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Hybrid fuzzy-PID design based on flower pollination algorithm for frequency control of micro-hydro power plant

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Abstract

Micro-Hydro Power (MHP) Plant System is the renewable energy resource that utilizes water potential energy. In MHP, the energy flows depend on the rotation speed of the generator which cause instability and nonlinearity in the frequency of electrical power. It is also supported by the fluctuation on the electricity load. Therefore, this study used Fuzzy Logic Controller combined with FPA-tuned PID to control the power frequency of the load. This test consisted of 4 stages, namely testing the system without a controller, testing the system using PID, testing the MHP system with a PID controller tuned to the Flower Pollination Algorithm, and testing the system using a Fuzzy PID tuned by the Flower Pollination Algorithm. Based on these tests, the Micro-Hydro Power Plant system response using a Fuzzy PID-tuned FPA controller performed best, especially in accelerating the time to a steady state, reducing overshoot and undershoot with the fastest rise time. As for the output signal from the controller used in the MHP, optimizing the Flower Pollination Algorithm for the Kp, Ki, and Kd parameters is effective and smooth in improving all elements in the Micro-Hydro Power Plant frequency stabilization. Meanwhile, the role of the fuzzy logic controller (FLC) is not very significant, and there is relatively a lot of noise in the output signal of the Fuzzy PID controller itself in terms of stabilizing the load frequency on the Micro-Hydro Power Plant.

1. Introduction

Micro-hydro or better known as green energy (green resources), uses sources that have been provided by nature and are very environmentally friendly. Micro-hydro power is also known as a power plant that utilizes water power as the driving force but on a small scale [1], [2], [3], [4]. The emergence of flowing water discharge is caused by the potential energy generated by river flows, irrigation canals, or the waterfall itself [5]. This potential energy can be transformed into mechanical energy, which is further transformed by the generator into electrical energy [6]. One of the problems often encountered in the MHP system is unstable rotation of the generator. This arises due to a nonliniearity in the load side. It caused fluctuations in frequency that caused damage to generation control equipment and consumer electrical equipment [7]. Therefore, load frequency control strategies is needed to stabilize the frequency when there is a sudden change in frequency [9].

It has been reviewed recently, and many researchers have researched load frequency control methods at Micro-Hydro Power Plant. One method that is often chosen by researchers is the PID Controller, and this method was chosen because of its easy-to-understand structure and its depiction in a system. This ratio benefits both in terms of performance and cost [9]. The problem will arise when the power system model is nonlinear, which results in reduced efficiency of the PID Controller due to the wide application of PID and the weakness of advanced control techniques [10]. Researchers think to improve the performance of PID Controller. Fuzzy Logic Controller (FLC) can be one solution because this controller can handle nonlinear motion and power systems. This dynamic performance is improved by combining FLC, such as rule bases, scaling inputs, membership functions, scaling factors, and others [11]. Therefore, some researchers spice up fuzzy logic with PID (FPID). The use of FPID for technical optimization has been studied in several journal articles, such as the Ant Colony Optimization (ACO) Method for Optimizing Fuzzy PID (FPID)[12], Hybrid Particle Swarm Optimization (PSO) [13], [14], and Pattern Search (PS) Optimized Fuzzy PI (FPI) Controller, Novel Hybrid Differential Evolution (DE) [15], [16] and Pattern Search (PS) Optimized Fuzzy PI/PID Controllers [17]. Based on the previous works, FPID control is very helpful in improving dynamic frequency control performance and has been adopted by researchers [7], [18]. In 2012, a Senior Research Scientist, Xin She Yang, discovered the Flower Pollination Algorithm (FPA). This algorithm is recognized as very efficient in processing and manifests an increase from the previous algorithm found by Xin She Yang [19].

This paper discussed the implementation of Fuzzy Logic Controller, and Flower Pollination Algorithm (FPA) was used to optimize PID to control the frequency in Micro Hydro Power Plants. The discussion was also complemented with several tests to show the performance of Fuzzy Logic Control combined with FPA.

2. Research Method

2.1 Micro-Hydro Modelling

The first step was to design a complete MHP system. Figure 1 below is a picture of a series of MHP systems designed using Matlab 2020a software which is equipped with a turbine (water) and a servo motor which later will run as the governor system. There are also an induction generator and several elements that are used as complementary facilities.

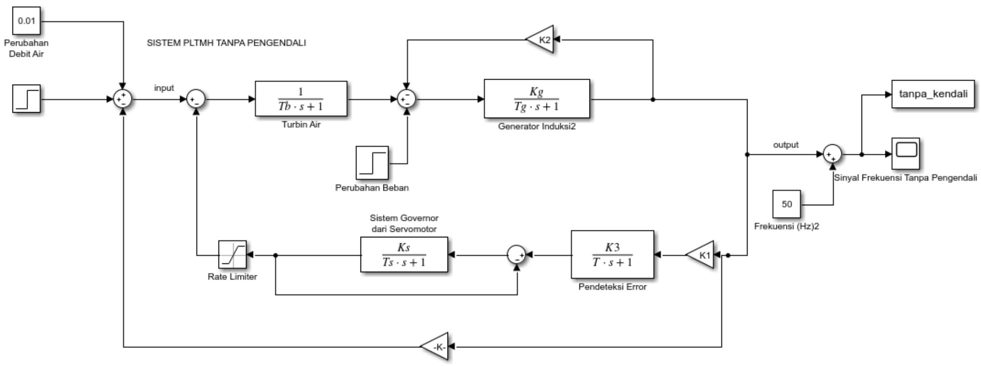

Figure 1. Micro-Hydro Power Plant with Proportional Controller

Figure 2 below depicts a series of MHP systems equipped with PID controllers. The Kp, Ki, and Kd parameters use the settings from the Matlab 2020a software as shown in Figure 3. Meanwhile, for the tuned Flower Pollination Algorithm (FPA) PID controller, the Kp, Ki, and Kd parameters need to be initialized, as shown in Figure 4.

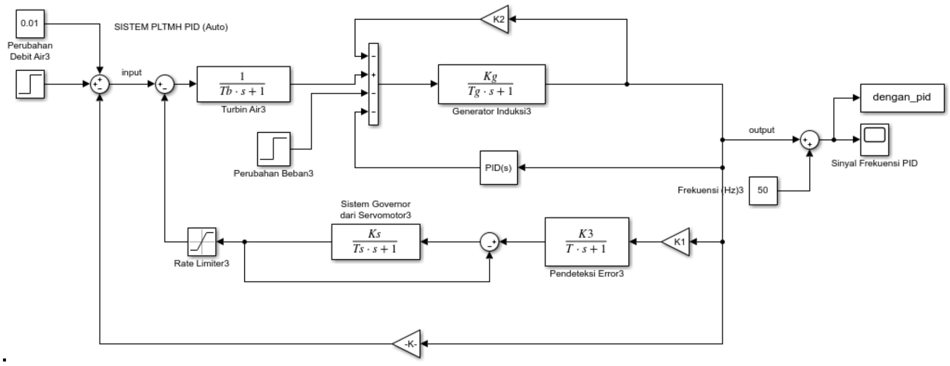

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Figure 2. Micro-Hydro Power Plant with PID

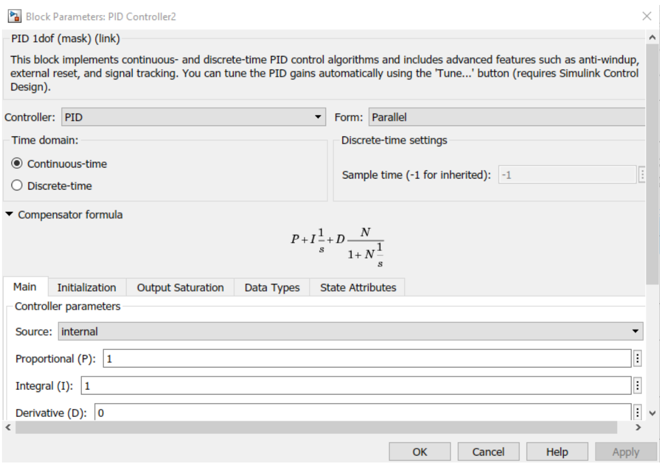

Figure 3. PID Parameters

Figure 4 below shows the design of the MHP system, which is equipped with a Fuzzy PID controller. The Fuzzy PID controller was not combined in one circuit, but it was installed in parallel.

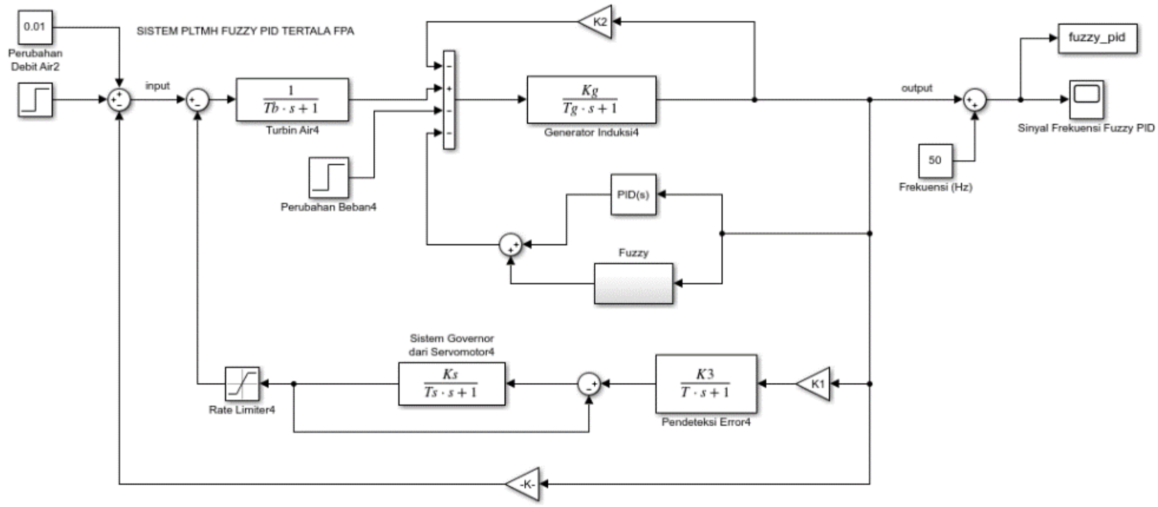

Figure 4. Micro-Hydro Power Plant with Fuzzy PID-FPA

The focus on controlling the frequency designed for this MHP system lies on the governor system. At the same time, the addition of the error detector will be used as feedback from the generator output to return to the water turbine. The addition of PID control, which is directly used as feedback from the generator output back to the generator input, is based on the controller's independence from the water turbine because the focus of control in testing this research lies on the load power of the induction generator itself.

Below, in Table 1, the parameter data that were used in modeling the MHP system is presented.

Table 1. Micro Hydro Power Plant System Parameters

Parameters	Unit	Value
f	Frequency (Hz)	50.00
Tb	Turbine Time Response (s)	1.00
Tg	Generator Time Response (s)	13.333
Ts	Generator Time Constant (s)	0.10
K1	Error Detection Gain	5.00
K2	Frequency Gain	8.520
K3	Error Gain Constant	0.004
Kg	Generator Controller Gain (s)	1.00
Ks	Gain Control of Governor Servo	2.50
T	Time Response of Error Detection	0.02

2.2 Fuzzy Logic Control Design

The function of the Fuzzy Logic Controller (FLC) system with two input signals is shown in Figure 5. The error signal generated from an induction generator and the derivative error (change error over the time), has been derived.

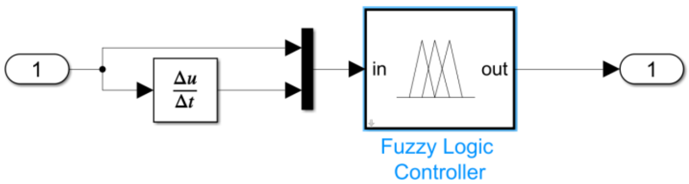

Figure 5. Fuzzy Design in Simulink

In detail, FLC consists of four main elements: fuzzification, fuzzy inference system (FIS), rule based and defuzzyfication. The rule base and defuzzification design in this research are depicted in Figure 6.

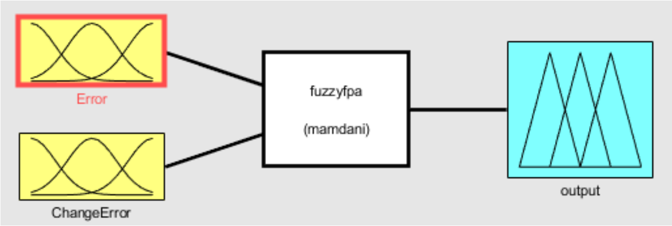

Figure 6. FLC Structure

Fuzzification converts numeric values into fuzzy sets, FIS, which is useful for executing all logic operations. The Rule Base consists of membership functions (MFs) and control rules. Fuzzy sets must be converted to real values by defuzzification. FLC effect also depends on MFs and rule base. The choice of MFs depends on the problem domain. Compared to Bell and trapezoidal MFs, triangular MFs are commonly used in FPID design of real-time applications because of their simplicity and ease of calculation.

Triangular MF is used with five fuzzy elements, such as positive big (PB), negative big (NB), zero (Z), negative small (NS), and positive small (PS), while in terms of determining both input and output [20]. MFs for error, change error, and FLC output.

Figure 7 shows the MFs for fuzzy error input and fuzzy error derivatives. Meanwhile, Figure 8 displays the MFs of the Fuzzy Logic Controller (FLC) output.

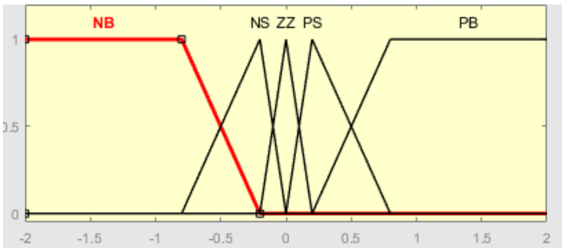

Figure 7. Membership Function of Error and Derivative Error

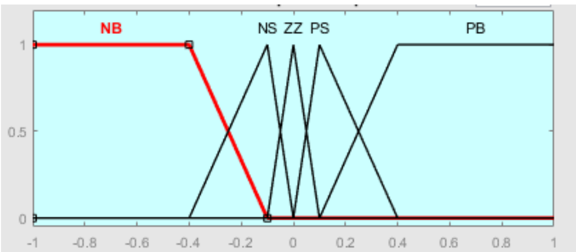

Figure 8. Membership Function for Output FLC

2.3 PID-FPA

In testing the stability of the Micro-Hydro Power Plant system, an objective function based on Integral Absolute Error (ITAE) is used. It can also facilitate FPA in terms of finding the right PID parameters. The objective function script itself is shown in Figure 9 as follows:

```
function J=objyt(x)
global Kp Ki Kd

Kp= x(1);
Ki= x(2);
Kd= x(2);

[t,~,y]=sim('Sistem_Kontrol_PLTMH',0:0.05:5);
J=sum(t.*abs(y).^2);
```

Figure 9. Pseudo Code of Objective Function in PID-FPA

Meanwhile, the process of determining the Parameters of KP, KI, and KD that can be searched through Pseudo Code FPA is displayed in Figure 10 as follows:

```
function [best, fmin, N_iter]=fpayt
n=10;           %Population size, typically 10 to 25
p=0.75;          % Probability switch 0 to 1
% Iteration parameters
N_iter=5;      % Total number of iterations
% Dimension of the search variables
d=3;
Lb=[0*ones(1,d)]; %Lower Bound
Ub=[5*ones(1,1) 1*ones(1,1) 1*ones(1,1)];  %Upper Bound
Fun = @(x)(objyt(x));
for i=1:n,
    Sol(i,:)=Lb+(Ub-Lb).*rand(1,d);
    Fitness(i)=Fun(Sol(i,:));
end
[fmin,I]=min(Fitness);
best=Sol(I,:);
S=Sol;
for t=1:N_iter,
    Current_Iteration = t
    %Loop over all bats/solutions
    for i=1:n,
        Current_i = i
        if rand>p,
        L=Levy(d);
        dS=L.*(Sol(i,:)-best);
        S(i,:)=Sol(i,:)+dS;
        S(i,:)=simplebounds(S(i,:),Lb,Ub);
        else
            epsilon=rand;
            JK=randperm(n);
            S(i,:)=S(i,:)+epsilon*(Sol(JK(1),:)-Sol(JK(2),:));
            S(i,:)=simplebounds(S(i,:),Lb,Ub);
        end
        Fnew=Fun(S(i,:));
        if Fnew<=fmin,
            best=S(i,:);
            fmin=Fnew;
        end
    end
    if round(t/100)==t/100,
    fmin
    end
end
disp(['Total number of evaluations: ',num2str(N_iter*n)]);
disp(['Best solution=',num2str(best)]);
disp(['fmin=',num2str(fmin)]);
function s=simplebounds(s,Lb,Ub)
  ns_tmp=s;
  I=ns_tmp<Lb;
  ns_tmp(I)=Lb(I);
  % Apply the upper bounds
  J=ns_tmp>Ub;
  ns_tmp(J)=Ub(J);
  % Update this new move
  s=ns_tmp;
% Draw n samples for the Levy flight from the Levy distribution
function L=Levy(d)
% For details of the Levy flights, see Chapter 11 of the following book:
% Xin-She Yang, Nature-Inspired Optimization Algorithms, Elsevier, (2014).
beta=3/2;
sigma=(gamma(1+beta)*sin(pi*beta/2)/(gamma((1+beta)/2)*beta*2^((beta-
1)/2)))^(1/beta);
% Mantegna's algorithm for Levy random numbers
u=randn(1,d)*sigma;
v=randn(1,d);
step=u./abs(v).^(1/beta);
L=0.01*step;             % Final Levy steps
```

Figure 10. Code of Flower Pollination Algorithm (FPA)

Based on the Pseudo Code FPA that is displayed above, it can be concluded that global pollination can occur when the random values given are smaller than the value of the opportunity, represented in Equation 1 as follows:

$$x_i^{t+1} = x_i^t + L(g^* - x_t^i) \quad (1)$$

Local pollination can also be carried out when the random value exceeds the probability value, expressed by the following Equation 2 below:

$$x_i^{t+1} = x_i^t + \varepsilon(x_j^t - x_k^t) \tag{2}$$

The KP, KI, and KD parameters are initiated as x (1), x (2), and x (3) in this algorithm which "x" itself is a calculation of local and global pollination that exists between the lower limits and limits. Therefore, we need to realize the possibility of an appropriate initialization value to obtain the expected results.

2.4 FPA Parameters

The selection of the parameters used in the Flower Pollination Algorithm (FPA) was conducted in several steps. The first step is determining the population size for the flower population itself, from numbers 10 to 25. The second step is probability switch, the probability used numbers 0 to 1. The third is iteration. Determining this iteration required trial and error. The fourth is the dimension. For the dimensions this time, we used three dimensions because we wanted to optimize three parameters: KP, KI, and KD. If we only want to optimize two parameters, two dimensions are enough. Fifth is the lower bound and upper bound. For the lower limit, the upper limit can be tried or searched for trial and error, and this program is tried to be run with the Micro-Hydro Power Plant system with KP, KI, and KD, which are manually arranged. Table 2 below is an attachment to the required FPA parameters, presented as follows:

Table 2. FPA Initalization Parameters

Flower Population	10
Probability	0.75
Iteration	5
Dimention	3
Lower Bound of PID Parameters	[0 0 0]
Upper Bound of PID Parameters	[5 1 1]

3. Results and Discussion

The following Figure 11 shows the testing the Micro-Hydro Power Plant system when the load is given with a time difference of less than 1s, with a very small load, less than 10% of the reference input.

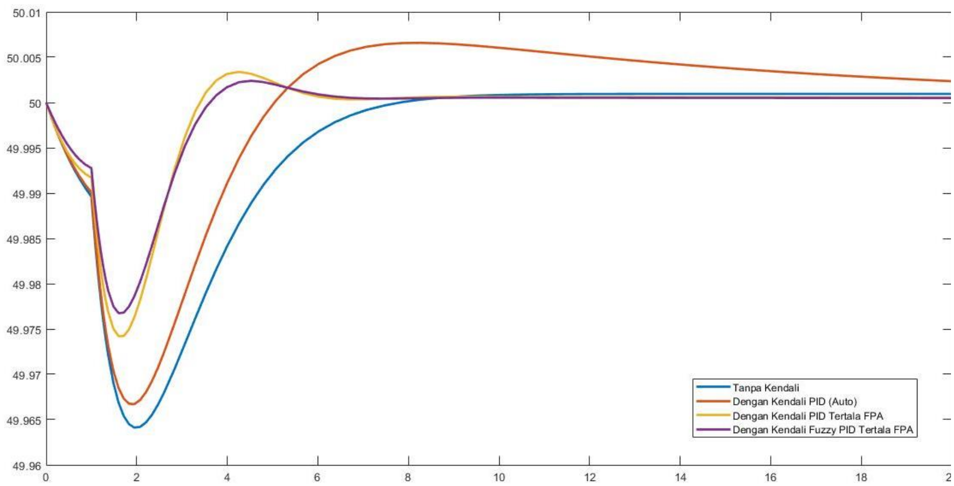

Figure 11. Comparison of Frequency Transient Response Micro-Hydro Power Plant

Table 3. Micro-Hydro Power Plant Test Result

Controller	Rise Time (s)	Over shoot (%)	Under shoot (%)	Peak Time (s)	Settling Time (s)
Proportional Gain=1	3.564	0.505	1.610	15.565	9.408
PID	2.177	19.880	1.686	8.114	18.569
PID-FPA	1.249	9.341	0.865	4.261	9.116
Fuzzy PID-FPA	0.9498	13.158	1.624	4.467	8.243

Based on Table 3 and Figure 11, it can be seen that although the FPA-based Fuzzy PID controller has higher overshoot than the Micro-Hydro Power Plant system with proportional controller, the Fuzzy PID-FPA can reduce the rise time to 2.2767(s), undershoot up to 1.465 (%), peak time up to 11.3401(s), and settling time which is 2.5545(s) faster than the system with proportional controller.

In Figure 13, it can also be concluded that optimizing the flower pollination algorithm to the Parameters of KP, KI, and KD is considered effective in improving all elements in adjusting the Micro-Hydro Power Plant frequency. In contrast, the Fuzzy Logic Controller is not too significant in the frequency adjustment. However, it can still fix the lack of Micro-Hydro Power Plant systems with the Flower Pollination Algorithm (FPA)-based PID controller.

3.1 Transient Respone Test without Load Change

The following figure displays the controller output signal ratio on the Micro-Hydro Power Plant system. A signal output will be displayed from the PID Controller, PID Controller FPA, and the last is the Fuzzy PID controller output signal based on Flower Pollination Algorithm (FPA). Testing the Micro-Hydro Power Plant system when the load is given with a time difference of less than 1s, with a very small load, less than 10% of the reference input.

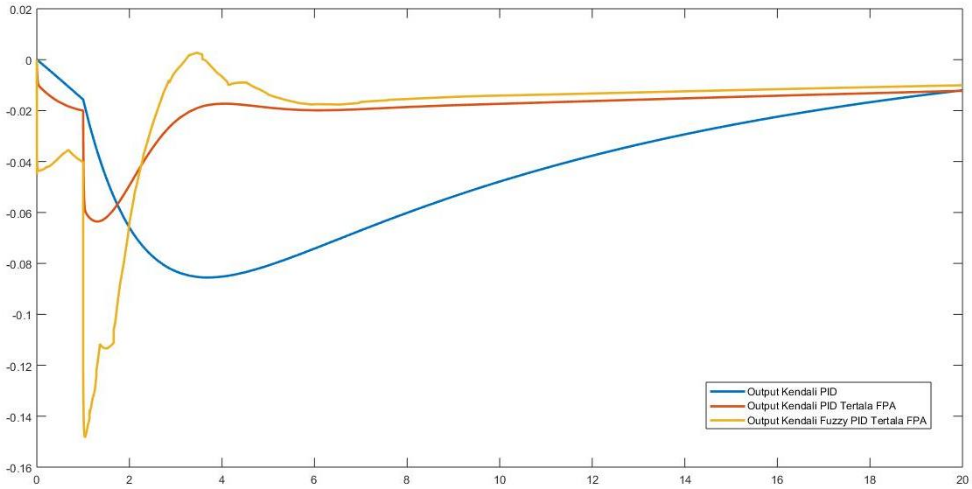

Figure 12 Comparison of Transient Response Micro-Hydro Power Plant

Table 4 Micro-Hydro Power Plant Test Result without Load Change

Controller	Rise Time (s)	Over shoot (%)	Under shoot (%)	Peak Time (s)	Settling Time (s)
PID	-	28.907	2.577	-	>20
PID-FPA	1.484	0.389	5.271	1.361	6
Fuzzy PID-FPA	0.9218	10.870	6.962	3.458	7

From the data above, namely Figure 12, which is then concluded in Table 4, it can be seen that although the FPA-based Fuzzy PID controller has higher overshoot than the Micro-Hydro Power Plant system without controlling, the FUZZY FPA can reduce the rise time to 2.2767(s), undershoot up to 1.465 (%), peak time up to 11.3401(s), and settling time which is 2.5545(s) faster than the system without controlling.

In Figure 12, it can also be concluded that optimizing the flower pollination algorithm to the Parameters of KP, KI, and KD is considered effective and smooth in improving all elements in adjusting the Micro-Hydro Power Plant frequency. Whereas the Fuzzy Logic Controller (FLC) is not too significant and relatively, there is much noise in the Fuzzy PID-controlled signal regarding the load frequency adjustment. In Figure 12, this is the most reliable Flower Pollination Algorithm-Based PID controller as a control signal in the Micro-Hydro Power Plant system.

3.3 Transient Respone Test With 20% Load

The following figure displays the ratio of the signal response to the transitional system of the Micro-Hydro Power Plant system loaded 20% between t = 1s to t = 7s. The signal to be displayed is the response signal of the Micro-Hydro Power Plant system transitional response with 20% without control, with the PID Controller, PID Controller is FPA, and the last is the signal of response to the transitional system of Micro-Hydro Power Plant with a 20% load with the Fuzzy PID controller FPA.

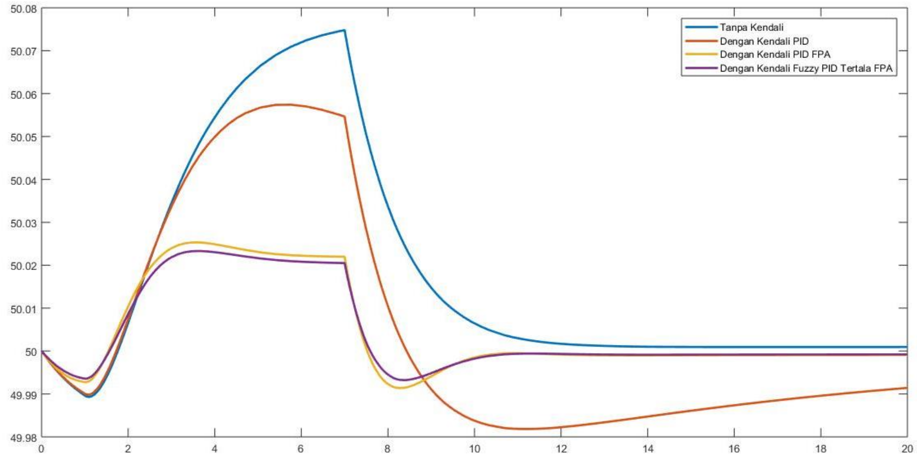

Figure 13. Comparison of Frequency Transient Response Micro-Hydro Power Plant with 20% Load

Table 5. Comparison of Micro-Hydro Power Plant Frequency Controller with 20% Load

Controller	*Rise Time (s)*	*Over shoot (%)*	*Under shoot (%)*	*Peak Time (s)*	*Settling Time (s)*
P Gain=1	3.070	0.581	1.482	7.000	13.337
PID	1.792	20.946	0.564	5.761	18.569
PID-FPA	1.183	0.649	1.674	3.637	12.507
Fuzzy PID-FPA	1.191	0.625	0.435	3.637	12.172

Based on Figure 13 and Table 5, it can be seen that although Fuzzy PID is FPA has a higher overshoot than the Micro-Hydro Power Plant system without controlling, the Fuzzy PID can reduce the rise time to 1.879 (s), undershoot up to 1.047 (%), peak time up to 3.363 (s), and a slightly different settling time of 1.165 (s) faster than the system without controlling.

In Figure 13, the ratio of response to the transitional system of the Micro-Hydro Power Plant system with a load of 20% of the reference input given later, the load is given at t = 1 to t = 7. It can be concluded from Figure 15 that optimizing from the flower pollination algorithm to the Parameters of KP, KI, and KD is considered effective in improving all elements in disputing the frequency of Micro-Hydro Power Plant. At the same time, the Fuzzy Logic Controller is not too significant in the frequency adjustment. However, it can still fix the lack of Micro-Hydro Power Plant systems with the Flower Pollination Algorithm (FPA)-based PID controller.

3.3 Controller output signal comparison with 20% Load

Figure 14 displays the controller output signal ratio in the Micro-Hydro Power Plant system loaded 20% between t = 1s to t = 7s. A PID Controller output signal will be displayed, the PID controller is a flower pollination algorithm, and the last is the Fuzzy PID Controller output signal Pollination Algorithm.

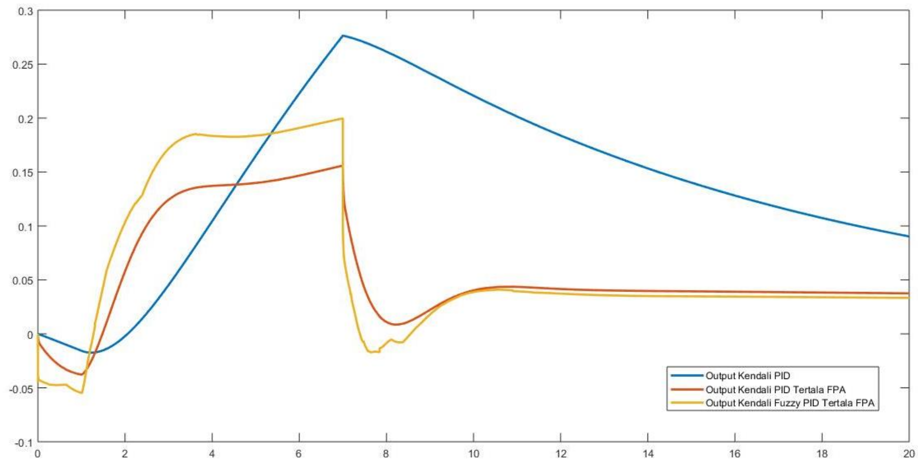

Figure 14. Comparison of control signal Transient Response Micro-Hydro Power Plant with 20% Load

Table 6. Comparison of FLC and PID with FPA on 20% Load

Controller	*Rise Time (s)*	*Over shoot (%)*	*Under shoot (%)*	*Peak Time (s)*	*Settling Time (s)*
PID	4.046	19.880	1.686	7	>20
PID-FPA	1.208	10.959	0.865	7	9.116
Fuzzy PID-FPA	1.396	18.627	1.624	7	9.116

Based on the Figure 14 and Table 6, it can be concluded that PID controller FPA can improve many aspects, including rest time, undershoot, and settling time values. At the same time, the Fuzzy PID Controller itself can complement the perfection of the control system about reducing overshoot in the PID controller FPA.

The ratio of responses to the controller in the Micro-Hydro Power Plant system with a load of 20% of the reference input given later, and the load is given at t = 1 to t = 7. It can also be concluded from Figure 14, that the optimization of the Flower Pollination Algorithm to KP, KI, and KD parameters are effective and smooth in improving all elements in the disbursement of Micro-Hydro Power Plant frequencies. Whereas the Fuzzy Logic Controller (FLC) is not too significant and relatively, there are many noises in the Fuzzy PID-controlled signal regarding the load frequency adjustment. In Figure 14, the most reliable Flower Pollination Algorithm-based PID controller is obtained as a control signal in the Micro-Hydro Power Plant system.

4. Conclusion

A fuzzy PID controller design based on the Flower Pollination Algorithm (FPA) for controlling the frequency of the Micro-Hydro Power Plant system has been tested and simulated. From the testing process, it can be concluded that to make a Fuzzy PID control design based on the Flower Pollination Algorithm begins by determining the output of the signal from the induction generator as an input for the controller of the fuzzy PID that is arranged in parallel which is used directly to the induction generator. To optimize the PID controller itself using a flower pollination algorithm, which is for the provision of parameters D, LB, UB, and iteration in the Flower Pollination Algorithm script itself is done by trial and error, and the best parameters are taken. Whereas to implement the Fuzzy PID controller based on Flower Pollination Algorithm (FPA) in controlling the Micro-Hydro Power Plant frequency, the load frequency control is focused on the load power of the induction generator. Due to the absence of attachment to the water turbine, in this system, the control of the load frequency of Micro-Hydro Power Plant is added by PID control, which is used as direct feedback, initially from the generator output leads to the input of the generator. For the response of the Micro-Hydro Power Plant system using the Fuzzy PID controller based on the Flower Pollination Algorithm (FPA) has the best performance in speeding up the time to the steady state, overshoot, and undershoot that is reduced and has the fastest rise time compared to other controllers.

Notation

g^* : best solution of current iteration
L : distance of pollination
x_i^t : $i-$vector of solution at $t-$iteration
x_j^t : $j-$vector of solution at $t-$iteration
x_k^t : $k-$vector of solution at $t-$iteration
ε : uniform random number$[0,1]$

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