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Design of Dual Mode Type-II Fuzzy Logic Load Frequency Controller for Interconnected Power Systems

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ABSTRACT

A design of dual mode Type-II fuzzy logic load frequency controller for interconnected two area thermal power systems is proposed in this paper. Due to increase in size & demand, load frequency controller has become more significant. In general proportional and integral (PI) controllers are used for load frequency control, which is generally tuned on the basis of classical approaches. Hence it is much more needed to have controllers which are capable of self tuning in nature according to situations. Fuzzy logic controller (Type –I) is a sophisticated technique that is easy to begin and implement, nevertheless the determination of membership functions and control rules is an essential part of design. The Type-I fuzzy logic controller is further be modified in to Type - II fuzzy logic controller, by giving grading to membership functions which are themselves fuzzy which leads to provide new design degree of freedom for handling uncertainties. Dual mode concept is incorporated in the proposed controller because it can improve the system performance. The comparison of proportional plus integral controller, fuzzy logic controller(Type -I) and the dual mode Type -II fuzzy logic controller shows that, with the application of dual mode Type -II fuzzy logic controller, the system performance is improved significantly. The proposed controller is also found to be less sensitive to changes in the parameters of the system.

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List of Symbols:

$\tilde{A}$	Type-II fuzzy set
$\tilde{A}_I$	Interval Type-II fuzzy set
FOU	Foot of uncertainty
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
$\overline{\mu}_{\tilde{A}}$	Upper membership function
f_i	Area frequency in Hz
P_{ei}	Total power exchange of area i in p.u. MW/Hz
P_{Di}	Area real power load in p.u. MW
P_{ci}	Area speed changer output in p.u. MW
X_E	Governor valve position in p.u. MW
P_G	Mechanical (turbine) power output in p.u. MW
T_P	Area time constant in seconds
R	Steady state regulation of the governor in Hz/p.u. MW
T_g	Time constant of the governing mechanism in seconds
k_r	Reheat coefficient of the steam turbine
T_r	Reheat time constant of the steam turbine in seconds
T_t	Time constant of the steam turbine in seconds
β_i	Frequency bias constant in p.u. MW/Hz
N	Number of interconnected areas
Δ	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
Min	Minimum
N_	Negative
P_+	Positive
Z_o	Zero
P_{tie}	Tie line power
ISE	Integral square error
ε_i	Switching limit

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Superscript:

T	transpose of a matrix

Subscripts:

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

INTRODUCTION

The dynamic behavior of many industrial plants is heavy influenced by disturbances and in particular, by changes in the operating stage. This is typically the case for power systems (Kothari *et al.*,1989). Load-frequency control (LFC) in power systems is very important in order to supply reliable electric power with good quality. The goal of LFC is to maintain zero steady state errors in a multi-area interconnected power system (Ramar *et al.*, 1989). In summation, the power system should meet the requested dispatch conditions. With an increasing requirement for electric power the electric power system gets more and more complicated. Thus the provision of electric power with stability and high reliability is needed. For this, different control blocks are used to control them. The power system runs in normal state which is characterized by constant frequency and voltage profile with certain system reliability. For a successful performance of power system under abnormal conditions, mismatches hence to be corrected via supplementary control (Dipti Srinivas *et al.*, 1995). Automation generation control (AGC) or LFC is a really significant issue in power system operation and control of supplying sufficient and dependable electric power with better quality (Dipti Srinivas *et al.*, 1995, Talaq *et al.*, 1999). 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. In each control area, all generators are assumed to form a coherent group. A power system has a dynamic characteristic meaning that it can be affected by disruptions and modifications at the operating point. The frequency of a system depends on active power balance. As frequency is a common factor throughout the system, a change in active power demand at one point is reflected throughout the system (Gang Feng, 2006). Load frequency control, a technical requirement for the proper functioning of an interconnected power system, is very important for supplying reliable electric power with better quality. The ends of the LFC are to maintain zero steady state errors in a multi -area interconnected power system and to carry out the requested dispatch conditions.

A number of control strategies have been used in the design of load frequency controllers in order to achieve better dynamic performance. Among the various types of load frequency controllers, the most widely employed is the conventional proportional integral (PI) controller (Hamed shabani *et al.*, 2013). Conventional controller can be simple for implementation only takes more time for control and moves over large frequency difference.

In recent year’s Type-I fuzzy logic controller have received increasing attention in power system engineering (Chaturvedi *et al.*, 1999). 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 (Shashi kant pandey *et al.*, 2013). The fuzzy logic system provided as an excellent framework to more completely and effectively model uncertainty and imprecision in human reasoning with the role of a linguistic variable with membership functions. Fuzzification offers superior expressive power, greater generality, and in improved capability to model complex problems at a low solution cost. The basic structure of a Type-I fuzzy inference system consists of three conceptual components: a “rule base”, which contains a selection of fuzzy rules; a “data base”, which defines the membership functions used in the fuzzy rules; and a “reasoning mechanism”, which performs the inference procedure upon the rules and given facts to derive a reasonable output or conclusion (Zadeh, 1988. Zadeh, 1989). In general, Type-I fuzzy inference system implements a nonlinear mapping from its input space to the output space. This mapping is accomplished by a number of fuzzy If - Then rules, each of which describes the local behaviour of the mapping. In particular, the antecedent of a rule defines a fuzzy region in the input space, while the consequent specifies the output in the fuzzy region. Fuzzy logic systems are made up of rules (Zadeh, 1989). Quite often, the knowledge that is used to build these rules is uncertain. Such uncertainty leads to rules whose antecedents or consequents are uncertain, which translates into uncertain antecedent (or) consequent membership functions. Hence the Type-I fuzzy sets, are unable to directly handle such uncertainties. This conflict may be resolved by introducing a new concept of a Type-II fuzzy set. It is introduced by Zadeh as an extension of the concept of an ordinary fuzzy set (Type-I fuzzy set) and investigated further by many researchers (Patricia melin *et al.*, 2013). 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 of 0 to 1, unlike a Type-I set 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, e.g., an uncertainty in the shape of the membership functions or in some of its parameters (Mendel *et al.*, 1999).

This paper proposes by taking advantage of the superior characteristics inherent in the Type-II fuzzy sets, a new design of the dual mode Type-II fuzzy logic load frequency controller for interconnected power systems. An important design concept of dual mode control is to improve the system operation and makes it flexible for application to actual systems (Thameem ansari *et al.*, 2010). 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

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 *et al.*, 2007)

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

$\upsilon = Cx$

$y = Hx$

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

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

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

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

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

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

where, A is the system matrix ,B is the input distribution matrix, Γ i s 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, *d* is 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, $\overline{y} = \left[\overline{y}_1^T \ldots \overline{y}_N^T\right]^T$

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

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

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

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

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

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

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

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

Design of Proposed Dual Mode Type-II Fuzzy Logic Controller:

A. Designing of the dual mode controller:

The steady state zeroes error be achieved by simply implementing the well designed proportional and integral controller, but the reaction of the system becomes slow resulting from high over/ under shoot and making up time. The proportional controller by itself will improve overshoot and the speed of the response. Obviously, the comportment of the proportional controller is compelling at transient state to make system response faster so as to reduce the overshoot. Simply incorporating the proportional controller alone fails to bring the steady state error to zero. So the usage of both the integral and proportional controller simultaneously seems urgent. The proportional plus integral control does not get rid of the difference between the static and dynamic accuracy. This dispute may be broken up by using the principle of Dual Mode control (Velusami *et al.*, 2006).

Since the Principle of dual mode control can improve the system performance a new design of dual mode Type-II fuzzy logic control is proposed in this section. This proposed controller operates in mode ‘A’ as long as the significant observed variables to the control actions and the system output error are sufficiently large i.e. greater than the switching limit of the controller otherwise it operators in mode ‘B’. Mode ‘A’ acts as proportional type Type-II fuzzy logic control and mode ‘B’ as integral type Type-II fuzzy logic control. Block diagram of dual mode Type-II fuzzy logic control is shown in Fig.1. Thus, the control structure of the system is changed when switching in each mode of operation (Thameem ansari *et al.*, 2010). Since the proposed controller is designed in this a way based on the switching limit of the controller, the performance of the controller gets improved significantly. Type-II fuzzy logic control is an advanced technique of Type-I fuzzy logic control.

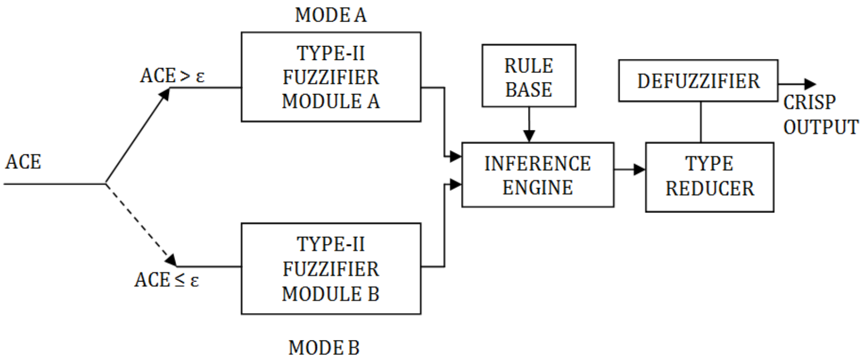


Fig. 1: Block diagram of dual mode Type-II fuzzy logic controller.

B. Design of Type-II Fuzzy Logic Controller:

A fuzzy system that uses Type-2 fuzzy sets and/or fuzzy logic and inference is called a Type-II fuzzy system. In general, a fuzzy system that contains ordinary fuzzy sets, logic, and inference is called Type-I fuzzy system. A Type-I fuzzy logic system has a grade of membership function that is crisp value, whereas a Type - II fuzzy logic systems has a grade of membership function that is fuzzy value (Oscar Castillo *et al*., 2014), so Type-II fuzzy logic systems are 'fuzzy-fuzzy' logic systems.

For a Type-I membership function, as shown in Fig.2 (a) we blur it to the left and to the right, and then a Type-II membership function is obtained as illustrated in Fig.2 (b).By shifting the points on the triangle either to the left hand side or to the right hand side and not necessarily by the same amounts, indicates the blurred Type-I MF as in Fig-2(b). At a specific value of x, X', the membership function does not possess a single value, but the membership function consider the values wherever the vertical line intersects the blur (Karnik *et al*., 1998. Mendel *et al*., 2002).

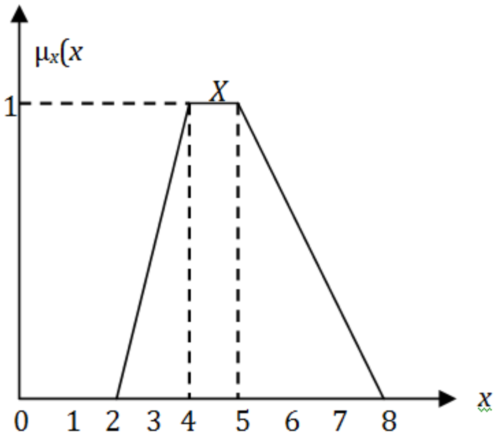


Fig. 2: (a) Type-1 membership function.

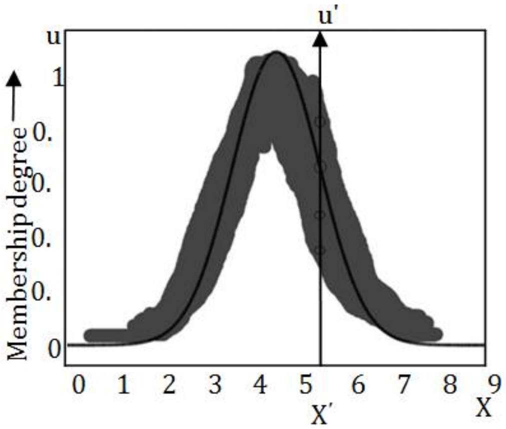


Fig. 2: (b) Interval Type-2 membership function.

These achieved values no need to have the same weights. That's why amplitude distribution is given to these achieved values. Keeping this in mind we develop 3 dimensional (3D) membership function is created which is nothing but Type-II membership function. Hence, a Type-2 fuzzy set can be defined as follows,

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

in which $0 \leq \mu_{\tilde{A}}(x,u) \leq 1$. J_x represents the primary membership function of x, and $\mu_{\tilde{A}}$ (x,u) is a Type-I fuzzy set known as the secondary set. 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. Finally fuzzy set consists of primary and secondary degree of membership.

Footprint of Uncertainty (FOU):

A set of all possible primary MFs embedded in a Type-II fuzzy set, is called as Footprint of Uncertainty (FOU) shown inFig-3. FOU gives an easy way to analyze the entire support of the secondary grades. The uniform shading for the FOU represents the entire interval Type-II fuzzy set and it can be described in terms of an upper membership function $\bar{\mu}_{\tilde{A}}(x)$ and a lower membership function $\underline{\mu}_{\tilde{A}}(x)$ .And also it provides to choose prompt MFs (Oscar Castillo *et al*., 2008, Sudha *et al*., 2012).

From the figure 3 it is clear to understood the concepts of upper and lower MFs which are represented as two Type-I MFs that are bounds for the FOU of a Type-II fuzzy set operation of Type-II fuzzy set is identical with an operation of Type-I fuzzy set, however on interval fuzzy system; fuzzy operator is done as two Type-I membership functions which limit the FOU (F), upper membership function (UMF) and lower membership function (LMF) to produce firing strength (Sudha and Vijaya santhi 2011) as shown in Fig.3.

The defuzzification is a mapping process from fuzzy logic control action to a non-fuzzy (crisp) control action. The defuzzification on an interval Type-II fuzzy logic system using centroid method is shown in Fig.4.

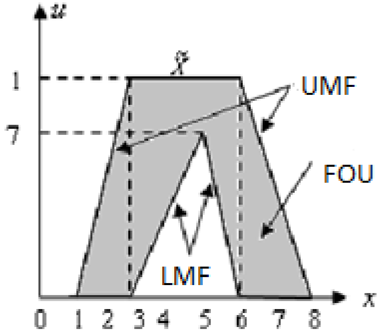


Fig. 3: Membership function interval Type-2 fuzzy logic set.

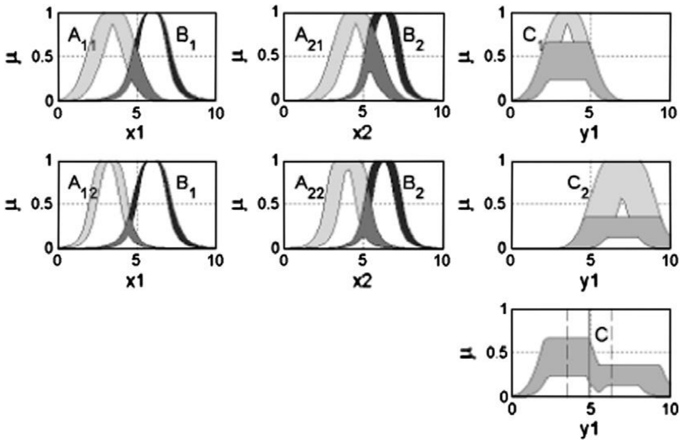


Fig. 4: Interval Type-II fuzzy reasoning.

Working principle of Type-II fuzzy set is similar to Type-I fuzzy set (Sudha and Vijaya santhi 2011). Unlike Type-I fuzzy logic system, the Type-II fuzzy logic system also have fuzzifier, rule base, inference engine, defuzzifier and type reducer. The structure of interval Type2 Fuzzy Logic System (T2FLS) is shown in Fig - 5.

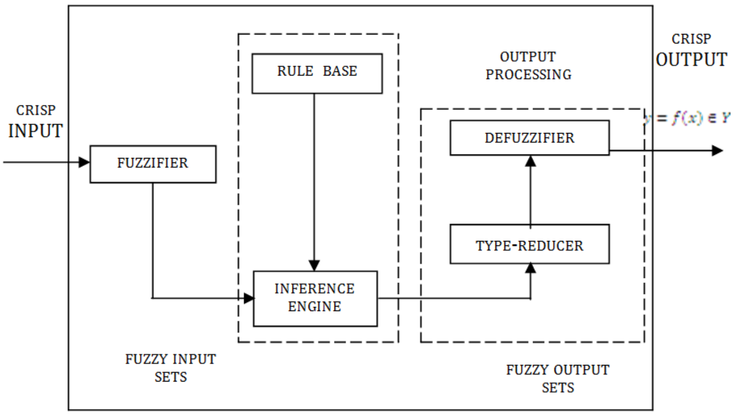


Fig. 5: Structure of Type-II fuzzy logic.

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.

Design of conventional PI controller and fuzzy logic Controller with output feedback:

The conventional PI Controller with output feedback are designed using integral square error (ISE) technique and the feedback gains are K_P=6.5 and K_I=0.31. The conventional fuzzy logic controller is also designed using the method given in (Ertugrul cam *et al.*, 2005). The system output is sampled at the normal sampling rate of two seconds and the controller output is also updated at normal sampling rate (Thameem ansari and Velusami 2010).

Simulation results and discussions:

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 (ε_1=0.003, ε_2 =0.003). The input variable of the proposed controller are ACE (error e) and ΔACE (change of error Δce). The membership function of the interval Type-2 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.

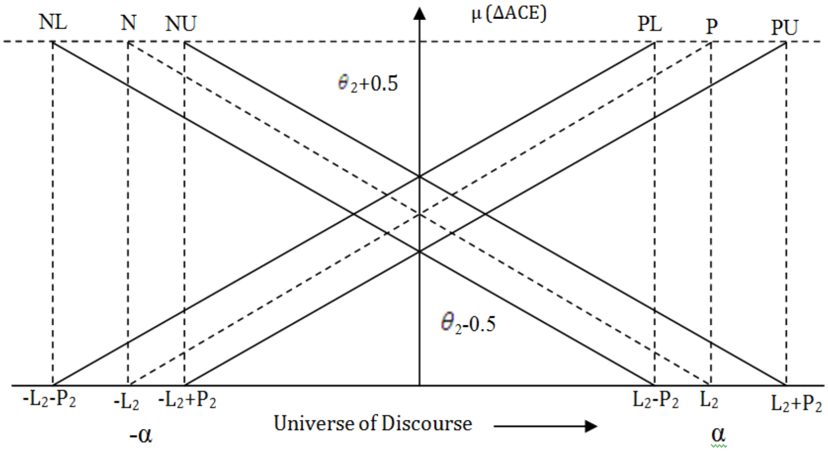


Fig. 6: Membership function of the interval type II fuzzy sets.

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 membership function for Type-II fuzzy set is shown in Fig.7.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.

The dual mode Type-II fuzzy logic controller 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 are shown in Fig.8. The performance of this controller is simulated for 0.01 p.u. Mw step load change in area one 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.9. 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 Fig.9. 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.10. From the result, it is observed that the proposed dual mode Type-II fuzzy logic controller has less overshoot and settling time. For easy comparison overshoot/undershoot and settling time is given in Table-2.

Table 1: Rule Base.

Δce e	NU	N	NL	Z	PL	P	PU
NU	PU	PU	PU	PU	P	P	PL
N	PU	P	P	P	PL	PL	PL
NL	P	P	PL	PL	PL	PL	Z

Z	NL	NL	NL	Z	PL	PL	PL
PL	Z	NL	NL	NL	NL	N	N
P	NL	NL	N	N	N	NU	NU
PU	NL	N	NU	NU	NU	NU	NU

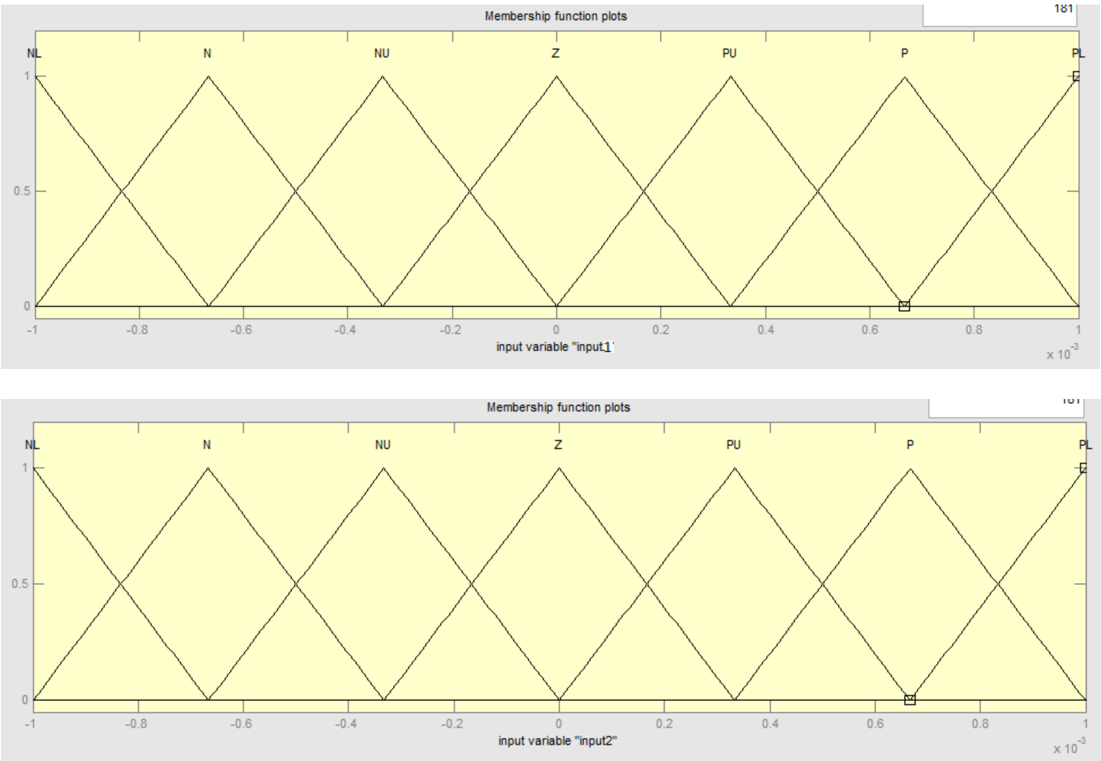


Fig. 7: Membership function for Type-2 fuzzy set.

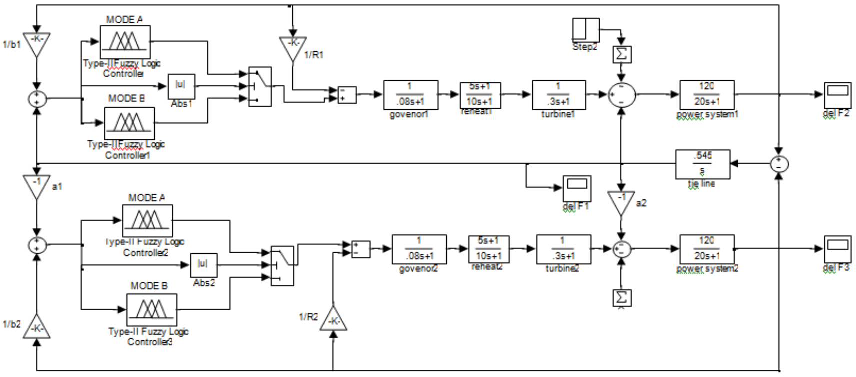


Fig. 8: The simulink block diagram of the proposed dual mode Type-II fuzzy logic controller.

Table 2:

Controller (Area – 1)	Overshoot/Undershoot Δf1	 Δf2	 Δptie	Settling Time Δf1	 Δf2	 Δptie
Conventional PI	+0.024 -0.017	+0.027 -0.023	+000 -0.0012	45.96	53.25	50.14
Type-I Fuzzy Logic Controller	+0.018 -0.03	+0.005 -0.032	+0.001 -0.002	15.30	20.00	24.25
Type-II Fuzzy Logic Controller	+0.003 -0.025	+0.001 -0.005	+0.000 -0.0005	7.25	12.20	12.30
(Area- 2)						
Conventional PI	+0.027 -0.029	+0.019 -0.025	+000 -0.0012	50.96	50.25	50.14
Type-I Fuzzy Logic Controller	+0.018 -0.09	+0.007 -0.032	+0.0019 -0.006	17.30	22.00	20.25
Type-II Fuzzy Logic Controller	+0.002 -0.029	+0.001 -0.007	+0.001 -0.0005	6.25	10.20	10.30

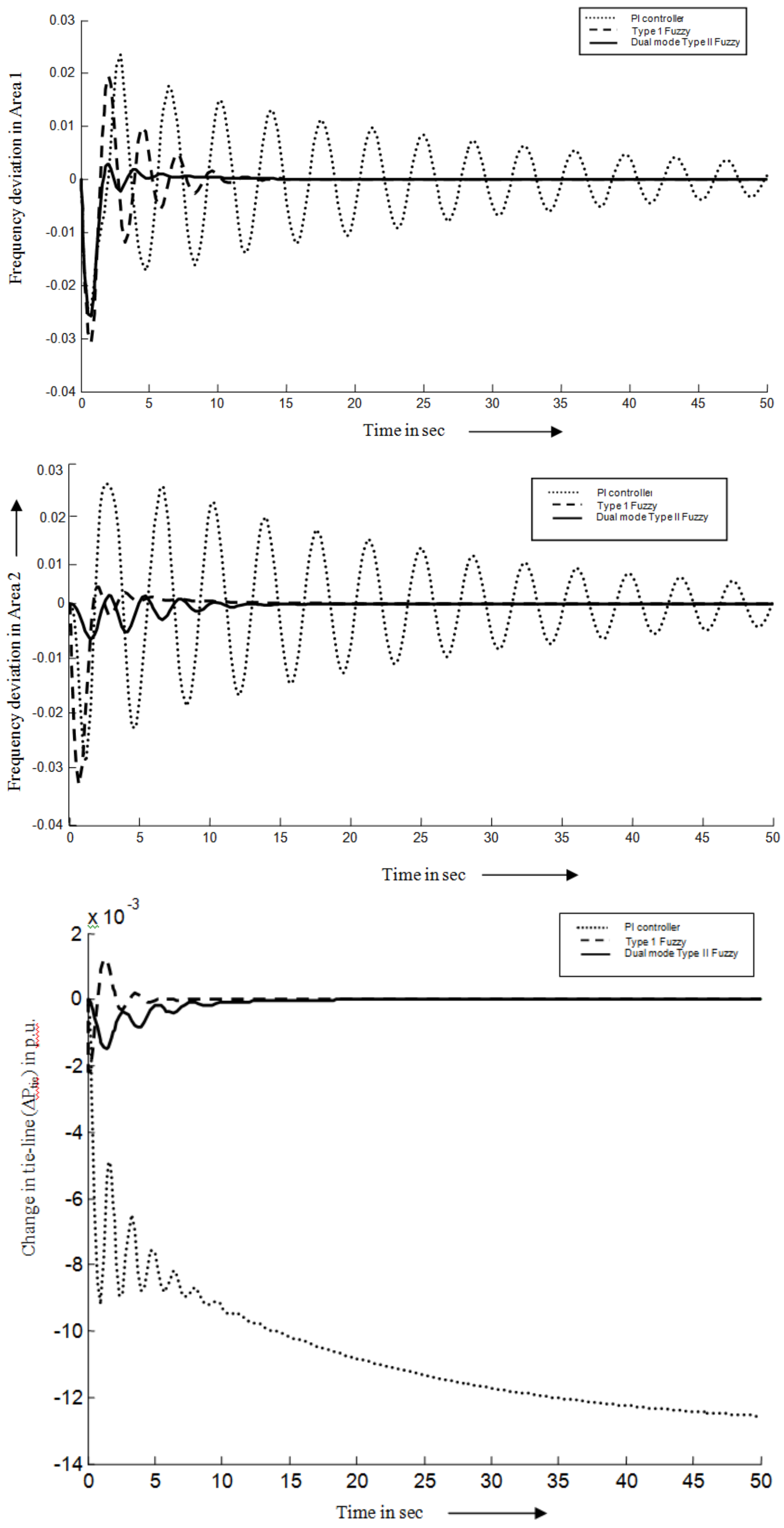


Fig. 9: The performance of controller is simulated for 0.01 p.u. Mw step load change in area 1 and the corresponding frequency deviation Δf_1 , Δf_2 and P_{tie} for PI controller, Type-I fuzzy logic controller and dual mode Type-II fuzzy logic controller.

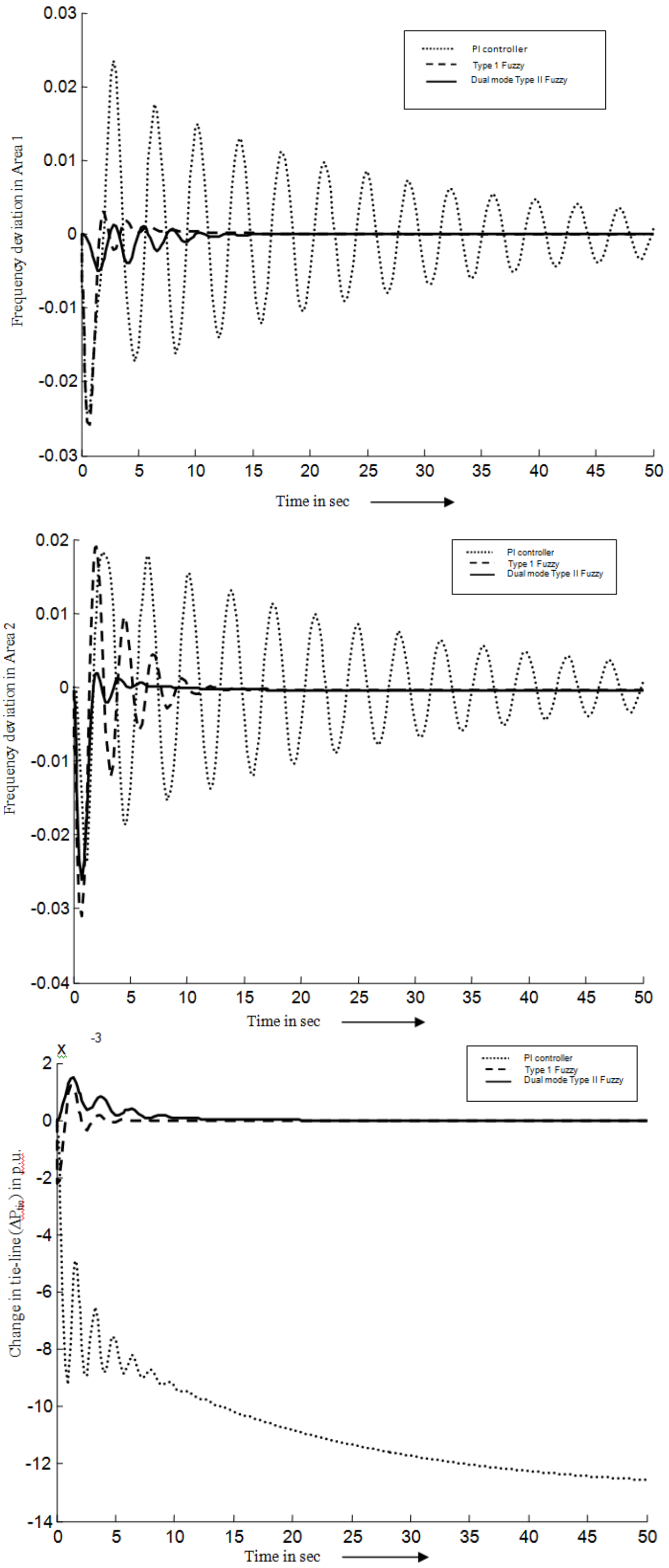
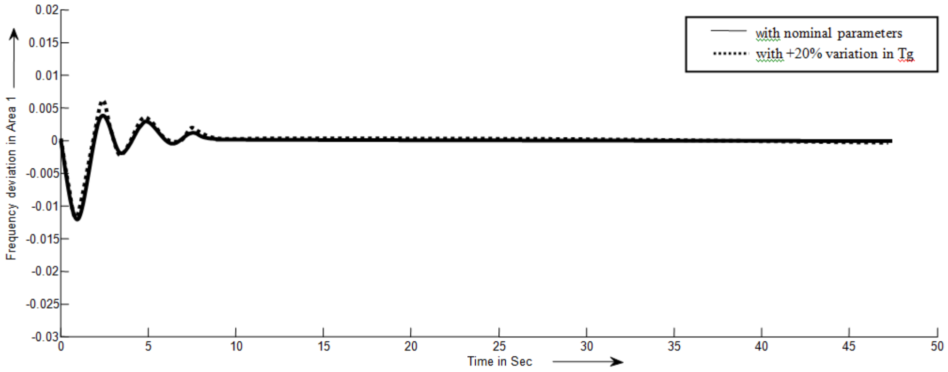
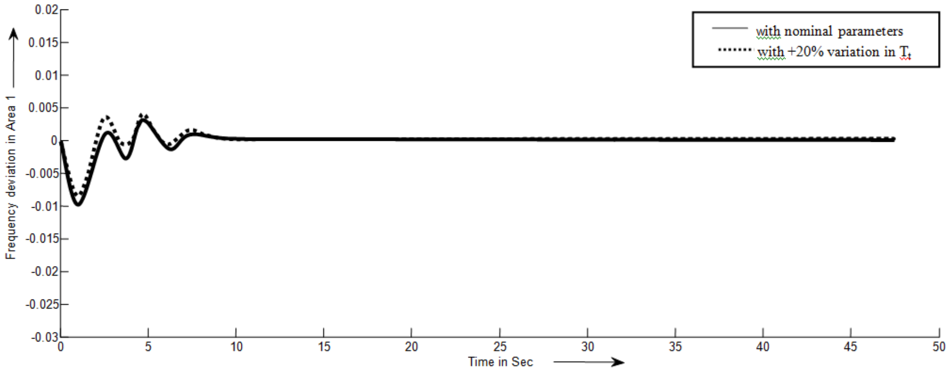


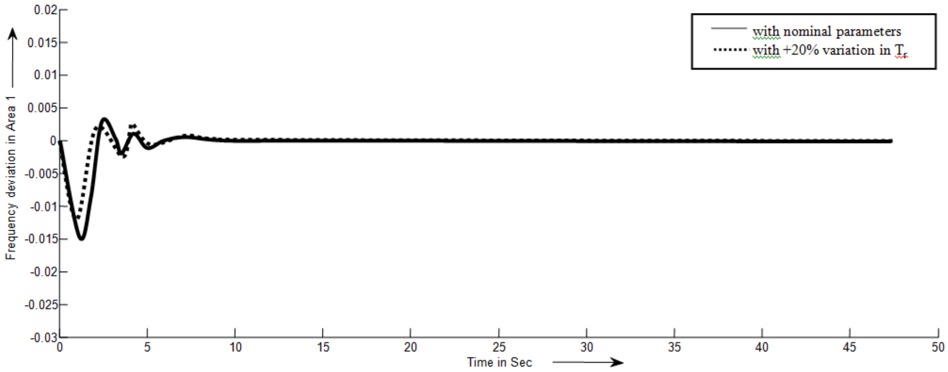
Fig. 10: The performance of controller is simulated for 0.01 p.u. Mw step load change in area 2 and the corresponding frequency deviation Δf_1 , Δf_2 and P_{tie} for PI controller, Type-I fuzzy logic controller and dual mode Type-II fuzzy logic controller.

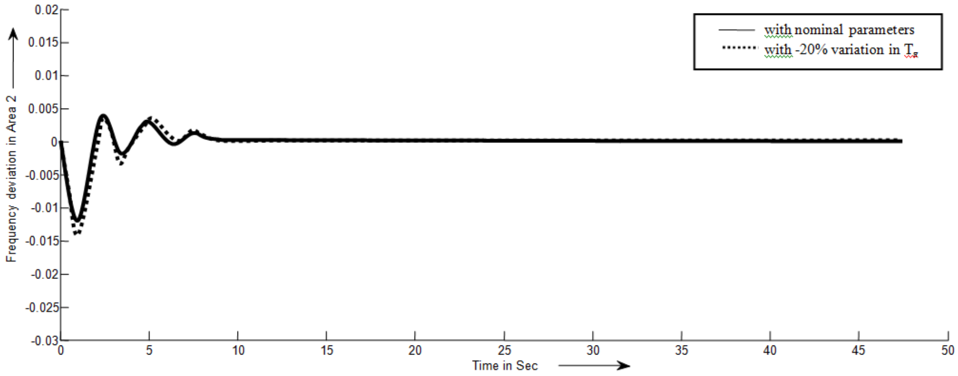
5.4. Performance analysis of the proposed controller under parameter variation:

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.11. From the results, it is found that the proposed dual mode Type-II fuzzy logic controller is less sensitive to parameter variation.









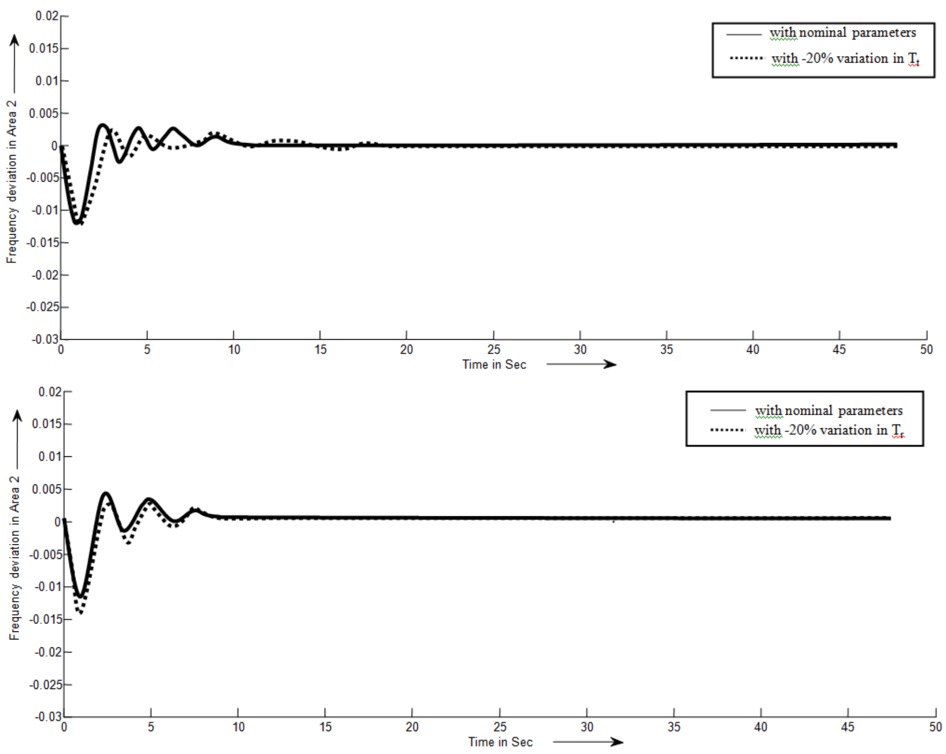


Fig.11: Comparisons of proposed type-II fuzzy logic controller of frequency deviations for area 1 and area 2 for 0.01 p.u K.W step load change with system parameter variation.

Conclusions:

This paper presents a new design based on dual mode Type-II fuzzy logic controller 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. Simulation study results of an inter connected power systems reveal that the proposed controller design provides a high quality transient and steady state response. Further, it is also observed that the proposed controller is less sensitive to changes in the parameters of the system. Thus, the overall performance of the proposed controller is found to be superior to that of the conventional PI and Type-I fuzzy logic controllers.

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Data for the interconnected two-area thermal reheat power system:

$K_{r1}=K_{r2}=0.5$; $R_1=R_2=3.2$ Hz/p.u.Hz; $T_{g1}=T_{g2}=0.08$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; $K_{ps1}=K_{ps2}=120$Hz/p.u.MW; $T_{ps1}=T_{ps2}=20$sec; $\beta_1=\beta_2=0.425$p.u.MW/Hz; $2\pi T_{12}=0.545$p.u.MW/Hz.

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