multilevel control lies in the freedom of the design of each layer [14]. The layers are designed to target particular objectives, so that design is simpler and performance improved. The controller design is simplify two-layer control architecture where the first layer is called pre-compensator, which is used to generate and update the reference value of ACE and assure its control performance in compliance with NERC’s control performance standards and fuzzy rules are design to reduce the wear and tear of the equipment. The other layer called feedback dual mode fuzzy logic controllers namely Proportional mode, or integral mode fuzzy logic controller. The dual mode control concept can be adopted in a fast manner in order to eliminate the static and dynamic error of PI controller. Thus proposed controllers operates by switching between proportional mode and Integral controller depending upon the magnitude rate of change of new Area Control Error (ACE_N) and assure compliance with control performance standards *CPS*1 and *CPS*2 set by NERC, and to reduce number of reversals of the generating units.

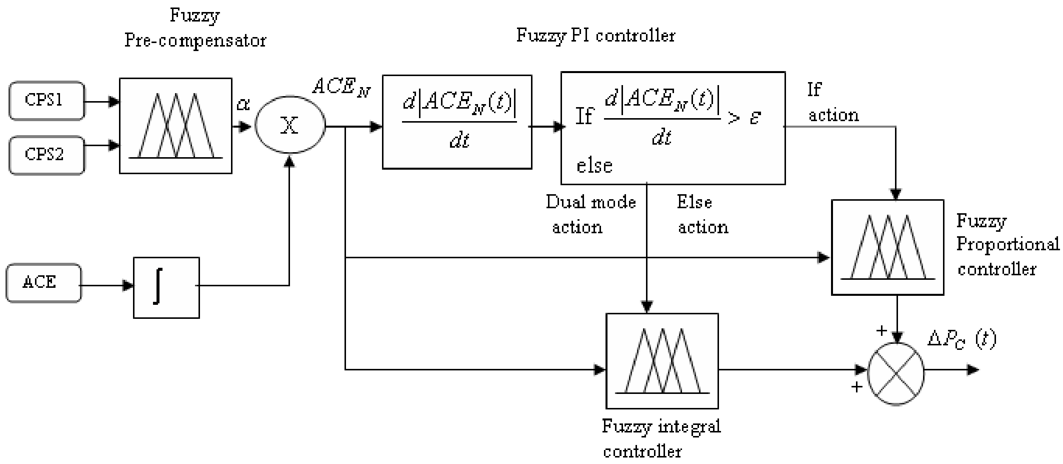


Figure 1: Control structure of proposed fuzzy based intelligent controller

Design of Pre-Compensator

The pre-compensator is constructed from fuzzy systems as a control supervisor based on the current Area Control Error (ACE) and the predicted change-of-ACE. The Control Performance Standard (CPS) criterion is introduced into the fuzzy pre-compensator design thus improves the dynamic quality of system. North American Electric Reliability Council (NERC) had proposed new control performance standards CPS1 and CPS2 to evaluate the control area performance in normal interconnected power system operation. Each control area is required to monitor its control performance and report its compliance CPS1 and CPS2 to NERC at regular intervals [11, 12].

Control Performance Standard 1(CPS1)

CPS1 assesses the impact of ACE on frequency over a certain period window or horizon and it is defined as follows: over a sliding period, the average of the "clock-minute averages" of a control area' s ACE divided by "10 times its area frequency bias" times the corresponding "clock- minute averages of the interconnection frequency error" shall be less than the square of a given constant, $\epsilon_{1,}$ representing a target frequency bound.

$$AVG_{period}\left[\left(\frac{ACE_i}{-10\beta_i}\right)_1 \Delta F_i\right] \leq \varepsilon_1^2 \qquad (3)$$

Where $ACE_i(t) = \beta_i \Delta F_i + \Delta P_{tie\ i-j\ error}$ and ΔF_i is the clock- minute average of frequency deviation, β_i the frequency bias of the i^{th} control area, ε_1 the targeted frequency bound and *n*-scaling factor for CPS1 and $\left(\frac{ACE_i}{-10\beta_i}\right)_1$ is the clock-1 min average. To calculate CPS1 (K_{CPS1}), a compliance factor (K_{CF}) is defined as:

$$K_{CF} = \frac{\sum\left[\left(\frac{ACE_i}{-10\beta_i}\right)_1 \Delta F_1\right]}{n\varepsilon_1^2} \tag{4}$$

CPS1 is then obtained from the following equation

$$K_{CPS1} = (2 - K_{CF}) * 100\% \tag{5}$$

1. When $K_{CPS1} \geq 200\%$, which means $K_{CF} \leq 0$, there is $\sum (ACE_1 * \Delta F_1) \leq 0$. Under this condition, ACE facilitates the frequency quality
2. When $100\% \leq K_{CPS1} < 200\%$, which means $0 < K_{CF} \leq 1$, there is $0 \leq \Sigma\left[\left(\frac{ACE_i}{-10\beta_i}\right)_1 * \Delta F_1\right] \leq n\varepsilon_1^2$. Then CPS1 standard is satisfied.
3. When $K_{CPS1} < 100\%$, which means $K_{CF} > 1$, there is $\Sigma\left[\left(\frac{ACE_i}{-10\beta_i}\right)_1 * \Delta F_1\right] > n\varepsilon_1^2$.

   ACE has exceeded the permitted range so that it has a bad effect on the frequency and quality of power grid.

Control Performance Standard 2 (CPS2)

The second performance standard, CPS2 (K_{CPS2}), limits the magnitude of short- term ACE values. It requires the 10-min averages of a control area's ACE be less than a given constant (L_{10}), as in the equation below:

$$AVG_{10\min}(ACE_i) \leq L_{10} \tag{6}$$

Where, $L_{10} = 1.65\,\varepsilon_{10}\sqrt{(-10\beta_i)(-10\beta_s)}$. Note that β_s is the summation of the frequency bias settings of all control areas in the considered interconnection, and ε_{10} is the target frequency bound for CPS2. To comply with this standard, each control area must have its compliance no less than 90%. A compliance percentage is calculated from the following equation:

$$K_{CPS2} = \frac{AVG_{10\min}(ACE_i)}{L_{10}} \tag{7}$$

In order to meet the requirements of the power grid frequency quality, the average ACE value during 10 min in each control region should be in the normal distribution as:

$$\sigma = \varepsilon_{10}\sqrt{(-10\beta_i)(-10\beta_s)} \tag{8}$$

Optimization rules based on Control Performance Standards

Suppose Control Performance Standard 1 ≥100% and Control Performance Standard 2 ≥90% to be goal of the LFC control strategy. Table 1 shows LFC optimization rules based on Control Performance Standard.

Table 1: LFC Optimization rules based on CPS

Condition		The state of LFC units
CPS1 ≥100% and CPS2 ≥90%		No optimization adjustment
CPS1<100% and CPS2 ≥90%	ACE*ΔF>0	Optimization adjustment
	ACE*ΔF<0	No optimization adjustment
CPS1≥100% and CPS2<90%		Optimization adjustment
CPS1<100% and CPS2<90%		Optimization adjustment

This paper uses the information that reflects compliance with CPS1 and CPS2 and is used as the input to form the fuzzy rules. The proposed fuzzy logic will lower the controller gain when the control area has high compliance. On the other hand, that the controller gain will be increased when the compliance with CPS1 of the control area is low. According to the optimized rules from the Table 1, the input and output membership functions of the pre-compensator, CPS1, CPS2 and α_i could be defined as shown in Fig.2 and Fig.3. Fuzzy rules are summarized in Table 2. The pre-compensation scheme is easy to implement in practice and assures control area compliance with NERC control performance standards *CPS*1 and *CPS*2. The fuzzy pre-compensator is used to update and modify the reference value of ACE which was used the input signals of the second layer. The control actions are taken only when necessary, when the compliance is low and close to violation of NERC standards. In such a case, the controller will produce a signal to timely adjust the generation and improve area compliance. However, when CPS compliance is satisfied the controller will not produce changes in governor set points, avoiding unnecessary maneuvering of the generating units.

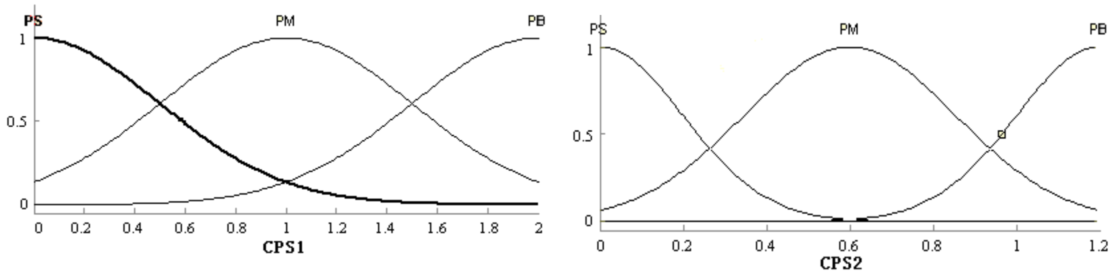


Figure 2: Membership function for the input variables (CPS1, CPS2)

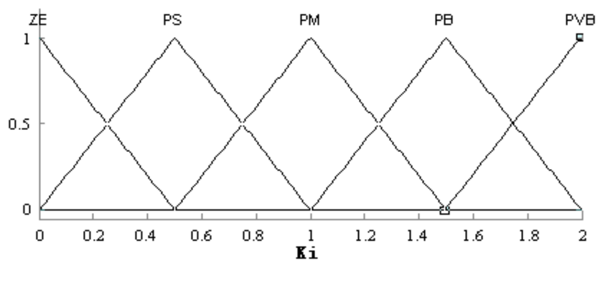


Figure 3: Membership function for the controller outputs (αi)

Table 2: Pre-compensator Fuzzy logic rules for CPS

CPS1 \ **CPS2**	PS	PM	**PB**
PS	ZE	PS	**PS**
PM	PS	PB	**PM**
PB	**PB**	**PVB**	**PVB**

Design of Feedback Fuzzy PI Controller

The second layer called feedback fuzzy PI controller. This controller strategy combines fuzzy proportional and integral controller with a fuzzy switch. 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. The dual mode control scheme is proposed in this paper, the control system will operate in this mode when the rate of change the new Area Control Error (ACE_N) exceeds specified limit. In the discontinuous mode, the control should switch between two different control algorithms in the feedback loop until the rate of change of the $ACE_{N,}$ signal enters singular strip permanently. The time at which these changes occur is determined in accordance with current value of the derivative of ACE_N signal. The control law employed during the transient period, i.e., the discontinuous mode, is switched between Eq (9) and Eq (10) depending on the magnitude of the rate of change of new Area Control Error signal $\left|\frac{dACE_N(t)}{dt}\right|$. Based upon the above mentioned facts, the dual mode concept is introduced in the following manner. The proportional controller will act during the transient period when the rate of change of error (ACE_N) is sufficiently larger, whereas the integral controller would be the better option when the rate of change of error is small. The dual mode control scheme of the fuzzy feedback PI controller is shown in Fig 1. For the proposed control scheme, the control law is taken as follows

$$\Delta P_c(t) = -K_p (ACE_N(t)) \quad for \left|\frac{dACE_N(t)}{dt}\right| > \varepsilon \tag{9}$$

$$\Delta P_c(t) = -K_I \int (ACE_N(t))dt, \quad for \left|\frac{dACE_N(t)}{dt}\right| \le \varepsilon \tag{10}$$

Where, ACE_N (t) the error signal at a particular instant, $\Delta P_c(t)$ output signal of the controller and ε is constant indicating the specified limit of error signal. When the error signal remains within the specified limit, i.e., $\left|\frac{dACE_N(t)}{dt}\right| < \varepsilon$, the system will operate in continuous mode. The integral control strategy is best suited to meet the requirements when system enters the continuous mode. Thus the fuzzy proportional controller is employed to penalize fast change and large overshoots in the control input due to corresponding practical constraints. The fuzzy integral controller stage is used in order to get disturbance rejection and zero steady state error. The both the fuzzy Proportional and fuzzy integral controller can use the same membership functions and the same rule base. Only the gains for the input and output signals have to be tuned with appropriate coefficients. The input signals of the proposed fuzzy Proportional and fuzzy integral controller are new Area control Error (ACE_N) and the rate of change of new Area control Error (ΔACE_N). The output signal of feedback fuzzy PI controller is ΔP_C . The input and output membership functions of the proposed feedback fuzzy PI controller are shown in Fig. 4 and Fig.5, respectively. The membership functions are the control gains K_P, K_I, to be large or small, as shown in Fig.4 and Fig 5. Hence, feedback fuzzy PI controller becomes a parameter time varying proportional and integral controller. The input membership functions "ACE_N" of the feedback fuzzy PI controller is divided into three areas based on magnitude and sign. These are positive small (PS), positive middle (PM) and positive (P). Also, the input membership functions "ΔACE_N" and the output membership functions "ΔP_C" of the feedback fuzzy PI controller are divided into three areas based on magnitude and sign. There are negative (N), zero (Z) and positive (P). Fuzzy control rules are constructed by using the control experience of operator having experiences about Load Frequency Control of the interconnected Restructured power system. The input variables "ACE_N and "ΔACE_N" have three membership functions, as shown in Fig 4. Using the combinations of the input membership functions, total nine fuzzy control rules can be generated a fuzzy output relating two input fuzzy sets as shown in Table 3.

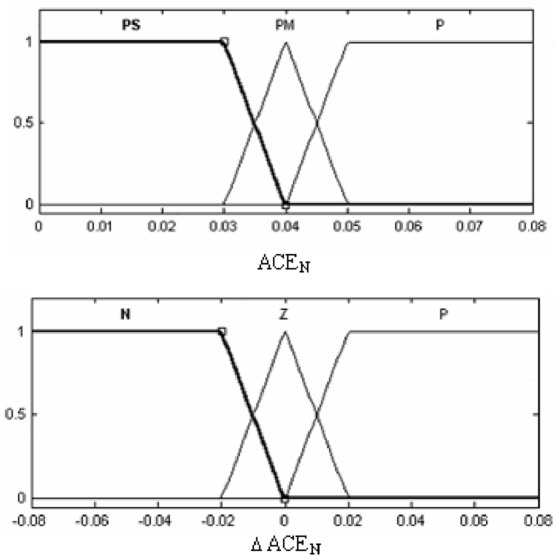


Figure 4: Membership function for the input variables (ACE_N, ΔACE_N)

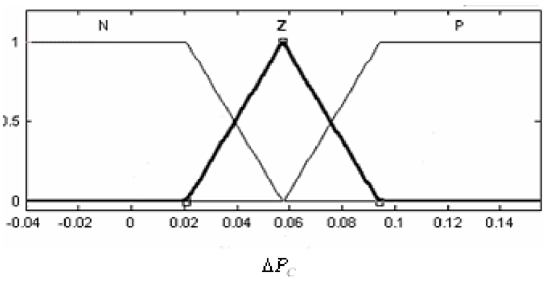


Figure 5: Membership function for the controller outputs ΔP_C

Table 3: Rule table for Feedback Fuzzy PI controller

ΔACE$_N$ / **ACE$_N$**	N	Z	**P**
PS	N	N	**Z**
PM	N	Z	**P**
P	**Z**	**P**	**P**

Application of Super Capacitor Energy Storage For An Interconnected Power System

Components of SCES 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 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.

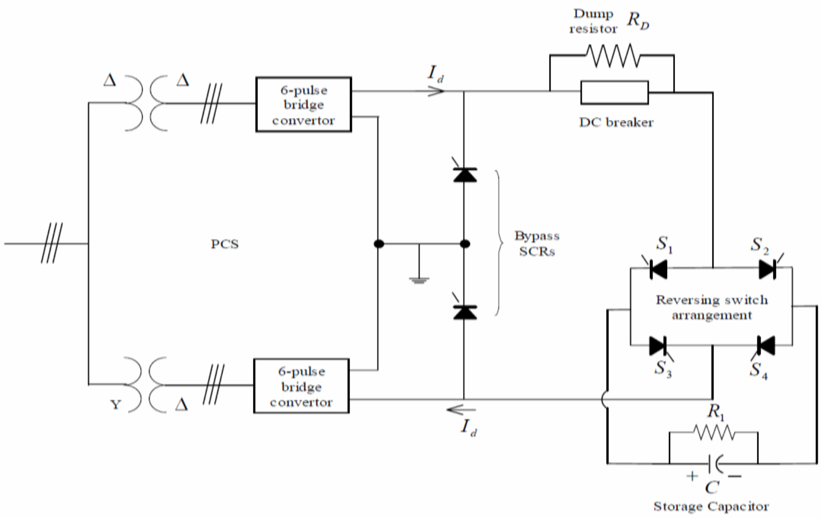


Figure 6: Super Capacitive Energy Storage Unit

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,

$$\frac{1}{2}CE_{d\max}^2 - \frac{1}{2}CE_{d0}^2 = \frac{1}{2}CE_{d0}^2 - \frac{1}{2}CE_{d\min}^2 \tag{11}$$

$$E_{do} = \frac{[E_{d\max}^2 + E_{d\min}^2]^{1/2}}{2} \tag{12}$$

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

$$P_d = E_d\, I_d \tag{13}$$

And, the initial power flow into the capacitor is

$$P_{d0} = E_{d0}.I_{d0} \tag{14}$$

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

$$P_{d0} + \Delta P_d = (E_{d0} + \Delta E_d)(I_{d0} + \Delta I_d) \tag{15}$$

so that the incremental power change in the capacitor is

$$\Delta P_d = (I_{d0}\Delta E_d + \Delta E_d\, \Delta I_d) \tag{16}$$

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

Mathematical Model of SCES unit

The block diagram representation of SCES unit is shown in Fig.7. The frequency deviation can be used as the control signal to the SCES unit ($\Delta error_i = \Delta f_i$). 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 SCES unit, then the deviation in the current, ΔI_{di} is given by

$$\Delta_{di} = \left[\frac{1}{1+sT_{DCi}}\right]\left[K_{CESi}.\Delta f_i - K_{vdi}.\Delta E_{di}\right] \tag{17}$$

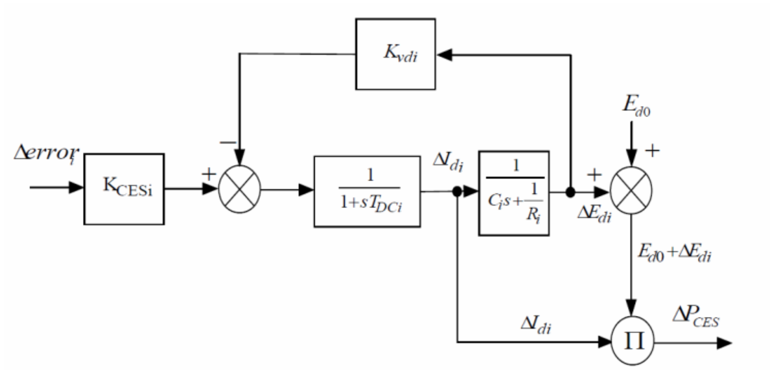


Figure 7: block diagram with capacitor voltage deviation feedback

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.

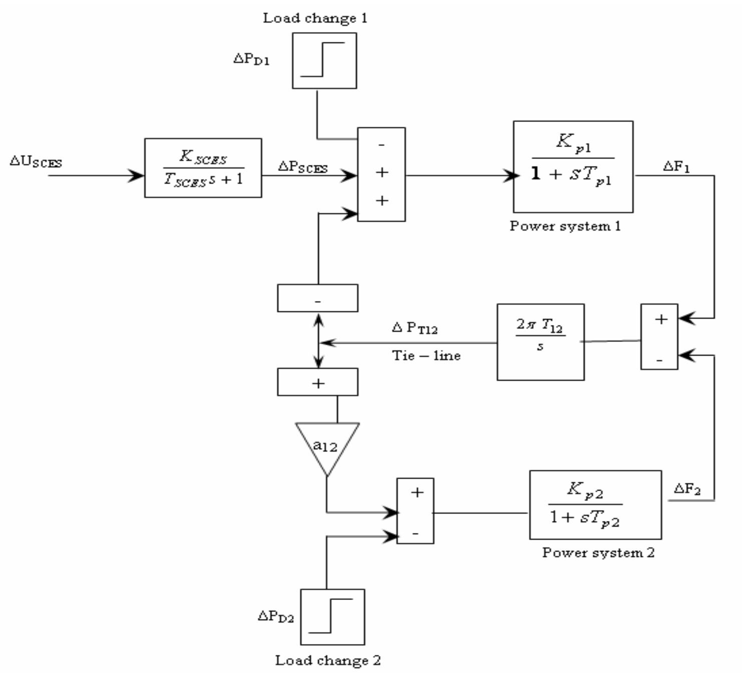


Figure 8: Linearized reduction model for the control design

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

$$\begin{bmatrix} \Delta\dot{F}_1 \\ \Delta\dot{P}_{T12} \\ \Delta\dot{F}_2 \end{bmatrix} = \begin{bmatrix} -\dfrac{1}{T_{p1}} & -\dfrac{k_{p1}}{T_{p1}} & 0 \\ 2\pi T_{12} & 0 & -2\pi T_{12} \\ 0 & \dfrac{a_{12}\,k_{p2}}{T_{p2}} & -\dfrac{1}{T_{p2}} \end{bmatrix} \begin{bmatrix} \Delta F_1 \\ \Delta P_{T12} \\ \Delta F_2 \end{bmatrix} + \begin{bmatrix} \dfrac{k_{p1}}{T_{p1}} \\ 0 \\ 0 \end{bmatrix} \begin{bmatrix} \Delta P_{SCES} \end{bmatrix} \tag{18}$$

Control design of SCES 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 unit 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 (18)

$$\frac{\Delta \dot{P}_{T12}}{2\pi T_{12}} = \Delta F_1 - \Delta F_2 \tag{19}$$

Setting the value of T_{12} in Eq (19) 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 (18) by $\frac{T_{p1}}{k_{p1}}$ and $\frac{T_{p2}}{a_{12}\,k_{p2}}$ respectively, then

$$\frac{T_{p1}}{k_{p1}}\Delta\dot{F}_1 = -\frac{1}{k_{p1}}\Delta F_1 - \Delta P_{T12} + \Delta P_{SCES} \tag{20}$$

$$\frac{T_{p2}}{a_{12}\,k_{p2}}\Delta\dot{F}_2 = \frac{-1}{k_{p2}\,a_{12}}\Delta F_2 + \Delta P_{T12} \tag{21}$$

By summing Eq (20) and Eq (21) and using the above relation $\Delta F_1 = \Delta F_2 = \Delta F$

$$\Delta\dot{F} = \frac{\left(-\frac{1}{k_{p1}} - \frac{1}{k_{p2}a_{12}}\right)}{\left(\frac{T_{p1}}{k_{p1}} + \frac{T_{p2}}{k_{p2}a_{12}}\right)}\Delta F + \frac{1}{\left(\frac{T_{p1}}{k_{p1}} + \frac{T_{p2}}{k_{p2}a_{12}}\right)}\Delta P_{SCES} + C\Delta P_D \tag{22}$$

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.

$$\Delta F = \frac{C}{s + A + K_{SCES}\,B}\Delta P_D \tag{23}$$

Where $$A = \left(-\frac{1}{k_{p1}} - \frac{1}{k_{p2}a_{12}}\right) \Big/ \left(\frac{T_{p1}}{k_{p1}} + \frac{T_{p2}}{k_{p2}a_{12}}\right),\ B = \frac{1}{\left[\frac{T_{p1}}{K_{p1}} + \frac{T_{p2}}{K_{p2}a_{12}}\right]}$$

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 (23) 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

$$C/(A + K_{SCES}\,B) \big/ (C/A) = R/100 \tag{24}$$

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

$$K_{SCES} = \frac{A}{BR}(100 - R) \tag{25}$$

The Linearized model of two- area reheat thermal interconnected power system considering nonlinearities with SCES unit using CPS1 and CPS2 as shown in Fig 9

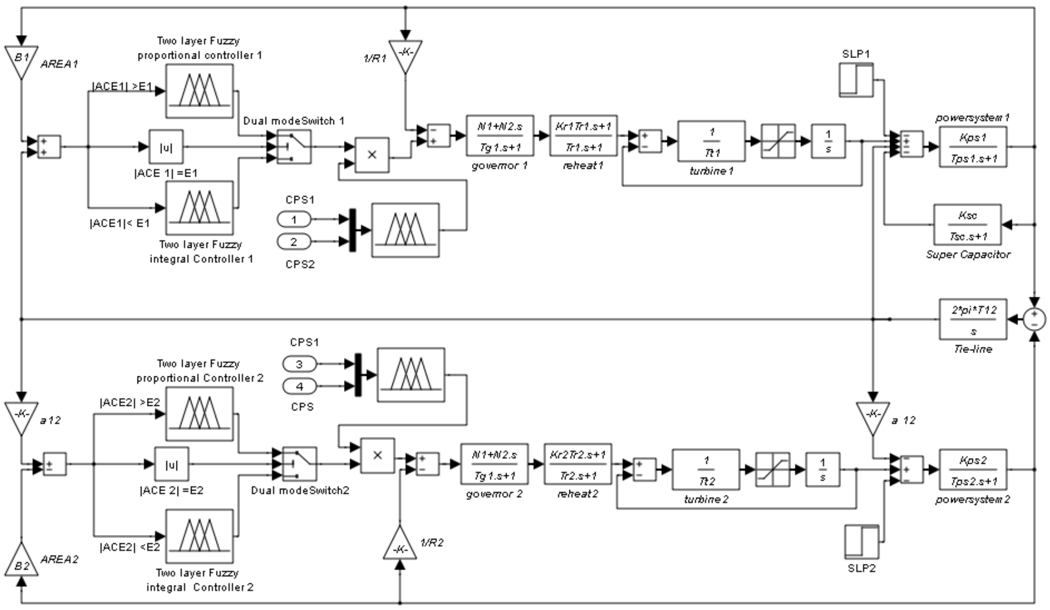


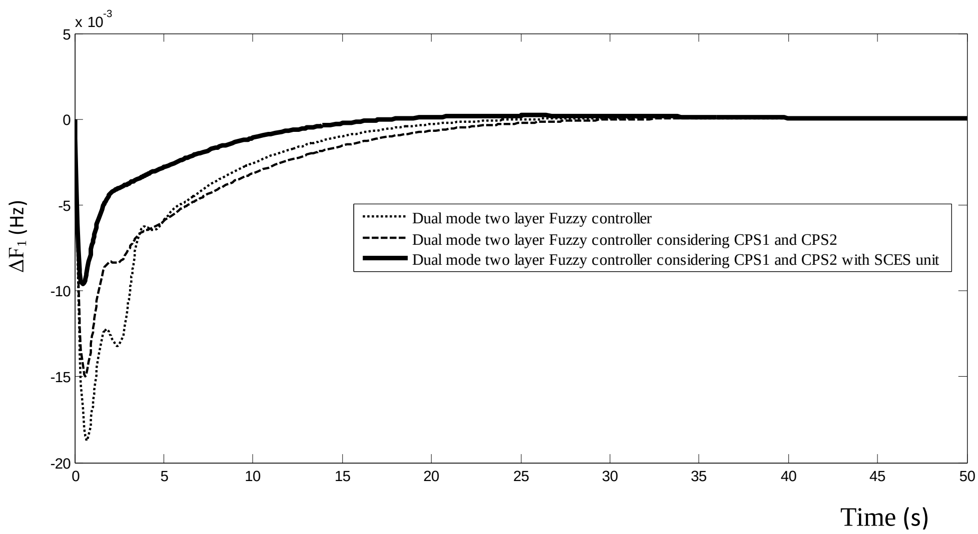
Figure 9: Linearized model of a Dual Mode Two Layered Fuzzy Logic Controller designed using CPS1 and CPS2 criteria for two- area interconnected reheat thermal power system with SCES unit considering GDB and GRC nonlinearities

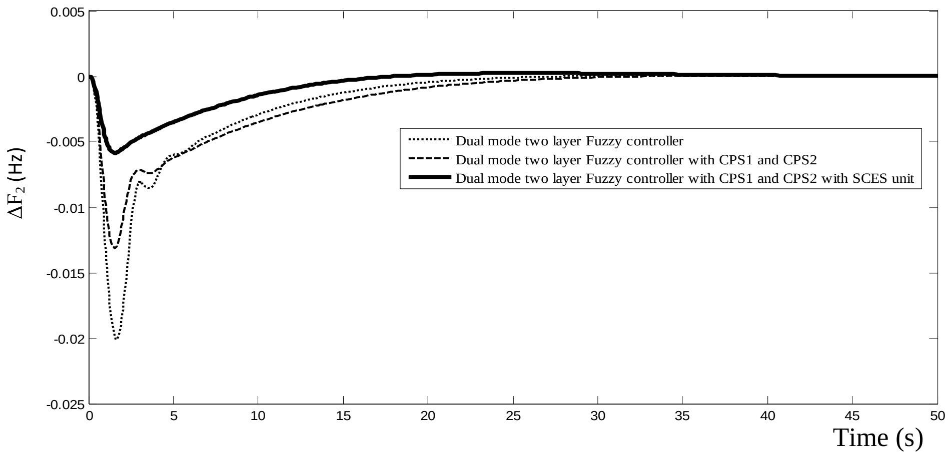
Simulation Results and Observations

The optimum gain values of the conventional PI controllers are determined on the basis of Integral Squared Error (ISE) criterion by minimizing the quadratic performance cost index using Eq (2) for two-area interconnected power system without and with SCES unit. These controllers are implemented in the two- area interconnected reheat thermal power system considering GDB and GRC nonlinearities 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 (25) for the given value of speed regulation coefficient (R) and found to be K_{SCES} = 0.67. The dual mode two layered fuzzy logic controller is designed and implemented in the interconnected two area power system with GDB and GRC nonlinearities using control performance standards *CPS*1 and *CPS*2 without and with SCES unit for 1% step load disturbance in area 1. From the output responses obtained as shown in Fig10 to12; it can be observed that the oscillations in area frequencies, tie-line power deviation and control input requirements have decreased to a considerable extent for the system adopted with Dual Mode Two Layer Fuzzy logic Controller using Control Performance Standards suggested by NERC 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 Fig 10 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 4 it can be observed that the controller design using dual mode Two layered fuzzy logic controller using control performance standards 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 4: Comparison of The System Performance For The Three Studies

Two area interconnected power system with nonlinearities	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 Two Layer Fuzzy Controller	13.64	8.463	19.73	0.0172	0.0225	0.0047
Case:2 Dual Mode Two Layer Fuzzy Controller considering CPS1 and CPS2 criteria	13.12	8.126	18.26	0.0142	0.0125	0.0036
Case:3 Dual mode Two layer fuzzy controller considering CPS1 and CPS2 with SCES unit	7.136	6.247	16.42	0.0078	0.0051	0.0021





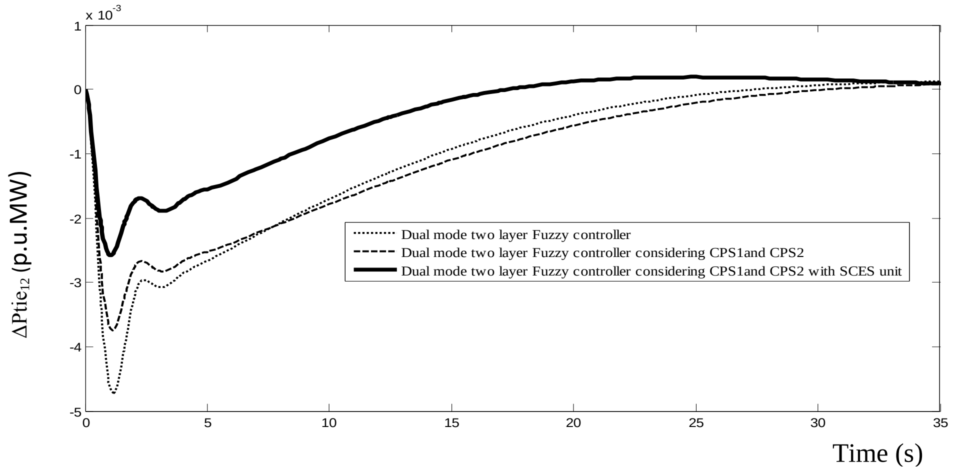
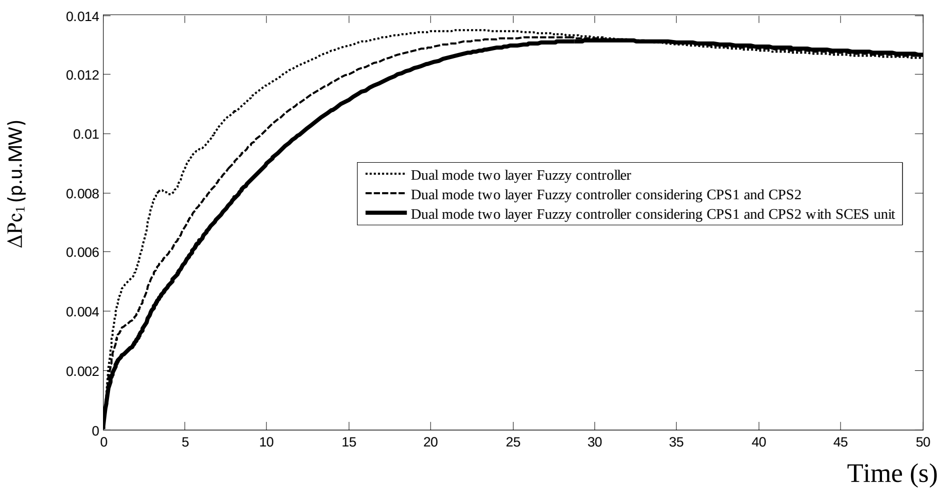


Figure 10: Dynamic responses of the frequency deviations and tie line power deviation of a two-are thermal reheat interconnected power system considering nonlinearities for a step load disturbance of 0.01p.u.MW in area 1



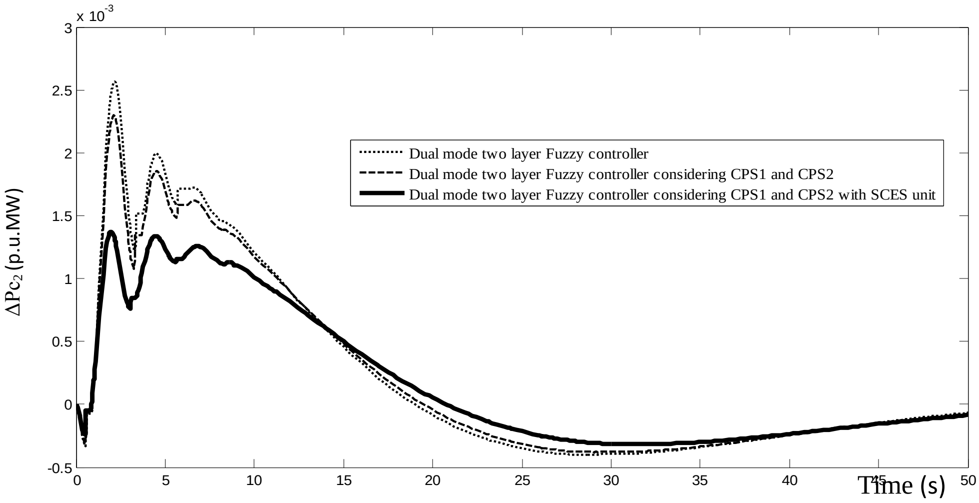


Figure 11: Dynamic responses of the Control input deviations of a two-area thermal reheat interconnected Power System considering nonlinearities with a step load disturbance of 0.01p.u.MW in area 1

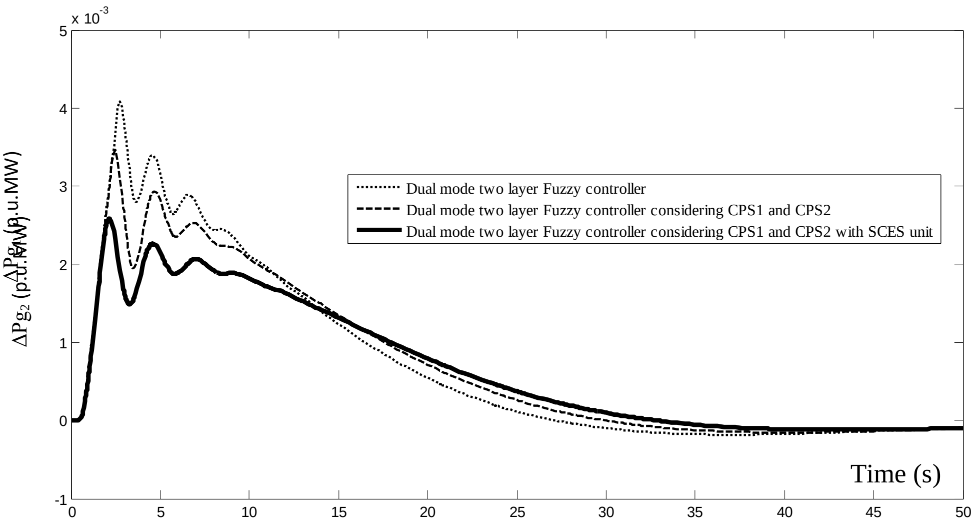


Figure 12: Dynamic responses of the required additional mechanical power generation for two-area thermal reheat interconnected power system considering nonlinearities with a step load disturbance of 0.01 p. u. MW

Conclusion

A new design of Dual Mode Two Layer Fuzzy Logic Controller is proposed to solve the LFC problem in two area interconnected power system. A control strategy is adopted by converting the usual fuzzy system to two-layered hierarchical fuzzy system to solve the rule explosion problem in multi-input usual fuzzy logic system. In this the control scheme update the reference value of ACE according to control area compliance with NERC' s standards and to manipulate the generator's set points only if need be to reduce the excessive maneuvering and hence minimize the cost of operation and maintenance associated with LFC. The concepts of dual-mode control in the fuzzy logic system eliminate the conflict between the static and dynamic accuracy. Simulation results show that the Dual Mode Two Layer Fuzzy Logic Controller is very effective and guarantees good robust performance against parametric uncertainties, load changes and disturbances even in the presence of GDB and GRC. The proposed scheme has superior steady-state and transient performance. Moreover the proposed controller has required less number of fuzzy rules thereby reducing computation time and improves the dynamic quality of system as compared with the usual fuzzy logic system. Due to the operational behaviour of the SCES unit the power system output response is found to be fast responsive nature and SCES unit contributes a lot in promoting the efficiency of overall generation control through the effective utilization not only in load levelling but also assuring the power quality. It can 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. SCES units can be utilized as a new ancillary service not only for the stabilization of the tie-line power oscillations even under congestion management environment of the power transfer but also to damp out the inertia mode and inter-area mode oscillations in an effective manner by suppressing the frequency deviation of two area system.

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References

[1] Omveer Singh, Prabhakar Tiwari, Ibraheem and Arunesh Kr. Singh, 2014 "A Survey of Recent Automatic Generation Control Strategies in Power Systems", International Journal of Emerging Trends in Electrical and Electronics, Vol. 7, Issue. 2, pp. 1-14, 2013.

[2] S.C.Tripathy, G.S.Hope, O.P.Malik, 1982, "Optimization of load frequency control parameters for power systems with reheat steam turbines and governor dead band non-linearity", IEE Proc., Vol. 129, Pt. C, No.1, pp.10-16.

[3] T.Hiyama, 1982 "Decentralized load-frequency control under generation rate constraints", Electrical Engineering in Japan, Vol.102, No.4, pp.65-71.

[4] J.Nanda, M.L.Kothari and P.S.Satsangi, 1983, "Automatic Generation Control of Reheat Thermal system considering Generation Rate Constraint

and Governor Dead band", IE (I)-Journal-EL,Vol. 63, pt E.L 6, pp. 245-252.

[5] Tsay Tain-Sou, 2011, "Load–frequency control of interconnected power system with governor backlash nonlinearities", Electrical Power and Energy Systems, Vol.33, pp.1542-1559.

[6] C.S.Indulkar and Baldevraj, 1995, "Application of fuzzy Controller to automatic generation Control", Electric Machines and Power Systems, Vol. 23, pp.209-220.

[7] M.K.EL-Sherbiny, G.EL-Saady, Ali M. Yousef, 2002, "Efficient fuzzy logic load frequency controller", Energy Conversion and Management Vol.43, pp.1853-1863.

[8] Ashok Kumar, O.P. Malik and G.S. Hope, "Power generation control using dual mode control", Electric Machines and Power System, Vol. 9, pp.335- 345,1984.

[9] S. Velusami and I.A. Chidambaram, 2007, "Design of decentralized biased dual mode controller for LFC of interconnected power system considering GDB and GRC nonlinearities", Energy Conversion and Management Vol.48, pp.1691-1702.

[10] Ali Feliachi and Dulpichet Rerkpreedapong, 2005, "NERC compliant load frequency control design using fuzzy rules", Electric Power System Research, Vol.73, pp.101- 106.

[11] N. Jaleeli and L. S. VanSlyck, 1999, "NERC's New Control Performance Standards," IEEE Transactions on Power Systems, vol. 14, No. 3, pp. 1092-1099.

[12] G.Gross and J.W. Lee, 2001, "Analysis of load frequency control performance assessment criteria", IEEE Transactions on Power System, 16(3):520-526.

[13] C. Chang, W. Fu, 1997, "Area load frequency control using fuzzy gain scheduling of PI controllers", Elect Power Sys. Res, vol. 42, pp.145–152.

[14] Moon.G.Joo, 2003, "A method of converting conventional fuzzy logic system to two layered hierarchical fuzzy system", 12^{th} IEEE International Conference on Fuzzy Systems, USA, Vol-2, pp.1357-1362.

[15] Kim. J.K, Park. J.H, Swale and Chong. K.P, 1994, "A Two-Layered Fuzzy Logic Controller for Systems with Dead zones", IEEE Transactions on Industrial Electronics, Vol-41, No. 2, pp.155-166.

[16] Burkea, 2000, "Ultra capacitors: why, how, and where is the technology", Journal of Power Sources, Elsevier Science, Vol.91, pp.37–50.

[17] Spykerr. L and Nelmsr. M, 2006, "Analysis of Double-Layer Capacitors Supplying Constant Power Load", IEEE Transactions on Aeronautical and Electrical System, Vol.36, No. 4, pp.1439–1443.

[18] Peter J Grbovic, 2014, Ultra-Capacitors in power conversion systems, John Wiley & Sons Ltd, West Sussex, UK.

[19] Rajesh Joseph Abraham, Das. D and Amit Patra, 2010, "Automatic Generation Control of an Interconnected Power System with Capacitive

Energy Storage”, International Journal of Electrical Power and Energy Systems Engineering, Vol.14, No.03, pp.611–616.

Appendix

(i) Data for the two-area thermal reheat Power System with Reheat Turbines [9, 11].
f^0=60Hz, PR_1=PR_2=2000MW, K_{p1}=K_{p2}=120Hz/pu.MW, T_{pS1}=T_{pS2}=20sec, T_{t1}=T_{t2}=0.3sec, T_{g1}=T_{g2}=0.08sec, K_{r1}=K_{r2}=0.5, T_{r1}=T_{r2}=10 sec, β_1=β_2=0.425 pu.MW/Hz, R_1=R_2=2.4 Hz/p.u MW, ΔP_{D1} = 0.01 p.u MW, T_{12}=0.545 pu.MW/Hz, N_1 =0.8,N_2= -0.2, $\Delta\ p_{gmax}$ =0.1 p.u.MW/ min, ε_1 =18mHz, ε_{10} = 5.7mHz,

(ii) Data for Super Capacitor Energy Storage unit [19]
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