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Comparative Analysis of Fuzzy Logic and Pid Based Frequency Control for Stand Alone Power Network

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ABSTRACT

In this work, Load frequency Control (LFC) based on Optimized Fuzzy Proportional Integral Derivative (OFPID) for stand-alone single area power system is proposed and compared with two other conventional techniques –Fuzzy and PID only, Compensated and Uncompensated with the primary purpose of determining which of the aforementioned techniques gives lower settling time of the frequency control loop and low frequency deviations. A dynamic systems model was developed in MATLAB/SIMULINK from first principles and based on an Integral Time Multiplied Absolute Error (ITAE). Results showed that using OFPID gives better settling time and lower frequency deviations. It is therefore recommended that OFPID be used as a frequency controller in standalone single area power systems.

Key words: Load Frequency Control (LFC), PID, OFPID

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1. INTRODUCTION

The main aim of power systems engineers is to provide the required power supply to customers with a given quality voltage and frequency. Considering the growing energy demand of customers, stability and reliability of power systems are important. Load-Frequency Control (LFC) problem in power system deals with sudden disturbances that disrupt normal conditions of system operation and occur due to outage and connection of loads on different hours in power system. Any change in active power demand is reflected throughout the system as frequency change. The problem of output active power control in response to power system frequency changes and between regional power system lines in a specified range is known as LFC problem. For optimal performance and operation, frequency changes must be maintained within certain limits. Many process control systems, such as computers, are sensitive to changes in frequency and their operation is impaired. For such systems, their frequency must be regulated and controlled [1]. Therefore, adequate supplementary controller to regulate and prevent frequency deviations must be used in the main control center. The purpose of LFC problem is to maintain uniform frequency and adjust/control converted power between areas of power system in a planned manner. In other words, solving LFC problem is aimed at keeping the system’s steady-state error on zero. In previous studies on solving LFC problem, various methods have been used. In the proposed methods, PI controller is most widely used in industry. Proportional Integral (PI) controller has a fixed gain that is designed in rated operating conditions and its utilization is simple, but frequency oscillations can also appear in this case. This means that PI controller indicates poor dynamic performance against system parameters variation and non-linear conditions such as generation rate constraint [2]. Different types of fixed gain controllers are designed in rated operating conditions while they are unable to achieve performance in practice under many changes in the operating conditions of the system. This method made the PID controllers unable to obtaining a dynamical performance for considerable range of operating conditions and also different scenarios of load variations in the three area-power systems in which the research was conducted [3]. In order to solve LFC problem and to minimize power system deviations, operating conditions and system parameters variations must be considered; genetic algorithms and other intelligent methods can be used to improve PI controller performance and optimize controller coefficients. As for the non-linearity of power system and inability to extract its precise mathematical model, in recent years the use of fuzzy logic method in design of controllers was proposed [4]. The aim of the study is therefore to perform comparative analysis of load frequency controllers of stand-alone power system network with the an objective to maintain steady state frequency and desired power output in power system network.

2. LITERATURE REVIEW

Difficulty in finding the right weighting factors limits the application of LQR based controller synthesis. In the proposed methods, PI controller is most widely used in industry and has a fixed gain that is designed in rated operating conditions and its utilization is simple, but frequency oscillations can also appear in this case. This means PI controller indicates poor dynamic performance against system parameters variation and non-linear conditions such as generation rate constraint; From Hameed simulation results, it was observed that the proposed Self-Tuning Fuzzy PI Controller (STFPIC) for Thyristors Controlled Series Capacitor (TCSC) improves system stability significantly [2, 5]. Different types of fixed gain controllers are designed in rated operating conditions while these controllers are unable to achieve performance in practice under many changes in the operating conditions of the system. In order to solve Load Frequency Control (LFC) problem and to minimize power system deviations, operating conditions and system parameters variations must be considered; genetic algorithms and other intelligent methods are used to improve PI controller performance and to optimize controller coefficients. As for the non-linearity of the power system and inability to extract its precise mathematical model, in recent years the use of fuzzy method in design of controllers was proposed [6-9]. In some studies, FL is used to adjust PI controller parameters. The output of Stand-Alone Power Plant varies without any prior schedule due to changes in Electrical load and as such power generation suffers the undesirable effect of frequency instabilities. Frequency instability is a condition whereby the generator output fluctuates in response to variation of load demands on the active power component. This challenge is capable of causing instability in power system. The needs and technologies for ubiquitous continuous fast acting distributed load participation in frequency control at different time scales have started to grow in the last decade or so. The idea however dates back to late 1970s. [10]. Its deployment is to "assist or even replace turbine-governed systems and spinning reserve". Schweppe [10] also proposed to use spot prices to incentivize users to adapt their consumption to true cost of generation at the time of consumption. Remarkably it was emphasized back then that such frequency adaptive loads would "allow the system to accept more readily stochastically fluctuating energy source, such as wind or solar generation. This point is echoed recently to have "grid-friendly" appliances, such as refrigerators, water or space heaters, ventilation systems, and air conditioners, as well as plug-in electric vehicles to help manage energy imbalance. [11]. Simulations in all these studies have consistently shown significant improvement in performance and reduction in the need for spinning reserves. The benefit of this approach can thus be substantial as the total capacity of grid-friendly appliances in the U.S is estimated to be about 18% of the peak demand, comparable to the required operating reserve, currently at 13% of the peak demand [12]. Feasibility of this approach is confirmed by experiments reported in (M. Donnelly [13]) that measured the correlation between frequency at 230 kV transmission substation and at 120V wall outlets at various places in a city in Montana USA. It shows that local frequency measurements are adequate for loads to participate in primary frequency control as well as in the damping of electro mechanical oscillations due to inter-area modes of large interconnected systems. Indeed, small scale demonstration project has been conducted by Pacific Northwest National Lab during early 2006 to March 2007 where 200 residential appliances participated in primary frequency control by automatically reducing their consumption (e.g. heating element of some clothes dryer were turned off while the tumble continued) when the frequency of the household dropped below a threshold (59.95 Hz) [14]. Field trials were also carried out in other countries around the globe, e.g., U.K. Market Transformation Program 2008. Even though loads do not yet provide second-by-second or minute-by-minute *continuous* regulation service in any major electricity markets, the survey of G. Heffner *et al* [15] finds that it already provides 50% of the 2,400MW contingency reserve in ERCOT (Electric Reliability Council of Texas) and 30% of dispatched reserve energy (in between continuous reserve and economic dispatch) in the U.K. market. Long Island Power Authority (LIPA) developed LIPA Edge that provides 24.9 MW of demand reduction and 75 MW of spinning reserve by 23,400 loads for peak power management [16]. While there are many simulation studies and field trials of frequency-based load control, there is not much analytic study that relates the behavior of loads and the equilibrium and dynamic behavior of a multi-machine power network. Indeed, this has been recognized and validated by the investigation carried out by D. Trudnowski [17] and D. Hammerstrom *et al*. [14] for U. K. Market Transformation Programme 2008. For safe and reliable operation of power system network, frequencies of individual generators must be monitored, regulated and controlled [1]. Thus provision must be made for the use of adequate and supplementary frequency controllers to regulate and as well as prevent frequency variations or deviations from prescribed limits in the main control Centre

3. METHODOLOGY

There are three parts of Load Frequency Control (LFC) scheme for single generating plant and it will be modeled accordingly. These are; Load and Generator, Turbine and Governing system for Turbine speed

3.1 Load and Generator Model

Application of synchronous machine swing equation to a small disturbance and perturbation is as shown in equation 3.1

$$\frac{2H}{\omega_s}\frac{d^2\Delta\delta}{dt^2} = \Delta P_m - \Delta P_e \qquad 3.1$$

Or in term of small change in speed:

$\frac{d\Delta\frac{\omega}{\omega_s}}{dt} = \frac{1}{2H}(\Delta P_m - \Delta p_e)$ 3.2

With speed expressed in unit without considering unit representation:

$\frac{d\Delta\omega}{dt} = \frac{1}{2H}(\Delta P_m - \Delta P_e)$ 3.3

Applying Laplace transform, Equation (3.3) becomes:

$\Delta\Omega(s) = \frac{1}{2Hs}[\Delta P_m(s) - \Delta P_e(s)]$ 3.4

Where; ΔP_m = change in mechanical power, ΔP_e = change in electrical power, H_S =Generator inertia, ω = frequency. This is shown in block diagram of Fig 3.1

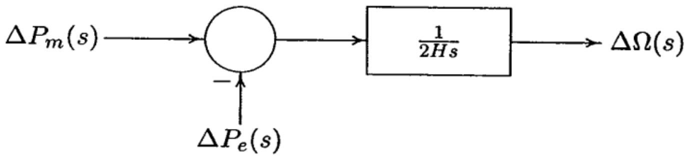


Fig. 3.1 Block Diagram of Generator model for power plant

System power input increases in two ways:

i) Rate at which kinetic energy is stored in the Generator rotor. ii) Changes in frequency responsible for changes in the motor load. This effect causes the speed also to be sensitive to changes in load.

3.2 Load Model

Electrical system loads comprises of different kinds of devices such as capacitive, inductive and resistive. Resistive loads like heating and lighting do not depend on frequency but, motor loads are sensitive to variations in frequency. Sensitivity of frequency depends on speed-load characteristics of all the driven devices. For multiple loads, speed-load characteristic is given as:

$\Delta P_e = \Delta P_L + D\Delta_W$ 3.5

Where,ΔP_L=Non-frequency sensitive load change,Δ_W= Change in Frequency, D= Ratio of the percentage change in load to frequency.

Combining the Generator model and load result in Fig 3.2 and modified diagram of Generator and Load model is shown in Fig 3.3

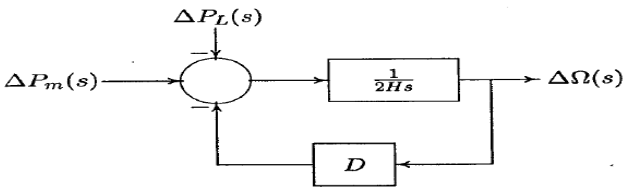


Fig. 3.2 Block Diagram of Generator and Load model

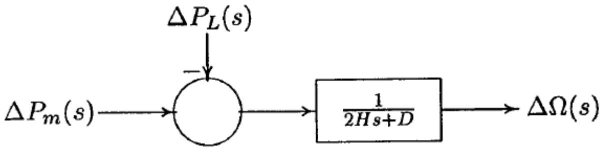


Fig. 3.3 Modified Diagram of Generator and Load model

3.3 Turbine System

Prime mover which is a source of mechanical power may be hydraulic, as water fall, steam or gas turbines. The turbine model relates variations in mechanical output powerΔP_m to change in the position of steam valve, ΔP_V. The simplest model of steam turbine for non-reheat with a single time constant can be represented by the transfer function of equation 3.6.

$G_T(s) = \frac{\Delta P_m(s)}{\Delta P_V(s)} = \frac{1}{1+\tau_T s}$ 3.6

$G_T(s)$ **=** Turbine gain, τ_T = Turbine time constant, Time constant r_T is between 0.2 to 2.0 seconds

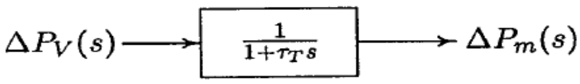


Fig. 3.4 Block Diagram for a simple non-reheat steam turbine

3.4 Speed Governing System

Sudden increase in Electrical load demands for increase in power generation to meet load demand. This increment in generated power exceeds mechanical power input. The deficiency in Mechanical power is provided by kinetic energy that is stored in the rotating system. Reduction in kinetic energy is responsible for reduction in turbine speed and when this occurs, generator frequency falls. Variation in speed is detected by turbine governor which adjusts its input by regulating the valve position to changes in mechanical output power to regulate the speed to steady-state. Watt governors were the first governors to regulate speed with rotating fly-balls and provide mechanical movement in reaction to speed changes. Some challenges and limitations of Watt type governors exist such as backlash and dead band. The design of these governors is purely mechanical. Thus, their operations are slower than electronic governors. Equations 3.7-3.8 and their respective block diagrams represent the speed governing system model. The speed control device performance like a comparator whose power output, $\Delta P_g(s)$is the difference between $\boldsymbol{\Delta P_{ref}(s)}$ and$\frac{\mathbf{1}}{\boldsymbol{R}}\boldsymbol{\Delta\Omega(s)}$.

$$\Delta P_g(s) = \Delta P_C(s) - \frac{1}{R}\Delta\Omega(s) \qquad 3.7$$

The hydraulic amplifier transformed$\Delta P_g(s)$ to the valve position of the steam$\Delta P_g(s)$. Considering a linear relationship, a simple time constant and gain constant K_g which is set at 1, we have:

$$\Delta P_V(s) = \frac{1}{1+rg}\Delta P_g(s) \qquad 3.8$$

K_g = Speed governor gain, R = governor speed regulation, r_g = speed governor time constant, P_v = setting of steam valve, P_g = output of generator which is equal to turbine output when losses are neglected, Ω= system frequency deviation. Fig 3.5 shows block diagram of speed governing system for steam turbine

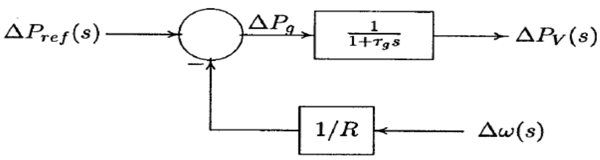


Fig. 3.5 Block diagram of speed governing system for steam turbine

Combining the block diagrams of Figs. 3.2 -3.5 gives load frequency control block diagram of an isolated power system as shown in Fig 3.6.

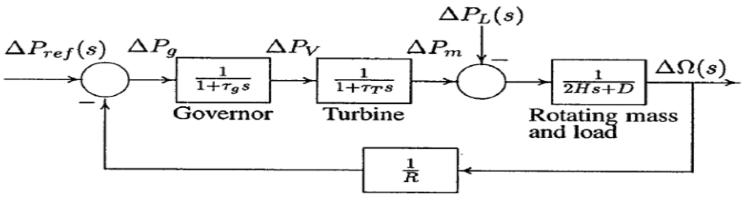


Fig. 3.6 Load frequency control of an isolated power system

Again, where load varies, -ΔP_L(s) is taken as input and the frequency deviation is ΔΩ(s).The output results in Fig.3.6. Thus, power systems model will include generator, turbine model, load model and speed governor which is needed for implementation of power systems frequency control. Fig 3.7 shows Load frequency control with input -ΔP_L(s) and output ΔΩ(s)

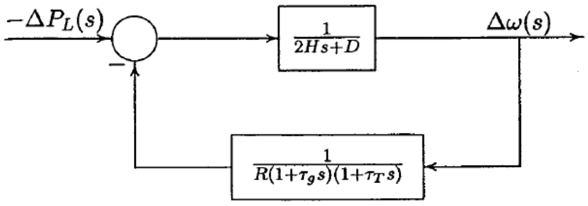


Fig. 3.7 Load frequency control with input -ΔP_L(s)and output ΔΩ(s)

. The architectural systems view of Optimal Fuzzy PID (OFP) model is as shown in Fig 3.8.

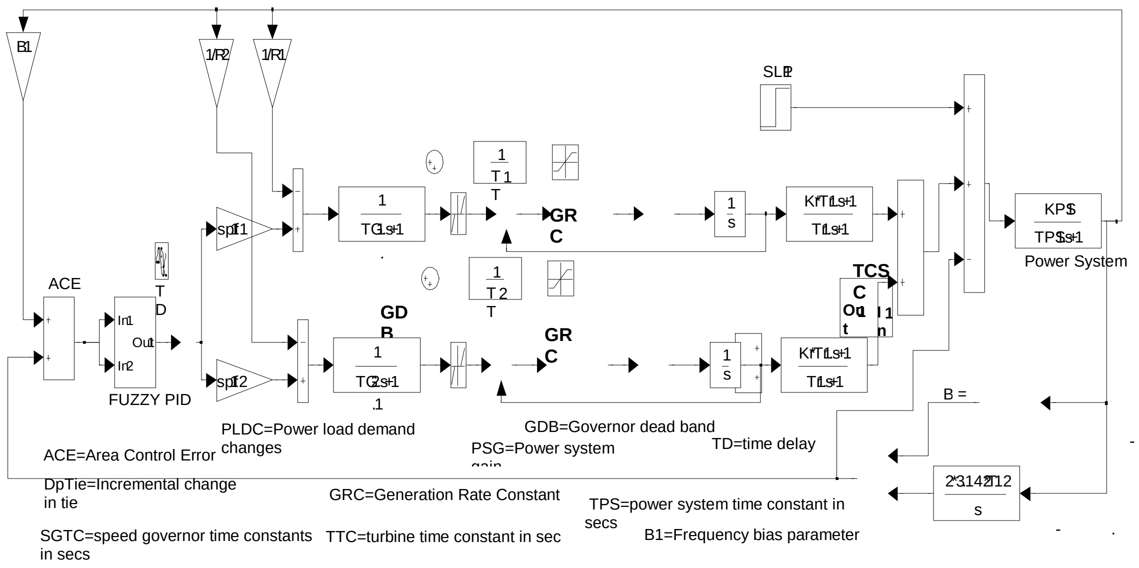


Fig. 3.8 Stand Alone Frequency Control Power System

3.5 Fuzzification

Fuzzification is the method of presenting actual values in form of numbers into a fuzzy set of variables. These variables are defined in accordance with the system to which FL is applied. For this paper, change in frequency (ΔF) and change in error (ΔE) are input variables to the FL controller. These inputs are linked to their corresponding fuzzy variables by matching membership values. The triangular membership function that has seven linguistic variables are used in this study. The linguistic variable is defined as a natural language representation of a variable. For this work, the linguistic variables used are: NL (Negative Large), NM (Negative medium), NS (Negative small), ZERO (ZE), PS (Positive small), PM (Positive Medium), PL (Positive Large). The respective linguistic variable has a membership value as presented in Fig 3.9

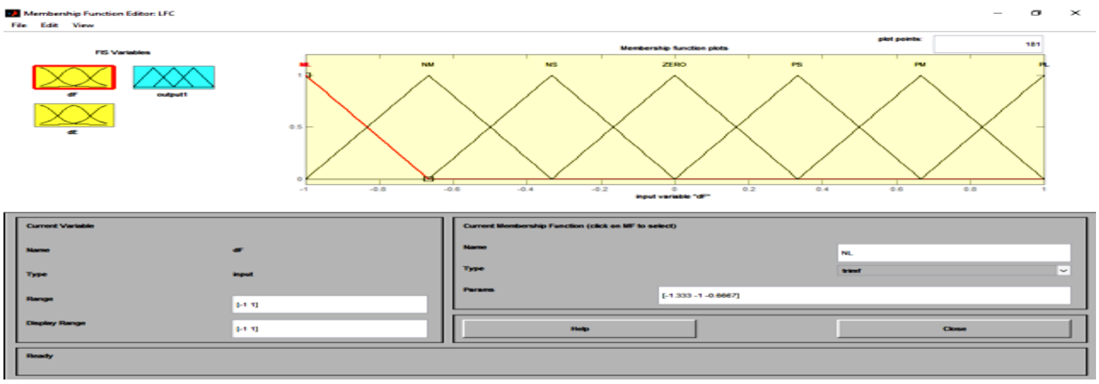


Fig. 3.9 Membership Function of Δf and ΔE

3.6 Knowledge Base

Knowledge base of FLC consists of set of rules of IF-THEN statements. These statements contain membership function of fuzzy subsets. The first rule highlighted in the Rule Editor is: *IF change in frequency (ΔF) is NL and change in Error (ΔE) NL, THEN output is NL. The rules are 49 in number*.

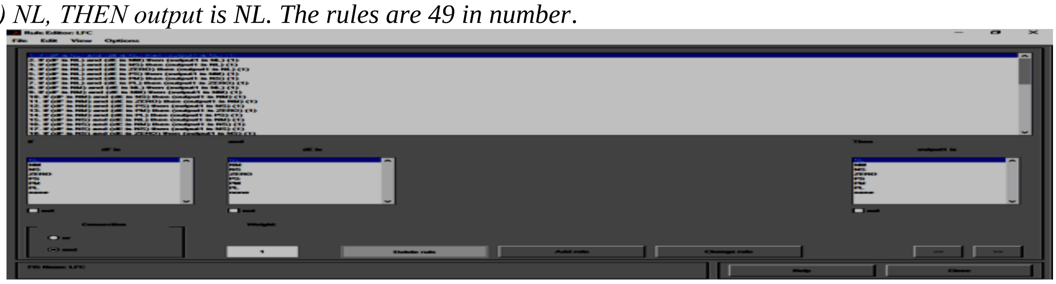


Fig. 3.10 Rule editor interface of FLC

Selection of the exact shape that matches the membership is obtained by permutations and at times by trial & error method. These rules relate input signals to output control signal. Because of computational simplicity of mamdani product implication inference, it was used to modify the output signal. Fuzzy inference system: The empirical rules of knowledge base are used to regulate fuzzy controller as shown in figure 3.10 and results of these rules is shown in the Table 3.1

Table -3.1 Rule base for FLC

ΔF / ***ΔE***	**NL**	**NM**	**NS**	**ZE**	**PS**	**PM**	**PL**
NL	NL	NL	NL	NL	NM	NS	ZE
NM	NL	NL	NL	NM	NS	ZE	PS
NS	NL	NL	NM	NS	ZE	PS	PM
ZE	NL	NM	NS	ZE	PS	PM	PL
PS	NM	NS	ZE	PS	PM	PL	PL
PM	NS	ZE	PS	PM	PL	PL	PL
PL	ZE	PS	PM	PL	PL	PL	PL

.

3.8 De-Fuzzification

De-fuzzification is adopted to transform the output fuzzy variable to a crisp value that is adaptable for control purposes. These crisp values are adaptable and suitable in practical applications. FLC action matches an increment in change of frequency (ΔF). Therefore, this type of controller will produce zero steady-state error for an input step variation with reference to any step disturbance. These membership functions, knowledge base and method of de-fuzzification basically regulate controllers' performance.

4. RESULTS AND DISCUSSION

The isolated power system under study has the following parameters:

Turbine time constant r_T= 0.5 s, Time constant of the Governor r_g = 0.2 s, Inertia constant of Governor H= 5 kg-m ^2, Regulation of the speed Governor= R.

If the load change by 0.8% for 1% change in frequency (D=0.8) .Regulation of speed governor is set as R = 0.05. The output of rated turbine is 10MW at a frequency of 50 Hz. Load varies suddenly by 2MW (ΔpL= 0.2 per unit) occurs. The task is to determine stable state frequency deviation in Hz and also to obtain time domain performance specifications using the four control techniques under study. Simulation is done in MATLAB R2013a and Simulink environment and to determine which yields better results.

4.1 Without Use of AGC

The time domain specifications and the step response is obtained from the following command and the plot is as shown in Fig 4.1.

pl= 0.2; num= [0.1 0.7 1];, den= [1 7.08 10.56 20.8]; t= 0:02:10; c= -pl* step(num,den,t); plot (t, c), xlabel('t, sec'), ylabel('pu') title('Frequency deviation step response'), grid time spec(num, den)

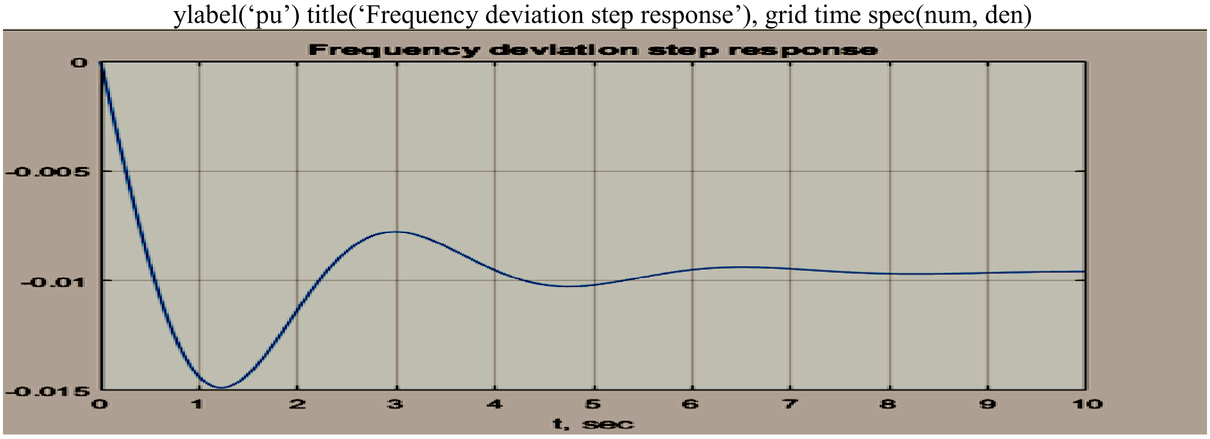


Fig. 4.1 Uncompensated frequency deviation step response without pole placement

Figure 4.1 shows plot of frequency deviation against time response with step increment of 1.0000 seconds for uncompensated system without pole placement. From the figure, it shows that between 0.00-1.200 seconds, there is sharp frequency drop (decrement) linearly from 0.0000 pu -0.0018 pu. After which there is increment in frequency from -0.0018 pu to about -0.009 pu for a time period ranging between 1.200 seconds-3.000 seconds. Then the system starts settling down between 3.000 seconds to 5.000 seconds with frequency deviation of -0.009 pu—0.01 pu and continue to settle until it remained steady at -0.01 pu from 5.00 seconds to 10.000 seconds. The transient response settles to a stable state of -0.0097 pu in about 6.8 seconds.

4.2 Using AGC

Applying equation 2.12, the Matlab program is written as shown:

pl= 0.2; ki= 7; num= [0.1 0.7 1 0]; den= [1 7.08 10.56 20.8 7]; t= 0:.02:12; c= -pl* step (num, den, t);
plot (t, c), grid xlabel (‘t, sec’), ylabel(‘pu’) title (‘Frequency deviation step response’)

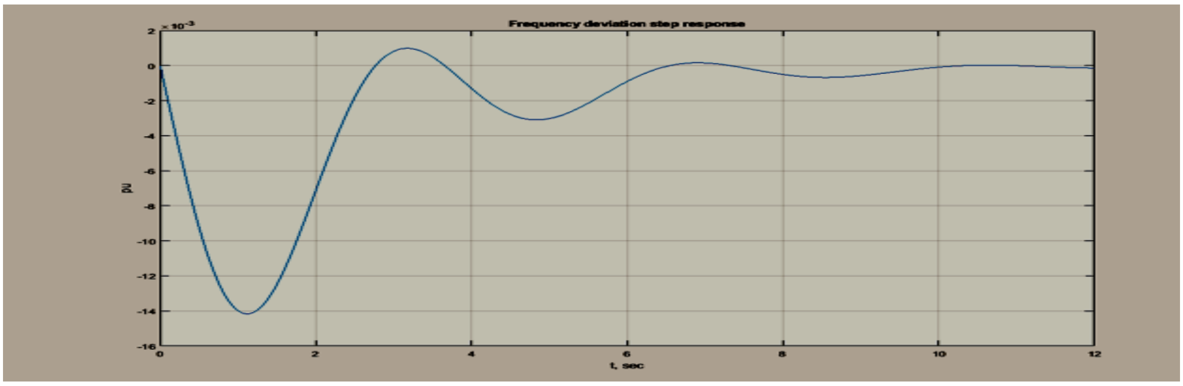


Fig. 4.2 Compensated Frequency deviation step response

Figure 4.2 shows plot of frequency deviation against time response with step increment of 1.0000 seconds for compensated system using AGC. From the figure, it shows that between 0.00-1.000 seconds, there is sharp frequency drop (decrement) linearly from 0.0000 pu -0.0014 pu. After which there is increment in frequency from -0.0014 pu to about +0.001 pu for a time period ranging between 1.000 seconds-3.000 seconds. Then the system starts settling down between 3.000 seconds to 10.000 seconds with frequency deviation of 0.001 pu—0.0009 pu and continue to settle until it remained steady at 0.000 pu from 10.00 seconds. Thus transient response settles to a steady state of 0.000 pu in about 10 seconds.

4.3 LFC Using Optimal Control Design

Performance index of J as given as $\boldsymbol{J} = \int_0^{\infty}\left(20X_1{}^2 + 15X_2{}^2 + 5X_3{}^2 + 0.15U^2\right)dt$

MATLAB CODE:

PL=0.2; A = [-5 0 -100; 2 -2 0; 0 0.1 -0.08]; B = [0; 0; -0.1]; BPL=PL*B; C = [0 0 1]; D = 0; Q = [20 0 0; 0 15 0; 0 0 5]; R = .15; [K, P] = lqr2(A, B, Q, R) Af = A - B*K, t=0:0.02:1; [y, x] = step (Af, BPL, C, D, 1, t); Plot (t, y), grid xlabel('t, sec'),ylabel('pu')

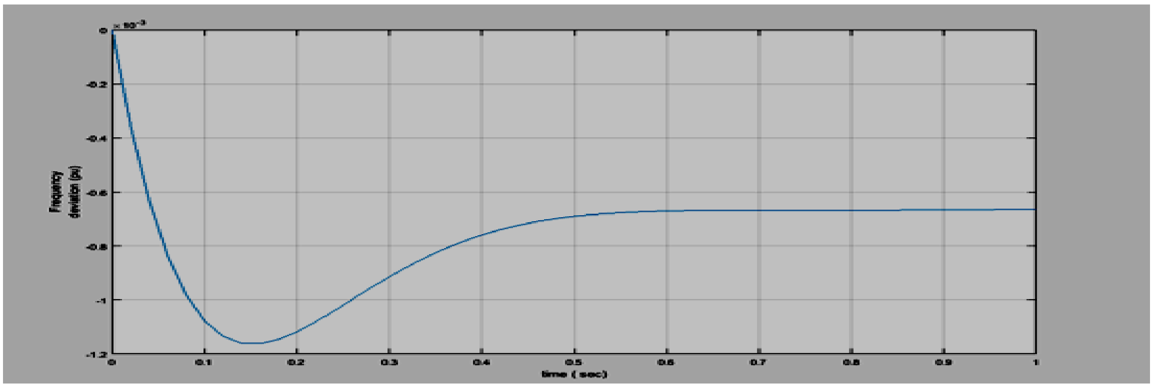
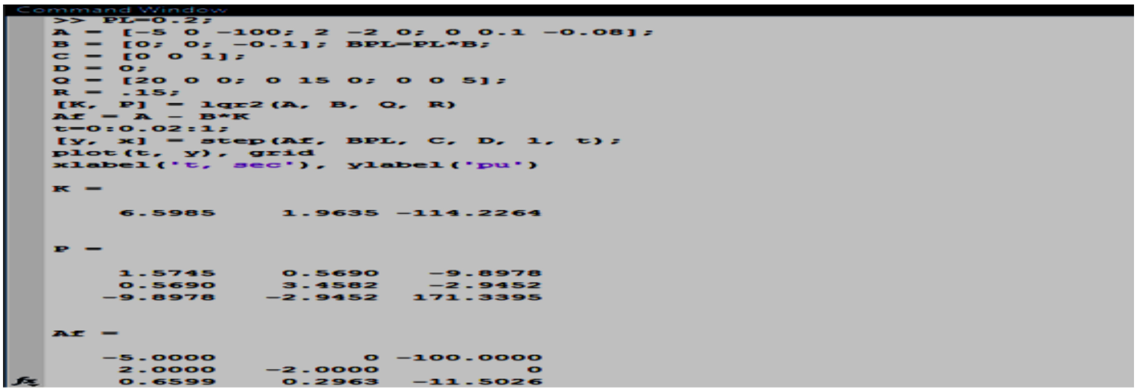


Fig 4.3: Frequency deviation step response of LFC using optimal control design

Figure 4.3 shows plot of frequency deviation against time response with step increment of 0.100 seconds for LFC using optimal control design. From the figure, it shows that between 0.00-0.1050seconds, there is sharp frequency drop (decrement) linearly from 0.000pu to -0.0011pu. After which there is increment in frequency from -0.0011pu to about -0.007 pu for a time period ranging between 0.105 seconds-0.500 seconds. Then the system starts settling down between 3.000 seconds to 10.000 seconds with frequency deviation of 0.001pu-0.0009 pu and continue to settle until it remained steady at 0.000 pu from 10.00 seconds. Thus transient response settles to a steady state of 0.000 pu in about 10 seconds. The transient response settles to a steady state of -0.0007 pu in about 0.6 seconds. The results for k, p and Af are shown in fig 4.4.



```
Command Window
>> PL=0.2;
A = [-5 0 -100; 2 -2 0; 0 0.1 -0.08];
B = [0; 0; -0.1]; BPL=PL*B;
C = [0 0 1];
D = 0;
Q = [20 0 0; 0 15 0; 0 0 5];
R = .15;
[K, P] = lqr2(A, B, Q, R)
Af = A - B*K
t=0:0.02:1;
[y, x] = step(Af, BPL, C, D, 1, t);
plot(t, y), grid
xlabel('t, sec'), ylabel('pu')

K =

    6.5985    1.9635 -114.2264


P =

    1.5745    0.5690   -9.8978
    0.5690    3.4582   -2.9452
   -9.8978   -2.9452  171.3395


Af =

   -5.0000         0 -100.0000
    2.0000   -2.0000         0
    0.6599    0.2963  -11.5026
```

Fig. 4.4 Values of K, P and Af

4.4. Load Frequency Control Using Fuzzy Logic and PID Design

Fuzzy logic and PID were simulated in a Simulink block of the studied FLC.

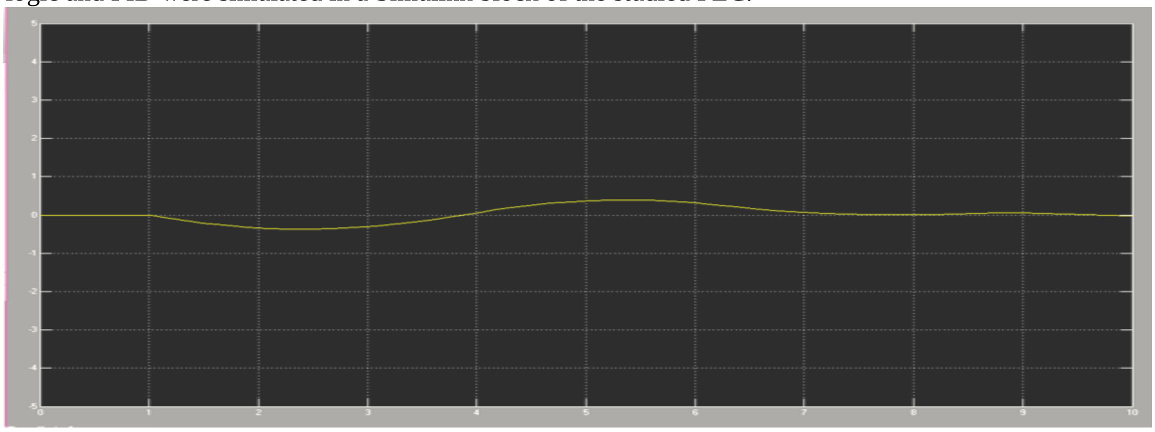


Fig. 4.5 Frequency deviation step response of LFC using PID and fuzzy logic design

Figure 4.5 shows plot of frequency deviation against time response with step increment of 1.000 second for LFC using PID and fuzzy logic design. From the figure, it shows that between 0.00-1.00 second, there is no increment in frequency as it maintain zero (0) value. After which there is decrease in frequency from 0.000pu to about -0.007pu for a time period ranging between 1.000second - 3.000seconds.Then there is increase in frequency from -0.007pu to about 0.003pu for a time period ranging between 3.000second - 6.000seconds Then the system starts settling down between 6.000 seconds to 10.000seconds with frequency deviation of 0.003pu-0.0009pu and continue to settle until it remained steady at 0.000pu from 7.00seconds. Thus transient response settles to a steady state of 0.000pu in about 10seconds. Thus the result shows that optimal controller and that of PID/Fuzzy logic controller have low settling time than the four other controllers considered in the work, but PID/Fuzzy logic controller is more stable with better performance than others.

4.5. Comparison of Controllers Settling Time and Frequency Deviation:

Table 4.1 shows comparison of various controllers used for the study. The result shows that optimal controller and that of PID/Fuzzy logic controller have low settling time than the other controllers considered in the work. More so, PID/FL controller is more stable with better performance than others.

Table -4.1 Comparison of Controllers

Controllers	**Frequency deviation**	**Settling time**
Uncompensated system	0.0097pu	6.8 seconds.
Compensated system	0pu	10 seconds
Fuzzy and PID	0pu	6 seconds
Optimal Control	-0.0007pu	0.6seconds

5. CONCLUSION

A model has been developed that can facilitate the design of Optimal FUZZY-PID (OFPID) frequency controllers. This very important requirement is needed by power systems engineers to model effectively the behavior or operational effects of standalone systems. Such a systems model can be further built into more sophisticated model including newer or better optimization algorithms in the nearest future. In this research, a 12.5MVA turbine that was installed at Oloma community in Bonny local government area fluctuates in its output due to load demand. To solve this problem different frequency controller were selected and studied to ascertain their efficiency with regards to settling time & frequency deviation. A discovery from the study shows that, the Optimal Fuzzy PID (OFPID) logic controller is suitable and stable than other controllers due to its minimal deviation.

PID controllers are widely used in industrial applications and also to solve control problems but do not provide system optimal control, thus giving poor performance when used alone because PID loop gains are minimized to avoid overshoot in the control system. They have difficulties when dealing with non -linear system as in case of frequency control due to time lag in responding to large disturbances. For this problem, a distributed LFC synthesis is formulated as an H- infinity-control problem which proffered solution by means of an algorithm that uses iterative linear matrix inequality to design PID controllers in power system of more than a single-area network. PID controllers were used in a power system of three-area network with a variation of wide range of load demand. The result obtained was that, the controllers were quite effective in minimizing the effect of disturbance and also maintaining robust performance. However, the drawback of this approach was that, the parameters of the PID controllers were manipulated using classical or trial-and-error method.

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