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Research paper

Design of Robust Decentralized Deregulated Fuzzy LFC-DR Model for an Interconnected Power System

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Abstract

From the past few years Demand Response (DR) is playing a prominent role in Load Frequency Control (LFC) This leads to focus on LFC-DR model. For aggregating the small scale controllable loads Demand Response Load Frequency Control(LFC-DR) is widely used for distant measurements and control. Communication delay latency also plays a vital role in LFC-DR model. This paper investigates the control design for the Deregulated LFC-DR model. Communication delay latencies are linearized using rational approximations. Here Padé approximation with equal degree is employed. A robust Fuzzified Proportional Integral Derivative (Fuzzy-PID) controller is designed to deal with the latencies and load perturbations with DR loop. Case studies based on the two-area deregulated LFC-DR model is demonstrated. The efficacy of the proposed controller is observed by comparing with conventional controller under Deregulated LFC(DLFC) and Deregulated LFC-DR with different control.

Keywords: *Demand Response, Fuzzy logic controller, Deregulated Environment., Load frequency control, Latency, Padé Approximation,*

1. Introduction

The frequency of each control region is maintained by way of load frequency Control(LFC), it also regulates the tie-line strength flows among adjacent control areas [1-4]. In a deregulated environment, the power system includes generation companies (gencos), transmission corporations (transcos), and distribution agencies (discos) and is operated in an open-investigate policy [5, 6]. The cause of deregulation of power industry is to restructure the electric enterprise in order that strength production and distribution are competitive, however the shipping remains regulated, monopoly franchise business [7, 8]. For that reason, the independent operator desires to expand a more dependable LFC provider. Then again, the increasing penetration of intermittent renewable electricity assets will increase the complexity of the LFC within the deregulated surroundings [9].

Historically, the Gencos are designed to offer enough backup generation capability to fulfill the height load, which makes substantial backup capacity be idle for maximum hours inside a year. Instead of supplying enough capacity, Demand Response(DR) controls the burden to stability the demand and the deliver and becomes a promising grid technology, particularly for accommodating intermittent renewable generations [10]. With this limitation, less efficiency, very high cost of storage devices, a real time smart responsive participation of load known as Demand Response (DR) came to existence which have been actively considered for balancing of power. This is achieved by dynamic consumer participation in real time ,thus maintaining balance between generation via two way communication[11].Therefore Demand response is defined as: "changes in electric usage by demand-side resources from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized" by Federal Energy Regulatory Commission (FERC)[12] . Now days, extra interest is given to the frequency control in the Demand Response In view of metering technology, electric home equipment can growth or decrease the energy usage in response to the frequency deviation, to guide the frequency control [13, 16].

The electrical appliances which take part in DR are commonly non-important Loads (i.e. Fridges, freezers and water warmers), that can hoard thermal electricity (warmness or bloodless), like batteries. Consequently, quickly growing or lowering their electricity consumption could no longer cause lots inconvenience to residents. Specializing in frequency manipulate strategies with the aid of the usage of DR, kind of control strategies.

Dynamic Demand Response (DDR) is one promising DR generation that can offer the subsequent advantages in frequency manage markets, providing a further control [17] and decreasing the spinning capability. In [18], it introduces demand response control loop in the traditional single-area LFC scheme. This LFC with DR model has the feature of optimal operation through optimal power between the supply side and the demand side. DDR seeks to reduce the peak needs throughout period whilst the frequency balance is beneath chance or strength marketplace fees are excessive. Market overall performance advantages consult with demand responses cost in mitigating provider’s ability to exercise market energy with the aid of raising energy costs considerably above the production expenses. Then market-wide financial advantages are the decrease wholesale market costs due to the fact call for reaction averts the want to use the maximum costly-to-run power plant life during intervals of otherwise excessive call for, driving manufacturing costs and charges down for all wholesale electricity purchasers [19,20,21]. These savings can be handed onto most retail customers as bill financial savings. In order to get very strong and successive convergent results it is necessary to linearize systems with time delays in control engineering. Among many rational approximations, Padé approximation is widely used [22,23,24,25]. For the dead time approximations and delays one of the method is "Rational Function Method". Using the polynomials quotients time delays are accurate. The widely recommended approximation used in theory of classical control system is same order of numerator and denominator. The main objective of this paper is to investigate Demand Response (DR) load frequency control to multi area system where the power system dynamics include the demand response control loop to the traditional LFC model in a Deregulated environment. It mainly focuses on the communication delay latency effects on the Multi area LFC-DR model(DLFC-DR). The latencies are linearized by the rational approximation of time delay. Here padè approximation is used for the latency linearization's and frequency control for the multi area LFC-DR is modeled using the conventional and intelligent controllers. Intelligent controllers play a vital role in many of the power system problems [26,27]. Robustness in the control of frequency is achieved [28, 29]by Fuzzy logic controller for the various latencies and operating conditions.

2. Modeling of LFC-DR Model in Deregulated Environment.

An Deregulation is the gathering of restructured policies and financial incentives that governments installation to govern and force the electric energy enterprise. As part of deregulation, the power utilities have been deregulated as separate entities consisting of generation corporations (GENCOs), transmission companies (TRANSCOs), and distribution agencies (DISCOs). Underneath this restructuring scheme, a crucial disassociated authority, referred to as the independent system operator (ISO), is given manage over spot market members. In a real-time power marketplace, maximum of the ancillary offerings of a vertically included utility (VIU) will have an exceptional function to play in some deregulated surroundings. Automatic generation control (AGC) is this type of ancillary offerings that offers an important position for making sure reliable operation by way of adjusting generation to decrease frequency deviations and alter tie-line flows. To investigate the demand response stratagem, here a Two Area power system is considered. The system is supplied by two Thermal Areas with non-reheat steam Generators. To this Demand Response control loop is added in a deregulated environment, thus a Multi area Deregulated Demand Response Load Frequency control. Each area is equipped with the three loops the primary, supplementary and DR control loop as shown in Fig 1. To enhance the stability in Power system operation and control DR control loop is implemented in each area with Communication Delay Latencies. If there occur any disturbances DR will be activated, thus to cause a change in PDR to the total demand enhancing and supporting the frequency control. Generally, thus including the Demand Response control (DR) loop to the traditional Power System dynamics shown in equation (1)

$$\Delta P_T(s) - \Delta P_L(s) + \Delta P_{DR} = 2H.s.\Delta f(s) + D.\Delta f(s) \tag{1}$$

As from many researchers it is well known that the spinning reserve in Magnitude and Power flow direction are performed by DR. Depending upon the change in frequency deviation i.e., negative (positive), turning ON/OFF responsive loads from the ancillary services (i.e., DR) is required where there is communication delay latency (e^{-sT_d}). The Power System balance equations for the three area Power System including the Area Control Error(ACE) are written in (2)

$$ACE_i = \Delta P_{tie,i} + B_i.\Delta f_i \tag{2}$$

The Base Powers of the areas are assumed. With respect to the design constraints the following must achieved i.e., The change in frequency following to the Load disturbance should be zero i.e., $[\Delta f_i] = 0$ and the steady state change in tie line power following the change in Load disturbance must be zero i.e., $[\Delta P_{tie,i}] = 0$.

The steady state equations of nonrenewable LFC are well articulated, e.g. [1], [2]. However, here in this study, the DR i.e Demand Response control loop is added to the Traditional LFC problem. Investigations are done earlier on the stability analysis and steady-state error with the impact of the DR control loop for a given power system. The above equations are Rewritten as Equations (3) -(6), the system's frequency deviation can be expressed as follows for Area i

$$\Delta f_i(s) = (2H_i.s + D_i)^{-1}[\Delta P_{T.i}(s) + \Delta P_{L.i}(s) + G(s).\Delta P_{DR.i}]$$

&& $$ACE(s) = \Delta P_{tie.i}(s) + \beta_i \Delta f_i(s) \tag{3}$$

Where

$$\Delta P_{Ti}(s) = H_i(s)[\Delta P_{si}(s) - \frac{1}{R_i}\Delta f_i(s)] \tag{4}$$

$$H_i(s) = \frac{1}{(1+sT_{t.i})(1+sT_{g.i})} \tag{5}$$

$$G(s) = \frac{-s^5 + \frac{30}{T_{d.i}}.s^4 - \frac{420}{T_{d.i}^2}.s^3 + \frac{3360}{T_{d.i}^3}.s^2 - \frac{15120}{T_{d.i}^4}.s + \frac{30240}{T_{d.i}^5}}{s^5 + \frac{30}{T_{d.i}}.s^4 + \frac{420}{T_{d.i}^2}.s^3 + \frac{3360}{T_{d.i}^3}.s^2 + \frac{15120}{T_{d.i}^4}.s + \frac{30240}{T_{d.i}^5}} \tag{6}$$

From the beginning of the distinct characteristics of GENCOs, TRANSCOs, DISCOs, and the ISO, many of the ancillary offerings of a vertically included utility should be modeled differently and, consequently could have a specific function to play, amongst those AGC which have ancillary offerings. Within the new situation, in my view with a GENCO for power, a DISCO can payment, and these dealings are executed beneath the supervision of the ISO; i.e., TRANSCOs, are handy to any GENCO or DISCO for wheeling of power. Once more, a manage area is described with the aid of physical obstacles as before, however in this case, a disco has the liberty to settlement with any GENCO, in its own region or in any other case, for a transaction of strength with a GENCO in another place. This is referred to as a "bilateral transaction." all transactions must be cleared by way of the ISO.

There can be numerous mixtures of combinations among DISCOs and GENCOs, which can be represented by using a DPM. The rows of a "DPM" correspond to GENCOs and columns to DISCOs that settlement power. Every access on this matrix is a Fraction of a complete load reduced in size by way of a DISCO (column) toward a GENCO(row). The sum of all the entries in a column on this matrix is unity; the structure of "DPM" for a two-area deregulated LFC-DR model is given by [30]

$$dpm = \begin{bmatrix} cpf_{11} & cpf_{12} & cpf_{13} & cpf_{14} \\ cpf_{21} & cpf_{22} & cpf_{23} & cpf_{24} \\ cpf_{31} & Cpf_{32} & Cpf_{33} & Cpf_{34} \\ cpf_{41} & cpf_{42} & cpf_{43} & cpf_{44} \end{bmatrix} \tag{7}$$

where cpf_{id} is the contract participation factor of the j^{th} GENCO in the load following the d^{th} DISCO.

In general, $\sum_i cpf_{ij} = 1.0$. The block diagonals of the DPM correspond to neighborhood needs.

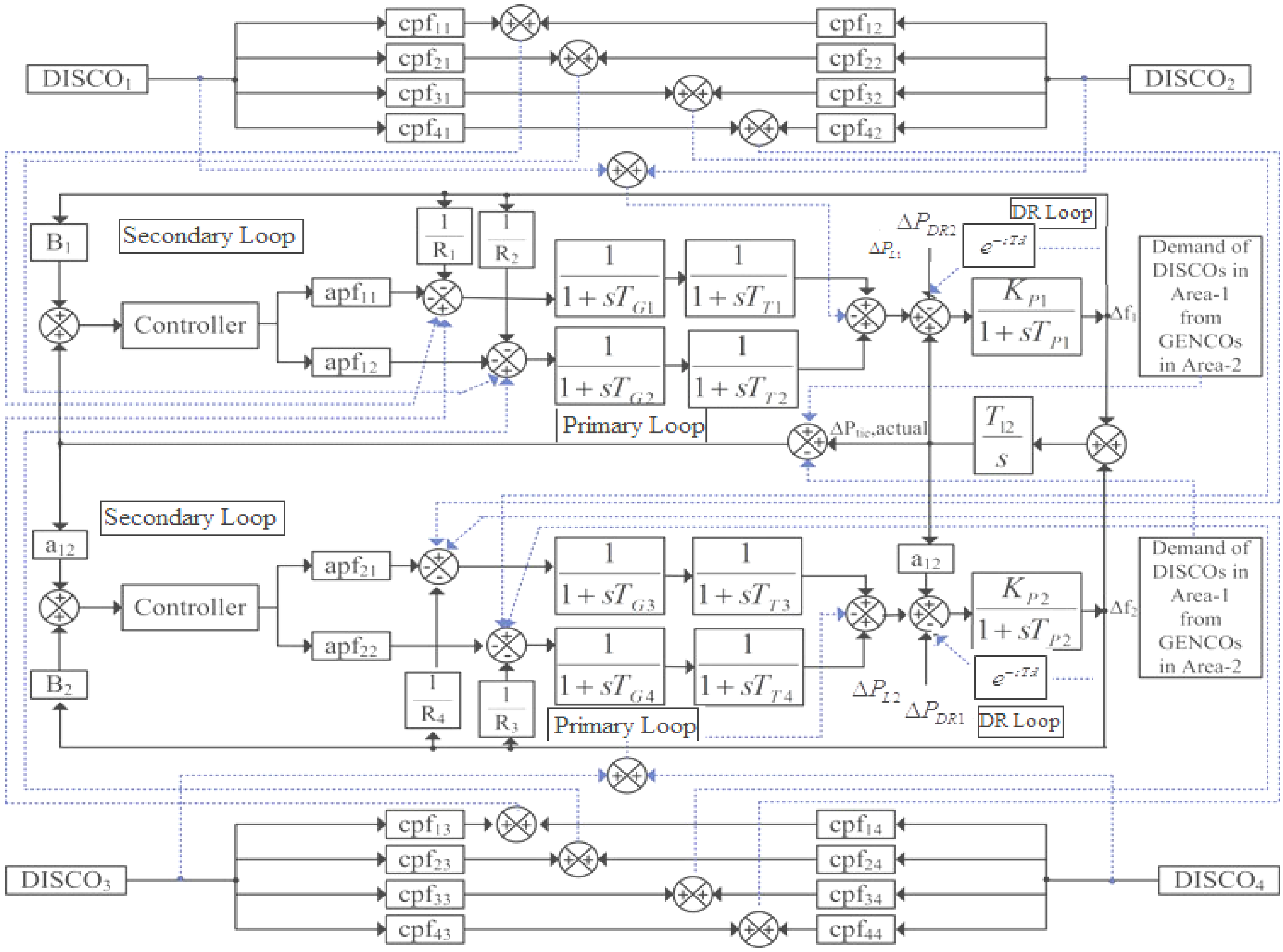

Fig.1:. Block diagram of an Two area deregulated LFC-DR model

Off-diagonal blocks correspond to the needs of the DISCOs in one place to the GENCOs in any other vicinity. As any entry in a “DPM” corresponds to a reduced in size load via a disco, it's miles to be demanded from the corresponding GENCO involved in the settlement and is to be pondered inside the manage loop.

Every time a load demanded by a DISCO adjustment, it's far pondered as a neighborhood load in the areas to which this DISCO belongs. This corresponds to nearby loads ΔP_{L1}, ΔP_{L2}, and change in DR loops ΔP_{DR1} ΔP_{DR2} which are to be contemplated within the deregulated AGC block diagram at the factor of input. As there are many GENCOs in each area, the ace sign needs to be dispensed among them in percentage to their participation inside the AGC. Coefficients that distribute the ACE to various GENCOs are called “ACE participation factors” $(apfs)$ and $\sum_{j=1}^{m} apf_j = 1$ where m is the number of GENCOs. Different to that of Traditional LFC-DR model, the DISCO, GENCO demands should reflect in the dynamics of the system subsequently the governor and turbine units have respond to the power demand.

The Two-area power system model with $P_{DR.i}$ as shown in Fig.1. In the DR control area as shown in Fig.1 is the communication delay latency which is primary obstacle which is given by e^{-sT_d} .This one of the factor which could affect the dynamic performance of the system. The rationalization of the delay latency is discussed in next section where the eq. (6) is achieved.

3. Rational Approximation of Time Delay and Control Technique

3.1. Padé approximation

To get very sturdy and successive convergent effects it is necessary to linearize systems with time delays on top of things engineering. Among many rational approximations, padé approximation is widely used [22-25]. This uses the strategies to approximate a dead-time with the aid of a rational function. It basically correct time delays with the aid of a quotient of polynomials. Traditional manipulate machine theory affords the primary relation, for an approximation with same numerator and denominator degree are most largely mentioned.

The time delay functions from the Padé approximation is given by

$$e^{-sT_d} \approx R_{mn}(-s.T_d) \tag{8}$$

It is as follows:

$$R_{mn}(-s.T_d) = S_m(e^{-sT_d}) / T_n(e^{-sT_d}) \tag{9}$$

Where

$$S_m(e^{-sT_d}) = \sum_{k=0}^{m} \frac{(a+b-k)!m!}{(a+b)!k!(a-k)!}(-s.T_d)^k \tag{10}$$

$$T_n(e^{-sT_d}) = \sum_{k=0}^{n} \frac{(a+b-k)!n!}{(a+b)!k!(b-k)!}(-s.T_d)^k \tag{11}$$

From the Equations (8) -(11), 'S' and 'T' are the polynomials of order 'a' and 'b', correspondingly. It also includes commonplace for the numerator and denominator of the approximation fractional capabilities to have the identical order, and the order generally varies among 1 and 10

From the various researchers, the 5th order padé approximation is suitable and is used for the simulation studies here. As the reduce(cut)-off frequency of the 'low pass filters', i.e., governor and turbine, within the version are normally much less than 15 rad/sec in a power system. The magnitudes of all orders of padé approximation in the frequency domain have additionally been as compared to that of pure time delay. Simulation studies are carried over one-of-a-kind values of conversation put off latencies (Td) and the proposed technique suggests the powerful and strong dynamic overall performance

3.2. Controlling Technique: Fuzzy logic controllers:

Fuzzy logic controllers (FLC) are the systems which are rule-based. These are helpful in the situation of composite ill-definite process particularly in those that can be forbidden by a human operator who is an experienced without the knowledge of their basic dynamics. The indispensable part of the system which contain Fuzzy logic control contains a customary of Control Rules of Fuzzy (FCRs) which are recounted by means of a compositional rule of inference and fuzzy implication. As it is well known that the dynamics of power system characteristics are multifaceted and unpredictable sometimes, so the desired result cannot be provided by traditional control method. Intellectual controllers can be substituted with classical controllers to get quick and excellent dynamic performance in LFC problems. In order to minimize the system output fluctuations and also to get rid of continuous attention of operator these are designed. Variables are adjusted automatically and are kept to the reference values. Fuzzy logic controllers can be an added advantage if the system robustness and reliability are additional importance, in fixing an extensive assortment of manage issues considering traditional or say classical controllers are sluggish and less effective in nonlinear stratagem programs.

The four principle components of a simple configuration of a Fuzzy-Logic Control(FLC) consists of: first fuzzification, end is defuzzification in-between a knowledge base, and an inference engine. The input crisp values into fuzzy variables for a normalized membership functions and input gains with usage are mapped fuzzifier. The proper control action of the fuzzy control inference engine is primarily based at the rule-base availability. The fuzzy manipulate action is decoded to the right value of crisp via the defuzzifier the use of normalized membership functions and gain outputs. The two input normalized variables, ACE and change in ACE (ΔACE) are inputs of FLC, are first fuzzified with the aid of fuzzy sets. The two inputs signals which are available are converted to fuzzy numbers first using three membership functions in fuzzifier which are Triangular, named as Negative big (NB), Negative Small (NS), and Zero (ZZ), positive Big (PB) and positive Small (PS). There are two outputs proportional (k), and integral (I). named as Small(S), Medium (M), Big(B), Very Big(VB) and VeryVery Big(VVB). A total of 25 rules are framed. Ultimately using the Central of Area (COA) the values in a defuzzifier is the output which represents actual i.e. crisp converted by the controller. Here the rules are designed for the controllers and applied. From the recommended model the rugged and robust performance is achieved. In Fig.2.the surface unit of Fuzzy Interference system is shown.

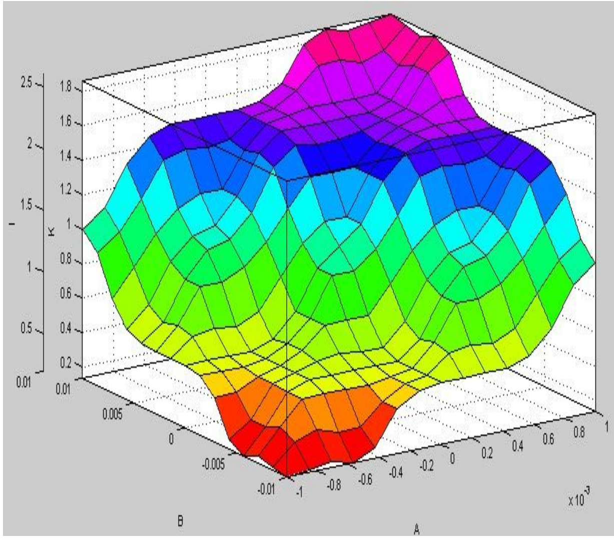

Fig. 2: Surface viewer representation of a Fuzzy logic system

4. Simulation Results

In this section various case studies are performed on the Deregulated multi area LFC-DR power system model to verify the proposed method is robust. To perform the simulation studies, the parameters are given in Appendix. Based on the discussion as stated [18], The availability of DR in LFC system, gives the higher reliability in Frequency regulation, now the supplementary control loop can be complemented using DR control loop. If at all in some cases if the supplementary control loop is unavailable then the regulation of frequency is promised by the DR loop, if there are abundant availability of DR resources. At steady state the Zero frequency deviation is obtained with split of supplementary and DR control loops by giving the correct control effort.

Considering all the above inferences, it is said that the cost at real –time electricity market with efficient control effort is splitted in two loops based on the availability of DR

$$\Delta P_{s1}(s) = \alpha \text{ Control Effort} \tag{12}$$

$$\Delta P_{DR1}(s) = (1-\alpha) \text{ Controleffort} \tag{13}$$

Finally the system is modified by the below equation which is based on the effort of Control w.r.to the Supplementary and DR ,the two loops .

$$(1-\alpha)G_i(s) + \alpha H_i(s) \tag{14}$$

From the above Equations (12) -(14), it clearly says about the share of regulatory services i.e. 0<α<1 in the necessitated effort of control ('Control Effort'). If the value α =1 then the services are provided classically i.e. Supplementary or if the α=0 then services are totally provided by DR which says that the DG type of generations. ISO/RTO decides the value of α w.r.to so many parameters such as Price for using DR regulatory services to that conventional services considering the market of real time given by so many authors [10]. considering the above things simulation are carried out considering the various α values.

For α=0.1: participation of DR is 90% and 10% supplementary regulatory services

For α=0.8: participation of DR is 20% and 80% supplementary regulatory services

Using the effort of control i.e. (control effort) of DR, effectiveness is verified considering the Multi area deregulated LFC-DR model with the proposed controllers by carrying studies using simulation results with system input as also load disturbance. considering each and every contract DISCOs, s for power GENCO as per given DPM, written in Eq(15)-(16) are carried out.

$$DPM = \begin{bmatrix} 0.5 & 0.25 & 0 & 0.3 \\ 0.2 & 0.25 & 0 & 0 \\ 0 & 0.25 & 1 & 0.7 \\ 0.3 & 0.25 & 0 & 0 \end{bmatrix} \quad (15)$$

The apf s values for the dynamic DR DISCO Demands are given by

$$APF = \begin{bmatrix} 0.75 \\ 0.25 \\ 0.5 \\ 0.5 \end{bmatrix} \ \& \ DISCO = \begin{bmatrix} 0.1 \\ 0.1 \\ 0.1 \\ 0.1 \end{bmatrix} \text{(p.u.MW)}. \quad (16)$$

Case.1: In the first simulation study, 0.1 p.u. load disturbance (10% Load perturbation), with control effort α=0.8 (which says DR participation is 20%) and with control effort α=0.1 (which says DR participation is 90%) was applied to the Deregulated multi area LFC-DR with communication delay latency of Td=0.1.With the above cases it is compared with traditional Deregulated LFC by applying the classical controllers, the response of the change in frequency deviations are quickly driven back to zero using the conventional controllers. The DR participation shows the best performance than the classical model as shown in Fig.3.and Fig.4. in terms of change in Frequency Deviation and Tie line powers shown in Fig 5.

Case.2: In the Second simulation study, 0.1 p.u. load disturbance (10% Load perturbation), with control effort α=0.8 (which says DR participation is 20%) and with control effort α=0.1 (which says DR participation is 90%) was applied to the Deregulated multi area LFC-DR with communication delay latency of Td=0.1. With the above proposed method, the response of the change in frequency deviations are quickly driven back to zero using the conventional and here with Intelligent controllers. The Fuzzy logic controller shows the best performance than the classical controllers as shown in Fig.6. and Fig.7.in terms of change in Frequency Deviation and Tie line powers are shown Fig.8. The numerical analysis in Table-I is carried out showing the Undershoot and the steady state value for all the areas using the classical and Intelligent Control Technique are shown in Fig.9 to Fig.14.when the delay latency is 0.1sec. From the analysis it is very clear that the Robustness is achieved by Fuzzy logic controllers.

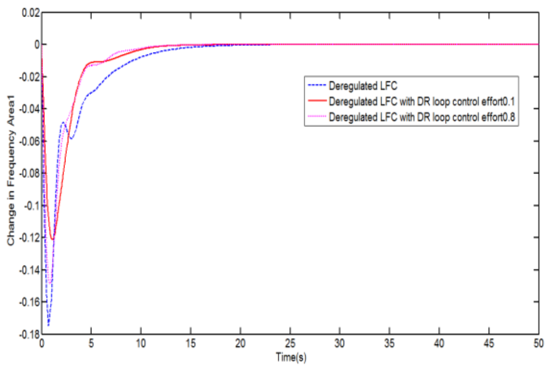

Fig.3: Change in Frequency for Area1 with and without DR for a Deregulated LFC with conventional controllers

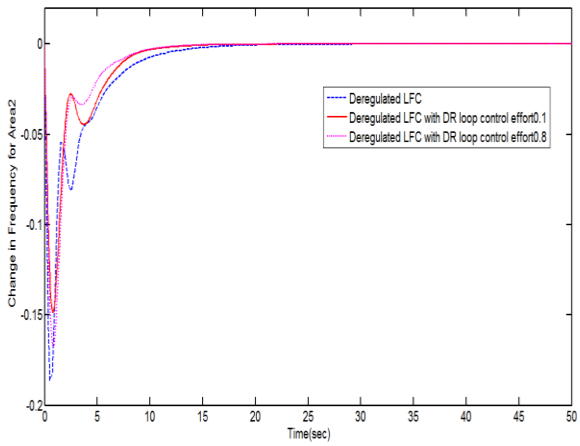

Fig.4: Frequency deviation for Area2 without and with DR for a Deregulated LFC

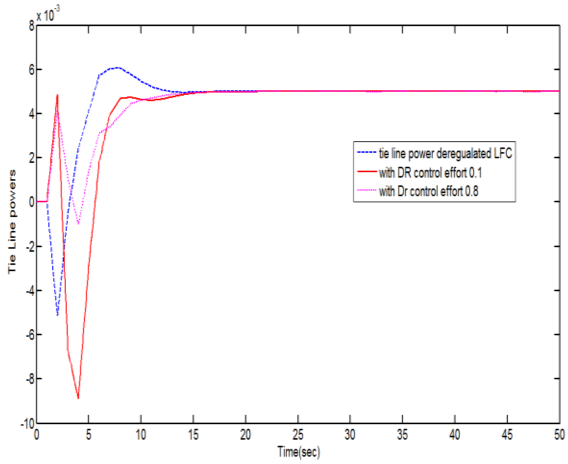

Fig.5: Comparison of Tie-line powers for different Power System Scenarios

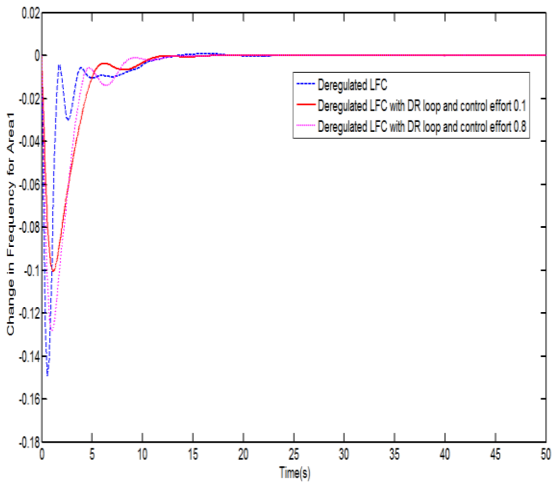

Fig.6: Change in Frequency for Area1 with and without DR for a Deregulated LFC with fuzzy controller

Table-! Numerical Analyis

Area	Δf	System Type	Settling Time (Sec)	Under shoot (p.u.)
Area1	Change in frequency, Δf_1(Hz)	Classical Deregulated LFC	>20	0.18
		Deregulated LFC-DR, α=0.8, PID	12	0.15
		Deregulated LFC-DR, α=0.1, PID	10	0.12
		Conventional Deregulated LFC with Fuzzy control	15	0.143

		Deregulated LFC-DR, α=0.8, Fuzzy control	10	0.13
		Deregulated LFC-DR, α=0.1, Fuzzy control	8	0.1
Area 2	Change in frequency,Δf_2(Hz)	Conventional Deregulated LFC	21	0.19
		Deregulated LFC-DR ,α=0.8, PID	12	0.17
		Deregulated LFC-DR, α=0.1, PID	10	0.16
		Conventional Deregulated LFC with Fuzzy control	15	0.17
		Deregulated LFC-DR, α=0.8, fuzzy control	9	0.15
		Deregulated LFC-DR ,α=0.1, fuzzy control	7	0.12

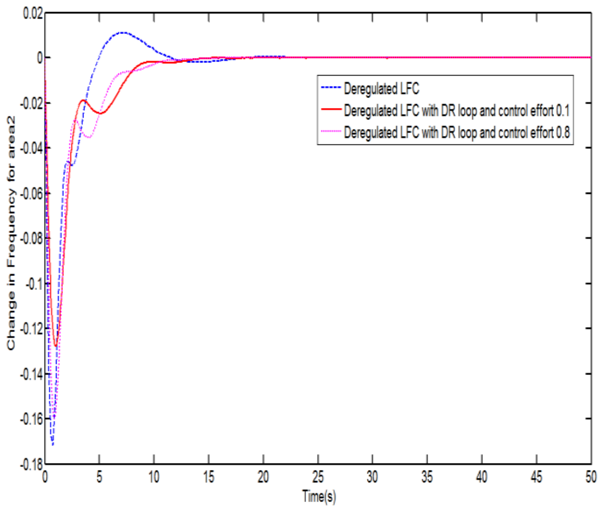

Fig.7: Frequency change for Area2 with and without DR for a Deregulated LFC with fuzzy controller

Fig.8: Comparison of Tie-line powers Fuzzy logic Controllers for different Power System Scenarios

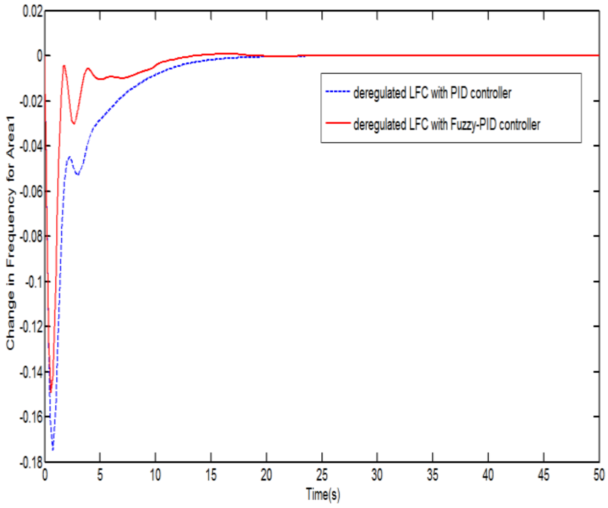

Fig.9: Comparison of Deregulated LFC for Area1 with PID and Fuzzy controllers

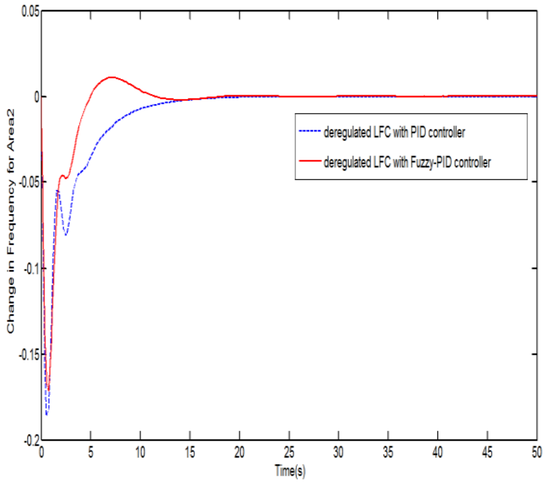

Fig.10: Comparison of Deregulated LFC for Area2 with PID and Fuzzy controllers

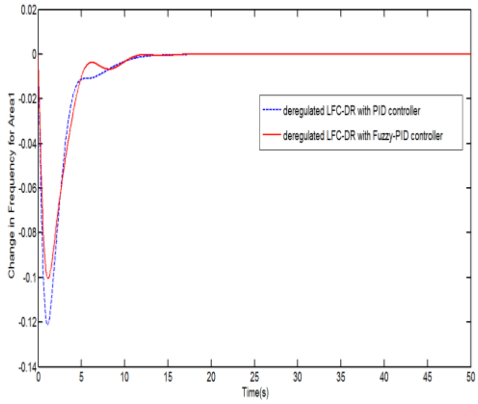

Fig.11: Comparison of Deregulated LFC with DR Control Effort α=0.1 for Area1 with PID and Fuzzy controllers

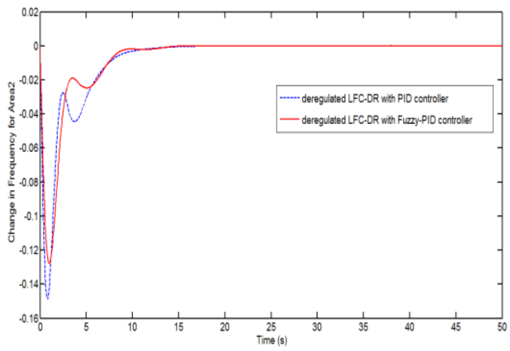

Fig.12: Comparison of Deregulated LFC with DR Control Effort α=0.1 for Area2 with PID and Fuzzy controllers

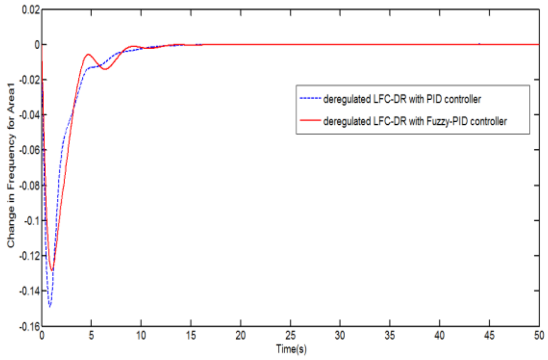

Fig.13: Comparison of Deregulated LFC with DR Control Effort α=0.8 for Area1 with PID and Fuzzy controllers

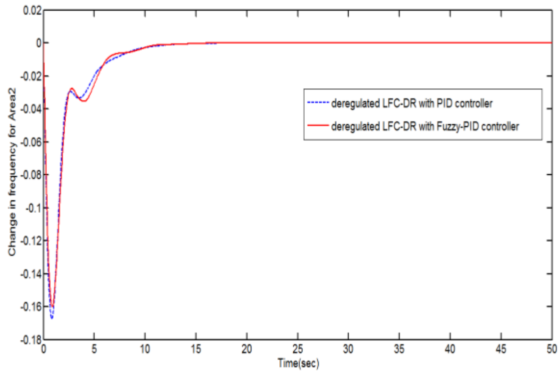

Fig.14: Comparison of Deregulated LFC with DR Control Effort α=0.8 for Area1 with PID and Fuzzy controllers

5. Conclusion

This paper concludes an Multi area Deregulated LFC-DR power system Model(DLFC-DR) with Fuzzy-PI controller. The method which is proposed was put on for a Thermal Non-Reheat power system model with operation at various i.e. as mentioned in previous section effort of control conditions(α). The results which are obtained from the simulation promises the robust performance and stability of the system. To validate the proposed method robustness, undershoot and settling time responses are being contemplated. With the proposed decentralized artificial controllers, the simulation results show better performance as compared to that of conventional Deregulated LFC and LFC-DR with wide operating condition and control efforts. In our future work, the application can be extended to LFC-DR in Hydro-Thermal power systems with optimal control and by considering the effect of different latencies.

Appendix

	area-1	area-2
K_P (Hz/p.u.)	120	120
T_P (sec)	20	20
B (p.u./Hz)	0.4250	0.4250
T_{ij} (p.u./Hz)	$T_{12} = 0.545$	
$Td._i$(sec)	*0.1*	

	GENCOs			
	1	2	3	4
Power rating (MW)	1000	1000	1000	1000
T_T (sec)	0.30	0.30	0.30	0.30
T_G (sec)	0.08	0.08	0.08	0.08
R (Hz/p.u.)	2.4	2.4	2.4	2.4

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