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# A New Design of Dual Mode Type-II Fuzzy Logic Load Frequency Controller For Interconnected Power Systems With Parallel AC-DC Tie-Lines And Capacitor Energy Storage Unit

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## Abstract

A new design of dual mode Type-II fuzzy logic load frequency (TIIFLC) controller for interconnected power systems with parallel AC-DC tie-lines and capacitor energy storage unit (CES) is proposed in this paper. Any optimum controller selected for load frequency control (LFC) of interconnected power systems should not only stabilize the power system, but also reduce the system frequency and tie-line power oscillations and settling time of the output responses. In general proportional plus integral (PI) controllers are used for LFC but it does not get rid of the difference between the static and dynamic accuracy. This dispute may be broken up by using the principle of TIIFLC to utilize expert knowledge and being adaptive in nature. A direct current (DC) link is connected in parallel with an existing alternating current (AC) tie-line to stabilize the frequency oscillations of the AC system. In summation, the capacitor energy storage (CES) unit is found to be advantageous for secondary control in the power system and keeps the power quality with the distributed power resources. The CES, which are not agreed to the frequent charging and discharging, has been a quick response and outstanding function during overload conditions. The comparability of the PI controller, Type-I fuzzy logic controller (TIFLC) and the proposed dual mode TIIFLC shows that, with the application of the proposed controller, the system performance is improved significantly. The proposed controller is also found to be less sensitive to the changes in the system parameters and also robust under different operating modes of the system.

**Keywords:** Load frequency control, PI controllers, AC-DC tie-lines, Dual mode Type-II fuzzy logic controller, Capacitor Energy Storage.

## List of Symbols

| | |
|---|---|
| $\tilde{A}$ | Type-II fuzzy set |
| $\tilde{A}_I$ | Interval Type-II fuzzy set |
| FOU | Footprint of uncertainty |
| $\overline{FOU}$ | Upper bound of FOU |
| $\underline{FOU}$ | Lower bound of FOU |
| $J_x$ | Interval $\subseteq [0,1]$ |
| U | Universe of discourse = [0,1] |
| $x$ | Input variable (crisp input) |
| $X$ | Universe of discourse (x domain) |
| $\underline{\mu}_{\tilde{A}}$ | Lower membership function |
| $\bar{\mu}_{\tilde{A}}$ | Upper membership function |
| $f_i$ | Area frequency in Hz |
| $T_{12}$ | Tie-line Synchronizing Co-efficient area 1& 2 |
| $a_{12}$ | Operator of area 1&2 |
| $T_{w1}$, $T_{w2}$ | Hydro Turbine Constant |
| $T_{R1}$, $T_{S1}$, $T_{R2}$, $T_{S2}$, | Transient droop Compensation for hydro system |
| $T_{H1}$, $T_{H2}$ | Hydro governor time constant |
| $T_{r1}$, $T_{r2}$ | Reheat time constant |
| $T_{t1}$, $T_{t2}$, | Steam turbine time constant |
| $T_{g1}$, $T_{g2}$, | Steam governor time constant |
| $R_{HY1}$, $R_{HY2}$ | Speed regulation droop for hydro system |
| $R_{TH1}$, $R_{TH2}$ | Speed regulation droop for thermal system |
| $H_{e1}$, $H_{e2}$ | Equivalent WECS inertia |
| $T_{wf1}$, $T_{wf2}$ | Washout filter time constant |
| $T_{a1}$, $T_{a2}$ | Controlled WECS time constant |
| $K_P$ | Speed regulator proportional constant |
| $K_I$ | Speed regulator integral constant |
| $N$ | Number of interconnected areas |
| $\Delta$ | Incremental change of a variable |
| S | Laplace frequency variable |
| $K_p$ | Proportional constant |
| $K_i$ | Integral constant |
| FLC | Fuzzy logic controller |
| ACE, $\Delta A\dot{C}E$ | Normalised input variables |
| FOU | Foot prints of uncertainty |
| $\mu_P$(ACE) | Positive intervals of Type-II fuzzy sets |
| $\mu_N$(ACE) | Negative intervals of Type-II fuzzy sets. |
| Min | Minimum |
| $N_{-}$ | Negative |
| $P_{+}$ | Positive |
| $Z_o$ | Zero |

| | |
|---|---|
| $P_{tie}$ | Tie line power |
| ISE | Integral square error |
| $\varepsilon_i$ | Switching limit |
| CES | Capacitor Energy Storage |

**Superscript**
Transpose of a matrix

**Subscripts**
*i, j* area indices ($i, j = 1, 2, \ldots, N$)

## 1. Introduction

The interconnected power system encounters a great challenge in power system design and operation. The load-frequency control (LFC) problem has gained much importance because of the size and complexity of modern interconnected power systems. The objective of LFC is to regulate the output power of the regulating plants so that the frequency of the power system and tie-line power is kept within prescribed limits. Many control strategies for LFC, of power systems, have been proposed and investigated by many researchers over the past several years [1,2,3]. The application of control strategy to the LFC problem has found wide acceptance because of its role in eliminating most of the problems associated with other multilevel control strategies. The PI controller is most widely applied for the LFC scheme [4].

It is a well accepted fact that the classical conventional solution of this problem has been one of the first practical applications for the LFC problem. An advantage of using proportional and integral (PI) controller is because of their simplicity, easy realization, low cost, robust and decentralized nature of the control strategy [5, 6]. However, the conventional controller reduces the steady-state to zero but it exhibits poor dynamic performance and it will not reach high performance. Furthermore, the settling time of the system frequency and tie-line power deviations are also relatively long. In the recent years, conventional PI controllers are replaced by fuzzy logic controllers (FLC) [7, 8]. FLC have received an important role in power systems.

A fuzzy logic controller (FLC), described completely in terms of Type-I fuzzy sets, (TIFS) are called a Type-I fuzzy logic system. Fuzzy logic is a logical system for formalization of approximate reasoning, and is used synonymously with fuzzy set theory, systems introduced by Zadeh and investigated further by fuzzy researchers [9,10,11,12]. Since it is able to model human decision making process and represents vague and uncertain data, fuzzy set theory is a theory about vagueness and uncertainty. This theory provides a methodology that allows modelling of the systems that are too complex or not well defined by mathematical formulation. Therefore, TIFLC becomes nonlinear and adaptive in nature, having a robust performance under parameter variations with the ability to get desired control actions for complex, uncertain, and nonlinear systems without the requirement of their mathematical models and parameter estimation. The general framework of fuzzy reasoning, handling much of this uncertainty, fuzzy systems employs TIFS, which represent uncertainty by numbers in the range [0, 1]. However, it is not reasonable to use an accurate membership function for something uncertain, so in this case, what we need is another type of fuzzy sets, those which are able to handle these uncertainties, the so called Type-II fuzzy sets (TIIFS). Hence, the amount of uncertainty in a system can be reduced by using TIIFLC because it offers better capabilities to handle linguistic uncertainties by modelling vagueness and unreliability of information [13, 14]. A TIIFS is characterized by a fuzzy membership function, i.e., the membership grade for each element of this set is a fuzzy set from 0 to 1, unlike a TIFS where the membership grade is a crisp number from 0 to 1. Such sets can be used in situations where there is uncertainty about the membership grades themselves.

In most of the LFC studies the, majority of the work carried out earlier is centred on interconnected power systems involving the area interconnection with a tie-line only. Nevertheless, there has been a marvelous development of the DC transmission system due to economic, environmental and performance advantages over the other options. Hence, it has been used widely in operating a DC link in parallel with an AC link interconnecting control area to produce an improved system dynamic performance with greater stability margin under small disturbances in the system [15].

The energy storage unit is an attractive alternative to augment demand side management implementation. The conventional load-frequency controller may no longer be able to attenuate the large frequency oscillation due to the slow reaction of the governor even though a more advanced controller is assumed. A quick-acting energy storage system, in accession to the kinetic energy of the generator rotors, provides adequate control to mute out the frequency oscillations. The problems like low discharge rate, increased time required for power flow reversal and maintenance requirements have contributed to the evolution of capacitor energy storage (CES) device for their applications also load frequency stabilizers. By using energy storage systems, a low cost source of electricity can be efficiently supplied to satisfy the peak requirement [16]. The CES will, in addition to load levelling, a function conventionally assigned to them, have a wide range of applications such as power quality maintenance of decentralized power supplies. The CES is excellent for short-time overload output and the response characteristics possessed in particular. The effect of generation control and the absorption of power fluctuation needed for power quality maintenance are required. In this survey, a two area power system with CES unit is taken to control power flows [17]. In each control area, all the generators are assumed to form a coherent group. An important design concept of dual mode control is contained in the proposed controller because it improves the system operation and makes it flexible for application to actual systems [18, 19]. The computer simulation results of application of the proposed controller with interconnected power systems prove that the proposed controller is effective and provides significant improvement in the system performance. Moreover, it has likewise been discovered that the proposed controller is less sensitive to system parameter variations and also robust under different operating conditions.

## 2. Statement of The Problem

The state variable equation of the minimum realization of the continuous model of the 'N' area interconnected power system is expressed as [19,20]

$$\dot{X} = Ax + Bu + \Gamma d \tag{1}$$

$$\upsilon = Cx$$

$$y = Hx$$

$x = \left[x_1^T, \Delta p_{ei} \dots x_{(N-1),}^T \Delta p_{e(N-1)} \dots x_N^T\right]^T$ $n$ – state vector

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

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

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

$\upsilon = [\upsilon_1 \dots\dots, \upsilon_N]^T$, $N$ – control output vector;

$y = [y_1 \dots\dots, y_N]^T$, $2N$ – measurable output vector;

where, A the system matrix ,B the input distribution matrix, Γ the disturbance distribution matrix, C the control output distribution matrix, H the measurable output distribution matrix, *x* the state vector, *u* the control vector, *d* the disturbance vector of load changes. It is known that by incorporating an integral controller the steady state requirements can be achieved. In order to introduce an integral function to the controller the system Eq.(1) is augmented with a new state variable defined as the integral of the area control error $ACE_i$ ($\int \upsilon_i$ dt), $i$=1,2,3,....$N$. The augmented system of the order ($N$+$n$) can be described as

$$\dot{\overline{X}} = \overline{A}\overline{x} + \overline{B}u + \overline{\Gamma}d \tag{2}$$

Where, $\overline{x} = \begin{bmatrix} \int \upsilon dt \\ x \end{bmatrix} \begin{matrix} \}N \\ \}n \end{matrix}$

$\overline{A} = \begin{bmatrix} 0 & C \\ 0 & A \end{bmatrix}, \overline{B} = \begin{bmatrix} 0 \\ B \end{bmatrix}$ and $\overline{\Gamma} = \begin{bmatrix} 0 \\ \Gamma \end{bmatrix}$

As the newly added state variables ($\int \upsilon_i$dt), $i$ = 1,2,….,$N$ will also be available for feedback in each area, the new measurable output vector $\overline{y}$ can be written as

$$\overline{y} = \overline{H}\overline{x}$$

Where, $\overline{y} = \left[\overline{y}_1^T \dots \overline{y}_N^T\right]^T$

$$\overline{H} = \left[\overline{H}_1^T \dots \overline{H}_N^T\right]$$

and $\overline{H} = \begin{bmatrix} 0 & 1 \dots 0 \\ 0 & 0 \dots H_i \end{bmatrix}$

The constant matrix $\overline{H}_i(i=1,2...N)$ is of dimension 2×(*N* + *n*). Hence, the matrix $\overline{H}$ is of dimension 2*N*× (*N* + *n*).

The problem now is to design the decentralized feedback output feedback control law

$$u_i = -k_i^T y_i \qquad i = 1,2...,N \tag{3}$$

To meet the objectives stated in the previous section. The control law, Eq.(3), can be written in terms of $\upsilon_i$ as

$$u_i = -k_{il}\int \upsilon_i dt - k_{i2}\upsilon_i \quad i = 1,2...,N \tag{4}$$

Where $k_i^T$ = [$k_{i1}k_{i2}$] is a two dimensional integral and proportional feedback gain vectors.

## 3. Description of Dual Mode Type-II Fuzzy Logic Controller With Output Feedback

Since the principle of dual mode control can improve the system performance a fresh conception of dual mode TIIFLC is proposed in this part. This proposed controller operates in mode A as longer as the significant observed variable to the control actions when the system output error is sufficiently large i.e. greater than the switching limit of the controller otherwise it operators in mode B [18]. Mode A acts as proportional type TIIFLC and mode B as integral type TIIFLC. Thus, the control structure of the system is changed when switching in each mode of operation. Since the proposed controller is planned based on the switching limit of the controller, the operation of the controller is found improved significantly. Block diagram of dual mode TIIFLCis shown in Fig.1.

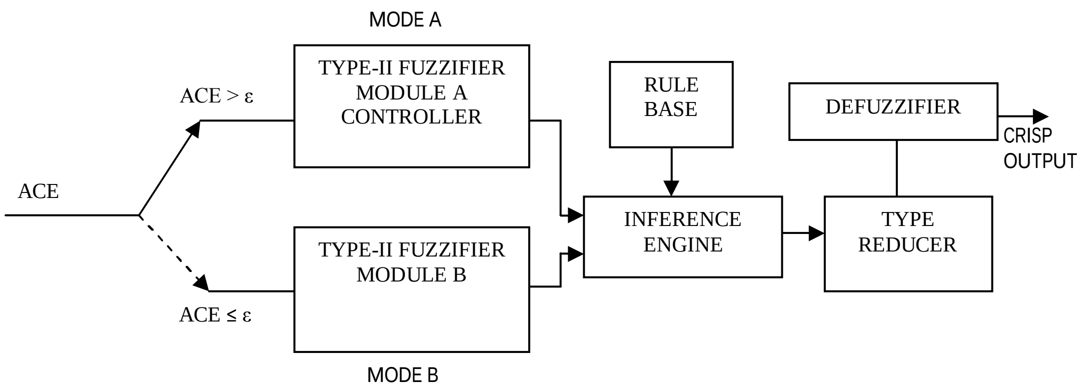



**Figure 1:** Block diagram of dual mode Type-II fuzzy logic controller

A TIIFS is characterized by a fuzzy membership function i.e., the membership grade for each element of this set is a fuzzy set in [0,1], unlike a Type-I set where the membership grade is a crisp number in [0,1].

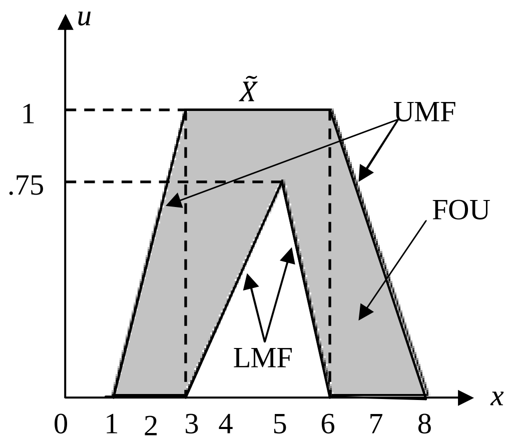



**Figure 2:** Membership function interval Type-2 fuzzy logic set

A Type-II fuzzy set $\tilde{A}$ , is characterized by the membership function:

$$\tilde{A} = \{((x,u),\mu_{\tilde{A}}(x,u)) \mid \forall x \in X, \forall u \in J_x \subseteq [0,1]\} \tag{5}$$

in which $0 \le \mu_{\tilde{A}}(x,u) \le 1$. In fact $J_x \subseteq [0,1]$ represents the primary membership function of x, and $\mu_{\tilde{A}}(x,u)$.Hence, a Type-II membership grade can be any subset in [0,1], the primary membership, and corresponding to each primary membership, there is a secondary membership (Which can also be in [0, 1]) that defines the possibilities for the primary membership.

The membership function of a general Type-II fuzzy set is denoted by $\tilde{A}$ ,

$$\tilde{A} = \int_{x \in X} \int_{u \in Jx} \frac{\mu_{\tilde{A}}(x,u)}{(x,u)}, J_x \subseteq [0,1] \tag{6}$$

In which $0 \le \mu_{\tilde{A}}(x,u) \le 1$.

An interval Type-II fuzzy set $\tilde{A}_I$ is defined as

$$\tilde{A}_I = \frac{\int_{x \in X} \left[\int_{u \in J_X \subseteq [0,1]} (1/u)\right]}{x} \tag{7}$$

$\mu_{\tilde{A}}(x,u), x \in X, u \in J_x$ is a secondary grade and the domain of a secondary membership function is called the primary membership of x, where $J_x \subseteq [0,1] \forall x \in X$, Uncertainty in the primary memberships of a Type-II fuzzy set consists of a bounded region that is called the Footprint of Uncertainty (FOU) [21,22] as shown in Fig.2. FOU characterizes Type-II fuzzy sets is given by,

$$FOU(\tilde{A}) = \bigcup_{x \in X} J_x$$

FOU is associated with the concepts of lower and upper membership functions and models the uncertainties in the shape and position of the Type-I fuzzy set; its uniform shading denotes interval sets for the secondary membership functions and represents the entire interval Type-II fuzzy set $\mu_{\tilde{A}}(x,u), x$ the upper and lower membership functions are in fact two Type-I membership functions that are bounds for the FOU of a Type-II fuzzy set $\tilde{A}.\tilde{\mu}_{\tilde{A}}(x)$, is the upper membership function (UMF) and is associated with the upper bound of FOU $(\tilde{A})$ It is also denoted as [23,24],

$$\overline{\mu}_{\tilde{A}}(x) \equiv \overline{FOU\ (\tilde{A})}, \forall x \in X$$

$\underline{\mu}_{\tilde{A}}(x)$ Is the lower membership function (LMF) associated with the lower bound of FOU and is also denoted as

$$\underline{\mu}_{\tilde{A}}(x) \equiv \underline{FOU(\tilde{A})}, \qquad \forall x \in X$$

The defuzzification is a mapping process from fuzzy logic control action to a non-fuzzy (crisp) control action. A TIIFLS is again characterized by IF-THEN rules, but its antecedent or consequent sets are now of Type-II. The TIIFLS can be used when the circumstances are too uncertain to determine exact membership grades such as when the training data are corrupted by noise. Similar to a TIFLS, a TIIFLS also have Type-IIfuzzifier, a rule base, fuzzy inference engine, and an output processor, as we can see in Fig.3. [25,26].

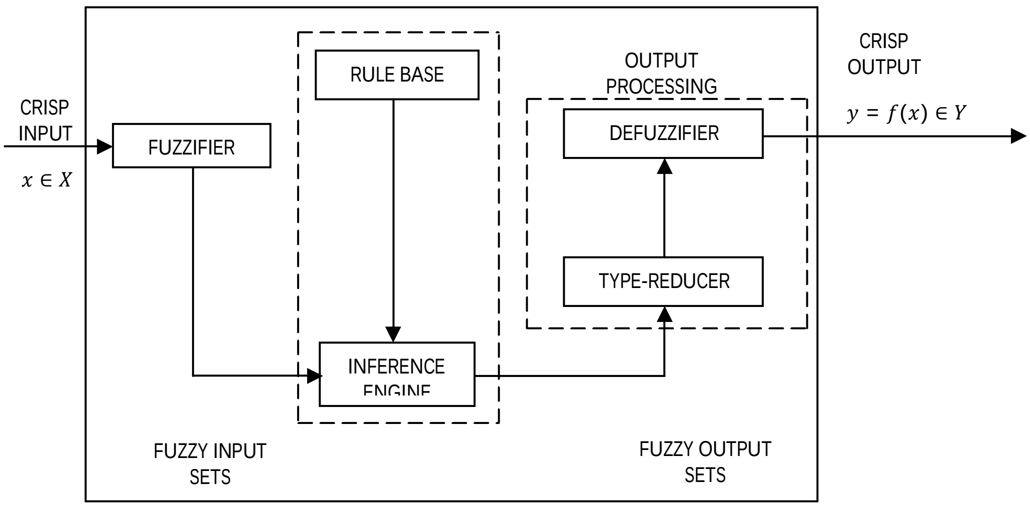



**Figure 3:** Structure of Type-II fuzzy logic system

## 4. Operating Principle of Capacitive Energy Storage System

### *4.1. Modelling of capacitive energy storage unit*

When there is a sudden rise in load demand, the stored energy is almost immediately put out through the power conversion system (PCS) to the grid as pulsed AC. As the governor and other control mechanisms start working to set the power system to the new equilibrium condition, the capacitor charges to its initial value of voltage. The action during sudden releases of load is similar. The capacitor immediately gets shot down towards its total value, thus soaking up 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 capacitor voltage reaches its normal value [27].

To show the effect of CES on LFC, a small rating CES unit having 3.8 MJ maximum capacities is considered. The capacitor voltage must not be permitted to deviate beyond certain lower and upper bounds. If the capacitor voltage goes too low during a system upset and if some other disturbance occurs before the voltage returns to normal, more energy will be pulled away from the capacitor [28]. This may lead to discontinuous control. To overcome this problem, the lower limits are placed on the capacitor rating, insulation level of the capacitor and the rating of the converter bridge.

The normal operating point of the capacitor is set at the maximum allowable energy absorption which equals the maximum allowable energy discharge. This makes the CES unit equally effective in damping the oscillations created by sudden increase, as well as decrease, in load. If $E_{dmax}$ and $E_{dmin}$ denote the maximum and minimum limits of voltage, respectively, and Edo denotes the set value of voltage then [29,30]

$$(1/2)CE^2_{dmax} – (1/2)CE^2_{do} = (1/2)CE^2_{do} – (1/2)CE^2_{dmin}$$

$$E^2_{do} = \frac{(E^2_{dmax}+E^2_{dmin})}{2} \quad (8)$$

### *4.2. System configuration of CES*

System configuration of capacitive energy storage unit is shown in Fig.4. The storage capacitor is connected to the AC grid through a power conversion system which includes a rectifier/inverter in 12-pulse configuration. The storage capacitor C may consist of many discrete capacitance units connected in parallel. The resistance R connected in parallel across the capacitor represent the dielectric and leakage losses of the capacitor bank.

The capacitor can be loaded to an asset value of potential drop from the utility grid during normal operation of the two power schemes. A reversing switch arrangement, using gate turn-off (GTO) Thyristors is provided to accommodate the change of direction of the current in the capacitor during charging and discharging, (i.e., during rated load period and peak load period). Since the focal point of current through the bridge converter cannot change, the charging mode of the switches S2 and S3 are OFF and S1 and S4 are ON. In the discharge mode, S2 and S3 are ON and S1 and S4 are OFF.

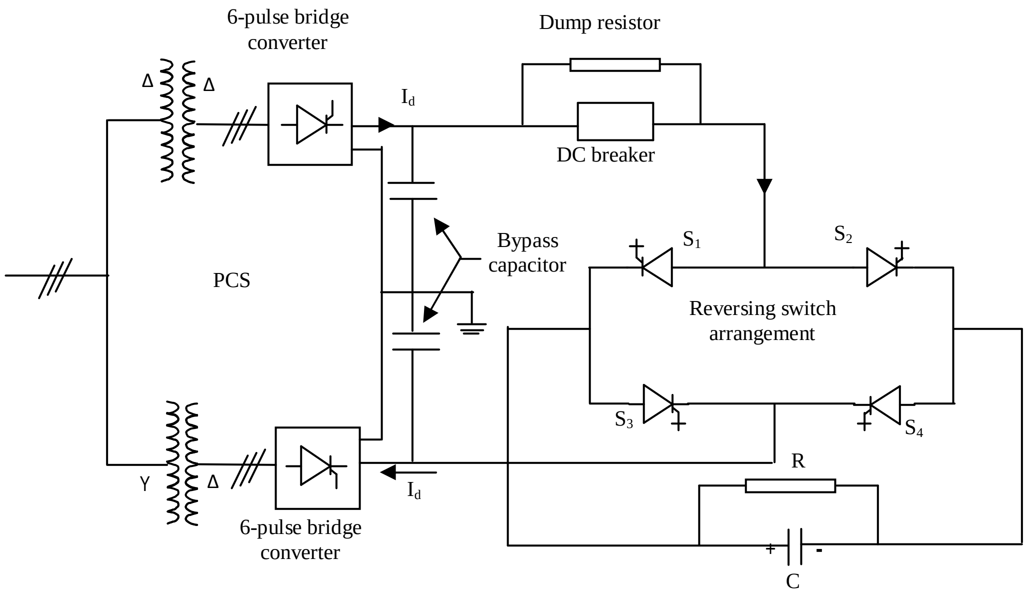



**Figure 4:** System configuration of capacitive energy storage unit

### *4.3. CES control logic unit*

The operation of CES unit, that is, charging, discharging, the steady state mode and the power modulation during the dynamic oscillatory period, is controlled by the application of the proper voltage to the capacitor so that the desired current flows into or out of the CES. This can be achieved by accomplishing the firing angle of the converter bridges [30].

Neglecting the transformer and the convertor losses, the DC voltage would be,

$$E_{do} = 2V_{do}\cos\alpha - 2I_dR_c \quad (9)$$

Where, $E_{do}$ the DC voltage applied to the capacitor (kV), α the firing angle (degree), $I_d$ the current through the capacitor (kA), $R_c$ the equivalent commutating resistance (ohm), $V_{do}$ the maximum open circuit bridge voltage of each 6-pulse convertor at $\alpha=0^o$ (kV). The capacitor is initially billed to its normal voltage, $E_{do}$ by the PCS. Once the voltage of the capacitor has reached $E_{do}$, it is kept floating at this voltage by continuing supply from the PCS to compensate for the dielectric and other leakage losses of the capacitor. The energy stored at any instant,

$$W_c = \frac{CE_d^2}{2} \quad MJ \quad (10)$$

Where, C the capacitance of CES in Farad.

The area control error (ACE) can be sensed and used to control the CES current $I_d$. The incremental change in CES current is expressed as,

$$\Delta I_{di} = \left[\frac{K_{CAi}}{1+ST_{dci}}\right] \Delta F_i \qquad i=1,2 \tag{11}$$

The area control error of the two areas (i=1, 2) is defined as

$$ACE_i = \beta_i \Delta F_i + \Delta P_{ij} \qquad i,j = 1,2 \tag{12}$$

Where, $\Delta F_i$is a deviation in frequency and $\Delta P_{ij}$is a deviation in tie-line power flow out of area i,j. If ACE is directly used for the control of CES, the gain constant $K_{CA}$ (kA/unit ACE) would be totally different from $K_{CF}$, the gain constant for frequency deviation as control signal. So a signal proportional to area control error $(\Delta F_i+(1/\beta_i)\Delta P_{ij})$ is used in such a scheme then,

$$\Delta I_{di} = \left[\frac{K_{CAi}}{1+ST_{dci}}\right] (\Delta F_i + 1/\beta_i \ \Delta P_{ij}) \qquad i,j = 1,2 \tag{13}$$

It is necessary to restore quickly the set value of the CES voltage after a load disturbance, so that the CES unit ia ready to act for the next load disturbance. The capacitor voltage deviation can be sensed and used as a negative feedback signal in the CES control loop to achieve fast restoration of the voltage. Then, thefrequency deviation as the control signal,

$$\Delta E_{di} \left[\frac{1}{Cs+1/R}\right] \Delta I_{di} \tag{14}$$

$$\Delta I_{di} = \left[\frac{K_{CAi}}{1+ST_{dci}}\right] [K_{CAi}\ \Delta F_i - K_{vdi}\ \Delta E_{di}] \tag{15}$$

Where,$K_{vdi}$ (kA/kV) is the gain corresponding to the $\Delta E_{di}$ feedback. If ACE is used as control signal then,

$$\Delta I_{di}= \frac{1}{1 + ST_{dci}} \ [K_{CAi}\ (\Delta F_i + 1/\beta_i\ \Delta P_{ij}) - K_{vdi}\Delta E_{di}] \qquad i,j=1,2 \tag{16}$$

Where,$K_{vdi}$(kA/kV) is the gain corresponding to the $\Delta E_{di}$feedback. The block diagram representation of such a control scheme is shown in Fig.5.

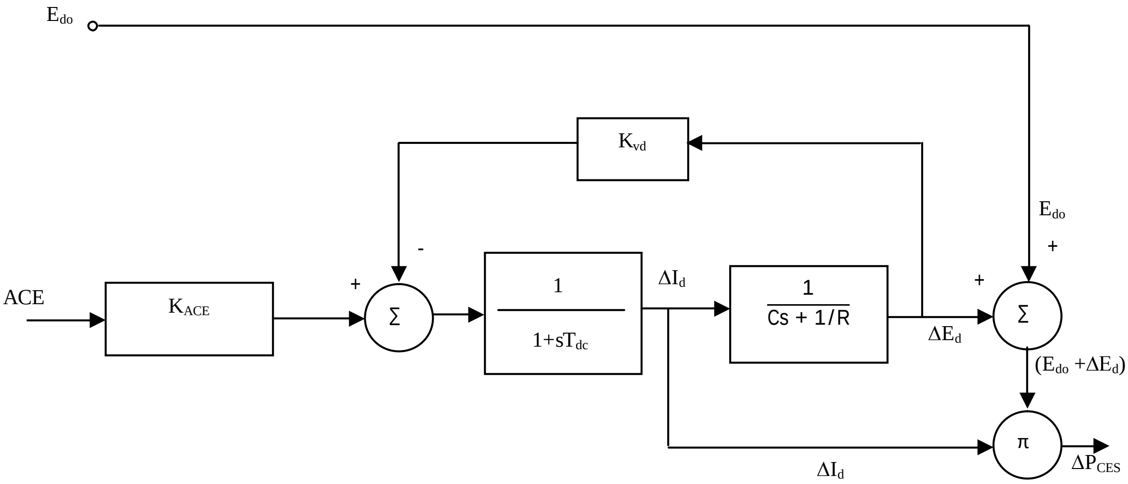



**Figure 5:** Transfer function model representation of the CES control with capacitor voltage deviation

## 5. Application of Dual Mode Type-II Fuzzy Logic Controller For Interconnected Power Systems

The proposed dual mode TIIFLC design is applied to interconnected two area reheat based thermal power systems. As the system is exposed to a small change in load during its normal operation, the linear model will be sufficient for dynamic [31] representation.

### *5.1.Design of conventional PI controller and fuzzy logic controller with output feedback*

The conventional PI Controller with output feedback is designed with square error (ISE) technique. Gain values of the PI controllers are $K_p$=6 and $K_i$=0. 61 were obtained according to the system response curve method. The conventional PI controls and fuzzy logic controller are also designed using the method presented in [32]. The system output is sampled at the normal sampling rate of two seconds and the controller output is also updated at a normal sampling rate.

### *5.2. Design of a proposed dual mode Type-II fuzzy logic Controller using the CES unit with output feedback.*

Design of proposed dual mode Type-II fuzzy logic controller with output feedback scheme is carried out for two area interconnected power systems. Since the switching limit value ‘ε’ should be greater than the steady state error of the system output ACE. The value of ‘ε’ is chosen as ($\varepsilon_1$=0.003, $\varepsilon_2$ =0.003). The input variable of the proposed controller are ACE (error e) and $\Delta\dot{A}$CE (change of error Δce). The membership function of the interval Type-II fuzzy set for the input variables (e and Δce) scheduled by only three fuzzy sets with the simple shape membership functions linguistically labelled as N, Z and P distributed over the intervals (-α, α) is shown in Fig.6. The membership function N denotes (NU, N, NL) similarly for P (PU, P, PL).

The value of α is chosen as (-α = -0.1 to α=0.1) for fuzzifier module A and (-α = -0.01 to α=0.01) for fuzzifier module B. The rule base for the above membership function is shown in Table -1. The feedback signal is sampled at the normal sampling rate of two seconds and the control output is also updated at normal sample rate.

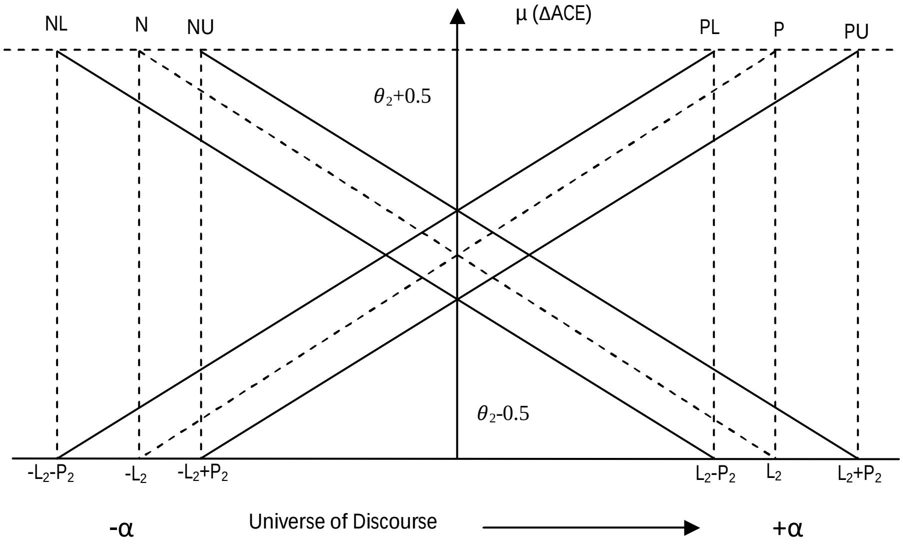



**Figure 6:** Membership function of the interval Type-II fuzzy sets

**Table 1:** Rule base for Type-II fuzzy logic controller

| | | $\Delta A\dot{C}E$ | | |
|---|---|---|---|---|
| ACE | | N_ | Zo | $P_+$ |
| | N_ | $P_+$ | $P_+$ | Zo |
| | Zo | $P_+$ | Zo | N_ |
| | $P_+$ | Zo | N_ | N_ |

***5.3. Simulation results and discussions***

The dual mode TIIFLCwith parallel AC-DC tie-line using CES unit is designed in the previous section is implanted in an interconnected reheat based thermal power systems. The simulink block diagram of the system with proposed controller is shown in Fig.7.

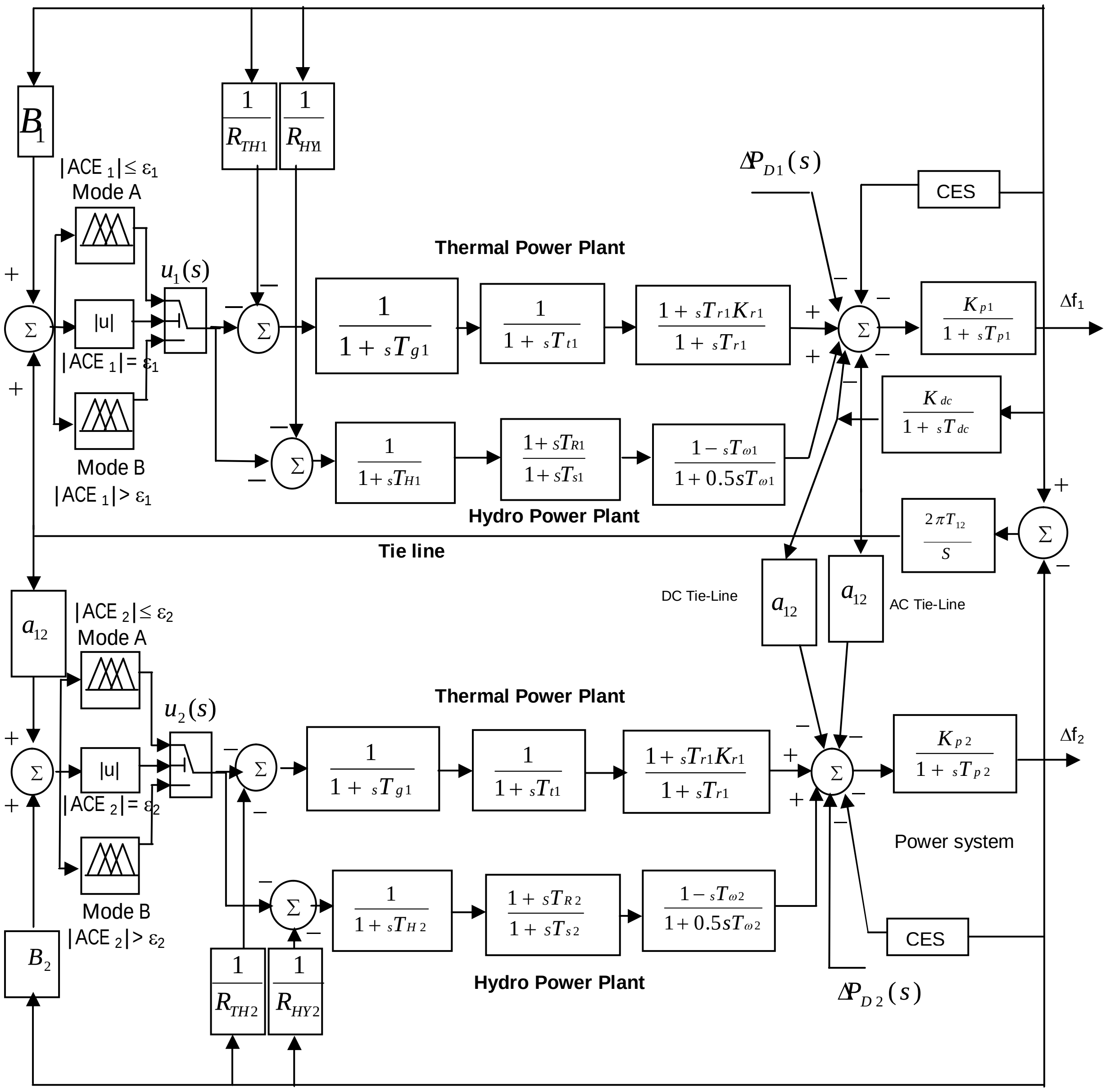



**Figure 7:** Simulink block diagram of dual mode Type-II fuzzy logic controller with parallel AC-DC tie-lines and CES unit for two area interconnected power system with reheat turbines

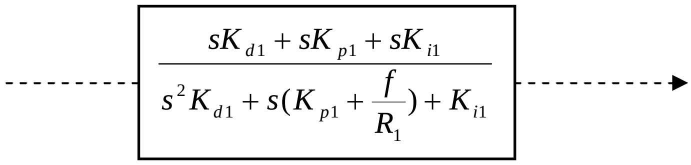
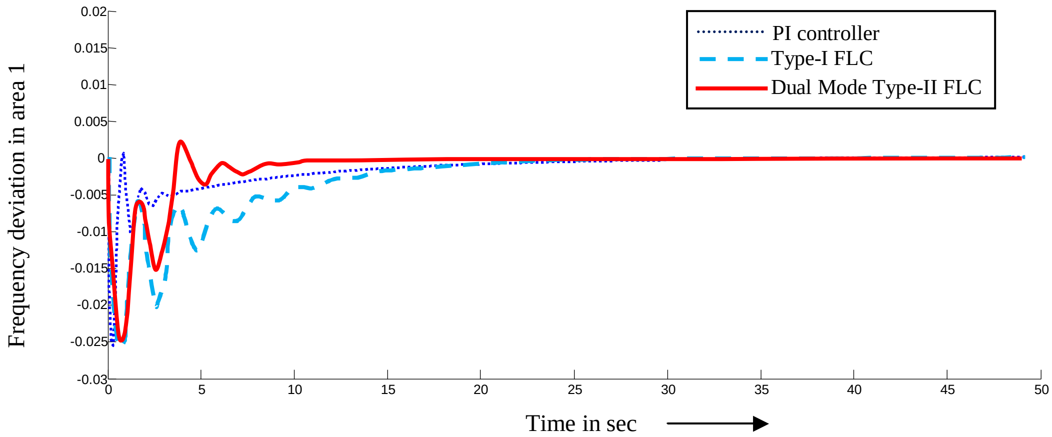



**Figure 8:** Transfer function model of electric governor

The transfer function model of electric governor is shown in Fig.8.The performance of this controller is simulated for 0.01 p.u. MW step load change in area 1 and the corresponding frequency deviation $\Delta f_1$ in area 1, frequency deviation $\Delta f_2$ in area 2 and tie line power deviation $\Delta P_{tie}$ are plotted in Fig.9. For easy comparison, the responses of $\Delta f_1$, $\Delta f_2$ and $\Delta P_{tie}$ of the system with the optimum PI controller designed on the basis of ISE criterion and Type-I fuzzy logic controller are also plotted in the same Fig.9. The nominal parameters are presented in Appendix A. The simulation results show that the proposed controller has superior performance in settling time and overshoot/undershoot when compared to conventional PI controller and Type-I fuzzy logic controller.



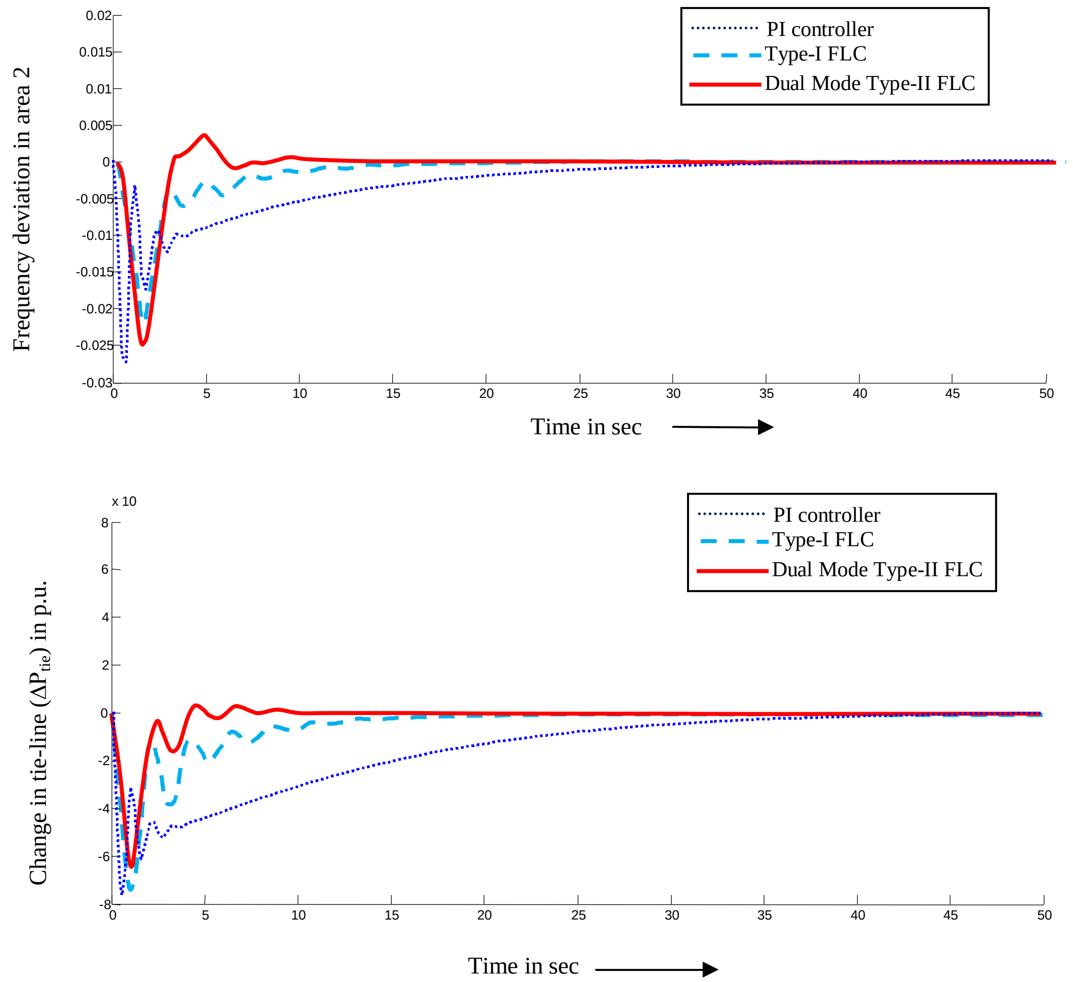



**Figure 9:** The performance of controller is simulated for 0.01 p.u. Mw step load change in area 1 and the corresponding frequency deviation $\Delta f_1$ , $\Delta f_2$ and $P_{tie}$ for PI controller, Type-I fuzzy logic controller and dual mode Type-II fuzzy logic controller with AC-DC tie – lines.

### *5.4. Performance analysis of the proposed controller under different operating Conditions.*

To examine the essence of the proposed controller under different operating conditions the following simulation is also taken away.

**Case (i):** *simulation with AC tie-line only*

In Fig.7 the DC tie-line is removed and simulation are carried out for 1% step load disturbance and the results are shown in Fig 10.

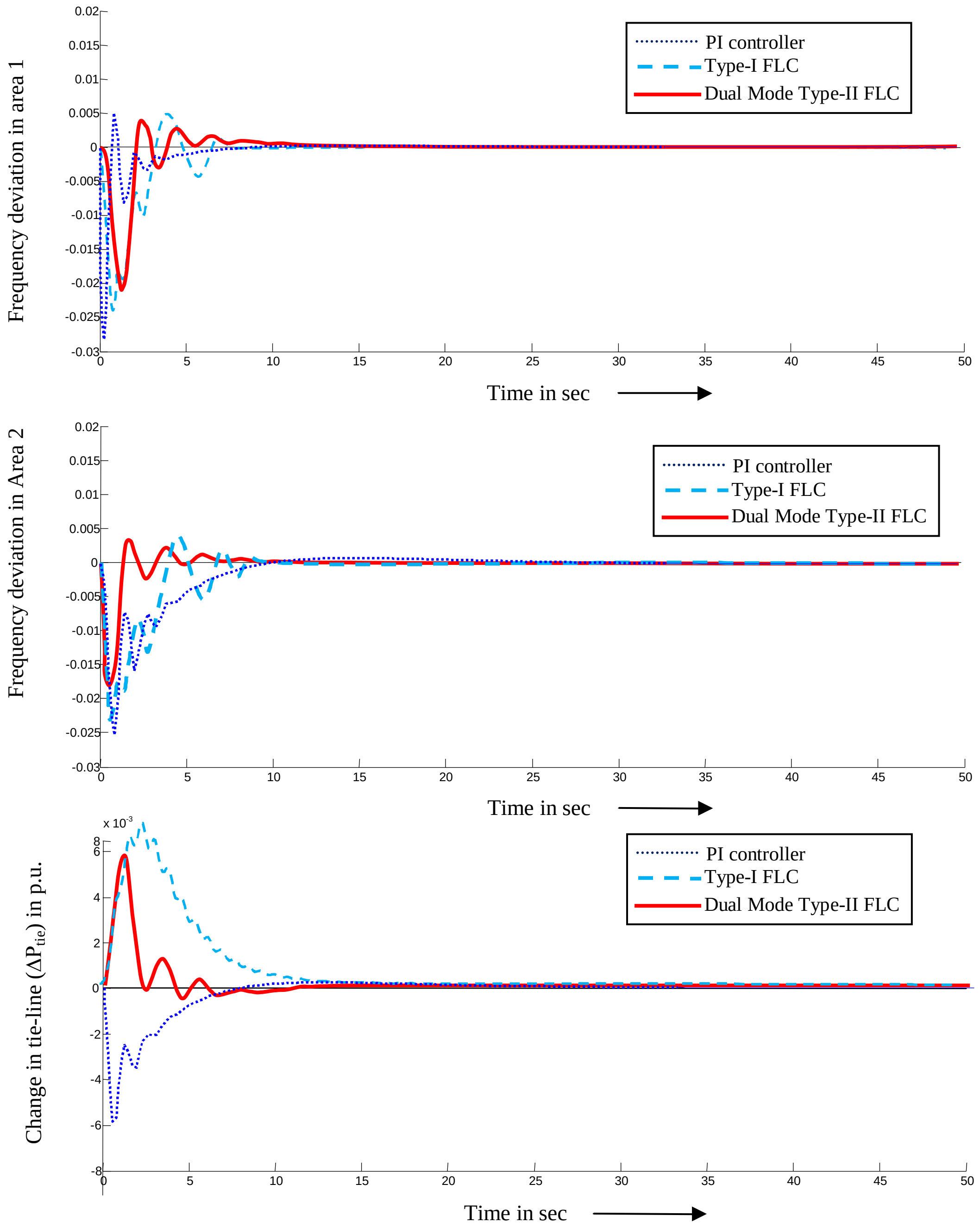



**Figure 10:** The performance of controller is simulated for 0.01 p.u. Mw step load change in area 2 and the corresponding frequency deviation $\Delta f_1$ , $\Delta f_2$ and $P_{tie}$ for PI controller, Type-1 fuzzy logic controller and dual mode Type-2 fuzzy logic controller with AC tie – line only.

**Case (ii):** *simulation with DC tie-line only.*

In Fig.7 the AC tie-line is removed and simulation are carried out for 1% step load disturbance and the results are shown in Fig 11.

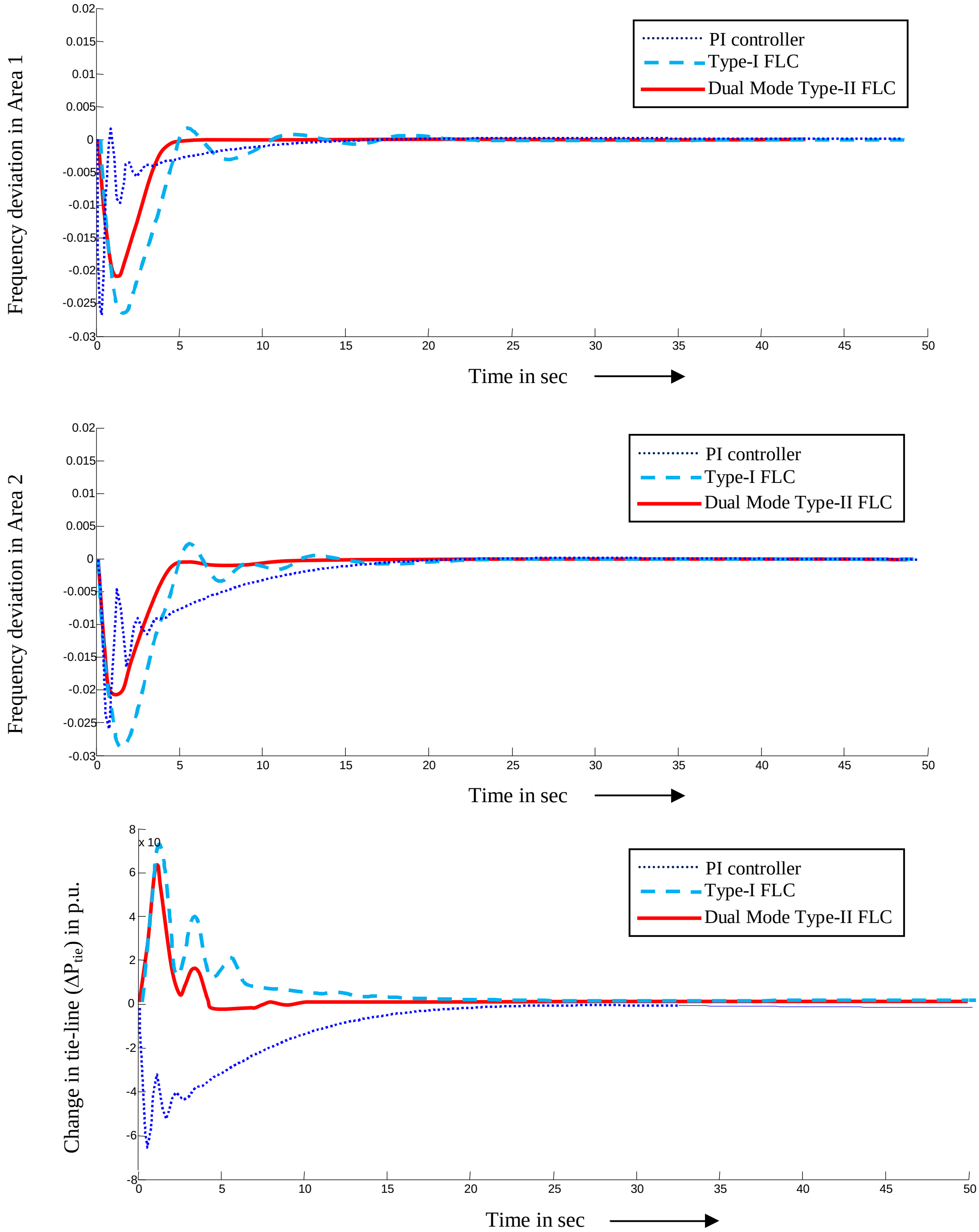



**Figure 11:** The performance of controller is simulated for 0.01 p.u. Mw step load change in area 1 and the corresponding frequency deviation$\Delta f_1$,$\Delta f_2$ and $P_{tie}$ for PI controller, Type-1 fuzzy logic controller and dual mode Type-2 fuzzy logic controller with DC tie – line only.

**Case (iii):** *simulation with electric governor.*

In Fig.7 the mechanical governor has been replaced with electrical governor as shown in Fig.8. Simulations are carried out for 1% step load disturbances in area 1 and the results are shown in Fig.12.

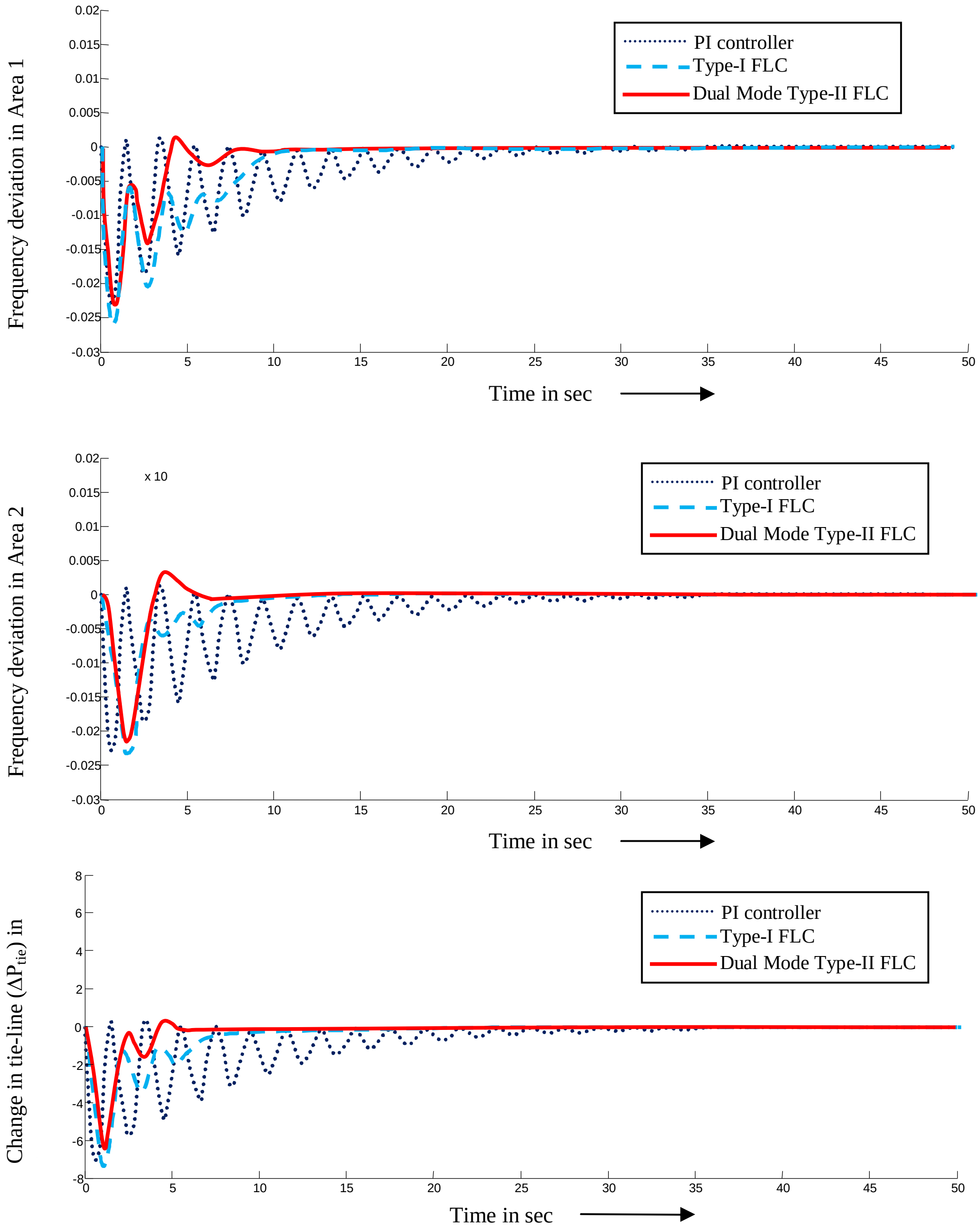



**Figure 12:** The performance of controller is simulated for 0.01 p.u. Mw step load change in area 2 and the corresponding frequency deviation $\Delta f_1$ , $\Delta f_2$ and $P_{tie}$ for PI controller, Type-I fuzzy logic controller and dual mode Type-II fuzzy logic controller using electric governor and AC-DC tie – lines

**Case (iv) :** *simulation with various step load disturbances for different time period.*

Simulations are carried away for varying load case also. Here the load varies in step of 1% for every 10 Sec. (For first 10 Sec the disturbance is 1% and for next 10 Sec the disturbance is 2% and so on) as shown in Fig 13.For easy comparison the disturbance and output response are plotted in the same form.

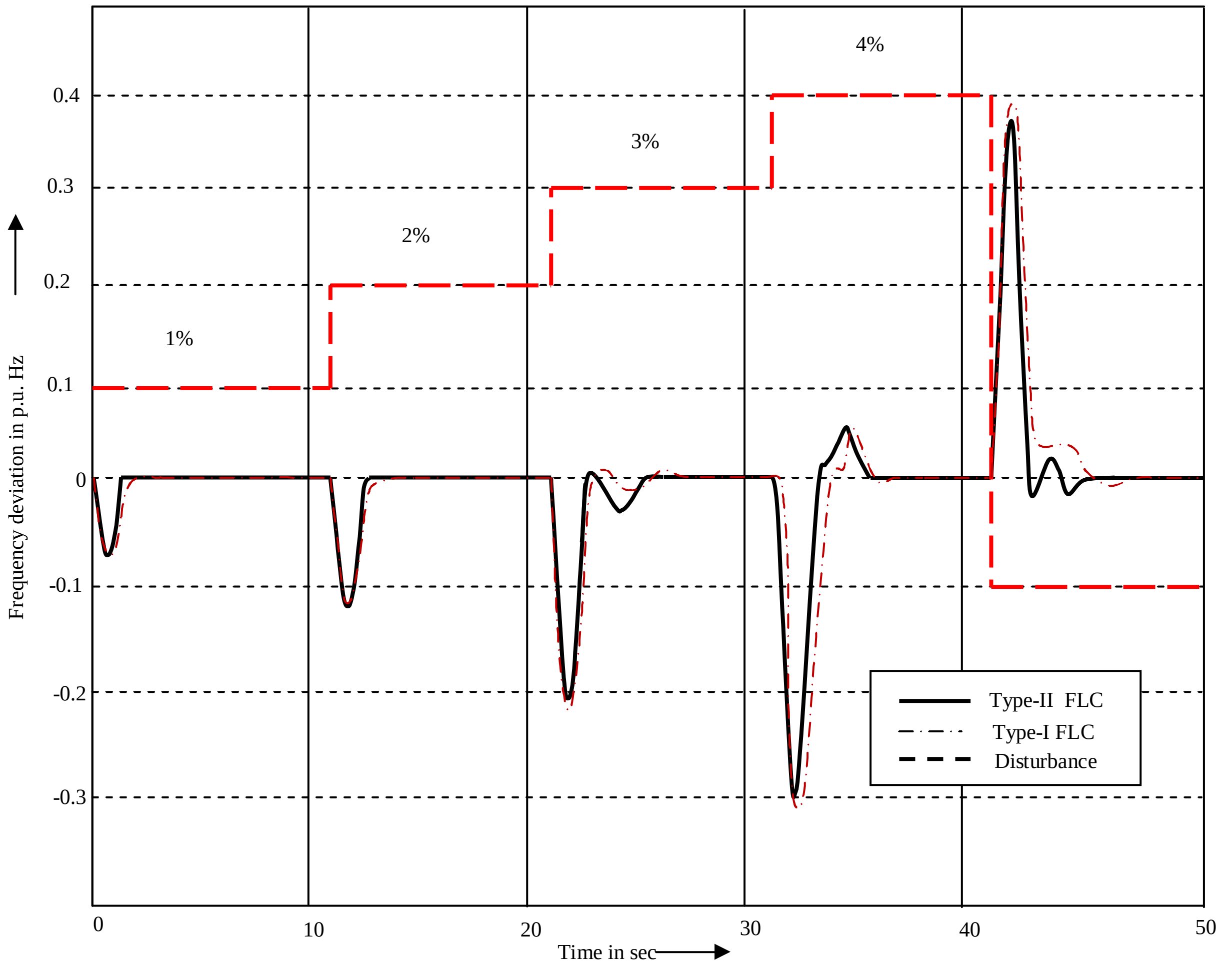



**Figure 13:** Performance comparison of frequency deviation in area-1for a different load disturbances

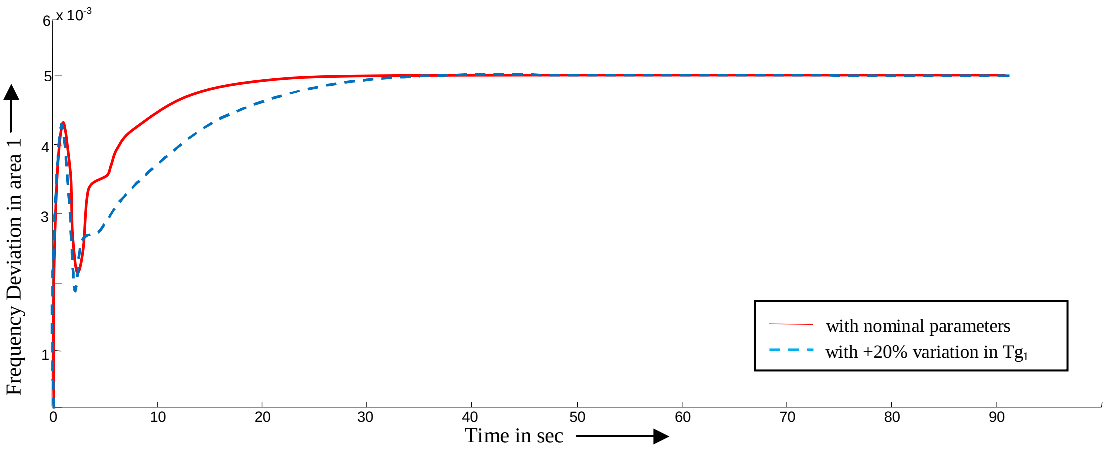
From the above case studies, it is found that the proposed controller provides good transient and steady state response even under different operating conditions. For convenience the results are summarized in a tabular form and presented in Table 2.

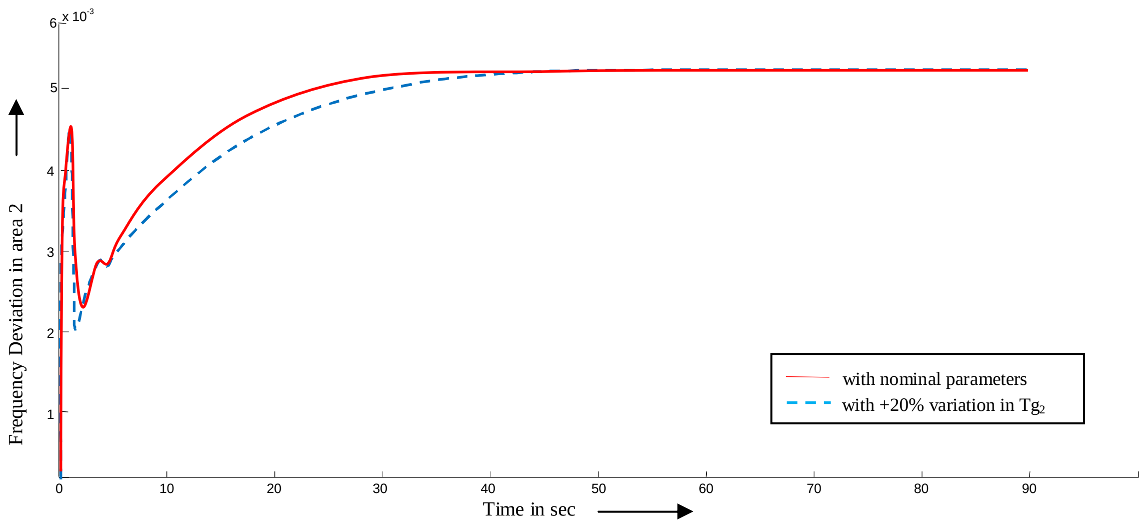
**Table 2:** Performance comparison of different control techniques

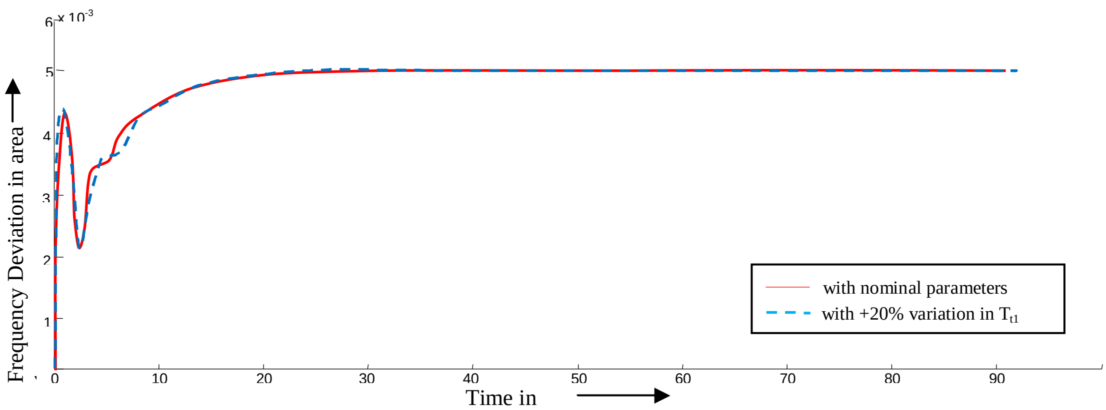
| controller | Operating condition | Settling time | | | Peak overshoot/ undershoot | | |
|---|---|---|---|---|---|---|---|
| | | $\Delta f_1$ | $\Delta f_2$ | $p_{tie}$ | $\Delta f_1$ | $\Delta f_2$ | $p_{tie}$ |
| Conventional PI controller | with AC tie-line | 27.50 | 26.80 | 24.25 | +0.0018 - 0.0098 | +0.0031 -0.015 | +0.0039 -0.0005 |
| | with DC tie-line | 25.02 | 24.02 | 23.25 | +0.003 -0.0065 | +0.005 -0.015 | +0.0065 -0.0042 |
| | with AC-DC tie-line | 35.00 | 34.90 | 36.25 | +0.001 -0.0063 | +0.0031 -0.015 | +0.0044 -0.0015 |
| | AC-DC tie-line with electric governor | 34.00 | 32.25 | 33.12 | +0.001 -0.0051 | +0.0011 -0.012 | +0.0027 -0.0010 |
| TIFLC | with AC tie-line | 17.32 | 13.25 | 15.01 | +0.005 -0.028 | +0.003 -0.023 | +0.008 -0.0005 |
| | with DC tie-line | 17.25 | 16.95 | 16.05 | +0.000 - 0.027 | +0.000 -0.029 | +0.0078 -0.0000 |
| | with AC-DC tie-line | 23.32 | 16.55 | 15.45 | +0.003 -0.025 | +0.005 -0.022 | +0.0003 -0.0077 |
| | AC-DC tie-line with electric governor | 10.95 | 9.80 | 10.00 | +0.001 -0.021 | +0.000 -0.023 | +0.000 -0.0079 |
| Dual mode TIIFLC | with AC tie-line | 15.00 | 11.25 | 14.90 | +0.000 -0.024 | +0.000 -0.020 | +0.006 -0.000 |
| | with DC tie-line | 05.10 | 04.90 | 10.00 | +0.000 -0.020 | +0.000 -0.019 | +0.0069 -0.000 |
| | with AC-DC tie-line | 11.25 | 10.22 | 11.23 | +0.012 -0.025 | +0.016 -0.024 | +0.012 -0.0060 |
| | AC-DC tie-line with electric governor | 4.80 | 7.23 | 7.77 | +0.001 -0.0230 | +0.002 -0.026 | +0.003 -0.0007 |

### *5.5. Performance analysis of the proposed controller under parameter variation*

The performance of the proposed controller has been analyzed under parameter variation. The parameters $T_{g1}$, $T_{g2,}$ $T_{t1}$ and $T_{t2}$ are varied by ±20% from the nominal value one at a time, and simulations are carried out. The simulation results are shown in Fig.14.


x 10-3
Frequency Deviation in area 1
Time in sec
with nominal parameters
with +20% variation in Tg1


x 10-3
Frequency Deviation in area 2
Time in sec
with nominal parameters
with +20% variation in Tg2


x 10-3
Frequency Deviation in area
Time in
with nominal parameters
with +20% variation in Tt1

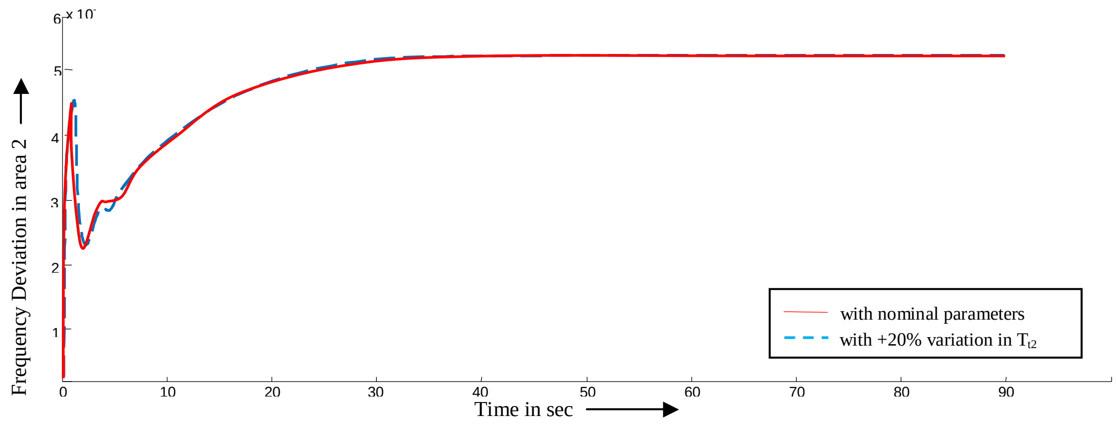



**Figure 14:** Comparisons of proposed Type-II fuzzy logic controller of frequency deviations for area1 and area 2 for 0.01 p.u K.W step load change with system parameter variation

From the results, it is found that the proposed dual mode Type-II fuzzy logic controller is less sensitive to parameter variation. The simulations are carried out for varying load conditions with PI, Type-I and Type-II controller, from the above figures, it is shown that the proposed controller provides good transient and steady state performance when compared with other two controllers.

## 6. Conclusions

This paper presents a design of dual mode Type-II fuzzy logic load frequency controller for interconnected two area hydro-thermal reheat power systems with parallel AC-DC tie-line using CES system. The proposed controller is designed by taking advantage of dual mode concept and TIIFLC. Simulation results are carried out using Matlab 2009b version demonstrated that the designed controller capable to guarantee the robust stability and robust performance such as precise reference frequency tracking and disturbance attenuation under a wide range of parameter uncertainty and area load conditions.The simulation results indicate that the proposed dual mode TIIFLC can guarantee the stability of the overall system for large parametric uncertainty and achieves good performance even for a less sensitive to change in the parameter of the system.

## Acknowledgement

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**APPENDIX A**

**(a) Data for the interconnected two-area hydro-thermal reheat power system,**
$K_{r1}=K_{r2}=0.55$; $R_{TH1}=R_{TH2}=2.4$ Hz/p.u.MW; $T_{g1}=T_{g2}=0.08s$; $T_{r1}=T_{r2}=10s$;$a_{12}= -1$; $\Delta P_{d1}=0.01$p.u.MW;$T_{t1}=T_{t2}=0.3$sec; $K_{p1}=K_{p2}=120$Hz/p.u.MW; $T_{p1}=T_{p2}=20$sec; $T_{H1}=T_{H2}=41.6$ Sec.; $T_{R1}=T_{R2}=10$ Sec.; $T_{S1}=T_{S2}=0.513$ Sec.; $R_{HY1}=R_{HY2}=2.4$ Hz/p.u MW.;$T_{\omega 1}=T_{\omega 2}=1$ Sec;$\beta_1=\beta_2=0.425$p.u.MW/Hz; $2\pi T_{12}=0.545$p.u.MW/Hz.

**(b)Data for capacitive energy storage unit,**
C = 1.0 F; R = 100Ω; $E_{dmax}$ = 2.76kV; $E_{dmin}$ = 0.6kV; $E_{do}$ = 2.0kV; $T_{dc}$ = 0.05sec; $K_{ACE}$ = 70kA/unit MW; $K_{vd}$ = 0.20kA/kV

**(c)Data for DC link,**
$K_{dc}$ = 1.0; $T_{dc}$ = 0.5sec.

**(d)Data for electric governor,**
$K_p=1.0$;$K_i=5.0$;$K_d=4.0$;f=50Hz.

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**Highlights:**

- We designed a new model to maintain the frequency deviation and tie-line
- A new approach of dual mode Type-II FLC is proposed in this paper
- Maintaining a nominal deviation of over shoot and under shoot
- AC-DC tie line and CES unit is incorporated with this model.
- Simulation results show the effectiveness of the proposed control strategy.