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A performance evaluation of fuzzy logic controllers for load frequency control in a single area network

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***Abstract*—Load frequency control is an essential operation performed by power plants to ensure that the system frequency is kept within strict bounds, in the presence of ever-changing loads. In this paper, we are investigating the effect of small step load changes on the frequency of a single area power network. To counteract the resulting frequency deviations, we propose fuzzy logic controllers. Simulations are carried out using Integral, PID (Proportional, Integral and Derivative), as well as fuzzy logic controllers, for small step load changes. The frequency responses are compared, in terms of frequency overshoots, undershoots, rise time, and settling times. A performance index that takes into account the frequency deviation, as well as the control energy of the governor is formulated. Simulations are performed using Matlab Simulink. The PID controller is initially tuned manually, then further tuned using the Matlab Tuner app, from the Control Toolbox. A fuzzy logic controller is designed and implemented. It is observed that that the fuzzy logic controller outperforms the PID, which in turn, is better than the Integral controller. The gains of the PID as well as the fuzzy logic controllers are tuned not only to minimize the frequency deviation, but also to provide an acceptable control energy to the governor, which gives an indication on the opening and the closure of the valves.**

Keywords— load frequency control, PID Controller, fuzzy logic

I. Introduction

The stability of a power system depends mainly on the system frequency and voltage. It has been established that a mismatch in the active power generated and demanded, causes frequency deviations, while reactive power differences causes voltage deviations [1]. Load frequency control (LFC) is used by power systems to ensure that there is a match between the power demand by customers and the power generated by the power station. This process enables the system frequency to remain constant at the nominal value. In practice however, the loads are always fluctuating, and thus the LFC function attempts to keep the frequency within specified limits, which are safe for the operation of the power system.

In the year 1970, Fosha and Elgerd's works on load frequency control, using modern control theory, have given a boost on this area of research [2][3]. Subsequently many advanced techniques have been proposed from various fields of control engineering. For instance, optimal control schemes have been used to tackle the LFC problems, by many authors from the eightees [4][5][6][7]. More recently, Sina et al., (2019) developed an optimal controller for LFC, applied to a deregulated environment. The authors considered a multi-area system, with multiple sources such as hydro, thermal reheat and non-reheat, in each area [8].

On the other hand, the long-established PID control, which is still popular today, has been adapted for LFC by several methods. Morinec and Villaseca (2001) proposed a PI controller, for a three-area interconnected power system, whereby the controller parameters are tuned by trial and error [9]. Further to this, Anwar and Pan (2015) utilized the direct synthesis method to develop a design methodology for a PID controller, in the frequency domain [10].Another scheme for PID controller for LFC was designed by Padhan and Majhi (2013), using Laurent series expansion [11]. Also, Tan (2010) proposed a method using Internal Mode Scheme (IMC) for a PID controller, for LFC [12]. In recent years, there was a focus on the use of artificial intelligence and soft computing control techniques for load frequency control in power systems. Altas et al. (2006) proposed a fuzzy logic controller for power systems. Their proposed model was simulated and compared with conventional controllers. The frequency overshoot was lesser, and settling time was shorter [13]. Further, Yesil et al. (2004) proposed a self-tuning fuzzy PID load frequency controller, based on a modified version of the peak observer idea, adapted to the LFC problem [14].

In most of the works reviewed, no information was provided regarding the signal at the governor's output. The main objective for the design of an appropriate controller was the reduction and eventually the elimination of steady state error, in the fastest time possible. In this work, a performance index is formulated, which that takes into account not only the frequency deviation but also the control energy of the governor. This parameter gives an indication on the opening and the closure of the valves.

II. Research Method

A. Dynamics of a Thermal Power System

The general block diagram of a single-area thermal power system is shown in Fig. 1 in which ΔP_{ref} represents the speed changer (input to the system), ΔP_L represents a disturbance in the form of load power changes, and Δf represents the frequency deviation from its nominal value (50Hz). The governor controls the opening and closure of the valve, based on the change in the speed, that it continuously monitors. The turbine is responsible for transforming the energy from the steam (for a steam power plant), into mechanical energy that is fed to the generator, which then transforms this mechanical energy into electrical energy.

B. Load Frequency Control

The IEEE Committee Report 1968 and 1973 have proposed standard models for frequency and voltage controllers. Based on these standards, mathematical models are devised for the prime mover, governor and the power network. Using the IEEE models, a block diagram for an isolated power station is constructed as shown in Fig. 1, for load frequency control.

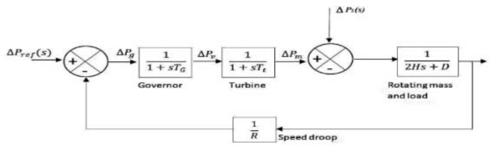

Fig. 1. Model of LFC for a Single Area Non-Reheat Turbine

T_t : time constant of the non-reheat prime mover
T_G: governor time constant
ΔP_L : non-frequency sensitive load change
D: percentage change in load divided by percentage frequency
R: Regulation of speed governor

C. LFC System With PID Controller

The long established PID controller has been extensively used in industry for several decades, due to its simple operation. Its popularity has grown after the development of the tuning method proposed by Ziegler-Nichols' [15]. The standard PID controller, described by Astrom and Hagglund [16], is given by the equation 1 and equation 2. A block diagram of the PID controller is shown in Fig. 2.

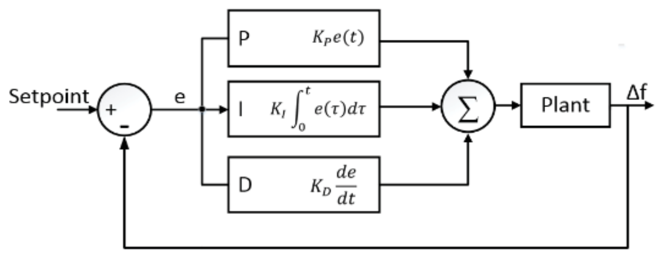

Fig. 2. Block diagram of a PID controller

$$U = K_P e(t) + K_I \int_0^t e(\tau)d\tau + K_D \frac{de}{dt} \quad (1)$$

Also

$$U = K_C \left(e + \frac{1}{T_i} \int_0^t e(\tau)d\tau + T_d \frac{de(t)}{dx} \right) \quad (2)$$

Where K_P, K_I and K_D are the proportional, integral and differential gains respectively. T_i, and T_d are the integral time, and the derivative time, respectively. U is the control signal and K_C is the controller gain. The ideal controller parameters are converted to the parallel form using the equations 3, 4 and 5.

$$K_P = K_C \quad (3)$$

$$K_I = \frac{K_C}{T_i} \quad (4)$$

$$K_D = K_C T_C \quad (5)$$

While designing a load frequency controller using a Proportional Integral and Differential (PID) structure, to give an adequate system response, the main considerations are the stability requirements as well as the performance of regulating units. Also controller design requires proper selection of PID constants so that the frequency oscillations are minimised. The aim of a PID controller is to minimize the steady state error, while improving the dynamic response. The deviation in frequency response is due to a change in consumers demand for energy. If the demand is higher than the generation, the speed of synchronous machines will tend to decrease which will result in a drop in the frequency, and vice versa.

D. Fuzzy Logic Controller

A Fuzzy Logic Controller (FLC) has the ability to mimic a human operator and adjust the input variables of a plant, by observing the latter's output. Fuzzy logic theory was introduced by Zadeh, and it has proved to be very useful for modeling complex systems [17]. The basic structure of a FLC is given in Fig. 3. It consists of an inference system, which is made up of three blocks: fuzzifier, rule base and defuzzifier. The process of fuzzification involves the conversion of a crisp set to a fuzzy set. The fuzzy set consists of linguistic variables, that are defined by membership functions. The rule base, also known as the decision table contains fuzzy IF-THEN rules, which maps the crisp inputs to the output. The concept of IF-THEN rule fits very well in human reasoning, and thus the fuzzy logic inference process successfully translates crisp quantities into human linguistic quantities, thereby yielding widely acceptable results.

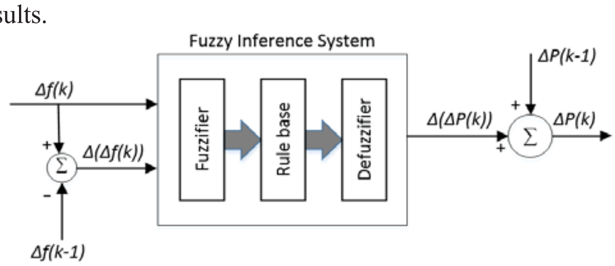

Fig. 3. The basic structure of an FLC

There are two main types of fuzzy inference methods, namely the Mamdani [18] and Sugeno [19] methods. In this research work, we will use only the Mamdani type, which is the most common one, and appropriate for load frequency control. The last block of the fuzzy inference system is the deffuzifier. This converts the fuzzy inputs back to crisp outputs. For the defuzzification methods, the most prevalent one is the Centroid

Method [20][21]. It is given by the expression shown in equation 6.

$$Z_{COA} = \frac{\int_z \mu_A(z).z\,dz}{\int_z \mu_A(z)} \tag{6}$$

z : output variable

$\mu_A(z)$: membership function of the fuzzy set A with respect to z.

The damping of frequency oscillations is one of the objectives of the load frequency controller. When there is no frequency deviation, that is the frequency is constant, no control action is required to be taken by the controller. In contrast, if there are frequency deviations, a control action is required. This control action ultimately commands the generator to increase or decrease the amount of power generation, depending on whether the deviation is positive or negative, with respect to the reference frequency. The rate of change of the frequency deviation also provides essential information on the increase/decrease of the frequency deviation. Hence the frequency deviation Δf and the change in frequency deviation Δ(Δf), are taken as the inputs of the FLC. As mentioned earlier, the fuzzy rules mimics human knowledge and experience in order to optimally operate a system. In the case of load frequency control, a fuzzy logic controller would attempt to minimize the error offset, and provide a rapid response to bring back the frequency to its nominal value, in the event of load disturbances. In order to achieve same, the values of Δf and its change Δ(Δf) are observed on different operating regions. The inputs to the fuzzifier determine whether the incremental output power, Δ(ΔP) should be raised or lowered, based on different operation regions. Based on this, a positive value of Δ(ΔP) indicates that ΔP has to be increased, and vice versa.

Fuzzy Rule Table

In order to develop a fuzzy logic controller with a better performance compared to a PID controller, the response signal of the latter is used as input for the rule table. A series of observations are carried out on the behavior of Δf, and its change Δ(Δf), to determine the action that a human expert would take [15].

Referring to fig. 4, in Regions I & II, Δf is negative, which implies that the actual value of frequency is higher than the reference value. Hence the power generation has to be decreased, that is the change in power, Δ(ΔP) is negative. Similarly in Region III, Δf is positive, hence Δ(ΔP) is positive. A preliminary rule can be formulated as such:

Δ(ΔP) takes the sign if Δf.

However at the lines A, C, D, F and H, Δf = zero, which technically means that no control action should be taken. However from Fig. 4, it can be observed that Δf is zero at a specific instant, and takes a positive or negative value at the very next instant. In such a case, the variation of the change of frequency deviation, Δ(Δf) provides useful information [13].

Referring to Fig. 4 again, considering line C, between Regions II and III, Δf is zero, but Δ(Δf) is +ve. This means that the frequency deviation is zero at line C, but since the rate of change of frequency deviation is positive, the error will become positive at the very next instant. Therefore, human reasoning, which is the basis of fuzzy logic system, indicates that the power generation should be increased, hence Δ(ΔP) is positive. Similarly, at line D, Δf is zero, but Δ(Δf) is negative, therefore Δ(ΔP) is set to be negative. Thus, considering all the regions I to VII, the preliminary rule can be amended as follows [13]:

IF Δf is zero, THEN Δ(ΔP) takes the sign of Δ(Δf), ELSE Δ(ΔP) takes the sign of Δf.

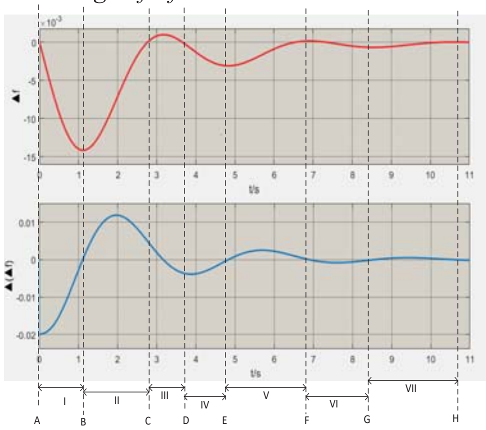

Fig. 4. Frequency deviation and Derivative of frequency deviation

A rule table, with three fuzzy sets can be constructed for Δ(ΔP), with nine rules, as shown in Table I, where 'N' means negative, 'ZE' means zero, and 'P' means positive.

TABLE 1. INITIAL RULE TABLE FOR Δ(ΔP)

Δf	Δ(Δf) N	Δ(Δf) ZE	Δ(Δf) P
N	N	N	N
ZE	N	ZE	P
P	P	P	P

Referring to Table 1, it can be noticed that in two cases (circled), there is a direct shift from N to P. In other cases, N goes to P through ZE. Therefore, the two entries of the table are adjusted and a symmetrical table is created, as shown in Table 2.

TABLE 2. MODIFIED SYMMETRIC RULE TABLE FOR Δ(ΔP)

Δf	Δ(Δf) N	Δ(Δf) ZE	Δ(Δf) P
N	N	N	ZE
ZE	N	ZE	P
P	ZE	P	P

Since humans are capable of differentiating between small negative/positive and large negative/positive values, the three fuzzy rule table can be expanded to a five fuzzy rule table [22]. Accordingly Table 3 is populated using the same rules from Table 2.

TABLE 3. A TWENTY FIVE RULE SYMMETRICAL TABLE FOR Δ(ΔP)

Δf	Δ(Δf) NL	NS	ZE	PS	PL
NL	NL	NL	NS	NS	ZE
NS	NL	NS	NS	ZE	PS
ZE	NS	NS	ZE	PS	PS
PS	NS	ZE	PS	PS	PL
PL	ZE	PS	PS	PL	PL

'NS' : Negative Small,
'NL' : Negative Large,
'PS' : Positive Small, and
'PL' : Positive Large.

III. SIMULATIONS AND ANALYSIS

A. *Scenario 1 : Single-Area Thermal power system with Integral and PID controller*

An isolated power station having the parameters as shown in Table 4, is simulated using Simulink.

TABLE 4. PARAMETERS OF THERMAL POWER SYSTEM UNDER CONSIDERATION

Parameter	T_g(s)	T_t(s)	H(s)	D	1/R	ΔP_L(pu)
Value	0.2	0.5	5	0.8	20	0.2

Several simulations were run for the following cases:

i) Uncompensated system, that is without controller
ii) Using Integral controller only, with value of integral gain varied from 1-15
iii) Using PID controllers

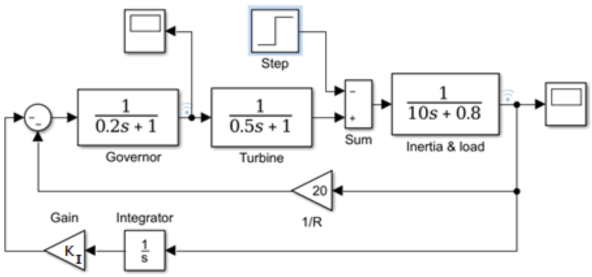

Fig. 5. Simulink Model of single area LFC for an I-compensated non-reheat power system

For the uncontrolled case, there is always a frequency offset at the settling time. The integral control, on the other hand gives rise to zero steady-state frequency error due to a step change in load. The simulation is performed for several values of K_I. It is found that in all cases, the steady state error eventually goes to zero. The best response is obtained when K_I is 6, for the given set of parameters. As K_I is increased beyond this value, the oscillations, as well as the overshoots increase, making the system unstable.

The simulation model of Fig. 5 is modified such that the integral controller is replaced by a PID controller. Manual tuning is performed, starting with the value of 6 for the integral gain (K_I). Through several trials, the following values of gains, gave the 'best' response: $K_P = 7$, $K_I = 10$, $K_D = 3$. The Fig. 6 shows that the PID controller has better performance characteristics than the integral controller, in terms of rise time, undershoot, oscillations, as well as settling time.

The Matlab Control System Toolbox includes tools for tuning PID controllers through the PID tuner app. The PID Tuner app uses an algorithm for tuning the PID gains in order to achieve both performance and robustness [23]. The PID controller was thus further tuned by the Matlab PID Tuner. The initial values used were $K_P = 7$, $K_I = 10$, $K_D = 3$. The controller parameters for both the Block (initial values) and the Tuned values were provided by the PID tuner application as well as a comparison of the performance and robustness characteristics, as shown in Fig. 7. From these values, it could be deduced that the PID tuner provides only a marginal improvement over the manually tuned controller.

B. *Scenario 2: Fuzzy Logic Controller (FLC) for Thermal power system – Non-Reheat model*

The Matlab Fuzzy Logic Toolbox was used to design a Fuzzy Logic Controller (FLC) for load frequency control. For the frequency deviation Δf, triangular as well as trapezoidal membership functions was chosen. 'NS', 'ZE' and 'PS' were triangular whereas 'NL' and 'PL' were trapezoidal functions, as shown in Fig. 8. These are preferred to bell, sinusoid, Gaussian, Cauchy and sigmoid functions, due to their linear structure, which renders modeling and simulation easier. The universe of discourse of Δf, that is the range of possible values of Δf was selected as [-0.015 0.015], since the maximum undershoot obtained from the integrator compensated controller was around -0.014, as shown in Fig. 6.

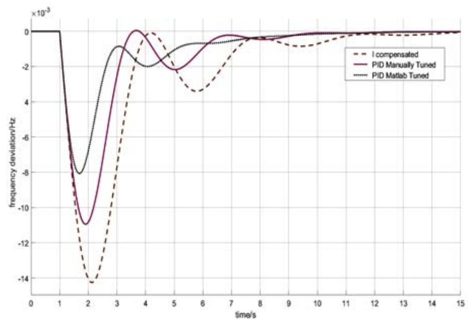

Fig. 6. Comparing PID and Integral controllers

Controller Parameters

	Tuned	Block
P	20.4737	7
I	13.3868	10
D	7.7309	3
N	281.2698	100

Performance and Robustness

	Tuned	Block
Rise time	4.72 seconds	4.47 seconds
Settling time	8.88 seconds	8.79 seconds
Overshoot	0 %	0 %
Peak	0.998	0.999
Gain margin	44.2 dB @ 35.3 rad/s	44.2 dB @ 21.7 rad/s
Phase margin	60 deg @ 2.46 rad/s	95.6 deg @ 0.502 rad/s
Closed-loop stability	Stable	Stable

Fig. 7. Controller parameters from PID Tuner

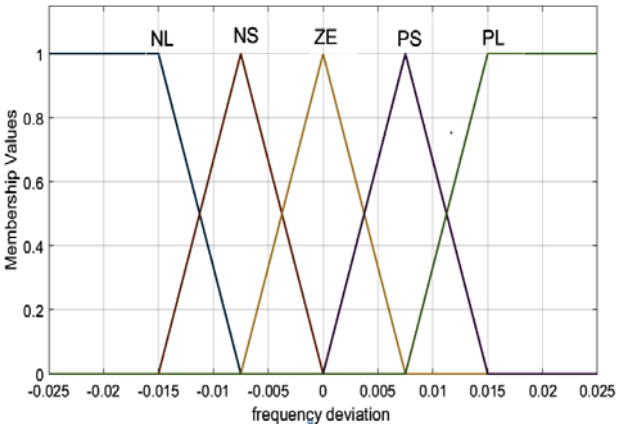

Fig. 8. Membership functions for frequency deviation, Δf

Similarly, for the second input to the FLC, $\Delta(\Delta f)$, triangular and trapezoidal membership functions were selected. The assigned universe of discourse for $\Delta(\Delta f)$ was set to [-0.001 0.001]. For the output of the inference engine, $\Delta(\Delta P)$, only triangular membership functions are selected within the range [-1 1]. A Mamdani type of Fuzzy Inference System was implemented. For the fuzzy rules, the Table 3 was used. A twenty five rule table is preferred to a nine rule table, since humans can clearly distinguish between a negative quantity that is small (NS), and another negative quantity that is large (NL). Three rules from the Table 3 are given below:

Rule 1: if Δf *is NL and* $\Delta(\Delta f)$ *is NL, then* $\Delta(\Delta P)$ *is NL*

Rule 2: else if Δf *is NL and* $\Delta(\Delta f)$ *is NS, then* $\Delta(\Delta P)$ *is NL*

Rule 3: else if Δf *is NL and* $\Delta(\Delta f)$ *is ZE, then* $\Delta(\Delta P)$ *is NS*

For the defuzzification, the Centroid Method was used. The FLC structure, as shown in Fig. 9 was simulated and its performance was compared to Integral and PID controllers, in terms of undershoot, overshoot and settling time. A performance index J was defined as shown in equation 7.

$$J = \int a\ (\Delta f)^2 + b\, u^2 \tag{7}$$

J is a function of both, the frequency deviation and the control energy u. The gains ‘a’ and ‘b’ represent different weights assigned to Δf and u. The objective is to design a controller which minimizes J.

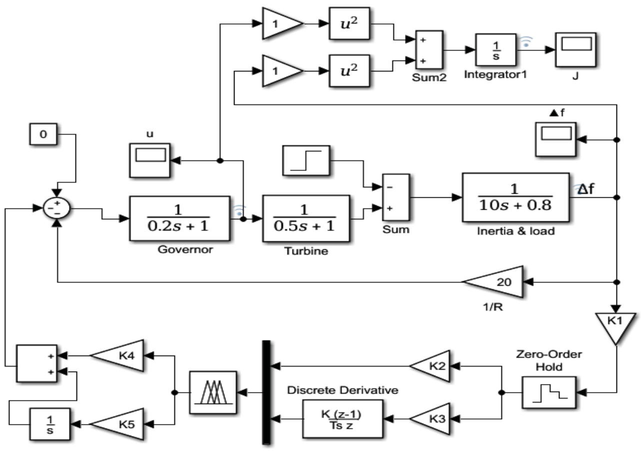

Fig. 9. Simulink Model of fuzzy logic controller

Simulations were performed for several values of gains K1, K2, K3, K4 and K5. In the first instance (Case 1), the objective was to reduce to the steady state error to zero, in the minimum amount of time, while keeping the overshoot as well as the undershoot to a minimum. After several simulation runs, the optimal values for Case 1 was obtained, as shown in Table 5. However, even though the frequency deviation was very low, as shown in Fig. 10, the control energy U at the governor was found to be highly oscillatory (Fig. 11), indicating that the steam flow to the turbine goes from a maximum to a minimum several times in one second. This situation is very undesirable in practice, and is normally avoided. The gains were thus further tuned, in order to obtain an acceptable control energy variation at the governor. These values of gains were tabulated as Case 2 values, in Table 5. Fig. 10, 11 and 12 show a comparison of different parameters for Case 1 and Case 2.

TABLE 5. GAIN FOR THE FUZZY LOGIC CONTROLLER

	K1	K2	K3	K4	K5
Case 1	1	5	2	9	5
Case 2	0.5	0.5	0.4	1.5	1.5

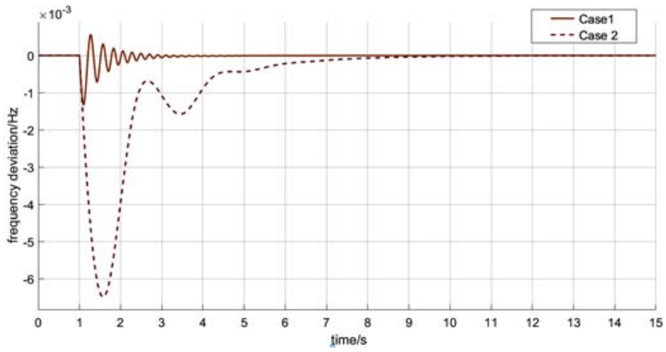

Fig. 10. Frequency deviation for Case 1 and Case 2

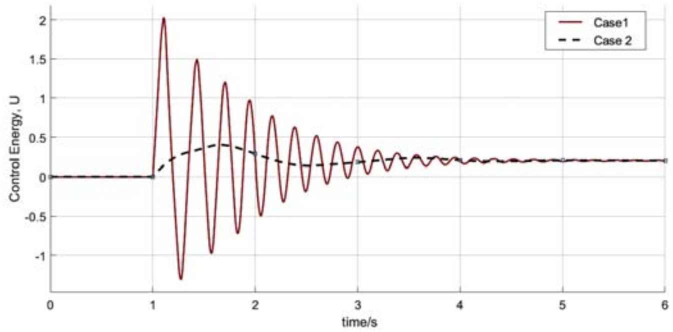

Fig. 11. Control energy of the governor for Case 1 and Case 2

The table 6 shows numerical values for the frequency overshoots, undershoots, settling times, and the performance index J. It can be deduced that Case 1 is not realistic and cannot be implemented in practice. We thus considered Case 2, and compared its performance with other types of controllers, in the next section.

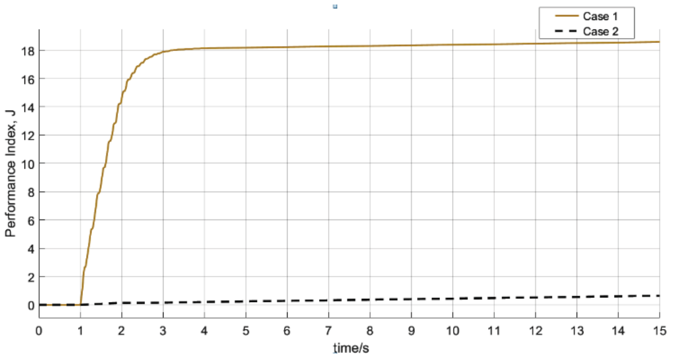

Fig. 12. Performance Index J for Case 1 and Case 2

TABLE 6. COMPARING CASE 1 AND CASE 2

	Frequency overshoot	Frequency undershoot	Settling Time/s	Control Energy u	J at settling time
Case 1	0.006	-0.0013	5.2	Highly oscillatory	18.4
Case 2	-	-0.0065	9.9	Stable	0.41

IV. PERFORMANCE EVALUATION FOR THE DIFFERENT CONTROLLERS

A performance evaluation was performed for the following controllers:

1. Integral controller ($K_I = 6$)
2. Manually tuned PID controller ($K_P=7$, $K_I=10$, $K_D=3$, $N=100$)
3. Matlab Tuned PID controller ($K_P=20.47$, $K_I=13.39$, $K_D=7.73$, $N = 281.27$), where N is the filter coefficient for the Simulink PID block
4. Fuzzy logic controller (Case 2).

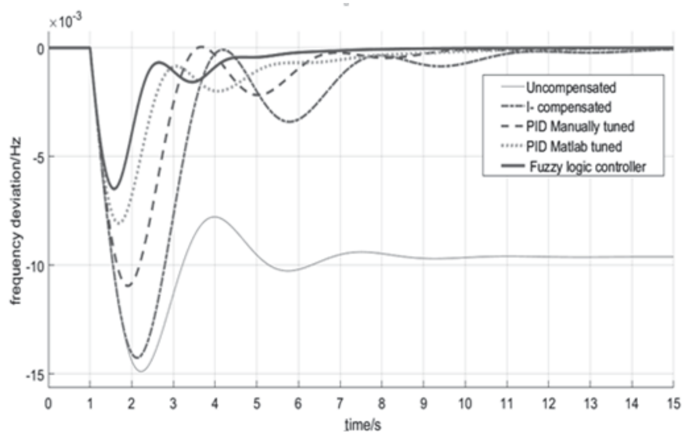

Fig. 13. Frequency deviations for I, PID, and Fuzzy logic controllers

TABLE 7. COMPARISON OF CONTROLLERS

	Under shoot	Fall tims/s	Rise time/s	Settling time/s	Performance Index J at settling time
I only	-0.0143	0.709	1.167	14	0.5
PID (manual)	-0.0109	0.569	1.006	13	0.54
PID (Matlab Tuned)	-0.0081	0.428	3.335	14	0.57
Fuzzy Logic	-0.0065	0.357	2.377	9.8	0.41

V. DISCUSSION

Fig. 13 shows the frequency deviations for the four types of controllers mentioned above. In Table 7, a comparison is made between the controllers. Since all the controllers were optimised, the overshoot is negligible. The undershoots however, are present in all the cases. This is due to the fact that we have simulated a step load demand, whereby the generators experienced a sudden decrease in kinetic energy, and hence a sudden decrease in speed and frequency. The primary frequency control scheme causes the fall in speed to be able to satisfy the step demand. At the same time speed governor commands an increase in generation. In case no controller is used, there is a frequency offset after the settling time, as depicted by the plot 'Uncompensated' in the Fig. 13. The other plots represent compensated systems, that is, secondary frequency control is enabled with the use of controllers that perform load frequency control. This brings back the frequency to its nominal value, thereby bringing the frequency deviation to zero. For any power system, it is desirable to have lesser frequency deviation and fast settling time. As such, from Fig.13, and Table 7, it can be deduced that the fuzzy logic controller gives a better performance than the PID controllers, which is in turn better than the Integral controller. However as mentioned in Section III, the fuzzy logic controller gains were selected so that the control energy at the governor is realistic and the scheme can be implemented in practice. The settling times as well as the performance Index J, are almost equal for the PID and Integral controllers. The system with the fuzzy logic controller, on the other hand, settles faster and has a lower J index. This confirms the superiority of fuzzy logic controllers.

VI. CONCLUSION

In this paper, the performance of different types of controllers for load frequency control are evaluated. Simulations were performed in Simulink, on the single-area network using a set of parameters shown in Table 4. The prime mover, governor and the load were modeled based on standard IEEE standards. Simulations for an uncompensated non-reheat power system gives a steady state error, which indicates the necessity of controllers to bring the steady state error to zero. Thus an Integral controller was used. The value of the integral gain K_I was found out through trial and error. Next the PID controller was implemented. The gains of K_P, K_I and K_D was also determined through trial and error. Further tuning was performed by the PID tuner app from the Matlab Control System Toolbox, which gave slightly better response, in terms of lower undershoots and faster settling times. Further to this, fuzzy logic controllers were designed and simulated using the Matlab Fuzzy Logic toolbox. In the first instance the objective was to minimize the frequency deviation as well as the settling time. However this resulted in large oscillations on the output of the governor. Practically this would mean that the governor valve need to open and close several times in one second, which is undesirable. The gains were then further tuned so as to obtain an acceptable control energy at the governor. It is found that the fuzzy logic controller are superior to the Integral and PID controllers in terms of undershoots, settling time, as well as lesser oscillations. Further works could be carried out for investigating the performance of fuzzy logic controllers for two-area and multiple area power systems.

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