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Performance Analysis of Adaptive Neuro Fuzzy Inference Systems (ANFIS) for Speed Control of Brushless DC Motor

Hidayat[#,*1], Sasongko P.H [#2], Sarjiya[#3], Suharyanto[#4]

[#] *Department of Electrical Engineering, Gajah Mada University*
Jl. Grafika 2 Yogyakarta Indonesia
[1]hdyttanjung@yahoo.com, [2]sasongko@te.ugm.ac.id,
[3]sarjiya@te.ugm.ac.id, [4]suharyanto@te.ugm.ac.id

[*] *Department of Electrical Engineering Bung Hatta University*
Jl. Gajahmada No. 19 Gunung Panggilun Padang Indonesia

***Abstract*— This paper presents a performance analysis of Adaptive Neuro Fuzzy Inference Systems (ANFIS) which is applied to control the speed of Brushless Direct Current Motor (BLDCM). The proposed strategy of speed BLDCM controller is operating which is similar to the conventional direct current motor. This strategy is implemented base on quadratic axis control and zero direct axis current. The aim of the speed controller is to obtain the speed motor operating similar to a speed setting. The input of the controller is speed measured by speed sensor encoder. The output is level voltage supplying stator windings BLDCM through pulse wide modulation controller of inverter. The ANFIS controller is used to decide the pulse wide to of the inverter. It has two input variables speed error, speed error rate and the output variable is the voltage to represent stator current. The variables are represented into fuzzy sets called fuzzy membership functions that their function form and number will be varied until acquired the best characteristic of dynamic response systems. Using MATLAB Simulink, the performance analysis at this strategy is emphasized on the transient parameter of dynamic response. The simulation results show that the best response of speed control is the bell function with five membership functions.**

Keywords— **BLDCM, speed control, ANFIS**

I. Introduction

BLDCM have been widely used as motor motion recently, because 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]. Therefore, many BLDCM had been applied in the industry (industrial drives ex pump, fans, blower, machine tolls, servo drives, automation process, internal transportations systems, robots, etc), the public life (air conditioning systems, catering equipment, coin laundry machines, auto bank machine, etc), the domestic life (kitchen equipment ex. refrigerators, microwave ovens, mixer, bathroom equipment, washing machines, toys, vision and sound equipment, security systems, etc), information and office equipment (computers, printers, plotters, scanners, etc), medical and healthcare equipment (dentist's drills, electric wheelchairs, trotters, rehabilitation equipment, artificial heart motors) and etc [1]. To control a speed of BLDCM, Atmel Corporation have produced the BLDCM using ATmega32M1 which apply a classic control. It is PID control. A quality control of BLDCM depends on the PID constant that is Kp, Ki, Kd. Tune Kp, Ki, Kd is done trial and error method [2]. This method is dangerous applied for the large capacity of BLDCM and difficult to achieve an accurate value.

In recent years, new artificial intelligent-based approaches have been proposed for speed control of BLDCM fuzzy logic controller has already applied, which results still show an oscillation on steady state response. Further, to decide on the domain of membership function is more difficult done [3]. The speed response of BLDCM that uses to fuzzy logic controller which apply the triangle membership function is better than that PID controller [4]. The Integration of fuzzy logic and neural network algorithm is an adaptive neuron fuzzy inference system (ANFIS). It had been applied to control the speed of conventional DC motor drive, so it compares with PI, IP, fuzzy, ANFIS controller. The results are response of ANFIS controller that is the best [5]. To improve speed response BLDCM, applied parallel fuzzy PID controller which consists of three parallel fuzzy sub controllers that update online the values of the proportional, integral, and derivative gains. The input of controller is error and the delayed control signal that represented to triangle functions [6]. Considering of the parameter uncertain and external disturbances of BLDCM applied an ANFIS controller which represented to become three input variables such as: error, rate error and load. The input variables are represented to belt function, so the result is compared with MRC (model reference neural network controller). The speed response of ANFIS is better than that of MRC.

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In this paper a systematic approach for designing ANFIS is developed to find the best speed response of BLDCM. The model of BLDCM base on field oriented control which controlled the BLDCM speed depend on quadratic axis current [7]. The input of ANFIS controller are error and error rate that represented to vary number and forming of membership function. The analysis emphasizes on transient of dynamic response. The ANFIS architecture is used the first-order Sugeno fuzzy models because of its transparency and efficiency [8]

II. BLDCM MODELLING

BLDCM is constructed of Permanent Magnet Synchronous Machine (PMSM) 3 phase star connection, 4 poles, inverter 3 phase voltage source inverter, rectifier, filter, rotor position sensor, speed sensor and algorithm control [9]. Figure 1 shows equipment of BLDCM. Power is supplied from the utility through a transformer, which is depicted as an equivalent voltage behind inductance. The transformer output is rectified, and the rectifier output is connected to the dc link filter, which may be simply an LC (L_{dc}, C_{dc}) but which may include a stabilizing filter (L_{st}, r_{st}, C_{st}) as well. The filtered rectifier output is used as dc voltage source for the inverter, which derives the PMSM. As can be seen, rotor position is an input to the controller. Based upon rotor position and other input, the controller determines the switching states of each of the inverter semiconductors. The command signal to the controller may be quite varied depending upon structure of the controls in the system in which the drive is embedded. Other inputs to the control the algorithms may include rotor speed, dc link voltage, and rectifier. Other outputs may include gate signals to the rectifier thyristor if the rectifier is phase controlled.

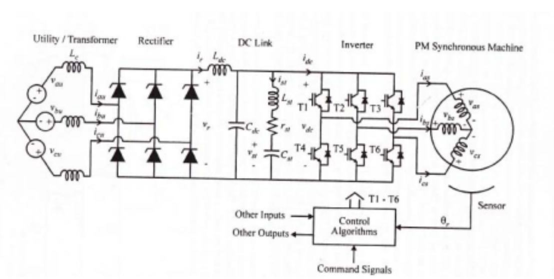


Fig.1 The circuit element of BLDCM [7]

To control BLDCM base on field oriented control is a part of the strategy to control AC machine's performance that likes DC machine. This strategy has been invited since 1970 to control speed of asynchronous machine and synchronous machine of separate winding excitation. The AC machine equations in frame 3 phases are transformed into frame rotor equations that it is known a *d-q axis* coordinate by R.H *Park* in 1920 [7]. The equivalent circuit of PMSM in dq-axis is shown in Fig. 2.

The voltage equation of PMSM in dq axis is:

$$V_q = R_s i_q + \omega_r \lambda_d + \rho \lambda_q \qquad (1)$$

$$V_d = R_s i_d - \omega_r \lambda_q + \rho \lambda_d \qquad (2)$$

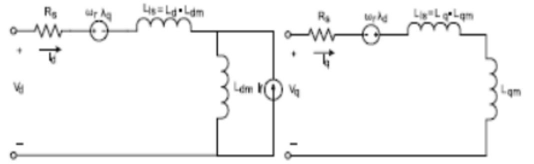


Fig. 2 The equivalent circuit PSMS [7]

Where V_q, V_d is the voltage in the q axis and d axis, R_s is the stator resistance per phase, ω_r is the rotor electrical speed, i_q, i_d is the current in the q axis and d axis, λ_q, λ_d is the flux linkage in the d axis, and ρ is the differential notation.

The Flux linkages are:

$$\lambda_q = L_q i_q \qquad (3)$$

$$\lambda_d = L_d i_d + \lambda_f \qquad (4)$$

Substituting equation (3) and (4) into (1) and (2), so in matrix form:

$$\begin{bmatrix} V_q \\ V_d \end{bmatrix} = \begin{bmatrix} R_s + \rho L_q & \omega_r L_d \\ -\omega_r L_q & R_s + \rho L_d \end{bmatrix} \begin{bmatrix} i_q \\ i_d \end{bmatrix} + \begin{bmatrix} \omega_r \lambda_f \\ \rho \lambda_f \end{bmatrix} \qquad (5)$$

The developed torque motor is being given by

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)(\lambda_d i_q - \lambda_q i_d) \qquad (6)$$

The mechanical torque equation is

$$T_e = T_L + B\omega_m + J\frac{d\omega_m}{dt} \qquad (7)$$

Solving for the rotor mechanical speed form (7) is

$$\omega_m = \int\left(\frac{T_e - T_L - B\omega_m}{J}\right)dt \qquad (8)$$

and

$$\omega_m = \omega_r\left(\frac{2}{P}\right) \qquad (9)$$

where ω_m is the rotor mechanical speed.

The stator windings are supplied by 3 phase source which is each phases different 120^o, as shown

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} \sin(\omega_r t + \alpha) \\ \sin(\omega_r t + \alpha - \frac{2\pi}{3}) \\ \sin(\omega_r t + \alpha + \frac{2\pi}{3}) \end{bmatrix} (I_m) \qquad (10)$$

where Im is the maximum current, α is the angle between the rotor and stator current vector. Represented the stator current in dq axis is given,

$$\begin{bmatrix} i_q \\ i_d \end{bmatrix} = I_m \begin{bmatrix} \sin\alpha \\ \cos\alpha \end{bmatrix} \qquad (11)$$

When the rotor angle and the stator current phasor is $\alpha = 90^o$, that perform making the torque that produced current i_q equal to the current I_m . Therefore $i_d = 0$ and $i_q = I_m$. Then the torque as equation (6) is given,

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)(\lambda_d i_q) \tag{12}$$

Assuming that:

$$k_t = \frac{3}{2}\frac{P}{2}\lambda_f \tag{13}$$

The torque is given by

$$T_e = k_t . i_q \tag{14}$$

According the equation that torque is dependent of the motor current, so the performance looks like the conventional DC motor. The simplification of speed control of BLDCM base on Fig. 2 is given by Fig. 3.

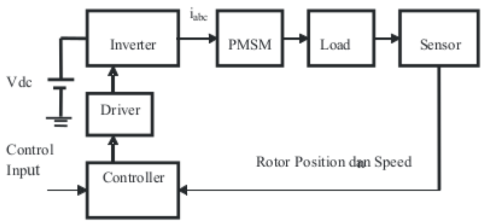


Fig. 3 Block diagram of speed control BLDCM

III. ANFIS Controller Modelling

A. ANFIS Principle

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. 4. The mechanism of Sugeno has two inputs x_1 and x_2 and one output y. For a first-order Sugeno fuzzy model [8], a common rule set with two fuzzy if-then rules is the following :

If x_1 is A_1 and x_2 is B_1 Then $y_1 = c_{11}.x_1 + c_{12}.x_2 + c_{10}$ (15)

If x_1 is A_2 and x_2 is B_2 Then $y_2 = c_{21}.x_1 + c_{22}.x_2 + c_{20}$ (16)

If α predicate for two roles are w_1 and w_2, then can be determined the weight average:

$$y = \frac{w_1 y_1 + w_2 y_2}{w_1 + w_2} = \overline{w_1} y_1 + \overline{w_2} y_2 \tag{17}$$

The function of every layer is:

Layer 1

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

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

$$O_{1,i} = \mu_{Ai}(x_1), \quad \text{for } i = 1, 2, \text{ or} \tag{18}$$

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

If membership function is given by the generalized bell function:

$$\mu(x) = \frac{1}{1 + \left|\frac{x-c}{a}\right|^{2b}} \tag{19}$$

where {a,b,c} is the parameter set. As the value of these parameters change, 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.

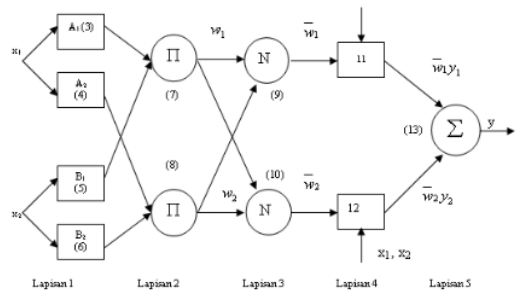


Fig. 4 The architecture ANFIS [9]

Layer 2

Every node in this layer is fixed node labelled Π , whose output is the product of all the incoming signals:

$$O_{2,i} = w_i = \mu_{Ai}(x_1) x \mu_{Bi}(x_2), \text{ for } i = 1, 2 \tag{20}$$

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.

(6)

Layer 3

Every node in this layer is a fixed node labelled 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

$$O_{3,i} = \overline{w_i} = \frac{w_i}{w_1 + w_2}, \quad i = 1,2 \tag{21}$$

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.

$$O_{4,i} = \overline{w_i} y_i = \overline{w_i}(c_{i1}x_1 + c_{i2}x_2 + c_{i0}) \quad i = 1,2 \tag{22}$$

where $\overline{w_i}$ is a normalized firing strength from layer 3 and $\{c_{i1}, c_{i2}, c_{i0}\}$ is 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:

$$O_{5,i} = \sum_i \overline{w}_i y_i = \frac{\sum_i w_i y_i}{\sum_i w_i} \qquad (23)$$

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.

B. ANFIS Controller

The ANFIS base control in this paper is the direct inverse control because of this is simply method and applicable. This method [10] seems straightforward and only one learning task is needed to find the inverse model of the plant, which is not valid in general. Inverse learning or general learning for control purpose is performed in two phases. In the learning phase, the plant ANFIS inverse model is obtained based on input-output data generated from the former ANFIS model of the system as illustrated by Fig. 5. In the application phase, the obtained ANFIS inverse model in used to generated the control action as illustrated by Fig. 6.

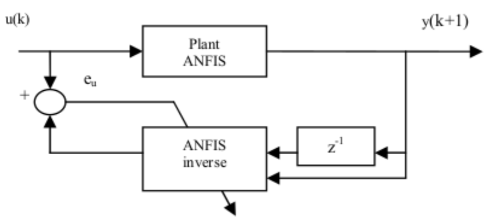


Fig. 5 Block diagram a training phase for inverse control method

The ANFIS controller generates change in the reference current iq base on error (e) and derivative error (de). Therefore, the input ANFIS controller is speed error (e) and rate speed error (de). The output controller (u(k)) is suitable signal matching with the input current into stator windings to preserve BLDC speed similar a setting. Every input and output variables are represented by membership function fuzzy, which domain of membership function is determined by learning process as shown above.

$$e = \omega_{ref} - \omega_r = \text{r (k)} - \text{y(k+1)} \qquad (24)$$

$$de = [d(\omega_{ref} - \omega_r)]/dt = \text{y(k)} - \text{y(k-1)} \qquad (25)$$

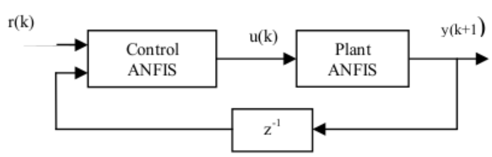


Fig. 6 Block diagram an application phase for inverse control method

IV. Simulation and Analysis

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

BLDC motor type	*: Amatek 119003-01*
Rating (P)	*: 106 Watt*
Number of Phase	*: 3 (star)*
Rated Speed	*: 4228 rpm*
Rated current	*: 6,8 A*
Stator equivalent resistance	*: 0,348 Ohm*
Stator equivalent inductance	*: 0,314 mH*
Moment of inertia (J)	*: 0,0019 N.m-s*^{2}
Number of pole (p)	*: 8*
Voltage current constant (λ*)*	*: 0,0419 V/rad/s*

The MASTS performance is simulated using MATLAB 7 Simulink program [12],[13], as shown in Fig. 7

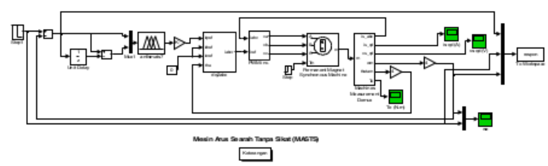


Fig. 7 Speed control circuit of BLDCM in MATLAB simulink

The simulation is done for several functions of membership functions, such as bell, triangle, trapezoid and number of membership function, such as 3, 5 and 7. Every function and number of membership functions is determined and evaluated the transient parameter, such as e, tr, tp, Mp and ts,

To training ANFIS is needed three data, such as two input data and an output data. They are acquired from the open loop experiment, as shown Fig.8. The input current is given the uniform random number function and then determines the current delay as input data too. The output simulation is speed, which will be used as output data of ANFIS training. The data for training ANFIS is shown by curves as Fig. 9. For the evenly distributed grid points of the time input range 0,03 second with time sampling 0,005, maximum value 20, and minimum value 0 is obtained 131 training data pairs.

The first experiment is making the bell function with 5 membership function for each input and output variables. The ANFIS used here contains 25 (5x5=25) rules, 95 total number of fitting parameters, including 20 (5x2+5x2) premise (non linier) parameters and 75 (3x25=75) consequent (linier) parameters. The training and root mean square (RMS) errors obtained from the ANFIS are 1,127 for 1200 epochs. Fig. 10 shows the initial membership function before training. Fig. 11 shows optimized membership function for *e* and *de* after trained.

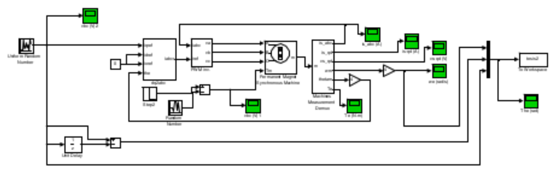


Fig. 8 Open loop circuit of BLDCM in MATLAB simulink

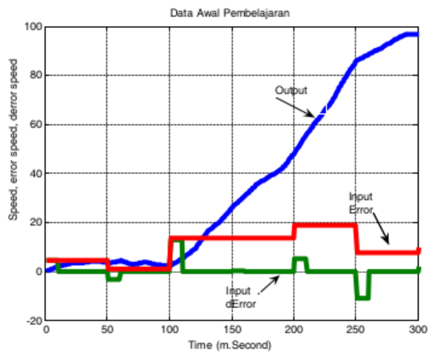


Fig. 9. Data of training ANFIS

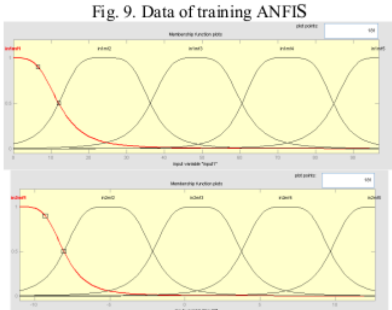


Fig. 10. Membership function of error (e) and derivative error (de) before training

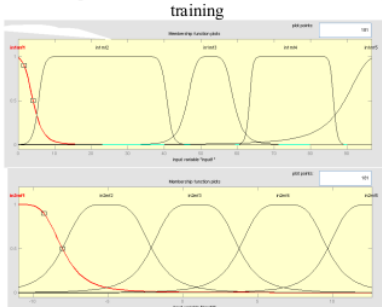


Fig. 11. Membership function of error (e) and derivative error (de) after training

For speed reference 2000 rpm, then program is run. The result of response transient is shown in Fig. 12,which obtained transient parameters ts 38 ms, tp 38 ms, td 50 ms, ess = 0% and Mp = 0%. Further, the experiment has done for 3 and 7 membership functions, so that transient response shown Fig.12 and transient parameters were shown by Table 1.

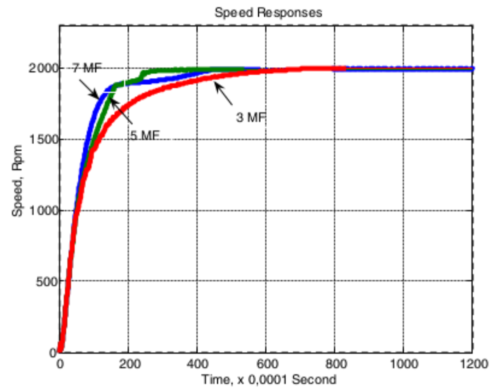
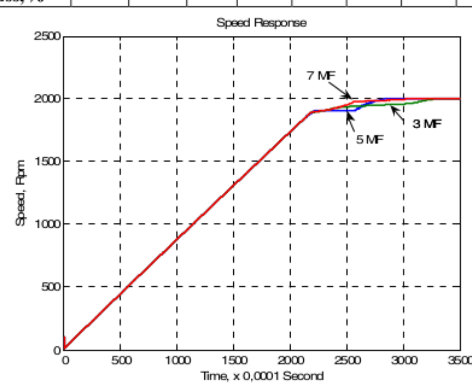


Fig. 12. Transient response speed control of BLDCM for 3. 5 and 7 Bell membership function

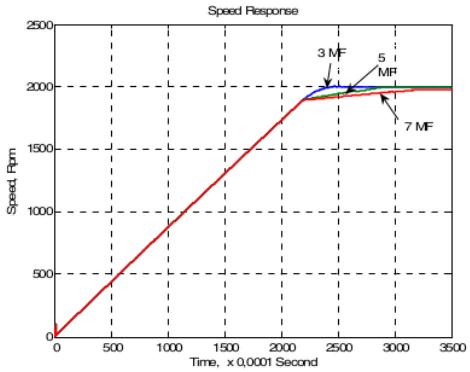
The next experiment has made for the triangular function with 3 and 7 membership functions for each input and output variables. Further, the trapezoidal membership function with number membership function 3, 5 and 7. The similar way of was obtained the result shown in Fig.13, 14 and Table 1.

TABLE I
RESPONSE TRANSIENT PARAMETER OF ANFIS CONTROLLER FOR SPEED CONTROL BLDCM

	Functions and numbers of membership function								
	Bell			**Triangle**			**Trapezoid**		
	3	**5**	**7**	**3**	**5**	**7**	**3**	**5**	**7**
Rules	9	25	49	9	25	49	9	25	49
Premise	12	20	28	12	20	28	12	20	28
coseq	27	75	147	27	75	147	27	75	147
Epoch	280	1200	500	1000	1500	2000	6300	3300	1050
RMSE	1,614	1,127	1,92	1,87	1,27	0.87	1,24	0,86	0.93
Ts,ms	65	38	45	325	280	275	250	280	320
Tp,ms	65	38	45	325	280	275	250	280	320
Td,ms	50	50	50	112	112	112	112	112	112
Mp,%	0	0	0	0	0	0	0	0	0
Ess,%	0	0	0	0	0	0	0	0	2,5



. Fig. 13. Transient response speed control BLDCM for 3. 5 and 7 triangular membership function



.Fig.14 Transient response speed control BLDCM for 3. 5 and 7 trapezoidal membership function

Comparing the results of simulation speed control BLDCM using ANFIS for varied number and function of membership functions that seemed as shown in Table 1. The best response is obtained on the bell of membership function. Caused the bell function has smoothness and concise notation, that's a, b and c parameters. Changing parameter c and a will vary the centre and wide of the membership function, and then use b to control the slopes at the crossover pints. All parameters are adjusted automatically by ANFIS, so that is faster to achieve desired output than any other membership functions. Seem that, the smallest RMS is obtained the smallest epoch.

The experiment also is done for various speed sets that are 2000 rpm then at 50 ms speed changed 1500 rpm. When the speed sets changed cause of the error suddenly had been increasing for 0,1 ms, after that, the error reverses zero. The characteristic response is shown in Fig. 14.

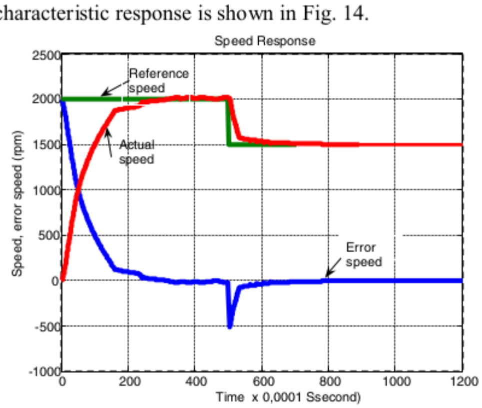


Fig.14. Transient response speed control BLDC for different speed setting

V. Conclusions

This paper has described the procedure of controller ANFIS to control speed BLDCM. The method has varied the input of functions and number membership function to obtain the best response. Contributions of this paper will be avaliable to guide to design the ANFIS parameters. According the results of simulation can be given conclusion :

:

1. Applying ANFIS controller was very easy to design of controller paramaters, because that parameters obtained automatically to throw learning process.
2. The best responce of speed controller BLDCM base ANFIS was obtained which was the bell function with 5 numbers of membership function, hybrid learning and linier premise parameter. It was decided after 1200^{th} epoch and RMSE 1,127.
3. The transient responce was relatively good that shown by time settling 38 ms, overshoot 0 % and steady state error 0 %.

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