



COMPARATIVE STUDY OF META-HEURISTIC AND CLASSICAL TECHNIQUES FOR AUTOMATIC GENERATION CONTROL OF A MULTI-SOURCE SINGLE-AREA HYDRO-THERMAL-GAS POWER SYSTEM

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ABSTRACT

The PID controller still remains a widely used and very effective means of achieving stability in control systems. Generally, the performance of the controller is determined by the proportional, integral and derivative gains of the controller. The classical techniques: Ziegler-Nichols (ZN) open loop method; ZN closed loop method; Chien-Hrones-Reswick (C-H-R) load rejection method; and meta-heuristic technique: the fuzzy logic algorithm, are used to determine the tuning parameters of the PID controller in this study. The performance comparison of these controllers is done for automatic generation control (AGC) of a multi-source single-area hydro-thermal-gas power system. In such power systems, each source has a participation factor that determines its contribution to total power generation. The root mean square error (RMSE) is deployed to determine the proportionate balance of each generator's output with its corresponding participation factor. The performance comparison of the controllers using Simulink/MATLAB shows that the fuzzy-PID controller achieved the most proportionate generation balance.

KEYWORDS

Automatic generation control, frequency stability, meta-heuristic, multi-source, classical techniques, fuzzy-PID.

1. INTRODUCTION

It has widely been reported that load disturbances in power systems result in corresponding system frequency changes (Fitri et al., 2017; Rahman et al., 2017). One of the main objectives of automatic generation control (AGC) is to sustain the system frequency as close to nominal as possible or within the specified range. The AGC is the system for adjusting the power output of generators. These generators usually receive kinetic energy from turbines which in turn receive potential energy from various fuel sources which include: hydro, steam (thermal), gas (combustion), wind, etc. Each of these sources acts alone in single-source power generation. Meanwhile, when two or more are combined, they create multi-source power generation. In multi-source (hybrid) power generation, each generator has a participation factor that determines its contribution to total power generation. The generators' outputs change in proportion to its participation factor. It has been established that the summation of participation factors of all participating generators, in each control area, is equal to unity (Barisal and Mishra, 2017).

The AGC has received attention in literature for several years now. According to Barisal and Mishra (2017), AGC was initiated by Cohn (1957). In the past decades, various works on AGC (Debnath et al., 2017; Elsisi et al., 2015; Jadhav and Vadirajacharya, 2012; Panigrahi et al., 2017; Pradhan et al., 2017; Rajesh and Rajagopal, 2017) have been proposed and implemented. It is readily observed in these works that the proportional-integral-derivative (PID) controller was used and various techniques were used to determine the gains of the PID controller. A PID controller continuously estimates an error value as the difference between a desired set point and a measured process variable and applies a correction based on the contribution of the proportional, integral, and derivative terms (Chen, 1996).

Techniques for determining the gains of the PID controller can basically be categorized into classical techniques and meta-heuristic techniques. The most widely used classical technique for PID tuning is the Ziegler-Nichols (ZN) tuning methods. Kumar and Patra (2016) applied ZN methods for tuning PID controller for a fourth order plant; Chandrakala et al. (2014) used ZN method to tune PI controllers of a designed multi-source multi-area system by keeping the process under closed-loop P control; Singh and Singh (2014) compared ZN tuned PID controllers for load frequency control of electrical plants using Matlab/Simulink. Basically, Ziegler-Nichols has two PID tuning methods: closed loop method and open loop method. The ZN closed loop method is often used more than the ZN open loop method. However, in this paper, both methods would be used for tuning the PID controller in order to ascertain the

effectiveness of both methods. Another classical tuning technique is the Chien-Hrones-Reswick (C-H-R) method which is a modification of the ZN open loop method. Chien, Hrones and Reswick made an observation that there is a difference when tuning for set point response and load disturbance response (Oonsivilai and Marungsri, 2007). Since AGC is aimed at tackling load disturbances, the C-H-R load rejection (0% overshoot) method is also used to determine the gains of the PID controller.

Various meta-heuristics methods have also been proposed and implemented for AGC and very good results were achieved. Guha et al. (2016) utilized quasi-oppositional grey wolf optimization algorithm for load frequency control of a large scale power system; Sahu et al. (2016) employed teaching learning based optimization algorithm for AGC of multi-area power systems with diverse energy sources; Oonsivilai and Marungsri (2007) optimally tuned PID controllers for an AGC system using adaptive tabu search while Panwar and Chahar (2016) compared a fuzzy tuned PID controller with ZN tuned PI and PID controllers for automatic load frequency control of a three-area power system. A meta-heuristic is a general-purpose algorithmic framework that can be applied to different optimization problems with relatively few modifications (Shakrokhii and Zomorodi, 2012). It is formally defined as an iterative generation process which guides a subordinate heuristic by combining intelligently different concepts for exploring and exploiting the search space using learning strategies to structure information in order to find efficiently near-optimal solutions (Dorigo and Gambardella, 1997). A widely used meta-heuristic technique is the fuzzy logic control. Fuzzy logic has proved to be a powerful tool in various fields due to the fact that it can readily accommodate a wide range of operating conditions and it is more readily customizable in natural language terms (Osman and Laporte, 1996). Combining the FLC with the PID controller creates a hybrid self-tuning controller. This is usually termed as the Fuzzy-PID controller.

In this paper, a multi-source (hydro, thermal and gas) single-area power system is modeled. Classical control techniques (ZN and C-H-R methods) and meta-heuristic technique (Fuzzy Logic) are used to determine the gains of the PID controller for AGC of the power system. The participation factors of the generators are varied to compare the proportionate balance of the generators' outputs of each source with its participation factor using the root mean square error (RMSE). The dynamic performances of the ZN, C-H-R and fuzzy logic tuned controllers are then compared using the following performance indices: integral square error (ISE), integral absolute error (IAE), integral time squared error (ITSE) and integral time absolute error (ITAE).

2. METHODOLOGY

2.1. Power system model

Fig. 1 shows the model of a multi-source single area power system. It comprises of hydro, thermal and gas generating units. The hydro unit has a hydraulic speed governor which is the main controller of the hydraulic turbine. The governor varies the water flow through the turbine to control its speed or power output (Al-Odienat and Al-Lawama, 2008). Similarly, the steam unit has its speed governor. Apparently, the governor controls the flow of steam into the turbine according to the power generation output. The steam unit also has a reheat turbine which is considered as prime mover for higher thermal efficiency (Thapar, 2015). In the case of the gas unit, the fuel system is associated with the valve positioner and the fuel system actuator. The valve positioner provides a control pressure to the actuator for controlling the valve. The fuel system generates the fuel supply signal based on fuel demand signal (Sarumathi et al., 2016).

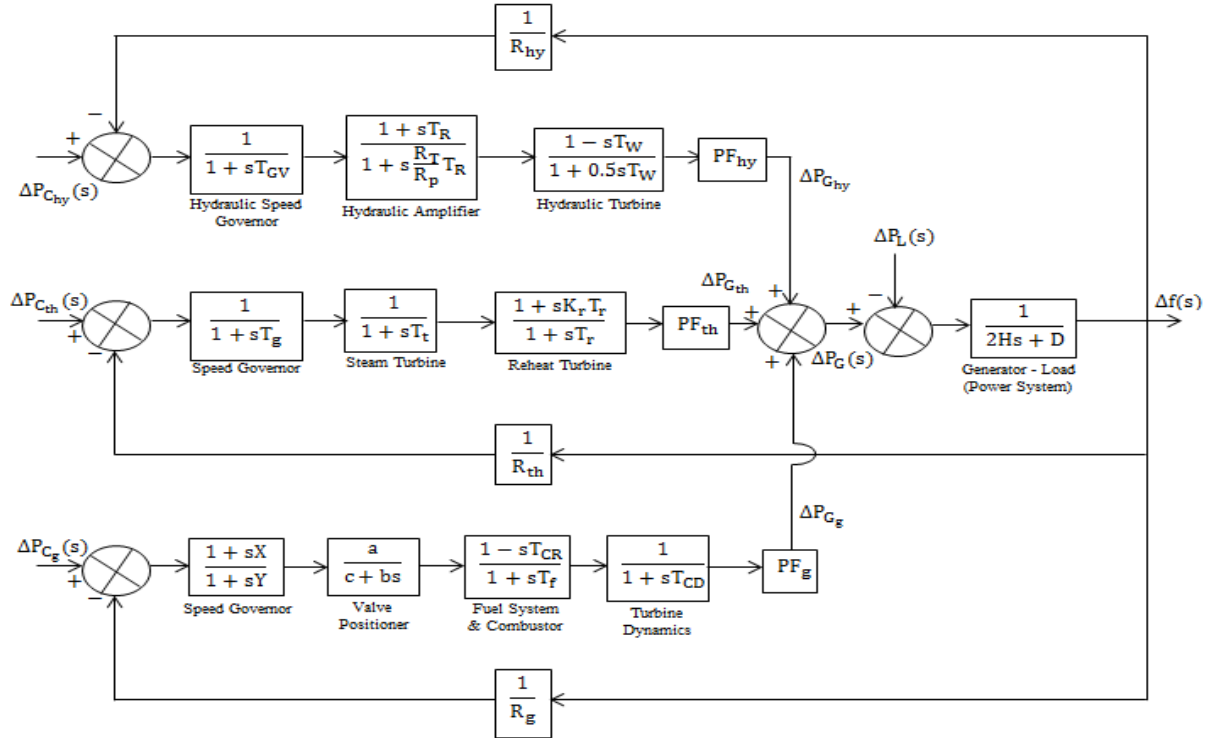


Fig. 1. A multi-source single-area hydro-thermal-gas power system.

The transfer function of a closed loop system with a positive feedback is given by (1).

$$\frac{C(s)}{R(s)} = \frac{G(s)}{1 - G(s)H(s)} \quad (1)$$

Where $G(s)$ is the transfer function of the plant/process and $H(s)$ is the feedback. If we assume that:

$$N = (sT_{GV} + 1)(0.5sT_W + 1)(sR_T T_R + R_{hy})(sT_g + 1)(sT_r + 1)(sT_t + 1)(sY + 1)(sb + c)(sT_f + 1)(sT_{CD} + 1)R_{th}R_g$$

$$O = (2Hs + D)(sT_{GV} + 1)(0.5sT_W + 1)(sR_T T_R + R_{hy})(sT_g + 1)(sT_r + 1)(sT_t + 1)(sY + 1)(sb + c)(sT_f + 1)(sT_{CD} + 1)R_{th}R_g$$

$$P = (sT_R + 1)(sT_W - 1)(sT_g + 1)(sT_r + 1)(sT_t + 1)(sY + 1)(sb + c)(sT_f + 1)(sT_{CD} + 1)PF_{hy}R_{th}R_g$$

$$Q = (sK_r T_r + 1)(sT_{GV} + 1)(0.5sT_W + 1)(sR_T T_R + R_{hy})(sY + 1)(sb + c)(sT_f + 1)(sT_{CD} + 1)PF_{th}R_g$$

$$R = (sX + 1)(1 - sT_{CR})(sT_{GV} + 1)(0.5sT_W + 1)(sR_T T_R + R_{hy})(sT_g + 1)(sT_r + 1)(sT_t + 1)aPF_g R_{th}$$

Then the overall transfer function of the system shown in Fig. 1 is given by (2).

$$\frac{\Delta f(s)}{-\Delta P_L(s)} = \frac{N}{O - P - Q - R} \quad (2)$$

For normal system operating condition, the total generation, P_G , is the sum of generation by each fuel source. This is given by:

$$P_G = P_{G_{hy}} + P_{G_{th}} + P_{G_g} \quad (3)$$

PF_{hy} , PF_{th} and PF_g represent the participation factors of the hydro, thermal and gas source respectively which determines their contributions to the total power generation. The sum of the participation factors is equal to unity.

$$PF_{hy} + PF_{th} + PF_g = 1 \quad (4)$$

From Fig. 1, the governor actions ensure that a large and sudden frequency fall or rise is prevented. This is known as primary control. However, to restore system frequency to its nominal value, secondary control (AGC) is required. To achieve secondary control, a negative feedback is introduced, weighted by a frequency bias constant, β , to the system. The frequency bias constant for a damping factor, D , is given by (5).

$$\beta = \frac{1}{R} + D \quad (5)$$

For the hydro unit, the temporary droop, R_T , is calculated using (6).

$$R_T = [2.3 - (T_W - 1)0.15] \frac{T_W}{2H} \quad (6)$$

The reset time, T_R , is also calculated using (7).

$$T_R = [5 - (T_W - 1)0.5]T_W \quad (7)$$

The parameters for the hydro, thermal (Jagatheesan et al., 2017) and gas (Moghadam and Jalilzadeh, 2014) plants used in modeling the power system are shown in Table 1.

Table 1. Parameters used in modelling the power system.

Source	Parameter	Value
Hydro	Inertia constant (H)	5s
	Damping factor (D)	0.5pu
	Nominal frequency (f)	50Hz
	Time constant (T_{GV})	0.2s
	Reset time (T_R)	5s
	Temporary droop (R_T)	0.23s
	Permanent droop (R_P)	0.046s
	Water starting time (T_W)	1s
	Regulation parameter (R_{hy})	2.4Hz/puMW
	Frequency bias constant (β_{hy})	0.9167puMW/Hz
Thermal	Speed governor time constant (T_g)	0.2s
	Speed reheat turbine time constant (T_t)	0.3s
	Steam turbine reheat coefficient (K_r)	0.5s
	Steam turbine reheat time constant (T_r)	10s
	Regulation parameter (R_{th})	2.4Hz/puMW
	Frequency bias constant (β_{th})	0.9167puMW/Hz
Gas	Speed governor lead time constant (X)	0.6s
	Speed governor lag time constant (Y)	1s
	Valve position constants (a, b, c)	1, 0.05, 1
	Combustion reaction time delay (T_{CR})	0.3s
	Fuel time constant (T_f)	0.23s
	Compressor discharge volume (T_{CD})	0.2s
	Regulation parameter (R_g)	2.4Hz/puMW
	Frequency bias constant (β_g)	0.9167puMW/Hz

The overall system model is shown in [Fig. 2](#).

2.2. Design of the controllers

The controller used is the PID controller which is tuned using Ziegler-Nichols (ZN) open loop and closed loop methods, the Chien, Hrones and Reswick (C-H-R) load rejection method and the Fuzzy Logic Controller (FLC). This is for the purpose of determining the effectiveness and efficiency of each tuning mechanism. An ideal PID controller has the transfer function:

$$G_c(s) = K_P \left[1 + \frac{1}{T_I s} + T_D s \right] \quad (8)$$

K_P is the proportional gain of the controller, τ_i is the integral time constant while τ_d is the derivative time constant.

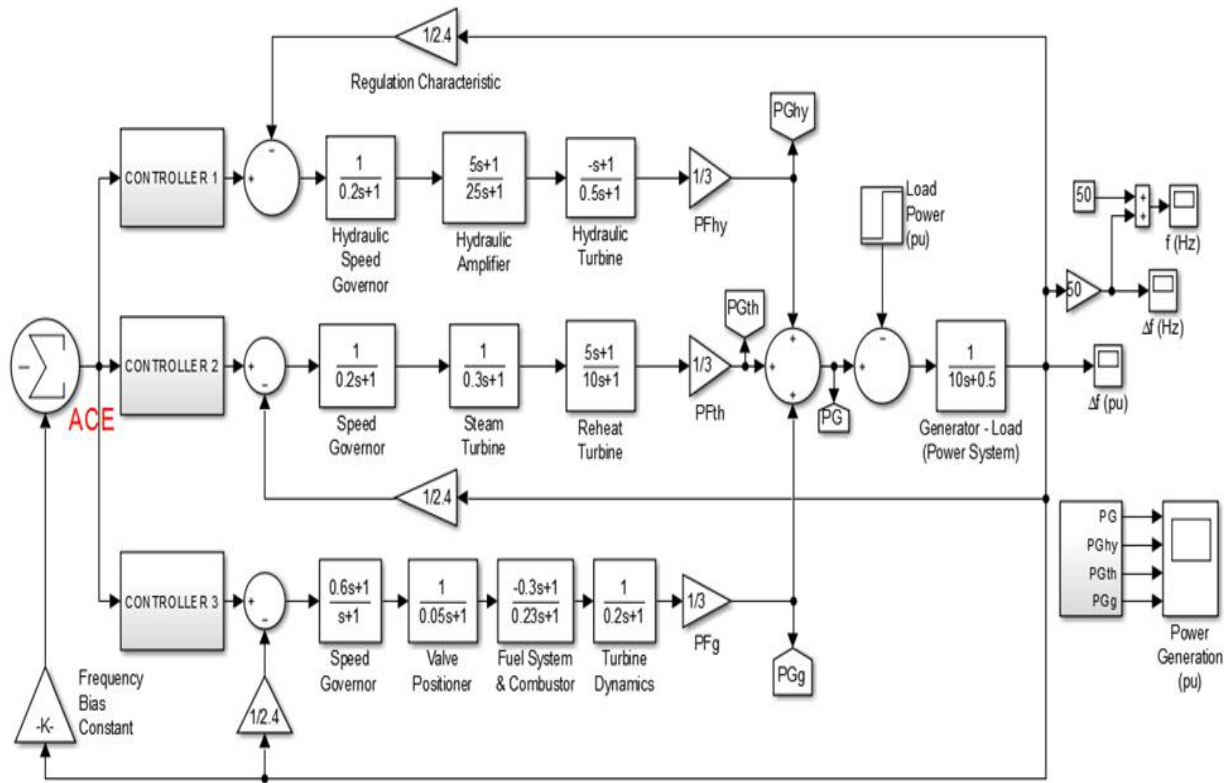


Fig. 2. Overall transfer function representation of the power system.

2.2.1. Ziegler-Nichols open loop and Chien-Hrones-Reswick methods

Ziegler and Nichols tuning methods are PID controller tuning methods through which the parameters of the controller are applied to the process or plant for optimal performance. The ZN open loop method is a robust and popular method for PID controller tuning. When using this method, the unit-step response of the system's open loop transfer function must exhibit an s-shape curve (point of inflection). This curve is characterized by the parameters: delay time, L , time constant, T , and gain, K , (Abdulameer et al., 2016). This is shown in Fig. 3 (Astrom and Hagglund, 1995).

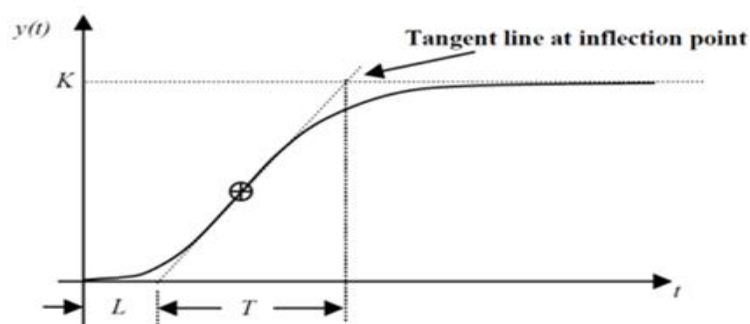


Fig. 3. Parameters for Ziegler-Nichols open loop tuning (Astrom and Hagglund, 1995)

The C-H-R method is also an open loop method. It is, in fact, a modification of the ZN open loop method because the tuning parameters are also based on the delay time and time constant of the system's open loop step response. The C-H-R method has different tuning parameters for set point responses and load disturbance responses (Shakrokh and Zomorodi, 2012). The ZN open loop method and C-H-R load rejection (0% overshoot) tuning parameters for the PID controller are shown in Table 2.

Table 2. Parameters for the PID controller

Tuning method	K_P	T_i	T_d
ZN open loop	$\frac{1.2 T}{K L}$	2L	0.5L
C-H-R load Rejection (0% overshoot)	$\frac{0.95 T}{K L}$	2.4L	0.42L

The primary loop transfer functions of the hydro, thermal and gas sources respectively when acting alone are:

$$\frac{\Delta f}{\Delta P_{C_{hy}}} = \frac{-5s^2 + 4s + 1}{25s^4 + 177.3s^3 + 263.7s^2 + 24.52s + 0.9167} \quad (9)$$

$$\frac{\Delta f}{\Delta P_{C_{th}}} = \frac{5s + 1}{6s^4 + 50.9s^3 + 107.5s^2 + 17.33s + 0.9167} \quad (10)$$

$$\frac{\Delta f}{\Delta P_{C_g}} = \frac{-0.18s^2 + 0.3s + 1}{0.023s^5 + 0.6992s^4 + 5.51s^3 + 15s^2 + 10.87s + 0.9167} \quad (11)$$

The step responses of the transfer functions are shown in Fig. 4.

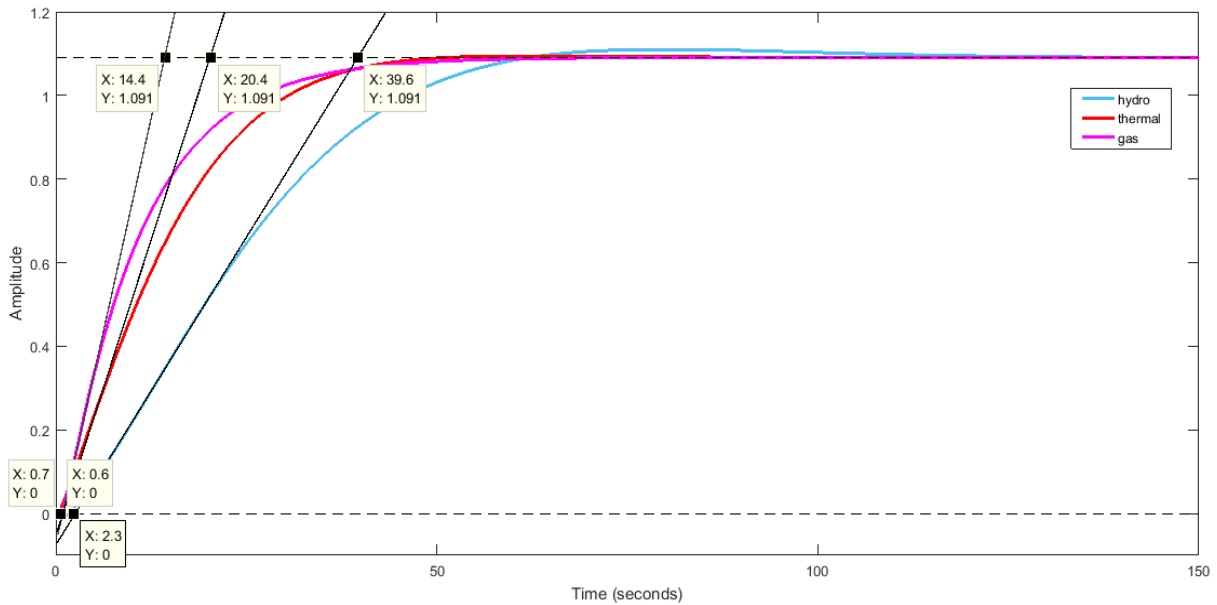


Fig. 4. Primary loop step response.

From Fig. 4, the delay time, L , and time constants, T , for each source, as well as the tuning parameters of the ZN open loop and C-H-R load rejection methods for the PID controller, using Table 2, are shown in Table 3.

Table 3. PID controller parameters using ZN open loop and C-H-R methods.

Tuning method	Source	T	L	K	T_i	T_d
ZN OL	Hydro	37.3	2.30	1.091	4.60	1.15
	Thermal	19.8	0.60	1.091	1.20	0.30
	Gas	13.7	0.70	1.091	1.40	0.35
C-H-R	Hydro	37.3	2.30	1.091	5.52	0.97
	Thermal	19.8	0.60	1.091	1.44	0.25
	Gas	13.7	0.70	1.091	1.68	0.29

2.2.2. Ziegler-Nichols closed loop method

This method has tremendously been implemented by earlier researchers. It is a trial and error method proposed by Ziegler and Nichols (1942). The tuning parameters of the PID controller for the ZN closed loop method are shown in Table 4 (Ziegler and Nichols, 1942).

Table 4. Tuning parameters of the PID controller for the ZN closed loop method.

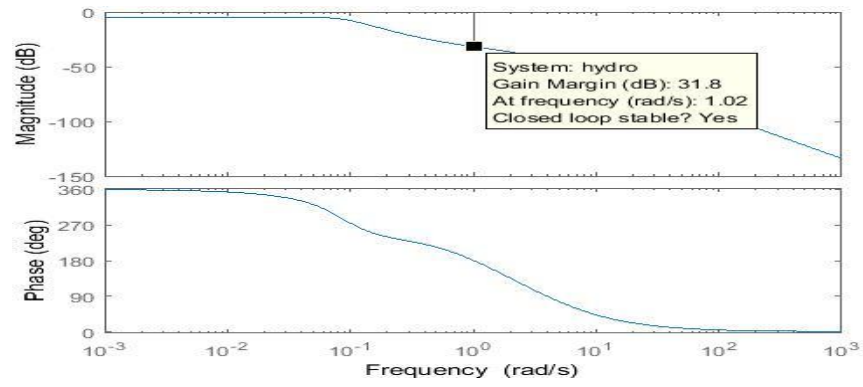
Control Type	K_p	T_i	T_d
Classic PID	$0.6K_{cu}$	$P_u/2$	$P_u/8$
Some overshoot	$0.33K_{cu}$	$P_u/2$	$P_u/3$
No overshoot	$0.2K_{cu}$	$P_u/2$	$P_u/3$

The ultimate control gain, K_{cu} , is the proportional value for which the system exhibits sustained oscillation. The gain margin, G_m , of the system is equal to the ultimate control gain. This is obtained at a gain crossover frequency, ω_{cg} .

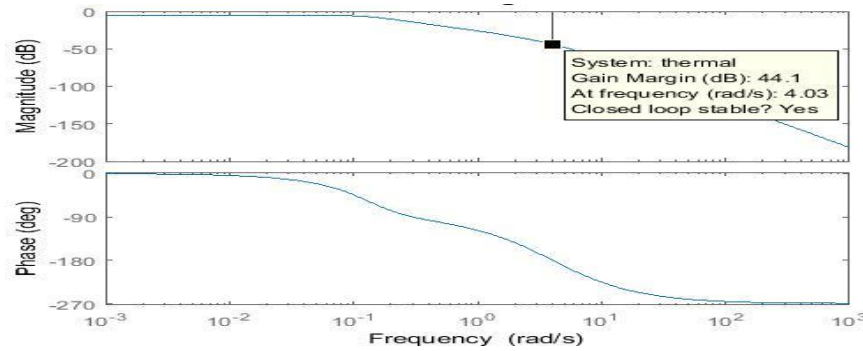
$$K_{cu} = G_m \quad (12)$$

The ultimate or oscillation period, P_u is calculated using (13).

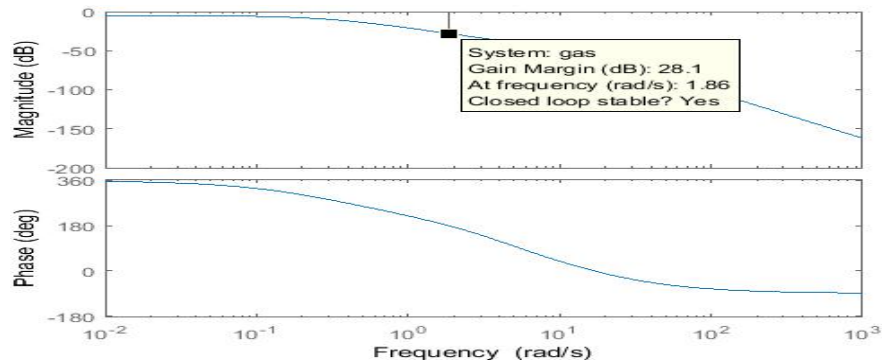
$$P_u = \frac{2\pi}{\omega_{cg}} \quad (13)$$



(a) hydro



(b) thermal



(c) gas

Fig. 5. Bode plots of the closed loop transfer functions.

From the Bode plots of the closed loop transfer function, in Fig. 5, of each source, the gain margins, G_m , and gain crossover frequencies, ω_{cg} , are shown in Table 5. The ultimate periods, P_u , are also shown, as well as the integral time constants, T_i , and derivative time constants, T_d .

Table 5. PID controller parameters using ZN closed loop method.

Source	G_m	ω_{cg}	P_u	T_i	T_d
Hydro	31.8	1.02	6.16	3.08	2.05
Thermal	44.1	4.03	1.56	0.78	0.52
Gas	28.1	1.86	3.37	1.69	1.12

The no-overshoot closed loop tuning parameters from Table 5 are used for the PID tuning. The proportional, integral and derivative gains of the controllers tuned using ZN open loop, C-H-R load rejection and ZN closed loop methods are shown in Table 6.

Table 6. PID gains of the controllers tuned using ZN and C-H-R methods.

Source	ZN open loop			C-H-R			ZN closed loop		
	K_p	K_i	K_d	K_p	K_i	K_d	K_p	K_i	K_d
Hydro	17.84	3.88	20.52	14.12	2.56	13.70	6.36	2.06	13.04
Thermal	36.30	30.25	10.89	28.73	19.95	4.99	8.82	11.31	4.59
Gas	21.53	15.38	5.38	17.04	10.14	2.94	7.21	4.27	8.08

2.2.3. Fuzzy-PID controller

The Fuzzy-PID Controller combines the Fuzzy Logic Controller (FLC) with the PID controller to create a hybrid controller. The Fuzzy interface is used to calculate the values of the PID control parameters (K_p , K_i , K_d). Therefore, it works as an automatic tuner for the PID controller (Jain and Beniwal, 2015). A typical Fuzzy-PID controller is shown in Fig. 6.

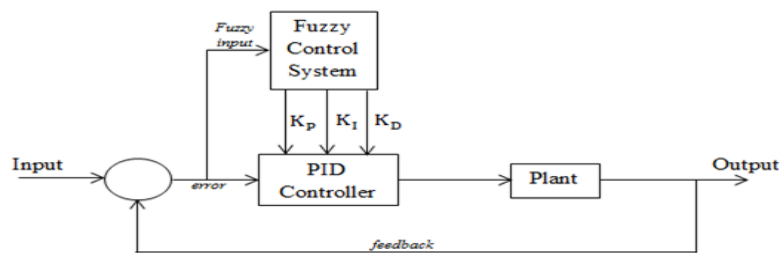


Fig. 6. A typical Fuzzy-PID controller.

Fuzzy Logic Control is described by a knowledge-based Algorithm. A Fuzzy Control System (FCS) basically involves three stages namely Fuzzification, Fuzzy Inference Process and Defuzzification. It requires a database which constitutes parameters obtained from the controlled object whereby this knowledge is used for fuzzification of the input and output. The numerical parameters of the input are converted into a linguistic value. This linguistic value is the fuzzy input. On the other hand, the fuzzy output is the linguistic value inferred by a rule-base as a result of the fuzzy input. In general, there are no systematic tools for forming the rule-base of the FLC (Reusch, 2006). The rule-base is made up of a group of logical rules that relate the input with the output of the FLC. The theoretical and practical understanding of the dynamics of the controlled object forms the basis for the knowledge behind the rule-base. In the design of the Fuzzy-PID controller, the area control error (ACE) and the rate of change of

the ACE (ACE') are taken as the Fuzzy inputs while the proportional, derivative and integral gains of the PID controller are taken as the fuzzy outputs. This is shown in Fig. 7.

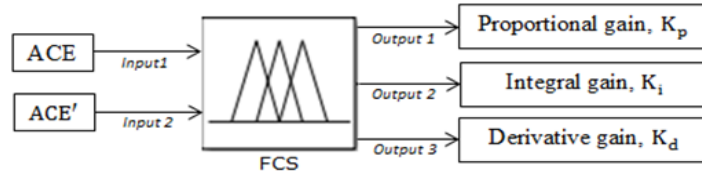


Fig. 7. Input and output variables for the fuzzy control system.

A Mamdani-type fuzzy inference system is used. All 5 inputs and outputs were mapped, using equally spaced Gaussian membership functions, into: {very low (VL), low (L), medium (M), high (H), very high (VH)}. The rules relating the inputs with each output are shown in Table 7.

Table 7. Rules relating the inputs with each output.

ACE \ ACE'	VL	L	M	H	VH
VL	VL	VL	L	L	M
L	VL	L	L	L	M
M	L	M	M	M	H
H	M	H	H	H	VH
VH	H	H	VH	VH	VH

2.3. Performance Indices

Performance Indices are measures used to determine the performance of a control system design for a process. The performance indices are a function of the error signal. Examples include: the integral square error (ISE), the integral absolute error (IAE), the integral time squared error (ITSE) and the integral time absolute error (ITAE) etc. These performance indices are used as the fitness functions for the performance comparison of the tuned controllers, with the change in frequency (Δf) taken as the error, $e(t)$.

In order to measure the proportionality balance between each generator's participating factor and its generation output, the root mean square error (RMSE) is used. The RMSE is the square root of the average of squared errors. It is used to measure the differences between values predicted by a model and observed values. It is given by (14).

$$RMSE = \sqrt{\frac{\sum_{i=1}^N (\hat{y}_i - y_i)^2}{N}} \quad (14)$$

In this case, $\hat{y}_i$ is the predicted/expected power generation and y_i is the actual power generation.

3. RESULTS AND DISCUSSION

Simulations are done using Simulink, MATLAB software for a period of 100 seconds. The multi-source single-area power system is subjected to a 1% (0.01pu) load disturbance using each classically and meta-heuristically tuned controllers. First, for an uncontrolled power system, the frequency dropped and eventually settled at 49.37Hz for a load disturbance of 0.01pu, as shown in Fig. 8(a). This deviation in frequency of the power system after the governors took action doesn't mean there is a lack of generation power but it is due to the characteristics of the governor, especially when the frequency deviation is small (Dinakin and Oluseyi, 2018). As seen in Fig. 8(b), the total power generation for a load disturbance of 0.01pu is 0.0072pu and this is inadequate.

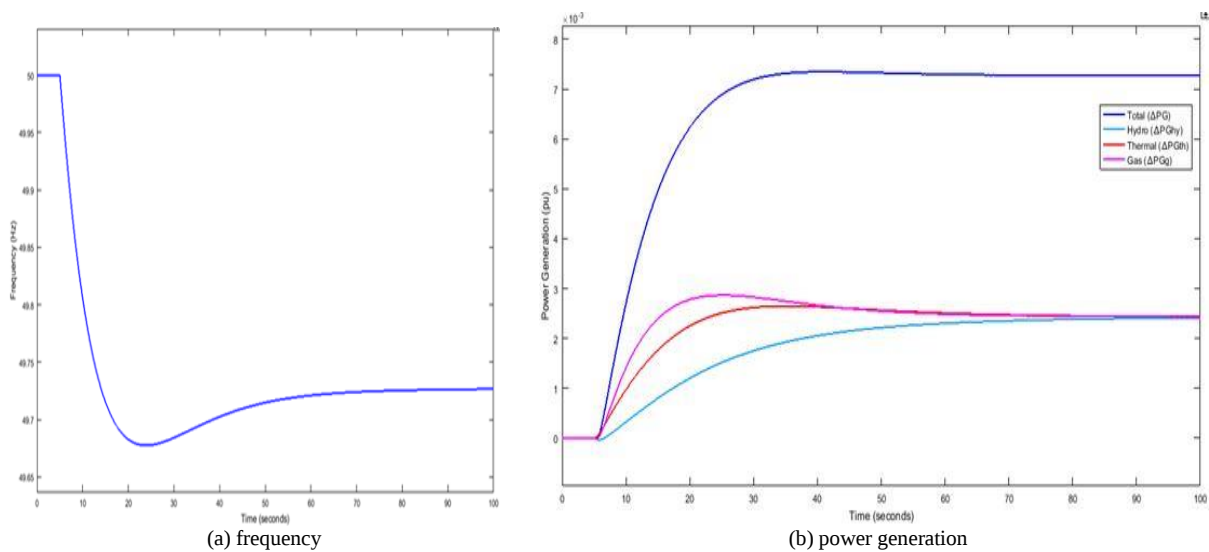
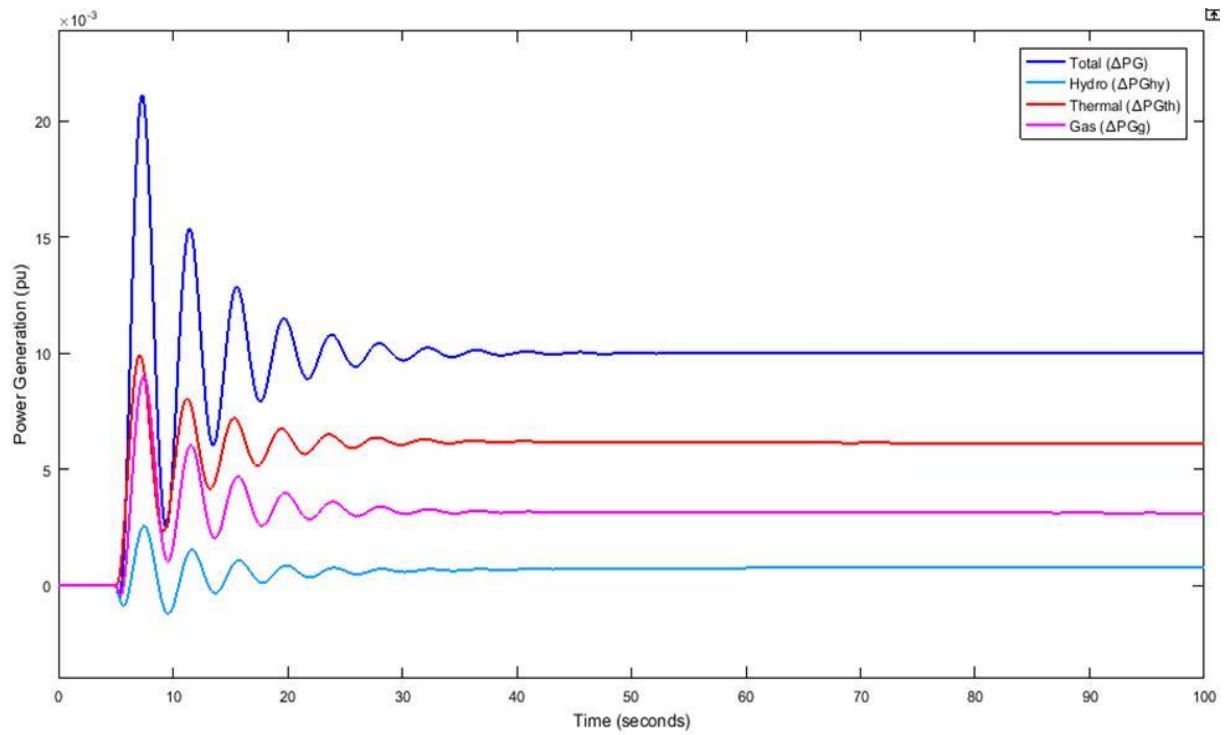
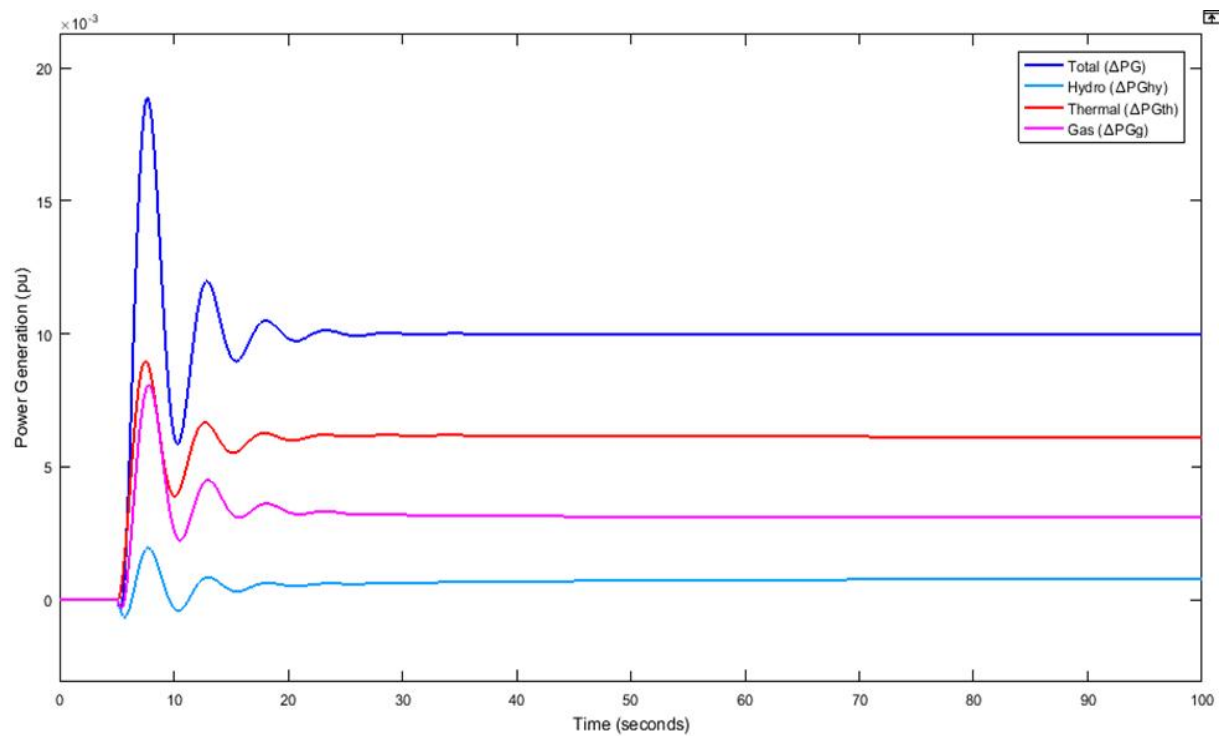


Fig. 8. Output for an uncontrolled system.

The power generation outputs for a 1% load disturbance, as a result of each controller action, for an equal participation factor for each source of 0.3333, are shown in Fig. 9 (a-d).

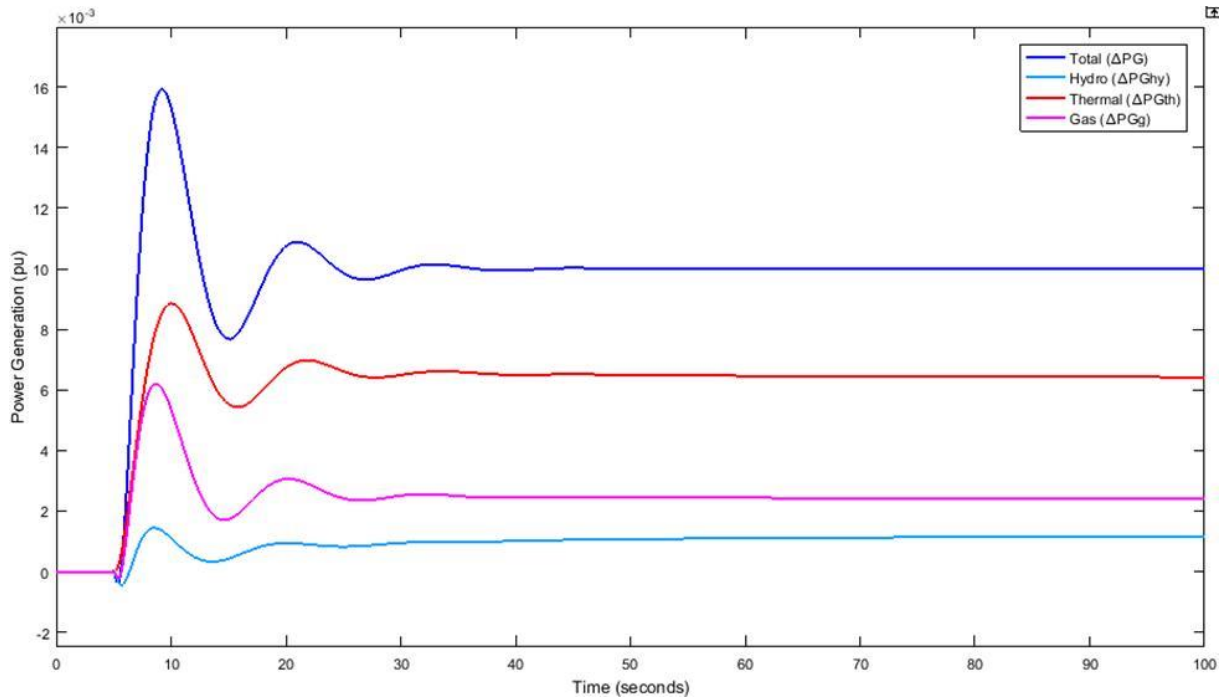


(a) Ziegler-Nichols open loop method

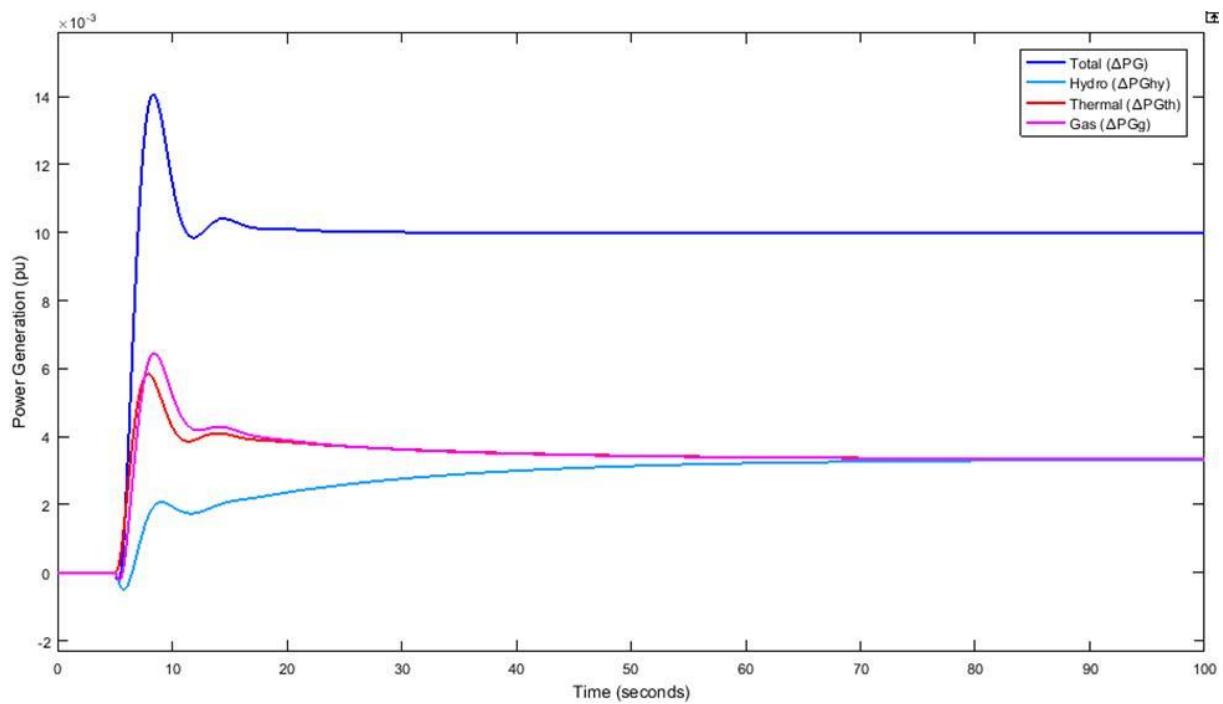


(b) Chien-Hrones-Reswick load rejection method

Fig. 9. Power generation outputs for a 1% load disturbance.



(c) Ziegler-Nichols closed loop method



(d) Fuzzy-PID

Fig. 9. Continued...

From the power generation plots, it is noticed that there is an uneven balance in generation from both ZN tuning methods and C-H-R method despite the participation factors being equal. The thermal source results in the highest generation output for all three methods with a generation output of 0.0061pu for the ZN open loop method, 0.0061pu for the C-H-R method and 0.0064pu for the ZN closed loop method. The generation from the gas source is next to the thermal source

with 0.0031pu, 0.0031pu, 0.0024pu for the ZN open loop, C-H-R and ZN closed loop methods respectively. While the hydro source produces the least power with 0.0008pu for the ZN open loop method, 0.0008pu for the C-H-R method and 0.0011pu for the ZN closed loop method. On the contrary, the Fuzzy-PID controller achieves a balanced generation from each source with an output of 0.0033pu after approximately 60 seconds from the time the system was subjected to the load disturbance. The participation factors of the sources are then varied systematically. The subsequent power generation outputs of each source and the RMSE values are shown in Table 8.

Table 8. Power generation outputs and RMSE values for different participation factors and 1% load disturbance.

Participation Factors			ZN Open Loop $\times 10^{-3}$ (pu)			C-H-R $\times 10^{-3}$ (pu)			ZN Closed Loop $\times 10^{-3}$ (pu)			Fuzzy-PID $\times 10^{-3}$ (pu)			RMSE (pu)			
PF_{hy}	PF_{th}	PF_g	$P_{G_{hy}}$	$P_{G_{th}}$	P_{G_g}	$P_{G_{hy}}$	$P_{G_{th}}$	P_{G_g}	$P_{G_{hy}}$	$P_{G_{th}}$	P_{G_g}	$P_{G_{hy}}$	$P_{G_{th}}$	P_{G_g}	ZN OL	C-H-R	ZN CL	Fuzzy-PID
0.1	0.1	0.8	Unstable			0.2	1.9	7.8	0.4	2.4	7.2	1.0	1.0	8.0	-	0.00070	0.00098	1e-05
0.1	0.2	0.7	Unstable			0.2	3.5	6.3	0.4	4.1	5.5	1.0	2.0	7.0	-	0.00107	0.00156	1e-05
0.1	0.3	0.6	0.2	4.9	4.9	0.2	4.9	4.9	0.3	5.5	4.2	1.0	3.0	6.0	0.00132	0.00132	0.00184	1e-05
0.1	0.4	0.5	0.2	6.0	3.8	0.2	6.0	3.8	0.3	6.6	3.1	1.0	4.0	5.0	0.00142	0.00142	0.00190	1e-05
0.1	0.5	0.4	0.2	7.0	2.8	0.2	7.0	2.8	0.3	7.5	2.3	1.0	5.0	4.0	0.00141	0.00141	0.00180	1e-05
0.1	0.6	0.3	0.2	7.8	2.0	0.2	7.8	2.0	0.2	8.2	1.5	1.0	6.0	3.0	0.00130	0.00130	0.00158	1e-05
0.1	0.7	0.2	0.2	8.6	1.2	0.2	8.6	1.2	0.2	8.8	1.0	1.0	7.0	2.0	0.00113	0.00113	0.00129	1e-05
0.1	0.8	0.1	0.1	9.3	0.6	0.1	9.3	0.6	0.2	9.3	0.4	1.0	8.0	1.0	0.00091	0.00091	0.00096	1e-05
0.2	0.1	0.7	Unstable			0.5	2.1	7.4	0.9	2.5	6.6	2.0	1.0	7.0	-	0.00108	0.00109	1e-05
0.2	0.2	0.6	0.5	3.8	5.8	0.5	3.8	5.7	0.8	4.3	4.9	2.0	2.0	6.0	0.00135	0.00135	0.00164	1e-05
0.2	0.3	0.5	0.4	5.2	4.4	0.4	5.2	4.4	0.7	5.7	3.6	2.0	3.0	5.0	0.00158	0.00159	0.00192	1e-05
0.2	0.4	0.4	0.4	6.4	3.2	0.4	6.4	3.2	0.6	6.8	2.6	2.0	4.0	4.0	0.00170	0.00170	0.00199	1e-05
0.2	0.5	0.3	0.4	7.4	2.2	0.4	7.4	2.2	0.6	7.7	1.7	2.0	5.0	3.0	0.00172	0.00172	0.00191	1e-05
0.2	0.6	0.2	0.4	8.3	1.4	0.3	8.3	1.4	0.5	8.4	1.1	2.0	6.0	2.0	0.00165	0.00165	0.00173	1e-05
0.2	0.7	0.1	0.3	9.0	0.7	0.3	9.0	0.7	0.5	9.0	0.5	2.0	7.0	1.0	0.00152	0.00152	0.00150	1e-05
0.3	0.1	0.6	Unstable			0.9	2.3	6.9	1.4	2.6	5.9	3.0	1.0	6.0	-	0.00152	0.00130	1e-05
0.3	0.2	0.5	0.8	4.1	5.2	0.8	4.1	5.2	1.2	4.5	4.3	3.0	2.0	5.0	0.00175	0.00175	0.00182	1e-05
0.3	0.3	0.4	0.7	5.5	3.8	0.7	5.5	3.8	1.1	5.9	3.0	3.0	3.0	4.0	0.00198	0.00198	0.00210	1e-05
0.3	0.4	0.3	0.7	6.8	2.6	0.7	6.8	2.6	1.0	7.0	2.0	3.0	4.0	3.0	0.00211	0.00211	0.00219	1e-05
0.3	0.5	0.2	0.6	7.8	1.6	0.6	7.8	1.6	0.9	7.9	1.2	3.0	5.0	2.0	0.00215	0.00215	0.00215	1e-05
0.3	0.6	0.1	0.6	8.7	0.7	0.6	8.7	0.7	0.8	8.7	0.5	3.0	6.0	1.0	0.00211	0.00211	0.00202	1e-05
0.4	0.1	0.5	1.3	2.5	6.3	1.3	2.5	6.3	2.0	2.8	5.2	4.0	1.0	5.0	0.00194	0.00194	0.00154	1e-05
0.4	0.2	0.4	1.1	4.4	4.5	1.1	4.4	4.5	1.7	4.7	3.6	4.0	2.0	4.0	0.00218	0.00218	0.00206	1e-05
0.4	0.3	0.3	1.0	6.0	3.0	1.0	6.0	3.0	1.5	6.2	2.3	4.0	3.0	3.0	0.00242	0.00242	0.00236	1e-05
0.4	0.4	0.2	0.9	7.2	1.8	0.9	7.2	1.8	1.3	7.3	1.4	4.0	4.0	2.0	0.00258	0.00258	0.00248	1e-05
0.4	0.5	0.1	0.9	8.3	0.8	0.9	8.3	0.8	1.2	8.2	0.6	4.0	5.0	1.0	0.00264	0.00264	0.00246	1e-05
0.5	0.1	0.4	1.7	2.7	5.5	1.7	2.7	5.5	2.7	2.9	4.4	5.0	1.0	4.0	0.00230	0.00230	0.00176	1e-05
0.5	0.2	0.3	1.5	4.8	3.7	1.5	4.8	3.7	2.3	4.9	2.8	5.0	2.0	3.0	0.00260	0.00260	0.00233	1e-05
0.5	0.3	0.2	1.4	6.4	2.2	1.4	6.4	2.2	2.0	6.4	1.6	5.0	3.0	2.0	0.00289	0.00289	0.00266	1e-05
0.5	0.4	0.1	1.2	7.8	1.0	1.2	7.8	1.0	1.7	7.6	0.7	5.0	4.0	1.0	0.00307	0.00307	0.00280	1e-05
0.6	0.1	0.3	2.3	3.0	4.6	2.3	3.0	4.6	3.4	3.1	3.5	6.0	1.0	3.0	0.00260	0.00260	0.00196	1e-05
0.6	0.2	0.2	2.0	5.3	2.7	2.0	5.3	2.7	2.8	5.2	2.0	6.0	2.0	2.0	0.00300	0.00300	0.00260	1e-05
0.6	0.3	0.1	1.8	7.0	1.2	1.8	7.0	1.2	2.4	6.7	0.8	6.0	3.0	1.0	0.00336	0.00336	0.00297	1e-05
0.7	0.1	0.2	3.1	3.4	3.5	3.1	3.4	3.5	4.2	3.3	2.5	7.0	1.0	2.0	0.00280	0.00280	0.00211	1e-05
0.7	0.2	0.1	2.6	5.9	1.5	2.6	5.9	1.5	3.5	5.5	1.0	7.0	2.0	1.0	0.00338	0.00338	0.00285	1e-05
0.8	0.1	0.1	4.0	3.9	2.0	4.1	3.9	2.0	5.1	3.5	1.3	8.0	1.0	1.0	0.00290	0.00290	0.00220	1e-05

Again, it is seen from Table 8 that the PID controller tuned by the ZN methods and the C-H-R methods result in uneven balance with the participation factors. It is also seen that the ZN open loop method exhibited some unstable system states for four different participation factor combinations. The fuzzy logic tuned PID controller, on the other hand, achieved approximately exact balance of power generation from each source in proportion to its participation factor.

The average generation outputs of each source from Table 8 are represented by the bar chart in Fig 10(a) while the average RMSE is shown in Fig. 10(b).

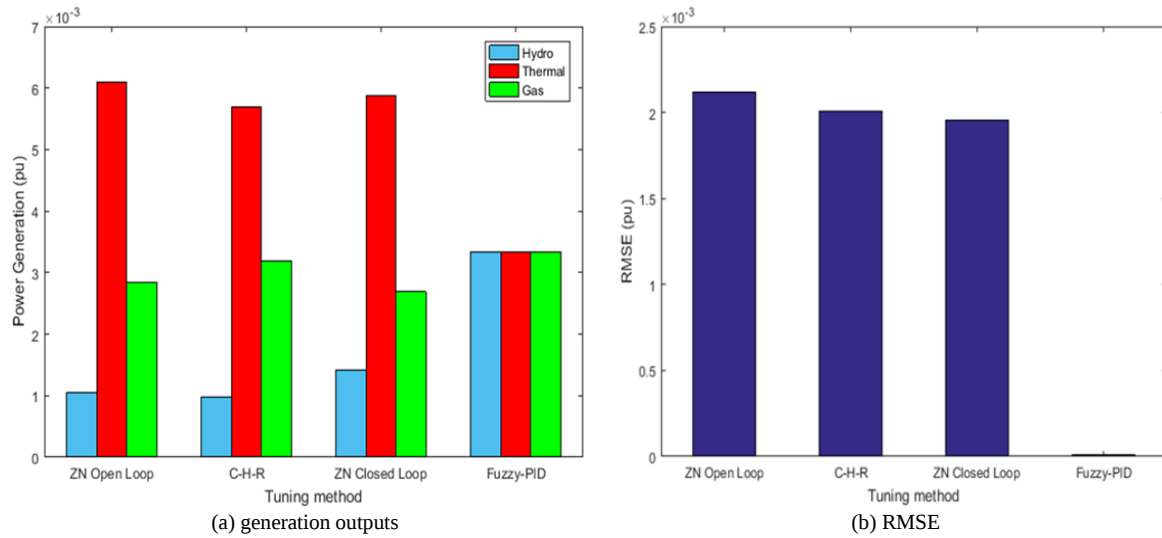


Fig. 10. Bar chart representation of average generation and average RMSE.

In order to achieve a balance between generation and load demand, the ACE must be equal to zero. For a load disturbance of 1%, the ACE based on the action of each controller is shown in Fig. 11(a). It is observed that each controller successfully achieved a zero ACE, thus indicating that total power generation equals load demand. The resulting frequency deviations (Δf), in Hertz (Hz), are shown in Fig. 11(b).

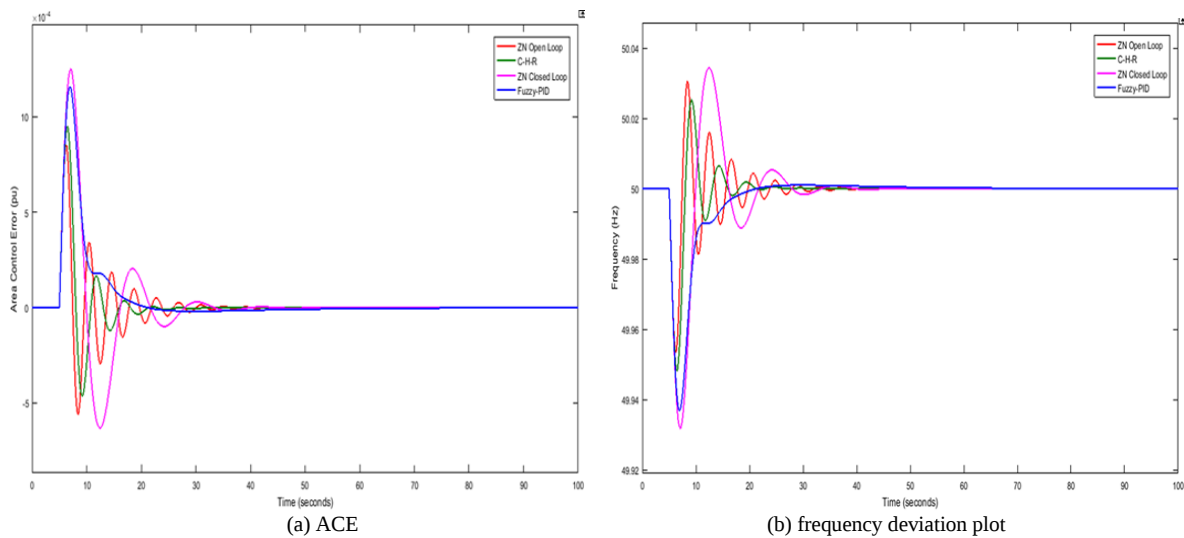


Fig. 11. Controller responses to 1% load disturbance.

All simulations above were done for a load disturbance of +1%. It is also necessary to ascertain that the controllers can adequately deal with negative load disturbances. Therefore, Fig. 12 shows the frequency deviation for a load disturbance of 1% applied after 5 seconds and a load disturbance of -1% applied after 50 seconds.

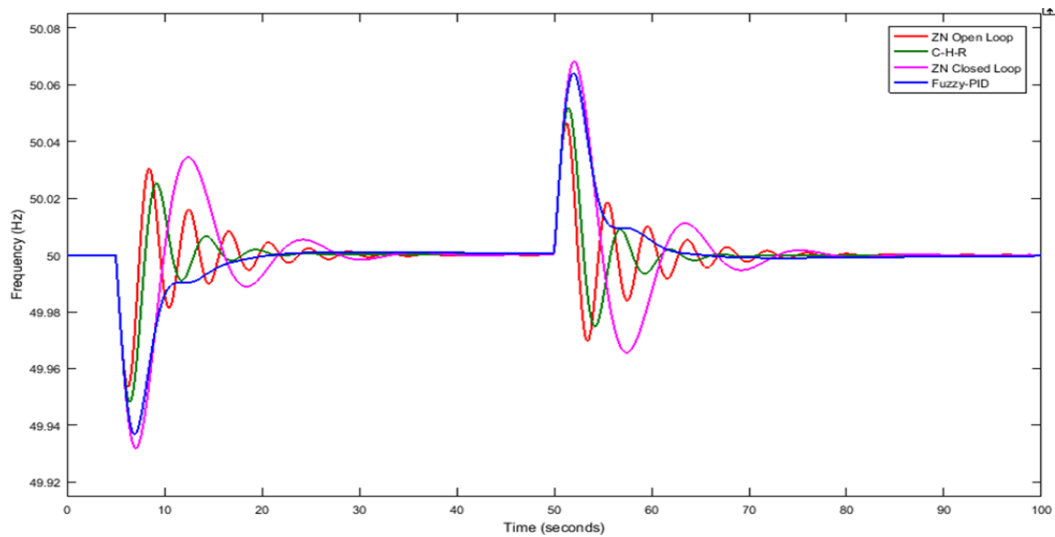


Fig. 12. Frequency response for +1% load disturbance and -1% load disturbance for each tuned controller.

It is observed that for negative load disturbances, a mirror image of the frequency deviation of the corresponding positive load disturbance is achieved. The dynamic performance of the controllers is determined using the performance indices: ISE, IAE, ITAE and ITSE, with the frequency deviation, in Hz, taken as the error function, $e(t)$. The values obtained are shown in Table 9.

Table 9. Performance comparison of the tuned controllers.

Tuning method	ISE	IAE	ITAE	ITSE	Settling time
ZN open loop	0.0044	0.2072	1.2980	0.0134	24.63
C-H-R	0.0049	0.1741	0.7084	0.0107	15.44
ZN closed loop	0.0148	0.4077	2.7730	0.0575	26.28
Fuzzy-PID	0.0099	0.2862	2.0900	0.0251	13.67

From Table 9, it is seen that the ZN open loop tuned PID controller achieved the best ISE value while the controller tuned using the C-H-R load rejection method achieved the best IAE, ITAE and ITSE values. The Fuzzy-PID controller had the fastest frequency settling time.

4. CONCLUSION

A performance comparison of classical techniques and meta-heuristic technique for PID tuning has been presented. The comparison was done for automatic generation control (AGC) of a multi-source single area power system. Each source contributed to total power generation based on its participation factor. The RMSE error was used to estimate generation proportionality with participation factor. With a RMSE value of approximately $1e-05$, the Fuzzy Logic tuned PID controller achieved the most proportional generation balance. This was followed by the

ZN closed loop method with a RMSE of $1.96\text{e-}03$ then the C-H-R load rejection method with a RMSE of $2.0\text{e-}03$ and lastly, the ZN open loop method with a RMSE $2.12\text{e-}03$. For the performance dynamics of the controllers, the C-H-R load rejection method achieved the least fitness function values with ISE, IAE, ITSE and ITAE values of 0.0049, 0.1741, 0.7084 and 0.0107 respectively for a 1% load deviation. From the frequency deviation plots, the Fuzzy-PID controller achieved the fastest settling time of 13.67 seconds. It can therefore be concluded that for AGC of multi-source single-area power systems, PID controllers tuned using the ZN open loop method and the C-H-R load rejection method, prioritizes achieving zero ACE and lower frequency deviation over a balance between generation output of each source and its participating factor. The Fuzzy-PID controller on the other hand achieves both with great results even if there was a slightly higher fitness function values when compared with the preceding methods. ISE, IAE, ITSE and ITAE values for the Fuzzy-PID controller are 0.0099, 0.2862, 2.09 and 0.0251 respectively.

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