A Comparative Study of PID, ANFIS and Hybrid PID-ANFIS Controllers for Speed Control of Brushless DC Motor Drive

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Abstract— **this paper presents a comparative study of various controllers for the speed control of Brushless Direct Current Motor (BLDCM) to improve a performance of control. The most commonly used controller for the speed control of BLDCM is Proportional Integral Derivative (PID) controller. However, the PID controller has advantages such as: a good response, the simple structure and robustness of method, but it has disadvantages such as: optimally tuning gains of PID have been quit difficult and it cannot adapt a non-linier state of plant. Further, ANFIS controller has the ability to automatically learn and adapt with a state of plant. A novel hybrid controller that combines the advantages of PID controller and ANFIS controller is desired to improve the response of plant. To model of BLDCM is used an identification system method. Simulation results are presented and analyzed for all the controllers. It is observed that hybrid PID-ANFIS based controllers give better responses than PID or ANFIS for the speed control of BLDCM drive.**

Keywords- PID; ANFIS; Hybrid PID-ANFIS; BLDCM drive; speed control.

I. INTRODUCTION

Recently, BLDCM have been widely used as motor motion in the industries, the public life, the domestic life, information and office equipment. This is caused the BLDCM has advantages than other motors, such as the efficiency is better 13 % than induction motor, the volume is smaller 40 % than conventional DC motor [1]. The other advantages, caused no brush so they require little or no maintenance, they generate less acoustic and electrical noise than conventional DC motor, they can be used in hazardous operation environments (with flammable products)[2]. In spite of, the control equipment of BLDCM is still a limit and it is seldom met in the market. As an example, Atmel Corporation has produced the speed control of BLDCM using ATmega32M1, which applies a classic control that the gain tuning uses a trial and error method [3]. It cannot be used to a high power BLDCM. PID control with its three-term functionality covering treatment to both transient, steady-states response, offers the simplest, and yet most efficient solution to many real world control problem. In spite of the simple structure and robustness of this method, optimally tuning gains of PID controllers have been quite difficult [4].

In recent years, new artificial intelligent-based approaches have been proposed for speed control of the BLDCM, on kind of them is fuzzy logic controller which results still show an oscillation on steady state response. Furthermore, to decide on the domain of the fuzzy logic membership function is more difficult to be done [5],[6]. It can be overcome by using ANFIS controller, where the domain of membership function and the rule of fuzzy can be determined automatically. The choice of the number and the function of membership function will determine quality control. The speed response of BLDCM using ANFIS controller is obtained the best response on the bell function and five membership functions [7]. To improve the speed response of BLDCM, where the parallel fuzzy PID controller is applied which consists of three parallel fuzzy sub controllers that online update of the PID proportional, integral, and derivative gains value. The controller inputs are the speed error and the delayed control signal and represented by triangle functions [8].The other controller structure to improve a performance of control was applied the fuzzy and neuro fuzzy controller for speed control of DC motor drive [9].

This research was applied three controller modes such as PID, ANFIS and Hybrid PID-ANFIS to control a speed of BLDCM. The aim is to obtain a good performance of control using MATLAB Simulink. Simulation results are presented and analyzed for all the controllers base transient parameter, such as: delay time (td), rise time (tr), settling time (tr), overshoot (Mp) and error (er). The model of speed control of BLDCM drive system used an identification system method base on dynamic response of a physical system.[10].

II. CONTROLLER STRUCTURES

A. PID Controller

PID (proportional integral derivative) control is one of the earlier control strategies, namely classical control that typical structure's is shown Fig.1. The error signal $e(t)$ is used to generate the proportional, integral, and derivative action, with the resulting signals weighted and summed to form the control signal $u(t)$ applied to the plant model. A mathematical description of the PID controller is [11]

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$$u(t)=K_p\left[e(t)+\frac{1}{T_i}\int_0^t e(\tau)d\tau+T_d\frac{de(t)}{dt}\right] \qquad (1)$$

where *u(t)* is the input signal to the plant model, the error signal *e(t)* is defined as *e(t) = r(t) – y(t)*, and *r(t)* is the reference input signal. The behavior of the PID controller is determined by K_p, T_i, T_d values. That can be tuned by Ziegler-Nichols tuning formula that obtained when the plant model is given the step input.

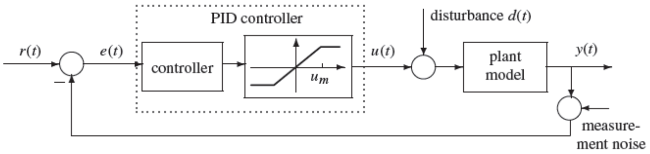

Fig.1. A typical PID control structure

There are two Ziegler-Nichols tuning formula such as: base on step response and frequency response. The tuning formula base on the step response must be obtain *L* and *T* when the response system a like Fig.2a, whereas base on the frequency response must be obtain *Kc* that causes oscillation system, further determined *Pc*, as shown Fig.2b.

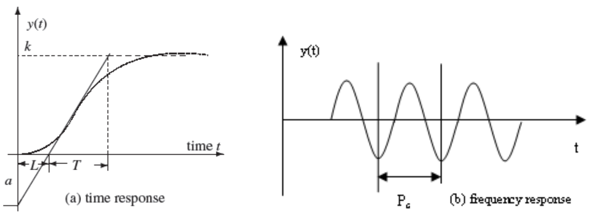

Fig.2. The response of the plant for Ziegler-Nichols tuning formula

TABLE I. ZIEGLER-NICHOLS TUNING FORMULAE

Controller type	from step response K_p	T_i	T_d	from frequency response K_p	T_i	T_d
P	$1/a$			$0.5K_c$		
PI	$0.9/a$	$3L$		$0.4K_c$	$0.8T_c$	
PID	$1.2/a$	$2L$	$L/2$	$0.6K_c$	$0.5T_c$	$0.12T_c$

B. ANFIS Controller

A typical architecture of an ANFIS which is used is Sugeno fuzzy models consist of five layers that every layer has the node. There are two kind of nodes that called the adaptive node (square symbol) and fixed node (circle symbol) as shown Fig. 3. The mechanism is designed using Sugeno with has two inputs x_1 and x_2 and one output y. For a first-order Sugeno fuzzy model [12],[13], a common rule set with two fuzzy if-then rules is the folowing

If x_1 is A_1 and x_2 is B_1 Then $y_1 = c_{11}.x_1 + c_{12}.x_2 + c_{10}$ (2)

If x_1 is A_2 and x_2 is B_2 Then $y_2 = c_{21}.x_1 + c_{22}.x_2 + c_{20}$ (3)

If α is predicated for two roles are w_1 and w_2, then can be determined the weight average as below

$$y=\frac{w_1y_1+w_2y_2}{w_1+w_2}=\overline{w_1}y_1+\overline{w_2}y_2 \qquad (4)$$

The layer function:

Layer 1

Every node i in this layer is an adaptive node which a node activation function parameter. The output of every node is the membership function degrees which given by input membership function as the following

$\alpha_{A1}(x_1), \alpha_{B1}(x_2), \alpha_{A2}(x_1)$ or $\alpha_{B2}(x_2)$.

$$O_{1,i}=\mu_{Ai}(x_1), \quad \text{for i = 1, 2, or} \qquad (5)$$

$$O_{1,i}=\mu_{Bi}(x_2), \quad \text{for i = 3, 4,}$$

If membership function is given by the generalized bell function as below

$$\mu(x)=\frac{1}{1+\left|\frac{x-c}{a}\right|^{2b}} \qquad (6)$$

where {a,b,c} are the parameter set. As the value of these parameters changes, the bell-shaped function varies accordingly, thus exhibiting various forms of membership functions for fuzzy set A. Parameters in these layers are referred to as premise parameters.

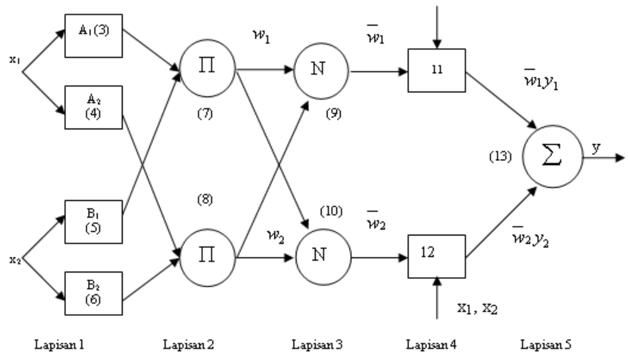

Fig. 3 The architecture ANFIS

Layer 2

Every node in this layer is fixed node is labeled Π, whose output is the product of all the incoming signals as below

$$O_{2,i}=w_i=\mu_{Ai}(x_1)x\mu_{Bi}(x_2), \text{ for } i=1,2 \qquad (7)$$

Each node output represents the firing strength (α predicate) of a rule. In general, any other T-norm that performs fuzzy AND can be used as the node function in this layer.

Layer 3

Every node in this layer is a fixed node labeled N. The i^{th} node calculates the ratio of the gain ratio i^{th} rule firing strength (α predicate) to the sum of all rules' firing strengths as below

$$O_{3,i}=\overline{w_i}=\frac{w_i}{w_1+w_2}, \quad i=1,2 \qquad (8)$$

For convenience, outputs of this layer are called normalized firing strengths.

Layer 4

Every node i in this layer is an adaptive node with a node function is

$$O_{4,i}=\overline{w_i}y_i=\overline{w_i}(c_{i1}x_1+c_{i2}x_2+c_{i0}) \qquad i=1,2 \quad (9)$$

where $\overline{w_i}$ is a normalized firing strength from layer 3 and $\{c_{i1}, c_{i2}, c_{i0}\}$ are the parameter set of this node. Parameters in this layer are referred to as consequent parameters.

Layer 5

The single node in this layer is a fixed node labeled Σ, which computes the overall output as the summation of all incoming signals as following

$$O_{5,i} = \sum_i \overline{w}_i y_i = \frac{\sum_i w_i y_i}{\sum_i w_i} \tag{10}$$

The parameter to be trained are a, b and c of the premise and c_{i1}, c_{i2} and c_{i0} of the consequent parameters. ANFIS is trained using hybrid learning algorithm that consists of two steps such as feed forward pass and backward pass. More specifically, in the forward pass of the hybrid learning algorithm, node outputs go to forward until layer 4 and consequent parameters are identified by the least squares method. In the backward pass, the error signal propagates backward and the premise parameters are updated by gradient descent.

C. Hybrid PID-ANFIS

The Hybrid PID ANFIS controller is combining two controller modes such as PID controller and ANFIS controller. There are two control structures of hybrid PID ANFIS controller are proposed, such as summing hybrid and selecting hybrid.

1) Summing hybrid

The summing hybrid structure, where the PID controller output is added to the ANFIS output controller. The block diagram summing hybrid PID ANFIS is shown in Fig. 4.

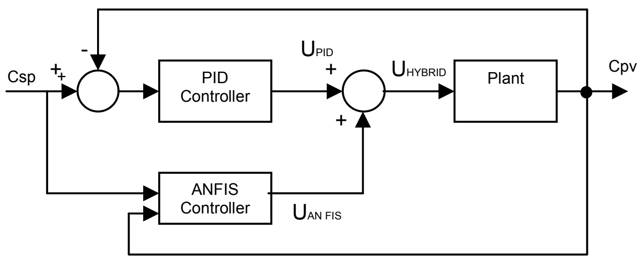

Fig. 4. The block diagram summing hybrid PID ANFIS

The controller output of summing hybrid is represented by

$$U_{HYBRID} = U_{PID} + U_{ANFIS} \tag{11}$$

2) Selecting hybrid

This structur, where the controller action is devided in two regions. The output of PID controller is as a main control signal and the output of ANFIS controller is as a recovery control signal which switched base on the persen speed error (ΔE_{rr}). Performance of the controller action depends on the abilty to determine the persen speed error value that can be found by trial and error. The structur of the selecting hybrid is shown in Fig.5.

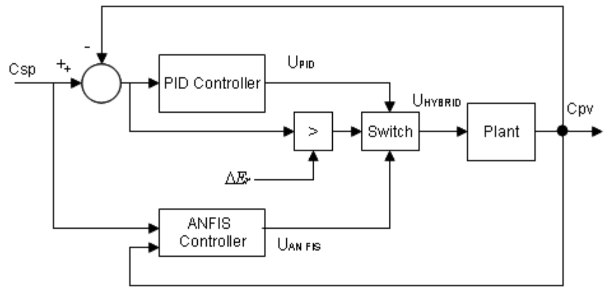

Fig. 5. The block diagram selecting hybrid PID ANFIS

The controller output of selecting hybrid is represented by,

$$U_{HYBRID} = \begin{cases} U_{PID}, & for \quad Error > \Delta E_{rr} \\ U_{ANFIS}, & for \quad Error \le \Delta E_{rr} \end{cases} \tag{12}$$

III. BLDCM MODELING

Generally, BLDCM is constructed of the Permanent Magnet Synchronous Machine (PMSM) 3 phase star connection, 2 poles, a AC source and rectifier, a rotor position sensor, 3 phase inverter and an algorithm control [13],[14], as shown in Fig.6. In practice, a BLDCM have been completed by those elements which generally consist of two parts of separate elements, such as a BLDCM driver and a BLDCM.

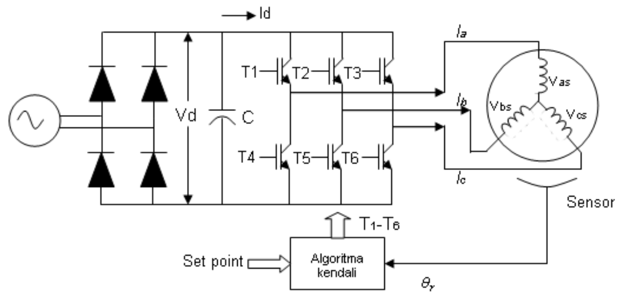

Fig.6 The circuit element of BLDCM

To model BLDCM base on estimation parameter uses an identification system. It is done to identify the discrete-time model from measured input and output data, further in Matlab toolbox is provide function *arx*(). If the measured input and output signals are expressed by column vectors u and y the orders of the numerator and denumerator as assumed to be m-1 and n, respectively, and the delay terms is d, the following statement can be used, as in [11],

H=*arx*([y,u],[n,m,d]) (13)

In this case, input is speed setting and output is actual speed that can be obtained by measuring dynamic speed response of BLDCM.

IV. SIMULATION AND ANALYSIS

According to the model of speed control systems for BLDCM drive mentioned above, some vital simulation works have been conducted. Motor model parameters used for simulation is such as [15]:

Model	: ZW60BL120-430
Voltage	: 48 V (DC)
Current	: 7 A
Power	: 250 W
Speed	: 3000 rpm
No.	: 110325001

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To determine BLDCM model base on identification model system is needed dynamic speed response of BLDCM. By using MATLAB programming has been given in (13), further according [11] obtained the transfer function of BLDCM model, as in

$$TF = \frac{0{,}05136z + 0{,}07078}{z^2 - 0{,}0573z - 0{,}03198}$$

PID costants Kp, Ki and Kd are tunned using Ziegler Nichols close loop method [16], furher obtained Kp = 0,86, Ki = 7,2, Kd = 0,018

Three data is needed to train ANFIS, such as two input data and an output data. The input data are actual speed and delay actual speed. The output data is training target that represented by ramp function. It represents speed respon of BLDCM when controller input increased step by step**.** The data for training are acquired from the open loop experiment, as shown Fig.7. For the evenly distributed grid points of the time input range 3 second with time sampling 0,001, maximum value 35, and minimum value 0 is obtained 2001 x 3 training data pairs.

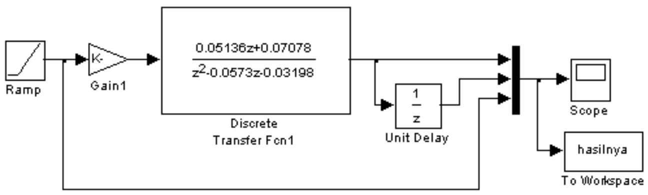

Fig. 7. Learning data of ANFIS controller

The experiment applied the bell function with 3-membership function for each input and output variables. The ANFIS used here contains 9 (3x3=9) rules, 45 total number of fitting parameters, including 18 (3x3+3x3) premise (non-linier) parameters and 27 (3x9=27) consequent (linier) parameters. The training and root mean square (RMS) errors obtained from the ANFIS are 0,00072442 for 30 epochs. The optimized membership function for input_1 and input_2 after trained is shown in Fig. 8.

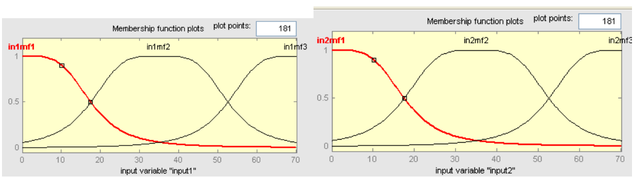

Fig. 8. The membership function for input_1 and input_2 after trained.

There are three control structurs that whill be applied in this experiment, shuch as PID, ANFIS and hybrid PID ANFIS controller. The hybrid PID ANFIS consists of a summing output PID and ANFIS controller, a selecting output PID and ANFIS controller. To select the operating of the PID or ANFIS output is determined by percent error that applied a trial and error method. The simulation circuit of BLDCM speed controller is showed in Fig.9

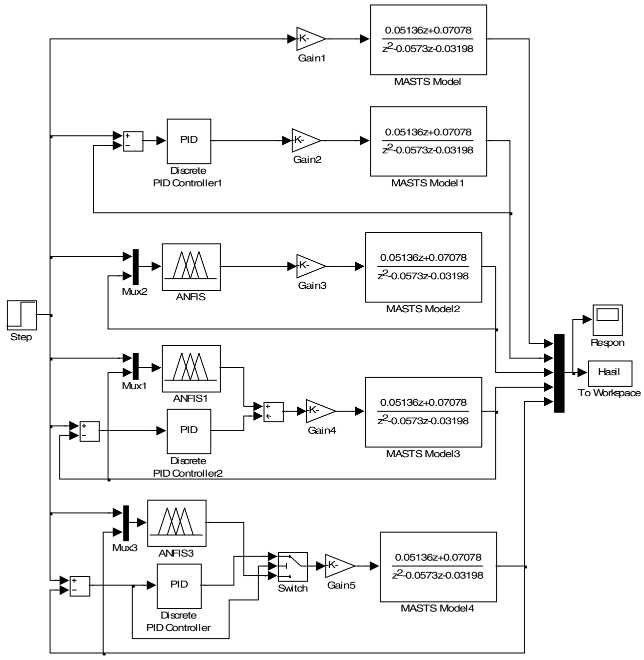

Fig. 9. Simulation circuit of BLDCM speed controller

The simulation was applied for a constant speed setting and change speed setting, further determined and evaluated the transient parameter, such as steady state error (error), rise time (tr), delay time (td), over shoot (Mp) and settling time (ts). The first experiment is given the speed setting 2000 rpm and 2500 rpm. The transient responses of all control structures are shown in Fig. 10 and Fig.11. The transient parameter is determined by plotting a horizontal axis that results as shown in Table II. The transient parameters for speed setting 2500 rpm were obtained similar to speed setting 2000 rpm. It shows that controller have ability to control system for all speed setting with a good performance.

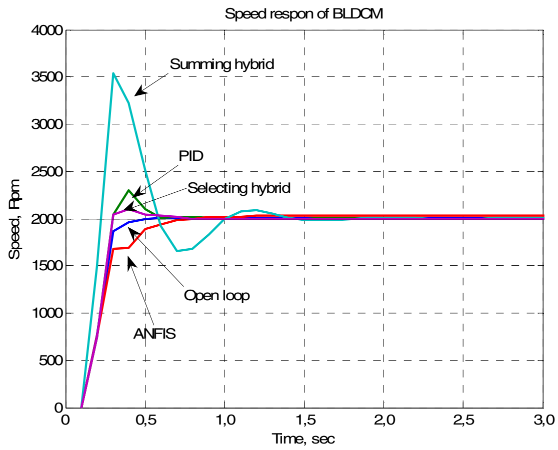

Fig. 10. Speed response of all control structures for speed setting 2000 Rpm

The responses of all controllers are stable with error similar to zero, but the ANFIS is more slowly than PID and hybrid PID ANFIS controller. The overshoot PID is higher than selecting hybrid PID ANFIS controller. The response of summing hybrid PID ANFIS is the fastest, but the overshoot increases 75%, the settling time 1,4 second. This is caused by each of the output signal controller to strengthen.

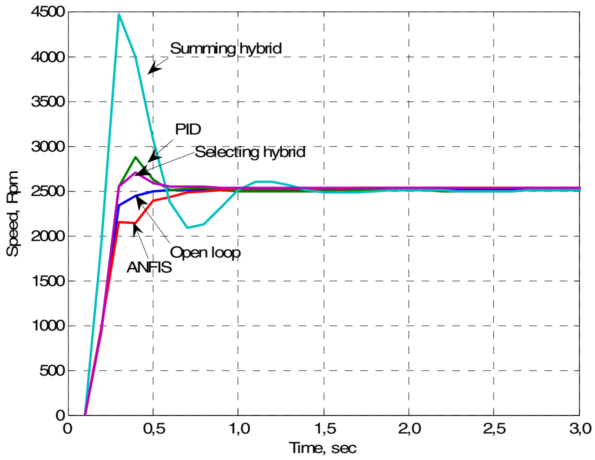

Fig. 11. Speed response of all control structures for speed setting 2500 Rpm

TABLE II. THE TRANSIENT PARAMETER OF BLDCM SPEED RESPONSE FOR SPEED SET 2000 AND 2500 RPM.

Controller structures	td (sec)	tr (sec)	rs (sec)	Mp (%)	Error (rpm)
PID	0,25	0,3	0.60	12.5	0
ANFIS	0,25	0,4	0.70	0	0
Summing Hybrid PID-ANFIS	0,15	0.20	1.40	75	0
Selecting Hybrid PID-ANFIS	0,25	0,3	0.55	5	0

The transient response of selecting hybrid PID ANFIS for the delta error less equal 10% ($\Delta E_{rr} \leq 0{,}1 E_{rr}$) was resulted the best response. It has corresponded to what really designed of the selecting hybrid PID ANFIS controller. It has ability to select the output controller acurrately.

The second experiment is given the speed setting 1000 rpm, then after 1,5 second it is increased to 2000 rpm which responses is shown in Fig. 12. The speed setting can be followed by actual speed for all control structures although the overshoot of summing hybrid controller is higher than others. It is caused by the output of summing hybrid controller is higher too, which is shown in Fig. 13.

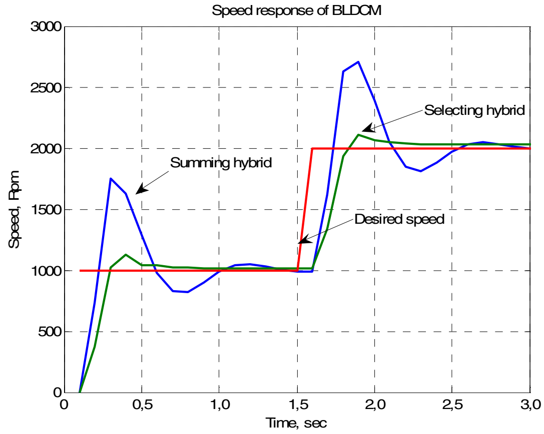

Fig. 12. Speed responses hybrid controller for speed setting changes from 1000 to 2000 rpm

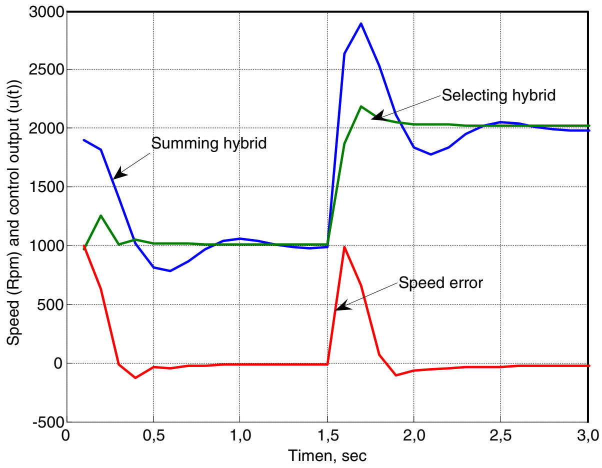

Fig. 13. The control output of hybrid controller for speed setting changes from 1000 to 2000 rpm

V. CONCLUSION

This paper has described to control the BLDCM speed, that compared the several control structurs. The model of BLDCM was constructed by identification system that represented of the real system that obtained to measure the dynamic response system. The hybrid PID ANFIS controller which applied the selecting error was obtained the best response. It was to obtained when the error less equal than 10% the ANFIS controller is done but the error great equal 10% the PID controller is done. Other word, the PID controller is as main control and the ANFIS is as recovery control. The hybrid PID ANFIS controller which applied the summing output PID controller and ANFIS controller can be made the rise time shorter but the overshoot increased.

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