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PROPOSED LOAD FREQUENCY CONTROL ACCORDING TO ADAPTIVE FUZZY CONTROLLER IN THE PRESENCE OF LOAD DISTURBANCE

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Abstract:

Changes in electrical load in each system lead to frequency and voltage deviations, and if these changes do not resolve quickly and efficiently, major problems such as customer failure and power outage will happen. Automatic production control is usually used to counteract these deviations in frequency and voltage and reduce them to acceptable levels. In this paper, a new frequency controller for multi-region power systems is designed based on direct and indirect adaptive fuzzy control. Frequency controllers for each area will be designed based on the frequency deviation of each area and the deviation of the power line between the zones. The ability of the fuzzy system approximation to develop appropriate adaptive control rules and algorithms for updating parameters are used to reduce the uncertainty effect in the communication lines of the frequency control regions of the load. The proposed comparative fuzzy controller efficiency is evaluated during load disturbance for a three-zone power system. The simulation results on this power system show the effectiveness of the proposed comparative fuzzy load frequency controller and is clearly demonstrated by comparison with the classic PID controller and the conventional fuzzy controller.

Key Words: Adaptive Fuzzy Controller, Load Frequency Control, Nonlinear Power System & Load Disturbance

1. Introduction:

Power systems provide electricity for factories and residential areas. In order to optimize the performance of electrical equipment, it is important to ensure the quality of electrical power. During power transmission, and reactive power balance must be maintained. Although active and reactive power has a combined effect on voltage and frequency. However, the problem of voltage and frequency control is completely separate. The frequency depends largely on the active power and the voltage to the reactive power. Therefore, the control problem in power systems is divided into two problems. Active power control is related to frequency and reactive power control is related to voltage. Active power control and frequency are referred to as frequency control of the load [1, 2].

Frequency control is the main function of automatic control of system production. The primary objectives of automated production control are to set the frequency of the system at a nominal value and maintain a balance between the powers of the control areas in the planned amount by regulating the output of the selected generators. Generally, the Automatic Gain Control (AGC) has three levels: the primary control system is responsible for the response to load variations to return the operating frequency of system to the optimal value, and this is done by the governor. The primary control is by speeding up the units of production that operates automatically. Secondary control is the return of the frequency to its nominal value and maintaining the power balance among the regions by selecting output from the generator. Control the third stage of economic distribution and restore the security level if necessary. The speed command provides the production in each unit. The initial speed control function and all production units cause overall production changes (regardless of where the load is changed), however, the initial control function that is usually used to restore the frequency of the system, in particular, in a linked power system it is not enough and a secondary control loop is required. Secondary control is usually referred to as the Load Frequency Control (LFC) [3].

Various types of load frequency control schemes have recently been developed [4-6]. The study of various load frequency control schemes and automated production control strategies is found in references [7, 8]. However, the simultaneous presence of nonlinear sections of the system, such as the dead Bandwidth and the limitation of the production rate of the system reduce the system operation [9]. This issue is also considered by studying the specific nonlinear saturation for Generation Rate Constraint (GRC) and the dead band for Governor Dead Band (GDB) [9, 10]. The implementation of the above load frequency control requires detailed information about the parameters of the control area, but these parameters are usually not readily available due to the approximation in modeling and changing work points. In addition, the nonlinear section of GRC and GDB must be specified exactly.

Hence, in the past decade, load frequency control methods have been developed based on different adaptive fuzzy logic [11, 12]. However, most of the adaptive fuzzy load frequency control schemes available in the research are based on If- Then fuzzy rules to rely on control or modeling of the Takagi and Sogeno. But extracting fuzzy rules in power systems is complex and difficult due to the extensive system and the large number of influential parameters.

Therefore, in this paper, an adaptive fuzzy logic control scheme based on the approximation for the multi-region power system is proposed. The studied multi-region power system has characteristics of indeterminate parameters (due to changes in work points), unknown relationship in subsystems (due to the indeterminacy or variation in power factor synchronization). In controller design, fuzzy logic systems will be used to build control rules. The proposed controller for each region is dependent on local conditions, including the frequency and power line distortion and tracking error. The key idea of using fuzzy logic systems is to develop a control rule that can achieve LFC goals and ensure the overall stability of the whole closed loop system in the presence of uncertain system parameters and unspecified nonlinear sections. The proposed controller consists of three parts: an initial control, an auxiliary control, and a third term used to approximate the uncertain connections between sub-systems and unspecified nonlinear sections. Auxiliary control will be included to reduce the effects of approximation errors and external disturbances in sensors. The fuzzy logic system approximation capability is used to develop appropriate adaptive control rules and parametric update algorithms for unspecified interconnected regions.

This article aims to achieve the goals such as increasing the load frequency control function in the presence of indeterminate and nonlinear parameters of the system, introducing an auxiliary control section to meet the tracking function for frequency and deviation of power between lines, introducing an adaptive fuzzy controller without the need to determine the IF-Then rules and load controlling design will be performed by the method of adaptive fuzzy logic control based on GRC and GDB as nonlinear parts of the system. On the other hand, one of the innovation aspects of the present paper is to provide an adaptive fuzzy load frequency control algorithm with the following characteristics:

- The proposed controller will have an auxiliary control section in order to satisfy the frequency tracking function and the power deviation between the lines.
- An adaptive fuzzy controller is independent of the definition of If- Then rules; in other words, access to fuzzy rules is not required to implement the control.
- In the design of the proposed adaptive fuzzy load frequency controller GRC and GDB will be considered as nonlinear parts of the system.

2. Frequency Control of the Load in a Single or Multi-Zone Power System:

A generator produces mechanical energy conversion to electrical energy by electromagnetic induction. The generator can be represented as a large rotating mass with two opposing torques. It is required to immediate response in order to prevent equipment damage. This is critical to maintaining a system equilibrium. Due to frequent changes in load demand, this trend is to maintain a repeatable balance. In addition, due to the presence of different generating units in the supply of power to the transmission system, allocation of load shift to these units is also very important [13]. To achieve this, control systems for production scheduling and load frequency control are installed in different units of the generator. Therefore, a main control unit or governor in each sector is responsible for maintaining the rotating speed, while a complementary control scheme such as AGC performs the distribution of the system's power output between different control areas in order to adapt the scheduled power exchange. In this case, the total power of the system is adapted to the total system load. The main control loop responds instantaneously to frequency variations, and sends the frequency change rate to zero in a few seconds [13].

The overall load frequency control loop of a separate power system unit is shown in figure 1. It shows a steam turbine is represented by the transfer function by the relation (1):

$$G_T(s) = \frac{K_T}{1+sT_T} \tag{1}$$

T_T is the turbine time constant andK_T is the constant turbine gain. The speed governor mechanism acts as a comparator in figure 1, and its output ΔP_g is equal to the difference between the adjustable power ΔR_{ref} reference and the $\frac{1}{R}\Delta f$ power (which is given by the governor characteristic). The ΔP_g command is converted to the steam valve via the hydraulic booster. Given a linear relationship and a time constant T_{SG} for a hydraulic amplifier, relation (2) is defined in Laplace domain [13]:

$$\Delta P_v(s) = \frac{K_{SG}}{1+sT_{SG}} \tag{2}$$

K_{SG} is the static gain of governor mechanism. If we assume that each control area in a interconnected power system has a separate production unit, then the control system can stabilize the frequency of the system directly by changing the load and maintaining the exchange in the lines. But in the real world there are many control areas with more production units that need to be adjusted according to the economic distribution. In addition, despite frequent changes in unrealistic load, we can determine the output value of each unit. This leads to the need for an AGC control plan that can manage the production and distribution of units. AGC schemes run in a central location where information is transmitted to controlled areas. Control measures are generated before being sent to the manufacturing units in a digital computer.

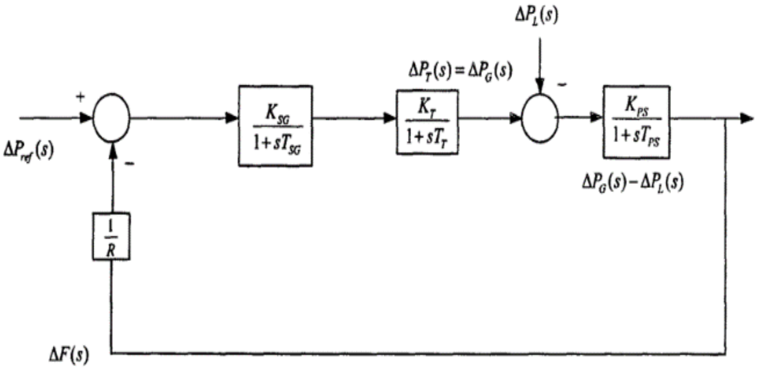

Figure 1: Primary frequency control loop for a separate power system

$$ACE_i = \Delta P_{net} + B_i \Delta\omega \tag{3}$$

Where the exchange of the power of the network with the frequency variations with ΔP_{net} and $\Delta\omega$ the frequency bias coefficient can be determined according to (4):

$$B_i = \frac{1}{R_i} + D_i \tag{4}$$

Controller input (usually PI) is the Area Control Error (ACE) value. The output control signal with limiting, delays, and gain constant, which is determined by the degree of participation of each unit in power generation [13]. Today, most power systems are connected to neighboring areas, and the connection of creating control areas creates a multi-region power system. In a multi-zone power system, each control zone provides normal conditions in its area unless it meets the power requirements of another area, with the agreement of two adjacent regions. Like the single-zone power system, in order to completely eliminate the frequency error, it is necessary to use the second control loop. The control error for each region is the linear combination of the power line and frequency error.

3. Modeling of Nonlinear Elements in Frequency Load System:

Some of the elements in the frequency load System are nonlinear and will be considered, as these will play an important role in system stability. One of the most important nonlinear effects in the system is the dead band in the governors. In fact, the governor does not react to changes in speed less than the bandwidth. The limitation of production increase in units is another nonlinear effect in the frequency load system. In other words, the increase or decrease of energy production is limited due to the maximum and minimum amount of production of units. Because, in practical terms, the production capacity can only be changed at a maximum speed, and these speed limits are intended to avoid wide variations in process variables such as temperature and pressure, for system safety.

3.1 Robust Control: In all control systems, control engineers are trying to set up specific system outputs at specific values by applying proper feedback signals, or to track specific variables well. One of the most important control system issues is the distortion and noise in the system. It should be noted that there is a major difference between distortion and noise. Disturbance has an external effect on the process of the system, which usually changes directly or indirectly the output and has a small frequency content. In order to analyze each of them, the complex mathematical model of the system is needed. In control theory, the closed loop system is always considered to the disturbances and uncertainties robustness of the system.

3.2 Adaptive Control: Simple controllers with constant control settings, for example, PIDs controllers in many cases can not meet the expected control goals [14-15]. In nonlinear processes with unknown dynamics, controlling engineers often encounter problems in controlling controller factors. Different characteristics of the response of a nonlinear process across operational areas have also made it impossible to select a fixed set of control factors [16-17]. In addition, in the event of unexpected changes in the process, a fixed constant controller will not be able to eliminate the losses caused by these changes [18]. Due to the uncertainty in time-varying nonlinear processes, the use of smart and flexible controllers is essential. The controller must be able to adapt itself to the dynamic changes of the system; such control systems are called adaptive control systems [19-21]. Therefore, the purpose of using adaptive control is to provide a controller design that can respond well to moderate changes in the system as well as modeling errors. The basis of comparative control is the parameter estimation, which is the branch of system identification. Common estimation methods include recursive least squares and descending gradients. Both methods provide update rules for parameters that are used to correct real-time estimates. Lyapunov's sustainability is used to extract these rules and update them and the convergence criterion [22-25]. The classification of comparative control approaches generally includes direct methods, indirect methods, and so on. In direct methods, the estimated parameters are directly used in the comparator controller. In contrast, there are indirect methods in which the estimated parameters are used to compute the parameters required by the controller. Combined methods are based on both parameter estimation and direct correction of control rules.

4. Designed Conventional Fuzzy Controller Design for Controlling the Load Frequency: In this paper, the Adaptive Fuzzy Logic Controller (AFLC) will be used to control the frequency of the load. In general, adaptive fuzzy control schemes are divided into direct and non-direct groups [26-28]. In direct AFLC a fuzzy system is used to generate a control signal, while in an Indirect AFLC (IAFLC), a fuzzy system is used to approximate the uncertain functions of the process. Here is a simple fuzzy system combining direct and indirect methods. This fuzzy system is used in each area to construct an initial control area, an approximation of unspecified connection terminals, and the uncertain functions of GDB and GRC. The controller parameters are updated to reduce the error between the subsystem output and the input reference signal. For the development of direct and indirect adaptive fuzzy logic controller (DIAFLC), a fuzzy system with centers of gravity defuzzification, multiplication inference system, and Singleton fuzzification system are considered. This type of fuzzy system is formulated in relation (5):

$$q(x_i) = \frac{\sum_{l=1}^{M} \bar{h}^{l} \left(\Pi_k^{n_i} \mu_{F_k^l}(x_k) \right)}{\sum_{l=1}^{M} \left(\Pi_k^{n_i} \mu_{F_k^l}(x_k) \right)} \tag{5}$$

$if\ x_1\ is\ F_1^l . x_2\ is\ F_2^l . and \ldots x_{n_i}\ is\ F_{n_i}^l . then\ h\ is\ G^l\ for\ l = 1.2. \ldots . M \ldots$ M

In order to study the stability of the whole closed loop system, the positive Lyapunov function has been investigated [27]. Therefore, the update rules for the vector of parameters must be chosen. The proposed direct-indirect adaptive fuzzy logic controller (DIAFLC) limited tracking errors and parameters of the LFC region of the closed loop, as well as the achievement of robust tracking performance H_∞ with the desired undervoltage level.

5. Simulation and Its Results:

The purpose of this section is to evaluate the performance of the proposed adaptive fuzzy controller in order to control the load frequency. For this purpose, the proposed controller is implemented on a connected three-zone power system and the results of the simulation of this controller with two conventional PID controllers, the conventional fuzzy controller, are compared [28]. Therefore, in this section, the dynamical model of the power system consists of three regions, along with its parameters and controllers. In the simulation simulation based on the disturbance, the performance of the three controllers is compared.

5.1 Describing Simulated Distributed Power System Model: Here, a connected three-zone power system presented in Ref. [22] is considered to evaluate the effectiveness of the proposed DIAFLC algorithm. In table 1, the parameters are shown. The one of sample system zones is shown in figure 2. All three areas are connected through common lines. Also, considering the parameter names and explanations in considered references, areas 1 to 3 of the power system are implemented in the Symbolic software environment of MATLAB.

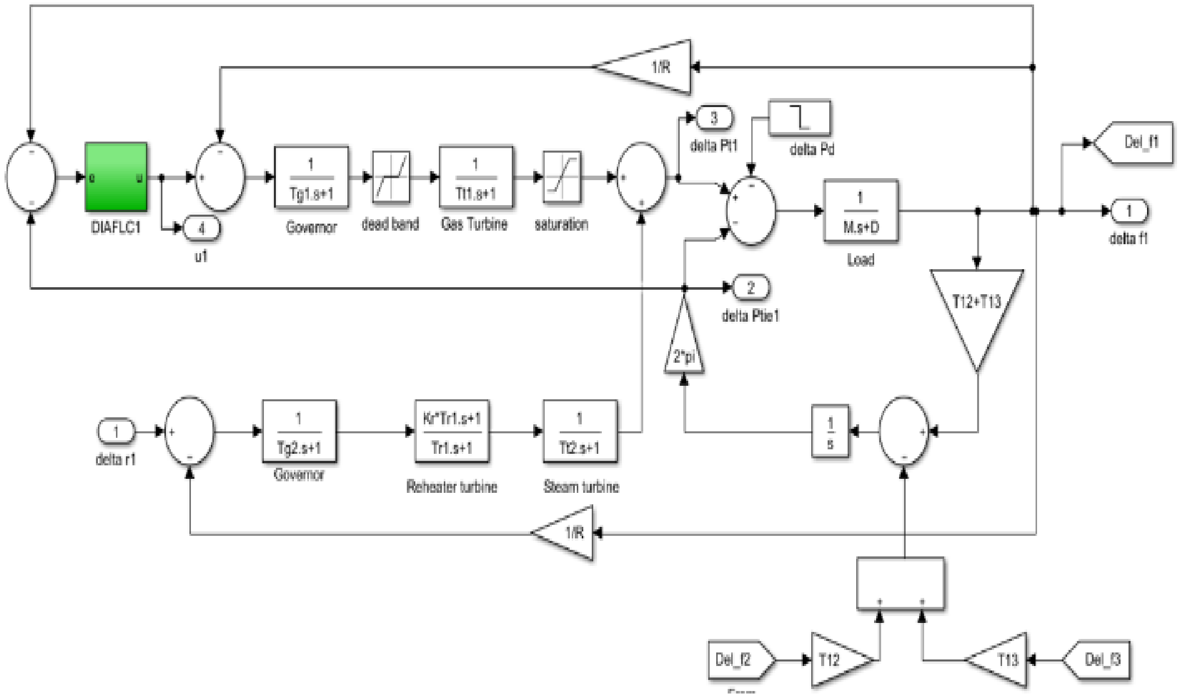

Figure 2: Implementing areas in MATLAB / SIMULINK

The proposed DIAFLC frequency frequency controller parameters are set for each area as listed in Table 2. In order to compare the performance of the proposed controller, a classic PID controller for each area is designed using the Ziegler-Nichols method [26-28]. In this method, the benefit of the final K_{ui} cycle should be increased until the system becomes oscillating. Then, using the T_{ui} oscillation period and the end K_{ui} coefficient, the PID controller parameters can be determined as:

$$\begin{aligned} K_{Pi} &= 0.6K_{ui} \\ K_{Ii} &= 2K_{Pi}/T_{ui} \\ K_{Di} &= K_{Pi}T_{ui}/4 \end{aligned} \tag{6}$$

According to the above description, the classical PID controller parameters for each region, as listed in Table 3, were calculated.

Table 1: Parameters of the distributive power system regions [22]

Parameters	Reg. 3	Reg. 2	Reg. 1
D_i	0.046	0.11	**0.24**
K_{ri}	-	0.3	**0.3**
M_i	23.25	89.5	**167**
R_i	0.04	0.04	**0.04**
T_{t1i}	0.1	0.4	**0.4**
T_{g1i}	0.4	0.1	**0.1**
T_{2i}	-	1	**1**
T_{2gi}	-	0.1	**0.1**
T_{ri}	-	1	**1**
T_{ij}	$1.5T_{31} =$	$2.3T_{23} =$	$\mathbf{8.4T_{12}} =$

Table 2: Setting the DIAFLC Controller Parameters in each Area

Region	$\boldsymbol{r}$	$\boldsymbol{\rho}$	**Q**	$\boldsymbol{\gamma_2}$	$\boldsymbol{\gamma_1}$
1	1	0.85	I0.01	2.5	1
2	1	0.85	I1.5	2.5	5
3	1	0.85	I0.5	2.5	2.5

Table 3: Setting up the classical PID controller parameters

Region	$\boldsymbol{K_D}$	$\boldsymbol{K_I}$	$\boldsymbol{K_P}$
1	4.5	0.21	1.8
2	0.8	0.0029	0.2
3	1.2	0.0052	0.6

To design a conventional fuzzy controller with the aim of controlling the load frequency, a fuzzy system with two inputs and one output is defined. The mentioned fuzzy system will have singleton fuzzifier and center average defuzzifier. There are also five Gaussian membership functions for frequency diversion inputs and common line power in each area. It should be noted that the rules If-Then for the above fuzzy controller are given in Table 4 and the 3D surface rules are also given in figure 3.

In this section, in order to evaluate the efficiency of the proposed fuzzy controller, two different simulation scenarios are considered. In the first scenario, the mentioned system is used, and a disturbance of 300 MW (0.3 p.u) is assumed in area 1. In the second scenario, the perturbation load of 0.3, 0.1, and 0.01 per unit was applied in regions 1, 2 and 3, respectively. It should be noted that load disturbance to each region is accomplished by an unit step function.

Table 4: Fuzzy rules for common fuzzy controllers

$\boldsymbol{ACE}$ $\boldsymbol{/A\acute{C}E}$	P	PS	Z	NS	N
N	Z	NS	NM	NB	NB
NS	PS	Z	NS	NM	NB
Z	PM	PS	Z	NS	NM
PS	PB	PM	PS	Z	NS
P	PB	PB	PM	PS	Z

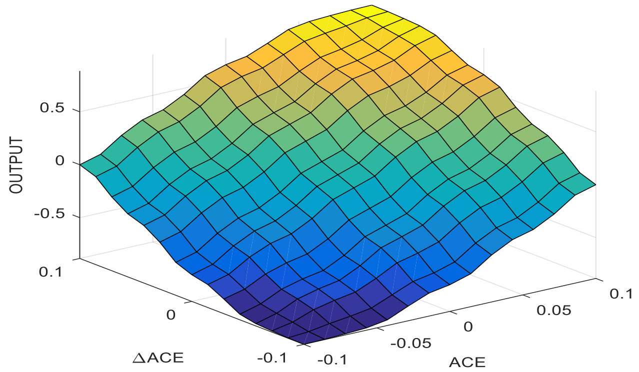

Figure 3: The three dimensional level of the rules

In Scenario 1, the perturbation load of 0.3 ppm / sec is entered into Region 1. The simulation results are shown in figures 4 to 6 for each of the three conventional DIAFLC, PID, and Fuzzy controllers. As shown in figure 6, the frequency deviation converges to zero at steady state in each region. It can also be seen that the proposed DIAFLC controller returns to the zero level for almost ten seconds after the turbulence of the load with a low oscillation, but the disturbance in the PID controller lasted roughly 60 seconds. The fuzzy controller, although within the same time period of ten seconds, has been able to eliminate the disturbance effect, but the resulting frequency deviation signal results in severe oscillations. Therefore, the proposed DIAFLC controller can perform better in controlling the load frequency than two other controllers. The mechanical power variation of each area is shown in figure 5, in this figure it is clearly seen that region 1 is able to provide the turbulence of its load.

Of course, the proposed DIAFLC controller has been able to compensate for zone 1 load disturbance faster than fuzzy controllers and PID controllers. Figure 6 shows the exchange of the power of the interconnection line between different regions. As can be seen, it is possible to achieve zero power exchange in each region in a steady state by all three controllers. But the DIAFLC controller's meeting time is lower than the PID controller. The control signals for each area for each of the three DIAFLC, PID, and fuzzy controllers are shown in figure 7. As can be seen, the control signal generated by the proposed DIAFLC controller has the lowest amplitude and oscillation than the PID and fuzzy controllers, so it would be simpler and cheaper to implement the proposed controller in practice, because the oscillation and the low signal amplitude need to be driven Power will not be fast and fast.

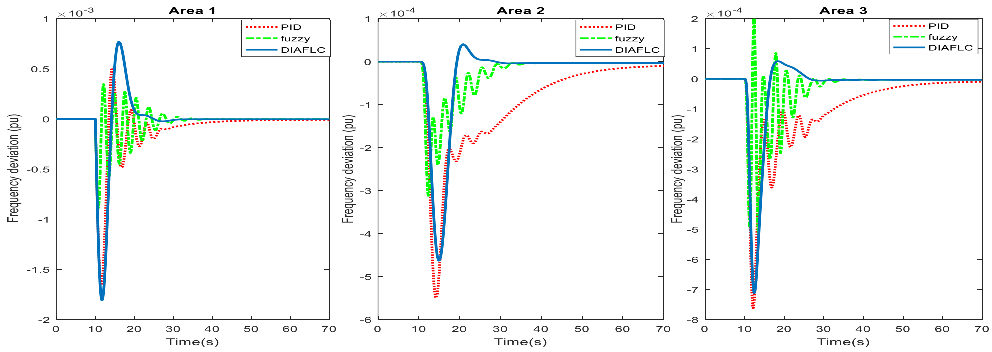

Figure 4: Frequency deviation in all three areas

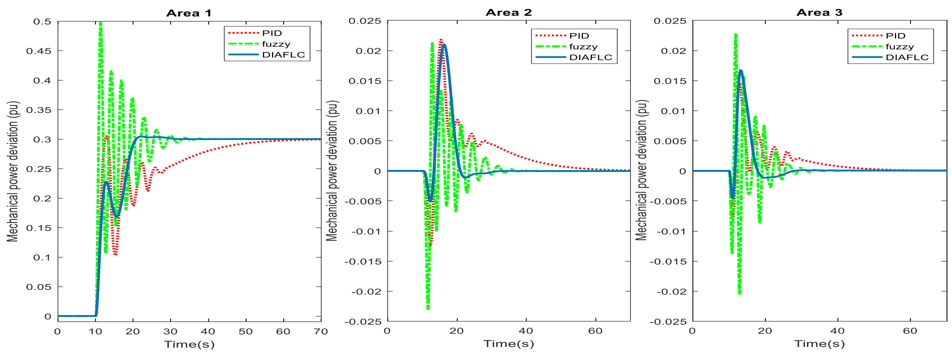

Figure 5: Mechanical power deviation in all three areas

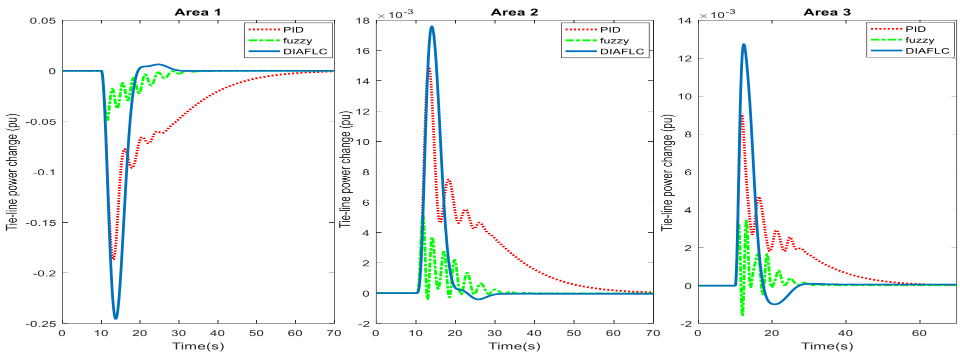

Figure 6: Linear power deviation between different regions

In scenario 2, the perturbation load of 0.3, 0.1, and 0.01 per unit was applied to regions 1, 2 and 3 in 5 seconds, respectively. It should be noted that load disturbance to each region is accomplished by a step change function. The results of the simulation of this scenario for each of the three DIAFLC, PID and fuzzy controllers are shown in figures 8 to 10. Figure 11 shows the frequency deviation in each area due to load disturbance. It is observed that all three controllers have been able to repel the load disturbance, and the frequency deviation signal resulting from all three controllers converges to zero at steady state. Also, the range of the frequency deviation of all of the controllers in the presence of load disturbance is approximately the same. However, it can be seen that the induction time caused by the proposed DIAFLC controller is less than two PID and fuzzy controllers. Therefore, it is possible to get the proposed DIAFLC controller in controlling the load frequency compared to the other two controllers with a faster response.

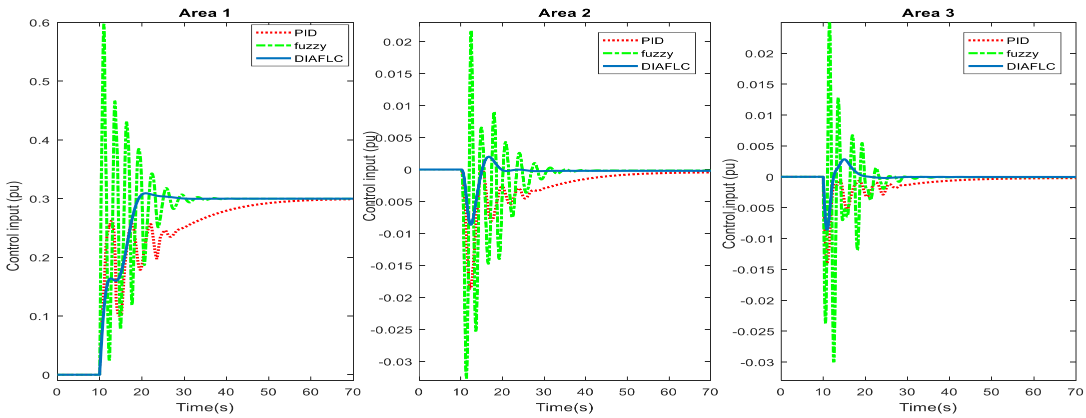

Figure 7: Control signals for each area

Figure 9 shows the mechanical power variation in each region, in this figure it is clearly seen that the fuzzy controllers, PID and DIAFLC in each of the three regions have been successful in providing load disturbance to that area.

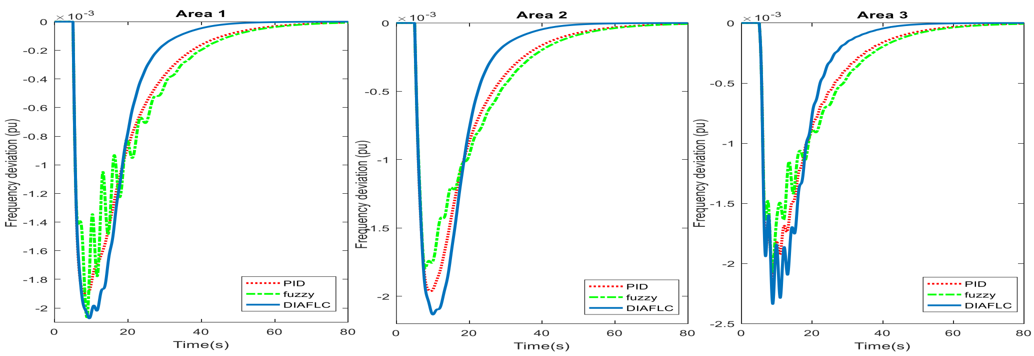

Figure 8: Frequency deviation in all three areas

As you know, in the ideal state, it is expected that the exchange of the power of the interconnection lines between zones by zero load changes in each zone. So one of the tasks of controlling the frequency of load sharing power line connecting the convergence between areas under different loading conditions, the amount is zero. This can be clearly seen in figure 10, where all controllers have been able to exchange power over interconnect lines after a transient state to a value of zero after the turbulence. Therefore, performance of controller has been satisfactory in this regard.

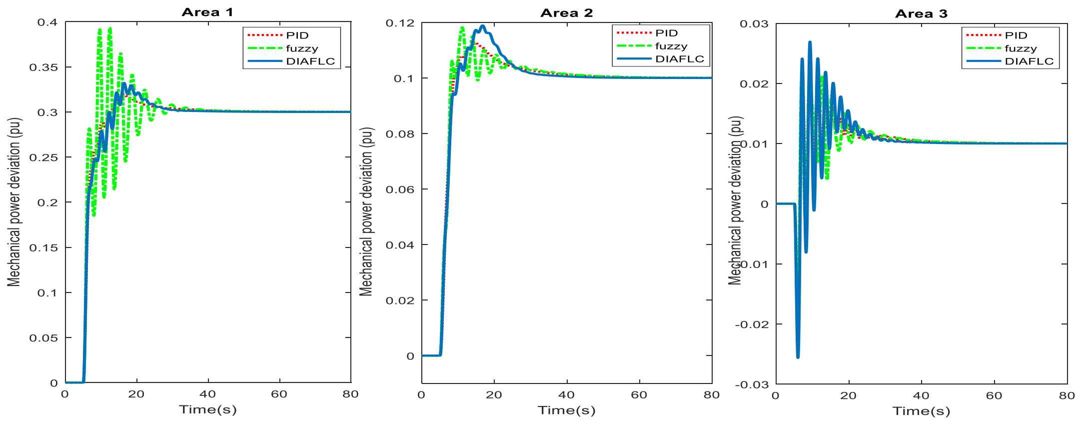

Figure 9: Mechanical power deviation in all three areas

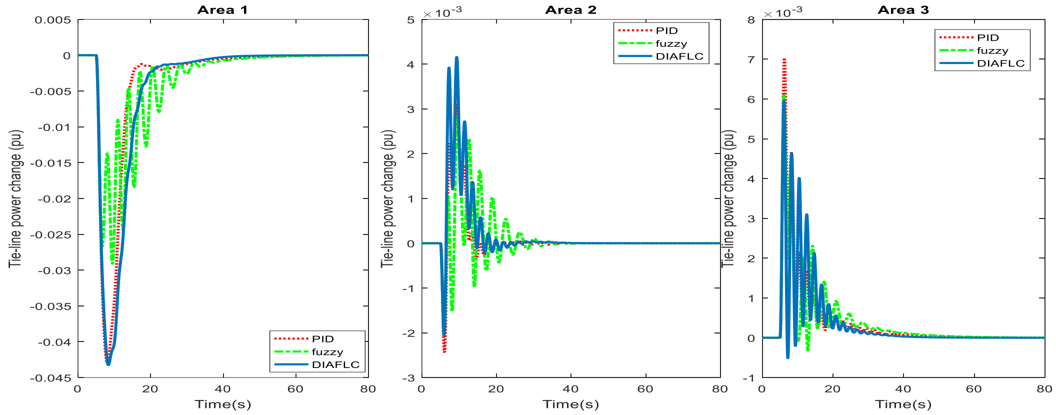

Figure 10: Linear power deviation between different regions

The control signals for each area for each of the three DIAFLC, PID, and fuzzy controllers are shown in figure 11. By observing this figure, it can be noted that the control signal generated by the conventional fuzzy controller is more distorted than the control signals from the other two controllers, which would be undesirable for the implementation of the closed loop system.

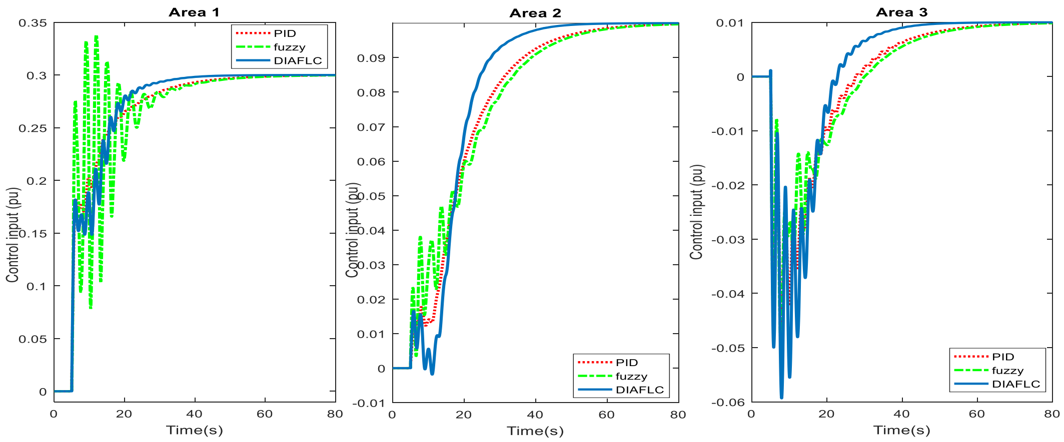

Figure 11: Control signals for each area

Because the fluctuations will require faster propulsion and will also result in faster wear and tear. In order to deal with this problem, a limiter can be applied to control signal changes.

6. Conclusions:

In this paper, a new load frequency controller was proposed for a multi-region power system with indeterminate parameters. The proposed controller was developed using the DIAFLC approach. The fuzzy system with center average defuzzification and singleton fuzzification system was used to design the initial control signal, the nonlinear nonlinear GRC and GDB functions, and uncertain internal connections. An auxiliary control signal was designed to compensate for fuzzy approximation errors and to achieve H_∞ robust tracking performance. A hybrid Lyapunov functions was also used to indicate the closed loop of the closed loop system tracking error. In order to validate the proposed approach, a three-zone power system with load turbulence was introduced. The simulation results showing that developed DIAFLCs are capable of achieving the LFC goals of achieving constant-frequency frequencies and deviations of common lines by zero. Advantage of the developed DIAFLC has been shown in terms of the speed of convergence of the response to the static error-free mode, the reduction of fluctuations in the transient state, and the reduction of control effort size over the classical PID and fuzzy controller.

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