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Design of Dual mode Type-II Fuzzy Logic Load Frequency Controller for Interconnected Power Systems using Redox Flow Battery Unit

[1]Nattanmai Jeganathan Vinoth Kumar and [2]M.M.T. Ansari

[1,2]Department of Electrical Engineering, Annamalai University, Annamalai Nagar – 608002, Tamilnadu, India.

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A B S T R A C T

Load frequency control in power systems is very important in order to supply reliable electric power with good quality. Electromechanical oscillations in a power system can be effectively damped by fast acting energy storage devices, because additional energy storage capacity is provided as a supplement to the kinetic energy storage in the moving mass of the generator rotor. The Redox Flow battery (RFB) energy storage devices have been implemented to share the sudden changes in power requirement in the load. In general proportional and integral (PI) controller are used for load frequency control, which is generally tuned on the basis of classical approaches and this will maintain control only during the normal changes in load and frequency. The proportional plus integral control does not eliminate the conflict between the static and dynamic accuracy. Type-I fuzzy logic controller is a sophisticated technique that is easy to begin and implement, nevertheless the determination of membership function the control rules is an essential part of design. To achieve satisfactory membership function and control rules, designer experience is necessary. Type-II fuzzy logic controller is achieved for the ability to utilize expert knowledge and being adaptive in nature. Dual mode concept is incorporated in the proposed controller because it can improve the system performance. The performance of the dual mode type-II fuzzy logic controller is compared with conventional controller and Type-I fuzzy logic controller with CES unit. The simulation results obtained that the proposed controller provides not only very good transient and steady state response but also effective in damping out the frequency of oscillation compared to the conventional PI controller and Type-I fuzzy logic controller. The simulation studies of the dynamic response are conducted with comparison with different configuration of the power system. The comparison is made with PI controller and Type-I fuzzy logic controller. The proposed controller is found to be less sensitive to change in the parameters of the system.

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INTRODUCTION

The dynamic behavior of many industrial plants is heavily influenced by disturbance and, in particular, by changes in the operating point. This is typically the case for power systems (Kothari, L., et al., 1989). Load-Frequency Control (LFC) is an important task in electrical power system design and operation. Since the load demand varies without any prior schedule, the power generation is expected to overcome these variations without any voltage and frequency instabilities. Therefore voltage and frequency controllers are required to maintain the generated power quality in order to supply power to the utility under constant voltage and frequency operating conditions. The goal of LFC is to maintain zero steady state errors in a multi-area interconnected power system (Ramar, K., S. Velusami, 1989). In addition, the power system should full fill the requested dispatch conditions. In order to full fill the requested dispatch some control strategies have been suggested based on conventional linear control theory. The PI controller is most widely applied for LFC scheme (Bhatta Praghnesh, Ghoshalb, S.P., 2010; Zribi, Al-Rashed M, M. Alrifai, 2005). An advantage of the PI controller is to reduce the steady-state to zero but it exhibits poor dynamic performance and it will not reach high performance. Since the dynamics of a power system, even for a reduced mathematical model, is usually nonlinear, time-invariant and governed by strong cross-couplings of the input variables, the controllers have to be designed with special care. For a successful operation of power system under abnormal conditions, mismatches hence to be corrected via supplementary control (Kothari, L., et al., 1989). Automation generation control (AGC) or load frequency control (Ramar, K., S. Velusami, 1989) is

Corresponding Author: Nattanmai Jeganathan Vinoth Kumar, Department of Electrical Engineering, Annamalai University, Annamalai Nagar – 608002, Tamilnadu, India.
E-mail: vinothkumarnj@gmail.com

a very important issue in power system operation and control for supplying sufficient and reliable electric power with good quality. Interconnected electrical power systems operate together adjusting their power flows and frequencies at all areas by AGC. In this study, a two area power system is considered to control power flows. To increasing interest and development in intelligent control techniques the fuzzy logic based controllers have become an attractive choice in solving power system control problems (Mehdi Rahmani, 2013). A FLCs, described completely in terms of Type-I fuzzy sets is called a Type-I fuzzy logic system (Type-I FLC).Type-I FLC have received increasing attention in power system engineering. Fuzzy logic is a logical system for formulization of approximate reasoning, and is used synonymously with fuzzy set theory systems introduced by Zadeh and investigated further by fuzzy researchers (Ali-Hamouz, Z.M. and Y.L. Abdel-Magid, 1993; Chang, C.S. and W. Fu, 1997; Dipti Srinivasan, Liew A.C., C.S. Chang, 1995). Due to its ability being able to model human decision making proces and represent 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 Type-I fuzzy logic controller (FLC) 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 Type-I fuzzy sets, which represent uncertainty by numbers in the range (Kothari, L., et al., 1989). When something is uncertain, like a measurement, it is difficult to determine its exact value, and of course Type-I fuzzy sets make more sense than using sets. 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. So, the amount of uncertainty in a system can be reduced by using Type-II fuzzy logic because it offers better capabilities to handle linguistic uncertainties by modelling vagueness and unreliability of information (Mendel, J.M., G.C. Mouzouris, 1999; Mendel, J.M., R.I.B. John, 2002). The concept of a Type-II fuzzy set, was introduced by Zadeh as an extension of the concept of an ordinary fuzzy set (Type-I fuzzy set) and investigated further by many researchers (Ertugrul Cam, 2007; Mendel, J.M., G.C. Mouzouris, 1999; Mendel, J.M., R.I.B. John, 2002). The concept of a Type-II fuzzy set was introduced by Zadeh as an extension of the concept of an ordinary fuzzy set (Type-I fuzzy set) and investigated further by many researchers (Hongwei, W., J.M. Mendel, 2001; Janusz, T., Starczewski, 2009; Mendel, J.M., 2005; Sudha, K.R., R. Vijaya Santhi, 2011). A Type-II fuzzy set is characterized by a fuzzy membership function, i.e., the membership grade for each element of this set is a fuzzy set in 0 to 1, unlike a Type-I set where the membership grade is a crisp number in 0 to 1. Such sets can be used in situations where there is uncertainty about the membership grades themselves, e.g., an uncertainty in the shape of the membership functions or in some of its parameters.

Energy storage unit is an attractive option to augment demand side management implementation (Shigematsu, T., 2011; Ponce deLeónC, 2006; Thameem Ansari M.Md, S. Velusami, 2010). The conventional load-frequency controller may no longer be able to attenuate the large frequency oscillation due to the slow response of the governor even though a more sophisticated controller is adopted. 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. Among electro chemical systems, redox flow batteries (RFBs) represent one of the most recent technologies and a highly promising choice for stationary energy storage. They are electrochemical energy conversion devices, stored in external tanks and introduced into the RFB when needed. By using energy storage systems, a low cost source of electricity can be efficiently provided to meet the peak demand. The effect of generation control and the absorption of power fluctuation needed for power quality maintenance are expected. In this study, a two area power system using RFB unit is considered to control power flows. In each control area, all generators are assumed to form coherent group. This paper proposes by taking advantage of the superior characteristics inherent in the design of dual mode Type-II fuzzy logic load frequency controller, using superconducting magnetic energy storage device for interconnected power systems. An important design concept of dual mode Type-II fuzzy logic control is incorporated in the proposed controller because it improves the system performance and makes it flexible for application to actual systems (Thameem Ansari M.Md, S. Velusami, 2010). The computer simulation results of application of the proposed controller with inter connected power systems prove that the proposed controller is effective and provides significant improvement in the system performance. Moreover, it has also been observed that the proposed controller is less sensitive to system parameter variations.

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 (Velusami, S., I.A. Chidambaram, 2007)

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

$$x = \left[x_1^T, \Delta p_{ci} .. x_{(N-1),}^T \Delta p_{c(N-1)} .. x_N^T\right]^T$$

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

$$u = \left[u_1, \dots, u_N\right]^T = \left[\Delta P_{C1} .. P_{CN}\right]^T,$$

N-control input vector

$$d = \left[d_1, \dots, d_N\right]^T = \left[\Delta P_{D1} .. P_{DN}\right]^T,$$

N – disturbance input vector

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

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

where A is the system matrix, B is the input distribution matrix, Γ is the disturbance distribution matrix, C is the control output distribution matrix, H is the measurable output distribution matrix, x is the state vector, u is the control vector and d is the disturbance vector of load changes.

3. Output Feedback Control Scheme:

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$_i$ ($\int v_i$ dt), i=1,2,3,....N. The augmented system of the order (N+n) can be described as

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

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

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

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 y can be written as y = $\overline{H}\overline{x}$

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

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

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

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

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

$$u_i = -k_i^T y_i \qquad i = 1,2..., N \qquad (3)$$

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

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

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

4. Description of Proposed Dual Mode Type-II Fuzzy Logic Controller with Output Feed Back:

Since the Principle of dual mode control can improve the system performance (Shigematsu, T., 2011), a new design of dual mode Type-II fuzzy logic controller is proposed in this section. This proposed controller operates in mode A as long as the significant observed variable to the control actions the system output error is sufficiency large i.e. greater than the switching limit of the controller otherwise it operators in mode B. Mode A acts as proportional Type-II fuzzy logic controller and mode B as integral type Type-II fuzzy logic controller. Thus, the control structure of the system is changed when switching in each mode of operation. Since the proposed controller is designed based on the switching limit of the controller, the performance of the controller is improved significantly. Block diagram of dual mode Type-II fuzzy logic controller is shown in Fig.1.

As per Mendel, “A Type-I fuzzy set (TI FS) has a grade of membership that is crisp, whereas a Type - 2 fuzzy set (TII FS) has a grade of membership that is fuzzy, so TII FS are ‘fuzzy-fuzzy’ sets”. To represent the fuzzy membership of fuzzy sets footprint of uncertainty (FOU) is employed, which is a 2-D representation, with the uncertainty about the right end point of the right side of the membership function and with the uncertainty about the left end point of the left side of the membership function. Uncertainty cannot be determined with its exact value, because of its complexity and rather Type-I fuzzy sets give much sensor than using crisp sets [21]. So, it is difficult to measure an uncertain membership function. To overcome this difficulty, we require another type of fuzzy sets, those which has ability to handle these uncertainties. Those type of fuzzy sets are called Type-II fuzzy sets. As the Type-II fuzzy logic has better capability to cope up with linguistic uncertainties, Type-II is a good replacement for Type-I fuzzy system.

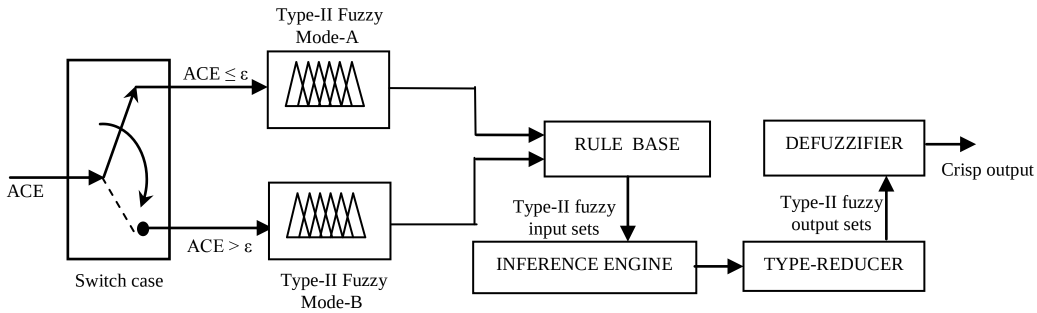


Fig. 1: Block diagram of dual mode Type-II fuzzy logic controller controller

A Type-II fuzzy set expresses the non-deterministic truth degree with imprecision and uncertainty for an element that belongs to a set. A Type-II fuzzy set denoted by $\overset{\approx}{A}$, is characterized by a Type-II membership function $\mu_{\overset{\approx}{A}}(x,u)$,

where $x \in X$, $u \in J_x^u \subseteq [0,1]$ and $0 \le \mu_{\overset{\approx}{A}}(x,u) \le 1$ defined in equation (5).

$$\overset{\approx}{A} = \left\{(x, \mu_{\overset{\approx}{A}}(x)) \mid x \in X\right\}$$

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

The Type-II membership function constructed in the Interval Type-II Fuzzy Logic System (ITIIFLS) are depicted in Fig.2.

If $\overset{\approx}{A}$ is continuous it is denoted in equation (6).

$$\overset{\approx}{A} = \left\{ \int_{x \in X} \left[\int_{u \in J_x^u \subseteq [0,1]} f_x(u)/u \right] / x \right\} \tag{6}$$

Where $\iint$ denotes the union of x and u. If $\overset{\approx}{A}$ is discrete then it is denoted by equation (7).

$$\overset{\approx}{A} = \left\{ \sum_{x \in X} \mu_{\overset{\approx}{A}}(x)/x \right\} = \left\{ \sum_{i=1}^{N} \left[\sum_{k=1}^{M_i} f_{xi}(u_{ik})/u_{ik} \right] / x_i \right\} \tag{7}$$

Where $\sum\sum$ denotes the union of x and u.

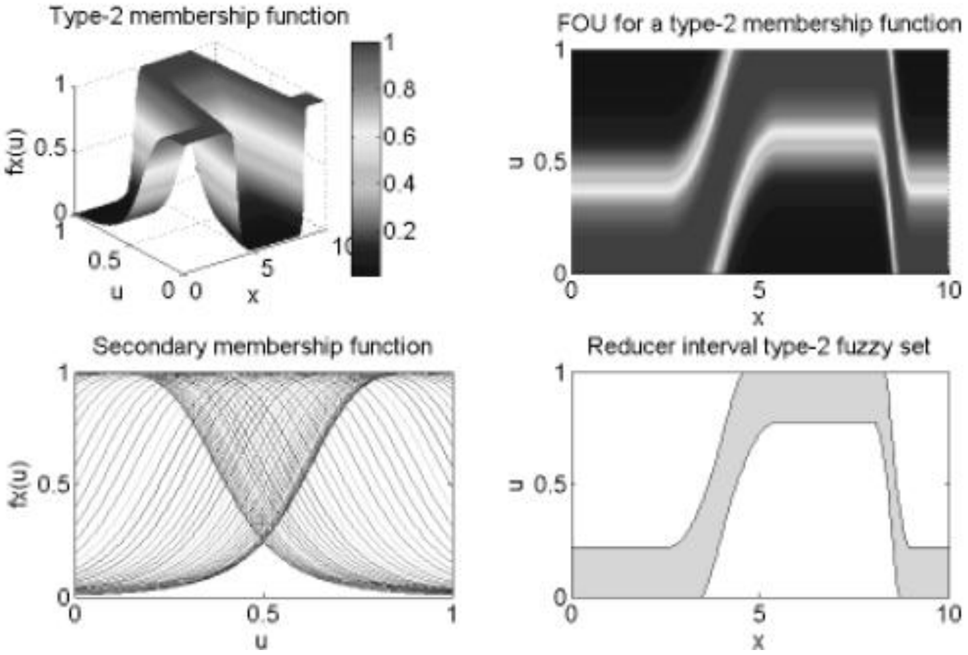


Fig. 2: FOU for Type-II membership function

If $f_x(u) = 1, \forall u \in \left[J_x^u, J_x^u\right] \subseteq [0,1]$, the Type-II membership function $\mu_{\overset{\approx}{A}}$(x) is expressed by one Type-I inferior membership function, $J_x^u \equiv \mu_A(x)$ and one Type-I superior, $J_x^u = \mu_A(x)$ Fig.3 then it is called an interval Type-II fuzzy set denoted by equ. (8) and (9).

$$\overset{\approx}{A} = \begin{cases} (x,u,1) \mid \forall x \in X, \\ \qquad \forall u \in [\mu_A(x), \mu_A(x)] \subseteq [0,1] \end{cases} \tag{8}$$

or

$$\overset{\approx}{A} = \left\{ \int_{x \in X} \left[\int_{u \in [J_x^u, J_x^u] \subseteq [0,1]} 1/u \right] / x \right\} \tag{9}$$

$$= \left\{ \int_{x \in X} \left[\int_{u \in [\mu_A(x), \mu_A(x)] \subseteq [0,1]} 1/u \right] / x \right\}$$

If $\overset{\approx}{A}$ is a Type-II fuzzy Singleton, the membership function is defined by equation (10).

$$\mu_{\overset{\approx}{A}}(x) = \begin{cases} 1/1 & si\ x = x' \\ 1/0 & si\ x \neq x' \end{cases} \tag{10}$$

In fact, the Type 1- fuzzy and Type-II fuzzy sets operation are similar, but while using with interval fuzzy system; by limiting the FOU, fuzzy operator is being done as two TI membership functions, upper membership function (UMF) and lower membership function (LMF) in order to produce firing strength which is shown in Fig.4.

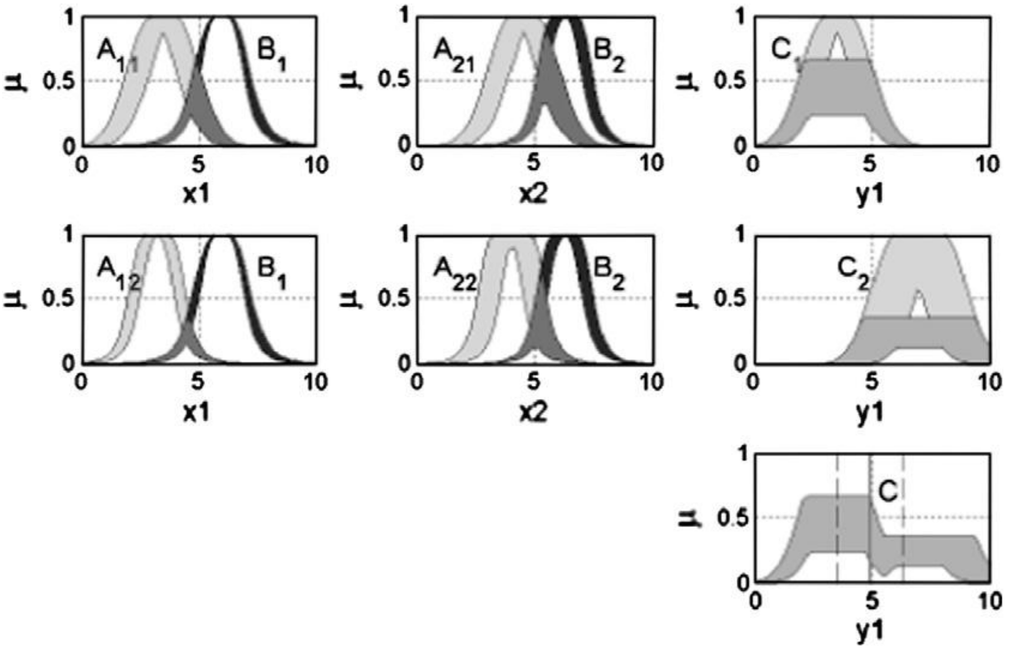


Fig. 3: Interval Type-II fuzzy reasoning

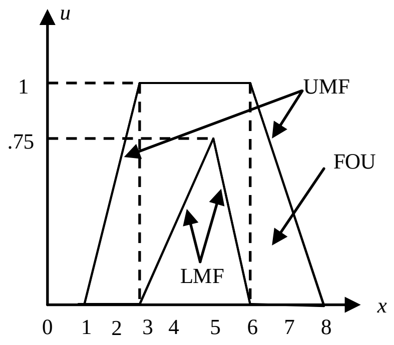


Fig. 4: Footprint of Uncertainty

Hence the Foot of Uncertainty [FOU] is not a single point but it designed over an interval. This method of taking the Foot of Uncertainty [FOU] over a range or at particular interval gives three-dimensional [3-D] appearance and it is the new third dimension that provides new design degrees of freedom for handling uncertainties. The basic structure of Type-II fuzzy logic controller is shown in Fig.5.

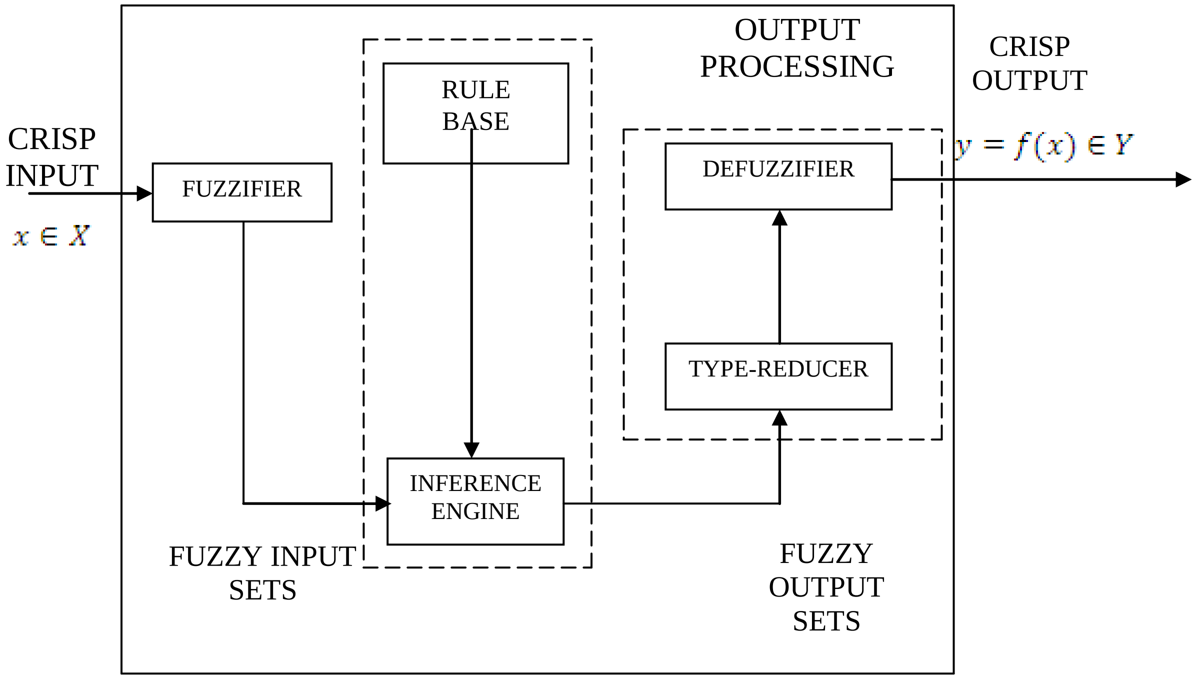


Fig. 5: Structure of Type-II fuzzy logic system

An Inference FS is a rule base system that uses fuzzy logic, instead of Boolean logic that is utilized in data analysis. Its basic structure includes four components are Fuzzification, Inference System, Type Defuzzificator/Reductor and Knowledge Base.

Fuzzification:

Translates inputs (real values) to fuzzy values.

Inference System:

To obtain a fuzzy output, fuzzy reasoning mechanism is applied.

Type Defuzzificator/Reductor:

To transduBES one output to precise values, defuzzificator is employed; the type reductor converts a Type 2 Fuzzy Set into a Type- 1 Fuzzy Set.

Knowledge Base:

It contains data base which consists of set of fuzzy rules and a membership functions. The two normalized input variables ΔACE and $\Delta A\dot{C}E$ are first fuzzified by two interval Type-II fuzzy sets as shown in Fig.6. as “positive” and “negative” and it is represented by μ_P(ACE) and μ_N(ACE), respectively. The primary memberships are generated by blurring the trapezoidal Type-I fuzzy sets 1 μ_P(ACE), μ_N(ACE), $\mu_P(\Delta A\dot{C}E)$ and $\mu_N(\Delta A\dot{C}E)$. The secondary membership functions of the interval Type-II fuzzy sets are all constant. The definitions of Type-I fuzzy sets are as follows [18-22]

$$\mu_p(\Delta ACE) = \begin{cases} 0 & [-\infty,-L_1] \\ (L_1+\Delta(ACE))/2L_1 & [-L_1,L_1] \\ 1 & [L_1,\infty] \end{cases} \qquad (11)$$

By shifting the membership functions of the Type-I fuzzy sets upward and downward by an angle of $\theta_1 \in [0, 0.5]$ for μ_P(ΔACE) and μ_N(ΔACE) along the membership axes, the boundary membership functions of the primary memberships of the interval Type-II fuzzy sets[8,9,21] are obtained. (i.e., μ_{PL}(ΔACE), μ_{PU}(ΔACE), μ_{NL}(ΔACE) , μ_{NU}(ΔACE)). These boundary membership functions form the shaded bands as shown in Fig.4 which are called footprint of uncertainty (FOU). The design parameters θ_1 and θ_2 are used to control the degree of uncertainty of the interval Type-II fuzzy sets, Zadeh fuzzy logic AND operator (i.e., min(.)) is used to realize the AND operations in the rules.

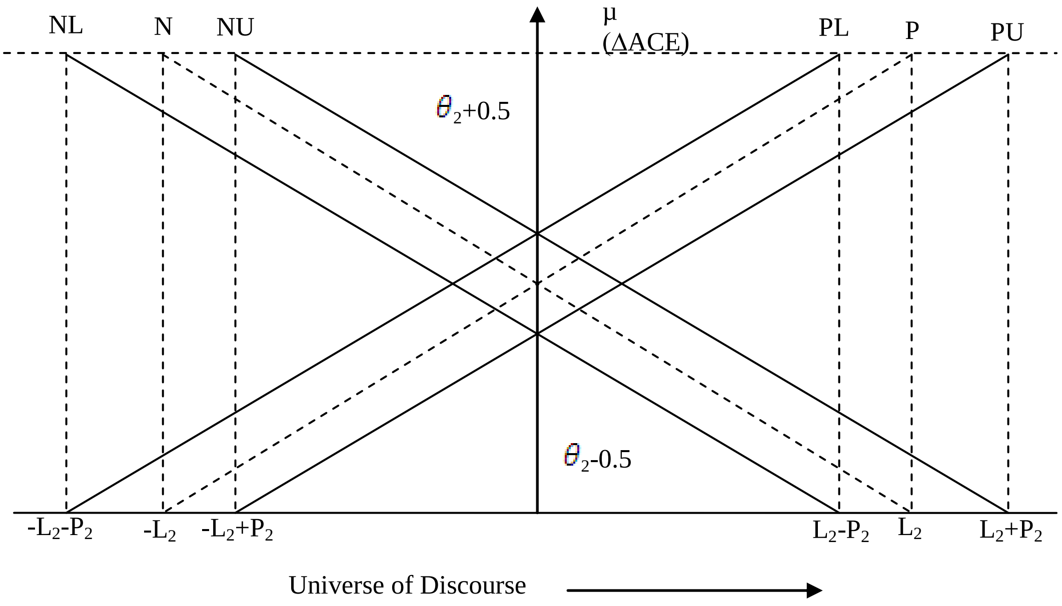


Fig. 6: Membership f

For Type-II fuzzy interface, the firing set becomes a firing interval $[R_L, R_U] = [\min(\Delta ACE\ P_L, \Delta A\dot{C}E\ P_L, UN_L), \min(\Delta ACE\ P_U, \Delta A\dot{C}E\ P_U, UN_U)]$. The rule base is given in Table.1 Similar to a Type-I fuzzy logic controller, a Type-II fuzzy logic controller includes Type-II fuzzifier, rule base, inference engine and substitutes the defuzzifier by the output processor. The output processor includes a type-reducer and a Type-II defuzzifier.

4. Description of Redox Flow Battery Energy Storage System:

4.1. Operating principles of RFBs:

RFBs represent one of the most recent technologies and a highly promising choice for stationary energy storage device. The configuration of RFBs is shown in Fig.7. The RFBs are an electrochemical storage system which allows energy to be stored in two solutions containing different redox couples. Sulfuric acid solutions containing vanadium ions is used as the positive and negative electrolytes, namely positive catholyte tank and negative anolyte tank and circulate to the battery cell. Thus unlike other RFBs vanadium redox flow batteries use only one element (vanadium) in both tanks, exploiting vanadium’s ability to exist in several states as shown in Fig.7.

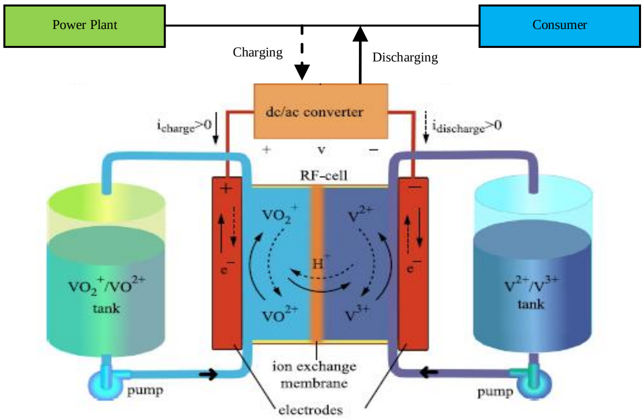


Fig. 7: Redox flow battery energy storage system

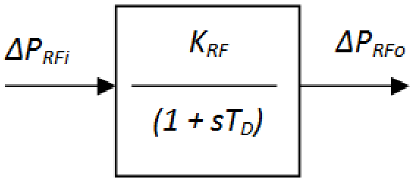


Fig. 8: Simplified transfer function block diagram of the RFB system

The electrolyte in the positive half-cells contains VO_2^{+} and VO^{2+} ions, the electrolyte in the negative half-cells contain V^{3+} and V^{2+} ions. In vanadium flow batteries, both half-cells are additionally connected to storage tanks and pumps so that very large volumes of the electrolytes can be circulated through the cell. The reaction that occurs in the battery cell during charging and discharging can be expressed simply with the following equations.

Positive Electrodes:
Negative Electrodes:

$$VO^{2+} \underset{Discharge}{\overset{Charge}{\rightleftarrows}} VO_2^{+} + e^{-}$$

$$V^{3+} \underset{Discharge}{\overset{Charge}{\rightleftarrows}} V^{2+} + e^{-}$$

When the vanadium battery is charged, the VO^{2+} ions in the positive half-cell are converted to VO_2^{+} ions when electrons are removed from the positive terminal of the battery. Similarly in the negative half-cell, electrons are introduced converting the V^{3+}ions into V^{2+}. During discharge this process is reversed. Unlike conventional batteries, the RFBs store energy in the solution so that the capacitor of the system is determined by the size of the electrolyte tank, while the system power is determined by the size of the cell stacks. These RFBs offers many features which are suitable for high- capacity system that differ from conventional power storage batteries. Some of main features are listed below. Fig.8. shows the transfer function model of RFB.

1. Simplicity of operation:

The battery reactions only involve a charge in the valence of vanadium ions in the electrolyte. Improved long battery life and service due to operate at normal temperatures ensures less deterioration of the battery materials due to temperature.

2. Increase system capacity:

The system capacity can be readily increased simply by adding more solution. The energy density of RFBs depends on the concentration of vanadium, the higher the concentration, the higher the energy density.

3. Simple in installation layout:

The system configuration is such that battery output and battery capacity can be separated; therefore layout of sections can be altered according to the place of installation. Land space can be saved by building underground electrolyte storage. This system offers greater safety since there is a less risk of instantaneously mixing the electrolytes and causing a sudden release of energy.

4. Superior environmental safety:

The electrolyte is relatively safe and assures superior environmental safety.

5. Superior recyclability:

Waste vanadium from power generating stations can be used. Furthermore, the vanadium in the electrolyte can be used semi-permanently. The Fig.8 shows the transfer function model of BES.

5. Application of dual mode Type-II fuzzy logic Controller for interconnected power systems:

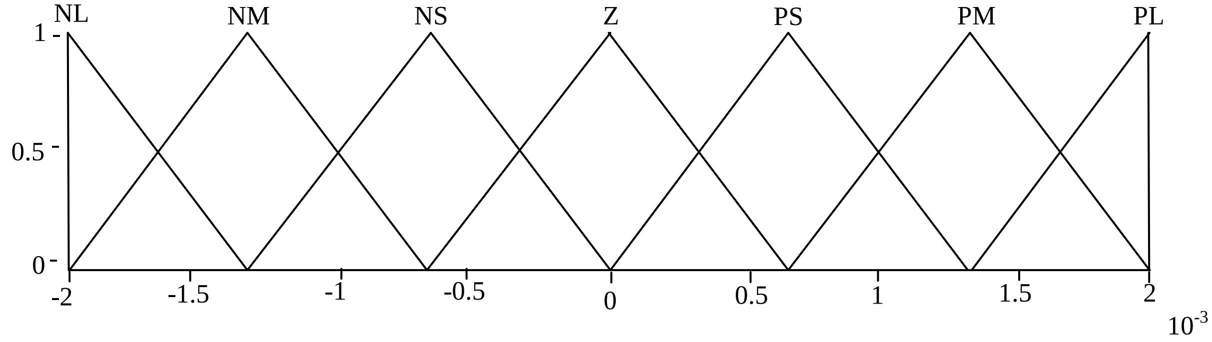
Proposed dual mode Type-II fuzzy logic controller design is applied to interconnected two area reheat based thermal power systems. As the system is exposed to a small change in load during its normal operation, the linear model will be sufficient for dynamic representation.

5.1. Design of conventional controller and fuzzy logic controller with output feedback:

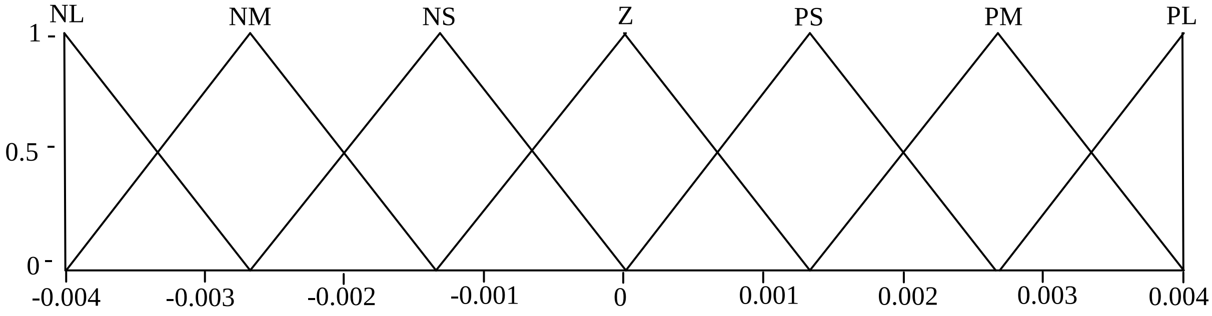
The conventional PI Controller with output feedback is designed with square error (ISE) technique. Gain values of the PI controllers are K_P=7.6 and K_I=1.55 were obtained according to the system response curve method. The conventional Type-I fuzzy logic controller is also designed using the method given in [15]. The system output is sampled at the normal sampling rate of two seconds and the controller output is also updated at normal sampling rate [15].

5.2. Design of proposed dual mode Type-II fuzzy logic Controller using RFB unit with output feedback:

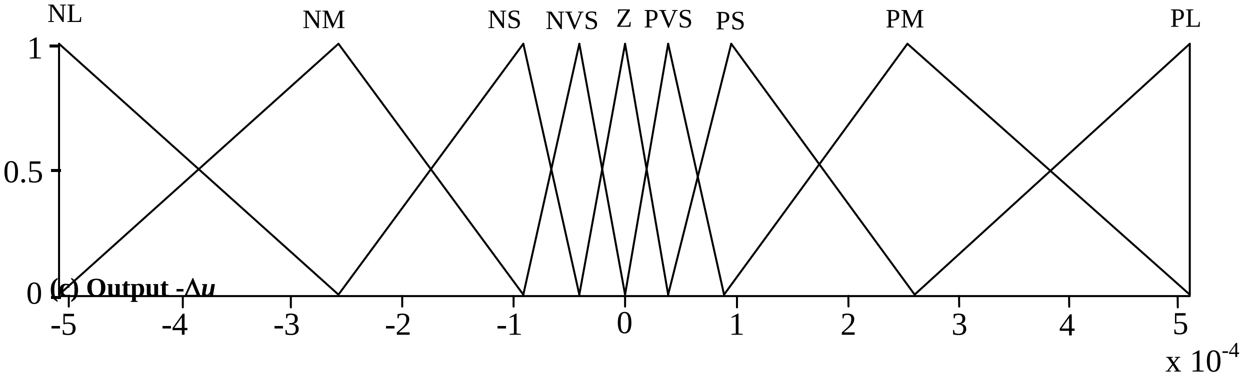
Design of proposed dual mode Type-II fuzzy logic controller using RFB unit with output feedback scheme is carried out for two area interconnected power systems. Since the switching limit value ‘ε’ should be greater than the steady state error of the system output ΔACE with only proportional Type-II fuzzy logic controller, it is chosen as 0.075 (ε_1=0.003, ε_2 =0.003).The input variable of the proposed controller are ΔACE (error e) and ΔȦCE (change of error Δce). Fig.9 shows the membership functions of DMT-II FLC 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 to α. The value α=0.002 for fuzzifier module A and α = 0.003 for fuzzifier module B. The output variable u is characterized by three fuzzy sets N, Z and P over the interval ($-5x10^{-3}$ to $5x10^{-3}$). The rule base 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.



(a) Input (error –e)



(b) Input (change in error-Δce)



(c) Output -Δ*u*

Fig. 9: Membership function for the input/output variables (e, Δce and Δ*u*)

5.3. Simulation results and discussions:

The dual mode Type-II fuzzy logic controller using RFB 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 dual mode Type-II fuzzy logic controller with RFB unit is shown in Fig.10.

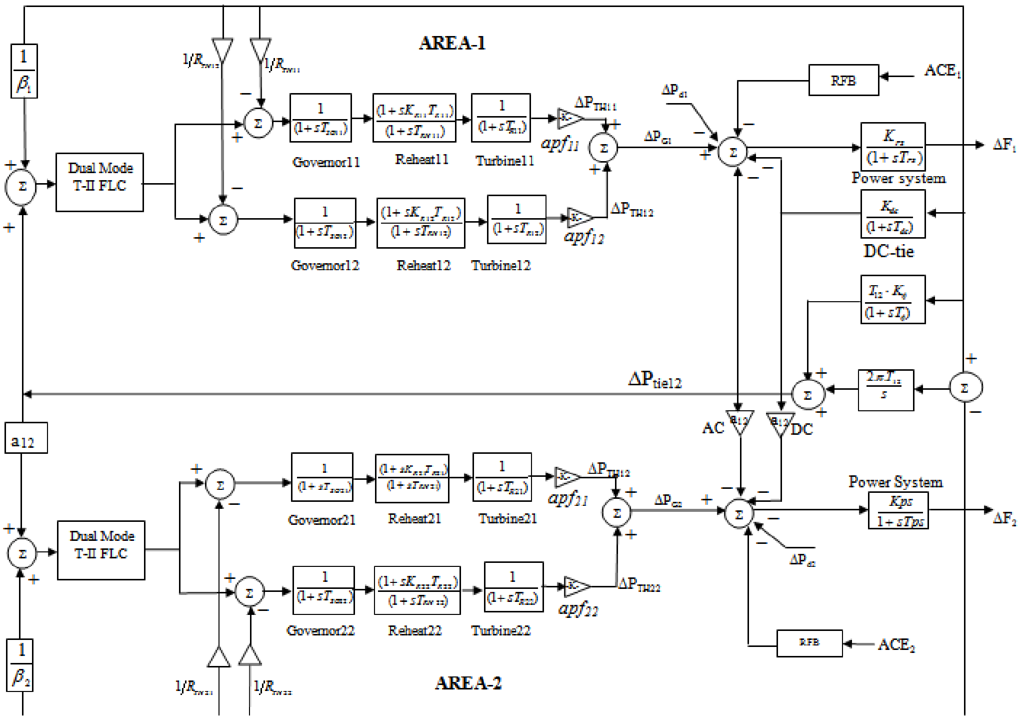
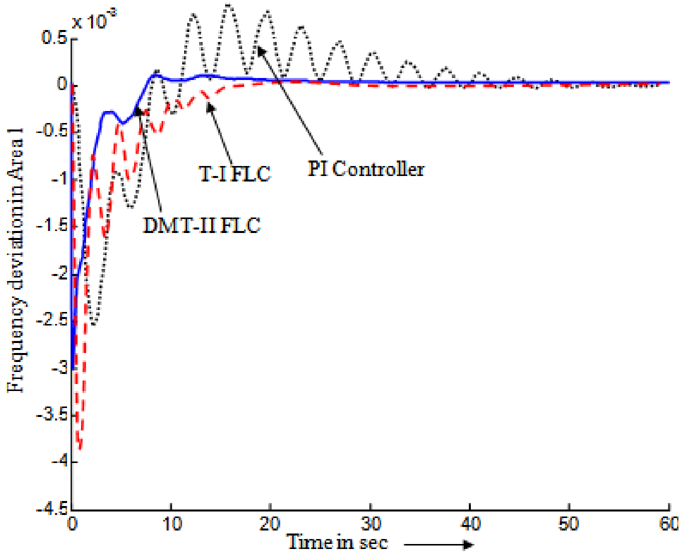


Fig. 10: Transfer function model of two-area interconnected power systems with AC-DC tie line and RFB unit.

The performance of this controller is simulated for 0.01 p.u. Mw step load change in area 1 and the corresponding frequency deviation Δf_1 in area 1, frequency deviation Δf_2 in area 2 and tie line power deviation ΔP_{tie} are plotted in Fig.11. For easy comparison, the responses of Δf_1, Δf_2 and ΔP_{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 Figure. Similarly the performance of the controller is simulated for 0.01 p.u. Mw step load change in area two and the corresponding frequency deviation and tie line power deviation are plotted with respect to time as shown in Fig.12. From the result, it is observed that the proposed dual mode Type-II fuzzy logic controller has less overshoot and settling time.



(a)

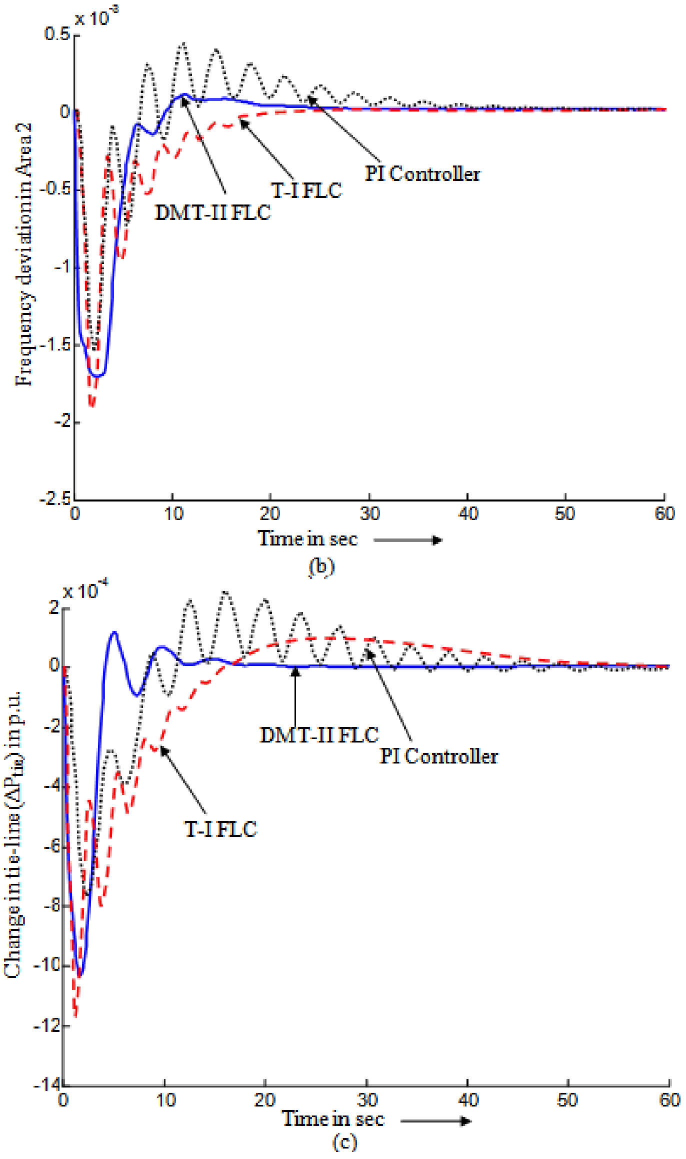
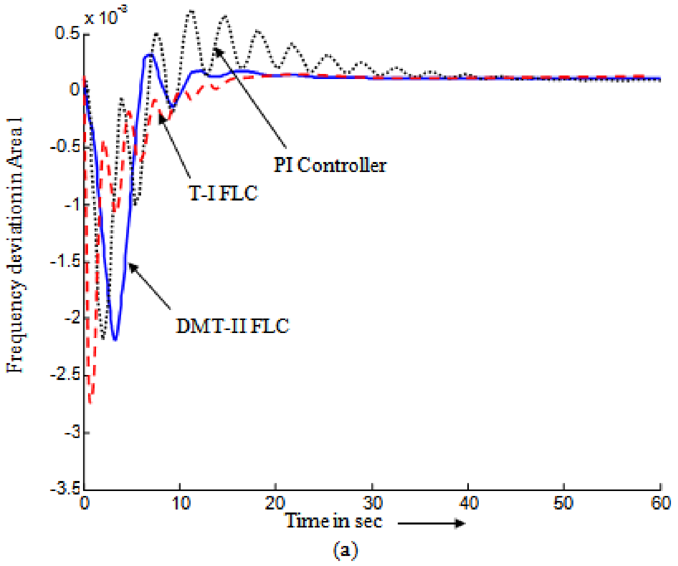
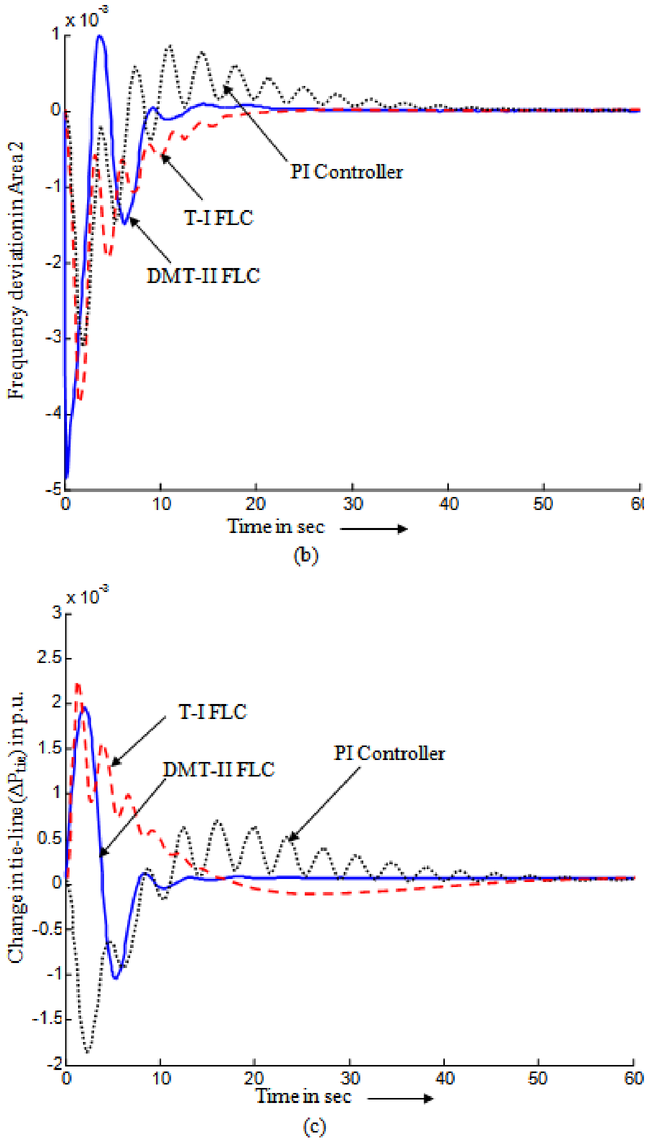


Fig. 11: Performance analysis of frequency deviations ΔF_1(a), ΔF_2(b) and tie-line power deviation ΔP_{tie} (c) of PI controller, T-I FLC, and DMT-II FLC for a step load change in area-1. (Power system +RFB+AC-DC tie – line).





(b)

(c)

Fig. 12: Performance analysis of frequency deviations ΔF_1(a), ΔF_2(b) and tie-line power deviation ΔP_{tie} (c) of PI controller, T-I FLC, and DMT-II FLC for a step load change in area-2. (Power system +RFB+AC-DC tie – line).

5.4. Performance analysis of the proposed controller under parameter variation:

The performance of the proposed controller has been analyzed under parameter variation. The parameters T_g, T_t, T_r are varied by ±20% from the nominal value one at a time, and simulations are carried out. The simulation results are shown in Fig.13. From the results, it is found that the proposed dual mode Type-II fuzzy logic controller is less sensitive to parameter variation.

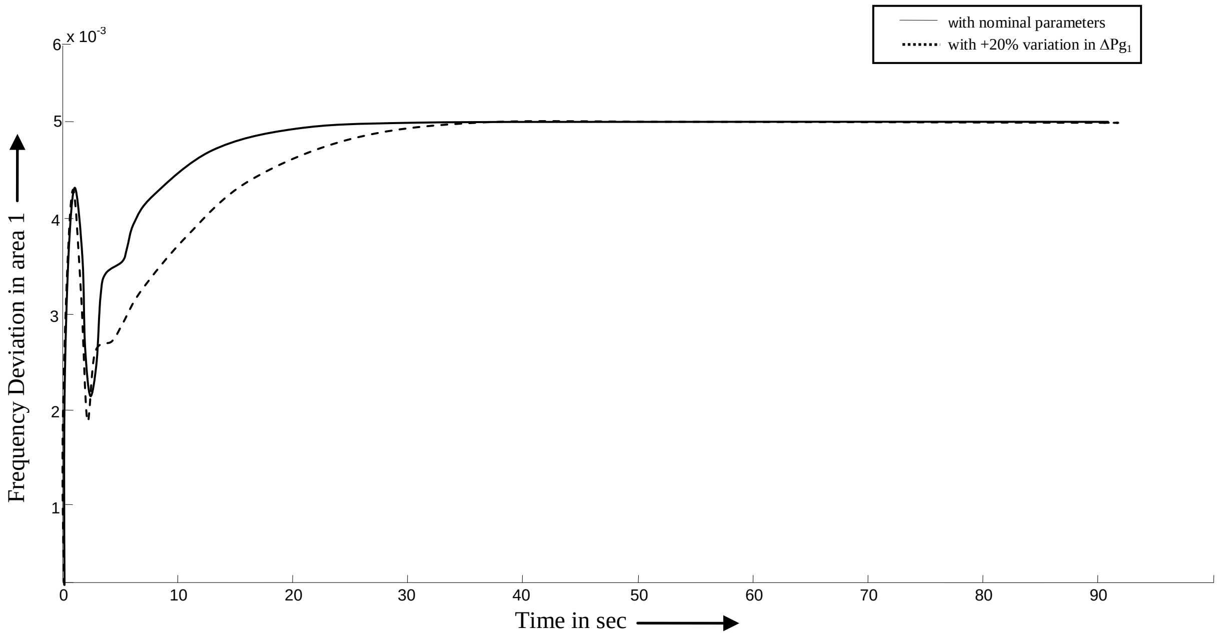
5.5. Effectiveness of the RFB unit:

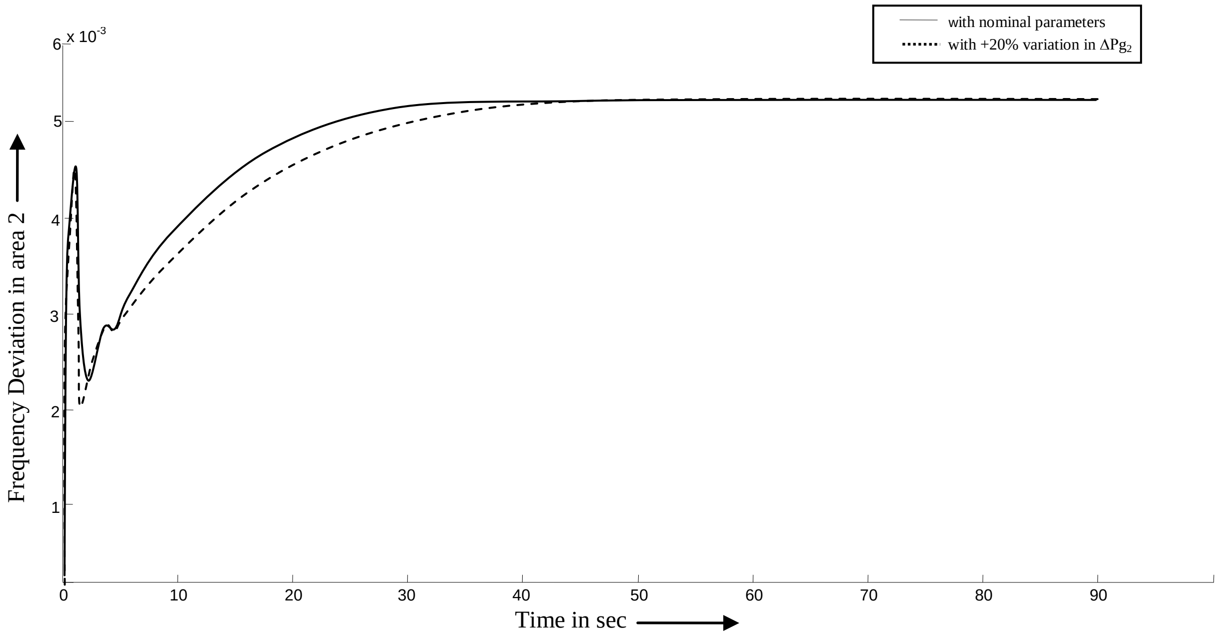
To study the effectiveness of the energy storage device, the RFB unit simulations are given in two phases.

Phase (i): Power system model + controller

Phase (ii): Power system model + RFB + controller

The performance of this controller is simulated for 0.01 p.u. MW step load change in area 1 and the corresponding frequency deviation ΔF_1 in area 1, frequency deviation ΔF_2 in area 2, and tie-line power deviation ΔP_{tie12} are superimposed in Fig.14. Similarly, the controller is simulated for 0.01 p.u. MW step load change in area 2 and the corresponding frequency deviation ΔF_1 in area 1, frequency deviation ΔF_2 in area 2 and tie-line power deviation ΔP_{tie12} are plotted in Fig.15. Figs.14 and 15 show the effectiveness of the RFB unit. System performance is better with RFB unit than without.


with nominal parameters
with +20% variation in ΔPg_1
x 10-3
6
5
4
3
2
1
0
10
20
30
40
50
60
70
80
90
Frequency Deviation in area 1
Time in sec


with nominal parameters
with +20% variation in ΔPg_2
x 10-3
6
5
4
3
2
1
0
10
20
30
40
50
60
70
80
90
Frequency Deviation in area 2
Time in sec

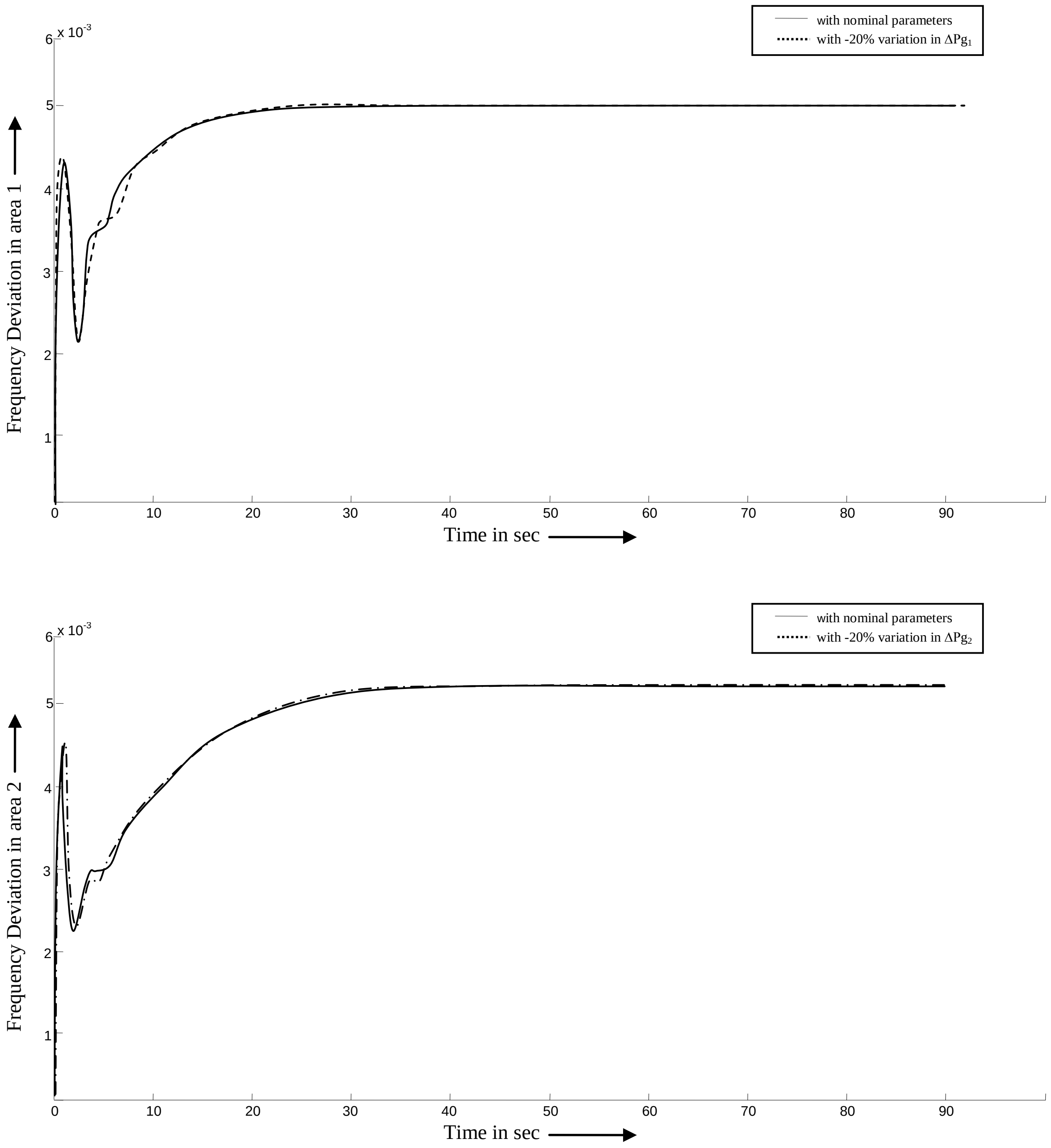


Fig. 13: Comparisons of proposed Type-II fuzzy logic controller of frequency deviations for area1 and area 2 for 0.01 p.u K.W step load change with system parameter variation.

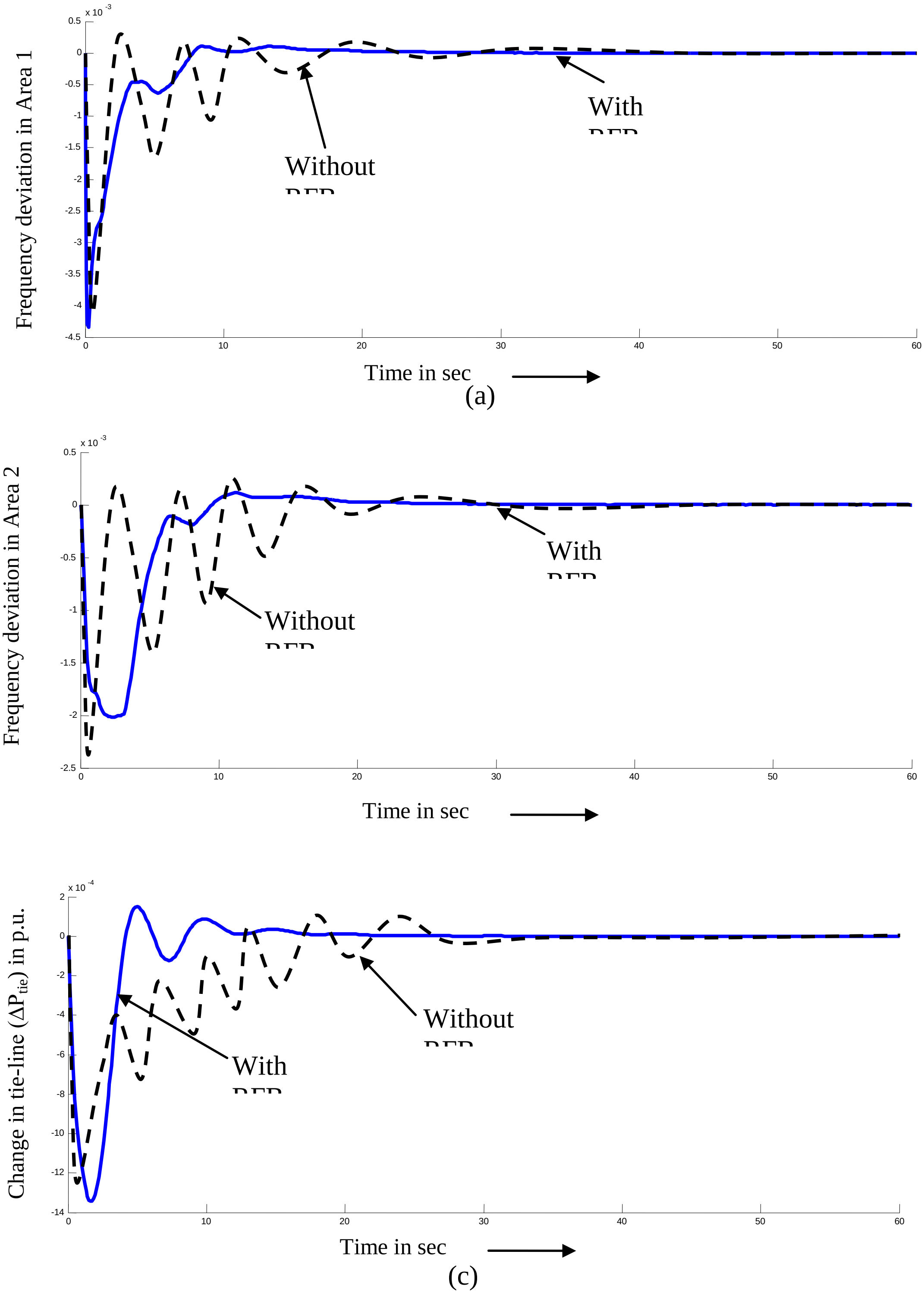
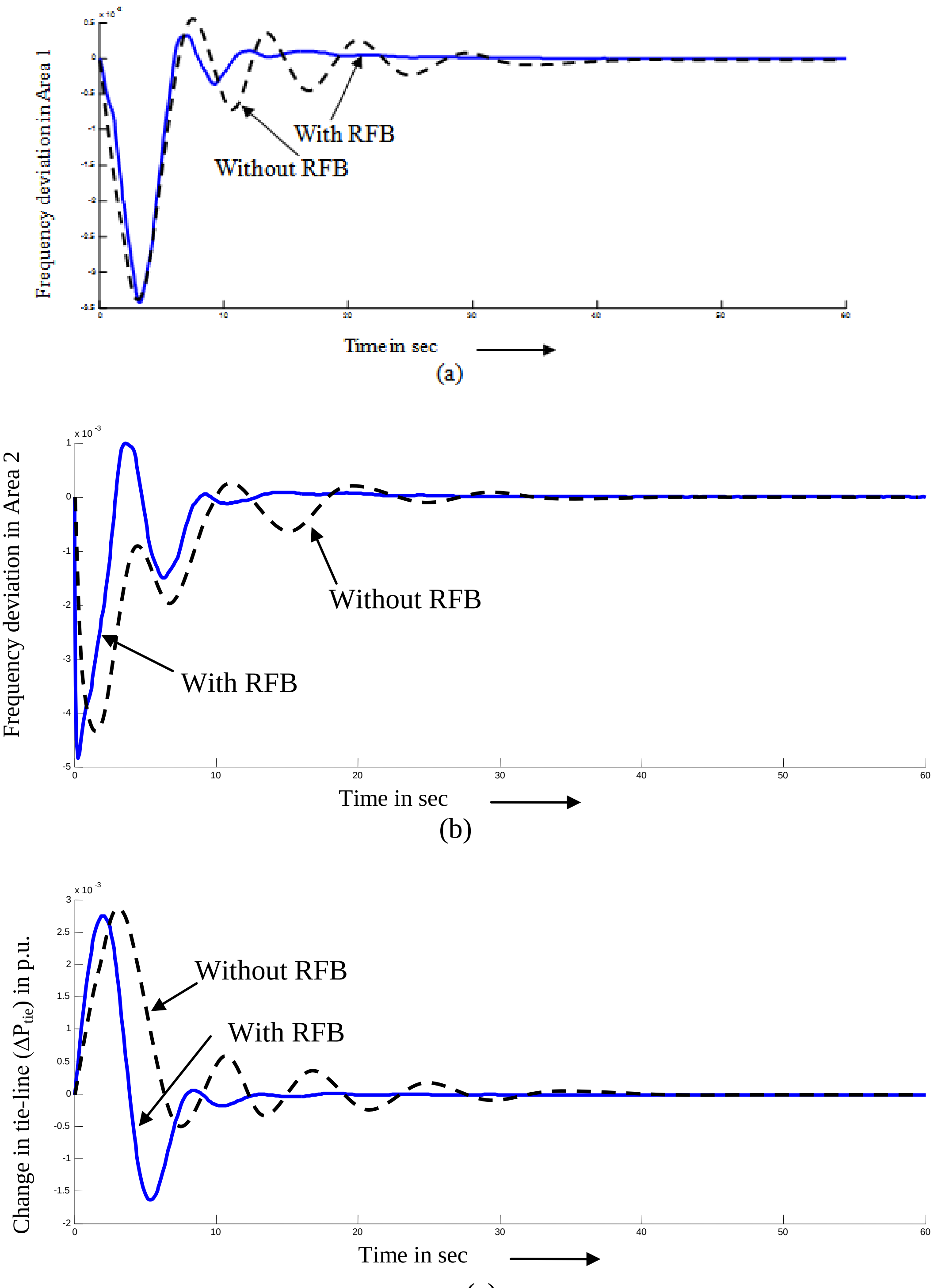


Fig. 14: The performance analysis of (a)ΔF_1, (b)ΔF_2 and (c)tie-line power deviation of ΔP_{tie} with DMT-II FLC for a step load change in area -1 for with and without RFB.



(a)

(b)

(c)

Fig. 15: Performance analysis of (a)ΔF_1, (b)ΔF_2 and (c)tie-line power deviation of ΔP_{tie} with DMT-II FLC for a step load change in area -2 for with and without RFB.

Conclusions:

This paper presents a new design based on dual mode Type-II fuzzy logic controller using BES unit is applicable to an interconnected reheat based thermal power systems. The proposed controller is designed by taking advantage of dual mode control concept and the Type-II fuzzy sets. The proposed controller has been success fully applied to interconnected thermal power systems with RFB unit. From the results, it is observed that the proposed controller performs better than the conventional PI controller and Type-I FLC. Further, it is also demonstrated that the proposed controller is less sensitive to change in the parameters of the system.

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Data for the interconnected two-area thermal power system:

$K_{r1}=K_{r2}=0.55$; $R_1=R_2=2.4$ Hz/p.u.MW; $T_{g1}=T_{g2}=0.08$s; $T_{r1}=T_{r2}=10$s; $a_{12}=-1$; $\Delta P_{d1}=0.01$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; $\beta_1=\beta_2=0.425$p.u.MW/Hz; $2\pi T_{12}=0.545$p.u.MW/Hz.

Data for Redox Flow Battery unit:

$K_{RF}=1.8$, $T_D=1$s

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