Design of PID-Fuzzy for Speed Control of Brushless DC Motor in Dynamic Electric Vehicle to Improve Steady-State Performance

Arman Jaya
Electrical Engineering Department
Electronics Engineering Polytechnic Institute of Surabaya
Surabaya, Indonesia
arman@pens.ac.id

Era Purwanto
Electrical Engineering Department
Electronics Engineering Polytechnic Institute of Surabaya
Surabaya, Indonesia
era@pens.ac.id

Melinda Badriatul Fauziah
Electrical Engineering Department
Electronics Engineering Polytechnic Institute of Surabaya
Surabaya, Indonesia
melfauziah@gmail.com

Farid Dwi Murdianto
Electrical Engineering Department
Electronics Engineering Polytechnic Institute of Surabaya
Surabaya, Indonesia
farid@pens.ac.id

Gigih Prabowo
Electrical Engineering Department
Electronics Engineering Polytechnic Institute of Surabaya
Surabaya, Indonesia
gigih@pens.ac.id

Muhammad Rizani Rusli
Electrical Engineering Department
Electronics Engineering Polytechnic Institute of Surabaya
Surabaya, Indonesia
ruslirizani@gmail.com

***Abstract*—Brushless DC Motor is a three phase permanent magnet motor that requires DC voltage as its supply. This kind of motor is widely used in electric vehicles due to high efficiency and high torque. Unfortunately, speed control method of brushless DC motor is still quite difficult if applied to electric vehicle. Electric vehicle that uses brushless DC motor works on dynamic load system with the varied set point. The use of conventional PID controller can't be applied to dynamic load system. If this controller still be applied, the system response to steady state will be long enough and cause the motor has a bad performance. The use of PID-Fuzzy is the solution to solve this problem. Simple PID algorithm and fuzzy logic in case of PID parameter tuning are expected to maintain the steady state condition of brushless DC motor speed at varied set point and dynamic load condition. So, the brushless DC motor performance will be improved.**

Keywords—Brushless DC (BLDC) Motor; PID Controller; Fuzzy Logic; PID-Fuzzy; Electric Vehicle.

I. INTRODUCTION

The use of electric motors in daily life has become a very important. Many tools use many electric motors, such as air conditioning, conveyor, vacuum cleaner, and electric vehicle. DC motor is one of electric motor that is often used as an electric vehicle drive because the speed is easy to control and has a wide speed variation. However, the use of brush of DC motor creates a problem. Brushless DC motor can replace a DC motor, which has advantages such as high efficiency, high torque, and easy maintenance [1-2]. The removal brush on the brushless DC motor can overcome the problems associated with the mechanical friction and electrical erosion.

The use of brushless DC motor in electric vehicle is often not optimal. The varied set point and dynamic load condition must be considered on electric vehicle. Set point represents as a reference speed from throttle and a dynamic load condition represents as a disturbance when the electric vehicle passes the incline. Conventional controllers can't perform well in dynamic load condition [3-4]. So it is necessary to control the speed of motor to keep the motor work up. This speed control refers to the actual speed as feedback and throttle as reference speed.

There are several methods already done in speed control of brushless DC motor, one of which is PID [5]. PID has a simple structure and has advantages in each parameter. A good controller should have a fast response, fast settling time without causing overshoot. However, the PID is still unable to generate a fast response in dynamic load condition and varied set point [6].

In addition to PID, the fuzzy logic controller is also often used in speed control of motor. Application of fuzzy on the system does not require an accurate mathematical model. However, fuzzy designing requires operator or human thinking to apply in the system so that it can generate dynamic response. But, fuzzy has a longer commutation time

978-1-5386-0712-1/17/$31.00 ©2017 IEEE

than PID because of the complex fuzzification and defuzzification processes [7-8].

The method used in this paper is to combine the PID and fuzzy logic. PID becomes the main controller on this system and fuzzy logic is used to tune the parameter of PID. Thus, this method can be used on dynamic system and generate steady state response speed control of brushless DC motor applied in electric vehicle.

II. BRUSHLESS DC MOTOR

A. Modeling of Brushless DC Motor

Brushless DC motor is a permanent magnet motor that has trapezoidal back emf. The commutation on the brushless DC motor uses six switching components (power transistors) in the three phase inverter to activate two phases on the BLDC motor simultaneously while the third phase will be floating. The position of the rotor used for the inverter switching algorithm is obtained from three Hall Effect sensors on the stator attached to one another 120 degrees electrically.

Modeling of brushless DC motor assumes that the stator is connected Y, the resistance of each phase is equal, the switching component of the inverter is ideal, and iron core losses including eddy current losses and hysterical losses are ignored [9-10].

The equivalent circuit of brushless DC motor can be shown as in Fig. 1.

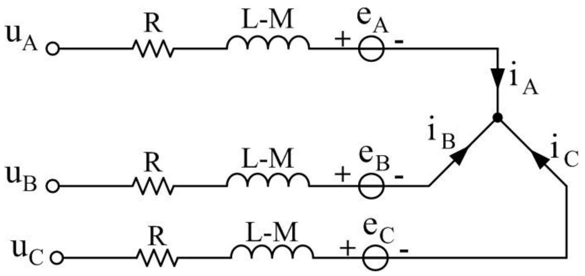

Fig. 1. Equivalent Circuit of Brushless DC Motor

The matrix from the phase voltage equation of brushless DC motor can be shown as

$$\begin{bmatrix} u_A \\ u_B \\ u_C \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} + \begin{bmatrix} L-M & 0 & 0 \\ 0 & L-M & 0 \\ 0 & 0 & L-M \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} + \begin{bmatrix} e_A \\ e_B \\ e_C \end{bmatrix} \quad (1)$$

Where, u_A, u_B, u_C is a phase voltage *A, B,* and *C*. *R* is a stator resistance, *L* and *M* is self-inductance and mutual inductance. i_A, i_B, i_C is phase current *A, B, and C*. e_A, e_B, e_C is phase back emf voltage *A, B,* and *C*.

The electromagnetic torque of brushless DC motor can be shown as

$$T_e = \frac{e_A i_A + e_B i_B + e_C i_C}{\omega_m} \quad (2)$$

Where, T_e is electromagnetic torque of brushless DC motor and ω_m is angular velocity of rotation in radians per second.

The equation to calculate the motion in order to build a complete mathematical model of electromechanical system can be shown as

$$T_e - T_L = J\frac{d\omega_m}{dt} + B_v \omega_m \quad (3)$$

Where, T_L is a load torque, *J* is a motor moment of inertia, and B_V is a viscous friction coefficient.

The electrical position of rotor and speed of rotor are related by

$$\frac{d\theta_r}{dt} = \frac{P}{2}\omega_m \quad (4)$$

Where, θ_r is a position of rotor with respect to d-axis in rads and P is number of poles.

B. Speed Control of Brushless DC Motor

Speed control of brushless DC motor in this paper based on PAM (Pulse Amplitude Modulation) control. In PAM control, the switching components (Power Transistors) will be On and Off at high speeds based on the switching commutation of inverter and also brushless dc motor was operated by varying the input voltage of inverter [11].

The block diagram speed control of brushless DC motor is shown in Fig. 2. There are two loops that used in the block diagram. The first loop is used for six step inverter commutation and the second loop is used for speed control of brushless DC motor.

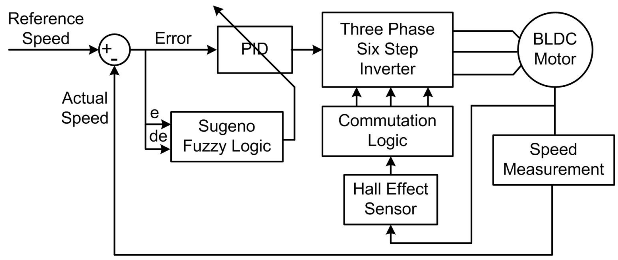

Fig. 2. Block Diagram Speed Control of Brushless DC Motor

Hall Effect sensor on the brushless DC motor has two functions, as position sensor and speed sensor. The Hall Effect sensor algorithm when detecting the rotor position is used as switching commutation on the inverter. When the coil is energized, the magnetic field will be form and the rotor will rotate. Meanwhile, hall Effect sensor as a speed sensor serves to obtain the current speed data which will be used to get the error value.

III. DESIGN OF CONTROLLER

The controller is used to return the desired set point value response, even if the set point value is changed. Stages of this controller planning include designing PID controllers and design of fuzzy logic controllers.

A. PID Controller

The PID Controller consists of parameters P (Proportional), I (Integral), and D (derivative) [12], where the block diagram is shown in Fig. 3.

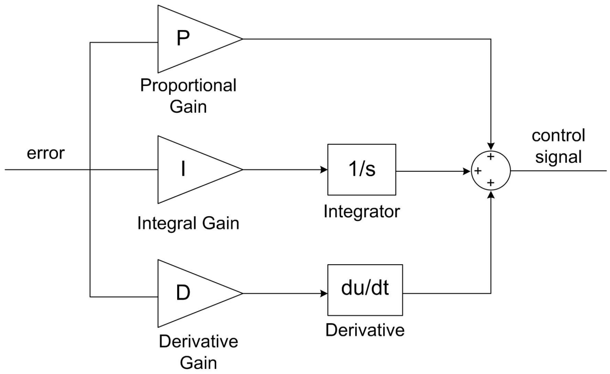

Fig. 3. Block Diagram of PID Controller

Any excess on each parameter P, I, and D can be parallelly integrated into a PID controller. PID controller has characteristics that can accelerate the rise time, reduce the steady state error in the system, and also reduce the oscillation.

The transfer function of the PID Controller [13] is shown as

$$u(s) = \left[K_p + \frac{K_i}{s} + K_d s \right] E(s) \tag{5}$$

The PID controller equation in time domain is shown as

$$u(t) = K_p e(t) + K_i \int^t e(t)dt + K_d \frac{de}{dt} \tag{6}$$

$$u(t) = K_p \left(e(t) + \frac{K_i}{K_p} \int^t e(t)dt + \frac{K_d}{K_p} \frac{de}{dt} \right) \tag{7}$$

$$T_i = \frac{K_p}{K_i} \ and \ T_d = \frac{K_d}{K_p} \tag{8}$$

$$u(t) = K_p \left(e(t) + \frac{1}{T_i} \int^t e(t)dt + T_d \frac{de}{dt} \right) \tag{9}$$

Where, K_p is proportional gain, K_i is integral gain, K_d is derivative gain, $e(t)$ is error, T_i is constant integral time, and T_d is derivative time constant.

B. PID-Fuzzy

PID-Fuzzy is a controller to optimize the work of PID controllers when the set point and load are dynamic. Fuzzy logic works to determine Kp, Ki and Kd parameters. PID-Fuzzy has two inputs consisting of error and delta error, and three outputs are Kp, Ki, and Kd. The PID-Fuzzy control scheme is shown in Fig. 4.

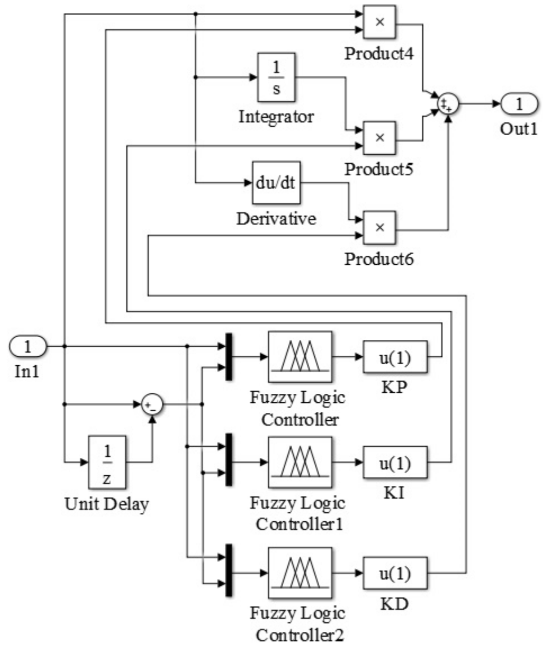

Fig. 4. Subsystem of PID-Fuzzy

Sugeno fuzzy type was chosen in this study because deffuzification process is more simple than Mamdani type. Fig. 5 and equation (10) shows the calculation of the output value of the fuzzy sugeno type [14-15].

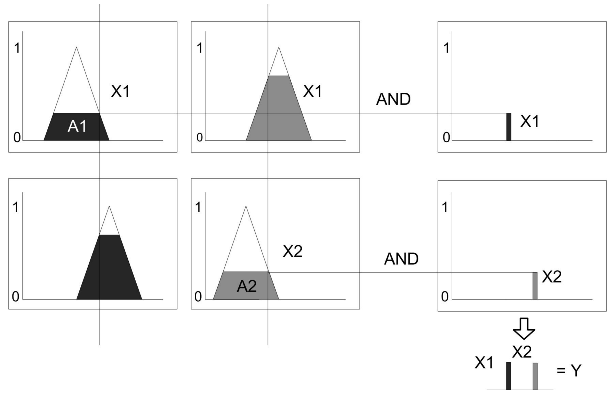

Fig. 5. Illustration of Sugeno Fuzzy Type Defuzzification Process

$$y = \frac{\sum C_n X_n}{\sum X_n} \tag{10}$$

The overall PID-Fuzzy control system designed to control the brushless DC motor is shown in Fig. 6 and the brushless DC motor speed and BLDC motor specifications is shown in Table 2.

The design of sugeno fuzzy type consists of two inputs namely error and delta error shown in Fig. 7. Where, NB, NS, Z, PS, and PB are Negative Big, Negative Small, Zero, Positive Small and Positive Big respectively. The maximum value of set point is 700, so each error and delta error has five membership functions ranging from -700 to 700.

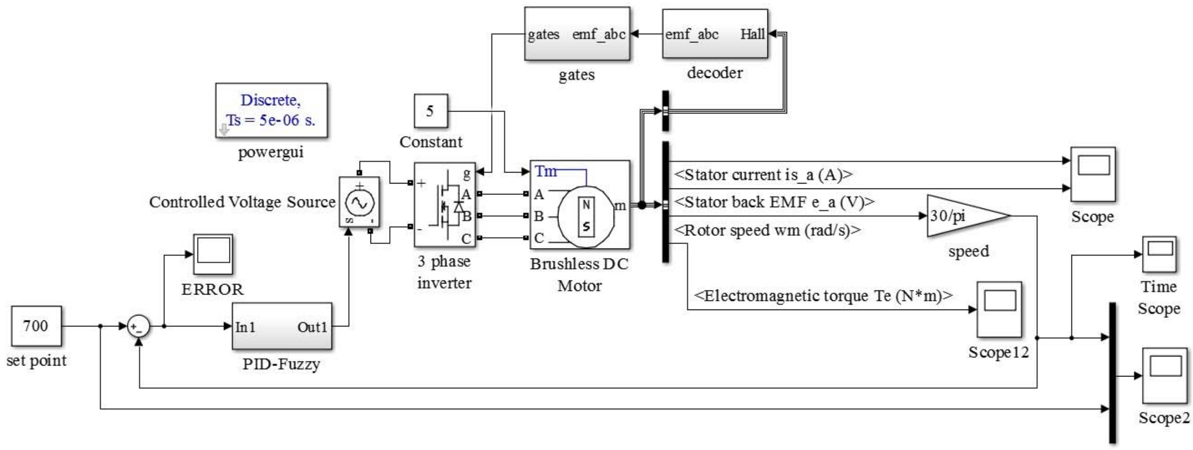

Fig. 6. Overall System of Speed Control Brushless DC Motor use PID-Fuzzy

TABLE II. BRUSHLESS DC MOTOR SPECIFICATION

Parameters	Value
Stator phase resistance Rs (ohm)	0.045
Stator phase inductance Ls (H)	6.85e-3
Voltage constant (V_peak L-L / krpm)	65.48
Back EMF flat area (degrees)	120
Inertia (J(kg.m^2))	0.0008
Viscous damping (F(N.m.s))	0.001
Pole pairs	13

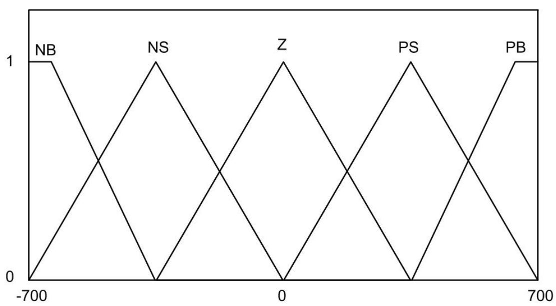

Fig. 7. Membership Function for error and delta error

While the fuzzy output consists of three output. There are output for Kp, output for Ki, and output for Kd. The membership function output of Kp, Ki, and Kd parameters is shown in Fig. 8, Fig. 9, and Fig. 10. respectively.

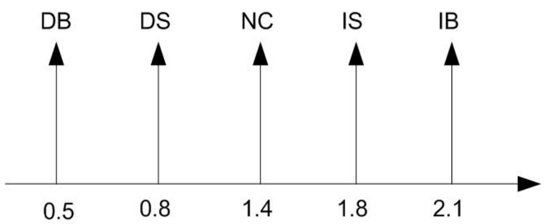

Fig. 8. Membership Function Output for Kp Parameter

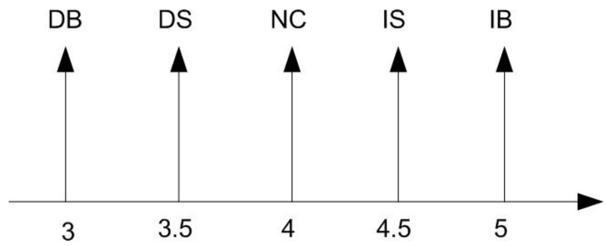

Fig. 9. Membership Function Output for Ki Parameter

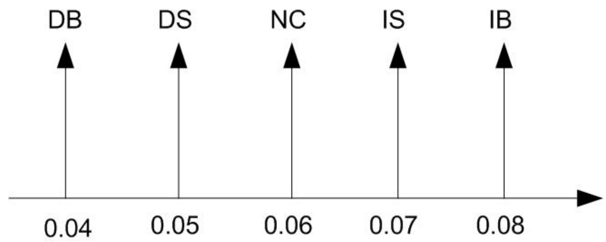

Fig. 10. Membership Function Output for Kd Parameter

Where, DB, DS, NC, IS, and IB are Decrease Big, Decrease Small, Not Change, Increase Small, and Increase Big respectively. The parameter values of Kp, Ki, and Kd at fuzzy output are obtained from the system tuning result using Ziegler Nichols method. So we get the value of Kp, Ki, and Kd at each set point and each load. The parameter value is used as a reference for fuzzy output.

Rule base for sugeno type for Kp, Ki, and Kd parameter is shown in Table. 3.

TABLE III. RULE BASE SUGENO FUZZY TYPE FOR KP, KI, AND KD PARAMETERS

e \ de	NB	NS	Z	PS	PB
NB	DB	DB	DB	DS	NC
NS	DB	DB	DS	NC	IS
Z	DB	DS	NC	IS	IB
PS	DS	NC	IS	IB	IB
PB	NC	IS	IB	IB	IB

IV. SIMULATION RESULT AND DISCUSSION

The simulation is performed using 48V; 1KW brushless DC motor, with nominal speed of 700 rpm. Fig. 11 and Fig. 12 show output response from PID-Fuzzy and conventional PID at set point 100 rpm and 700 rpm with no load.

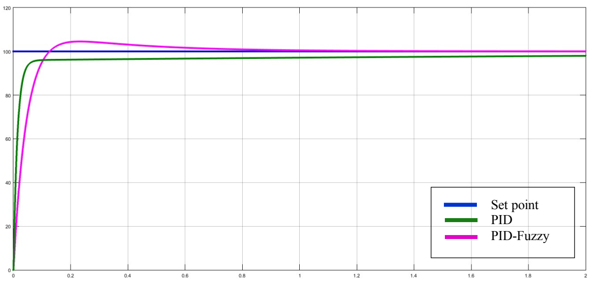

Fig. 11. Speed Response of 100 rpm with no load

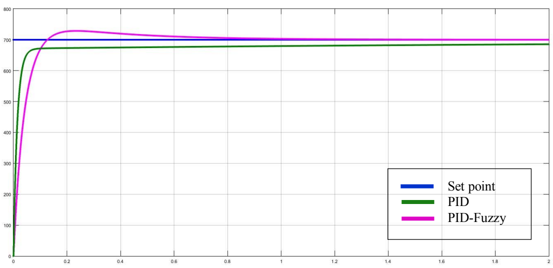

Fig. 12. Speed Response of 700 rpm with no load

PID response at set point 100 rpm with no load has a rise time 34.483 ms with overshoot of -1.751%. At set point 700 rpm, the response shows the rise time of 35.374 ms and the overshoot of -1.748%. While the PID-Fuzzy response on the 100 rpm set-point with no load has a rise time of 66 ms with an overshoot of 9.783%. At set point 700 rpm, the response indicates a rise time of 68.764 ms and an overshoot of 7,447%. At no load, the speed response indicates an overshoot on PID-Fuzzy, but its response can reach the steady state condition with the settling time of 0.233 s at set point 100 rpm and settling time of 0.235 s at set point 700 rpm.

Fig. 13 and Fig. 14 show the output response of the PID-Fuzzy and conventional PID at the set point of 100 rpm and 700 rpm with load. The given load is 5 Nm.

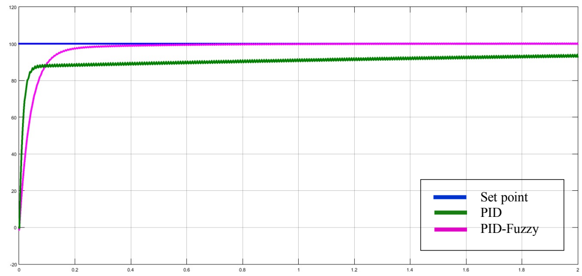

Fig. 13. Speed Response of 100 rpm with load

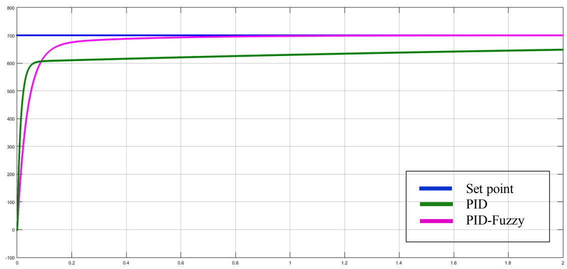

Fig. 14. Speed Response of 700 rpm with load

When the system is loaded on each set point, the PID response at the set point 100 rpm has a rise time of 36.441 ms with an overshoot of -1.453%. At set point 700 rpm, the response shows rise time of 80.687 ms and overshoot of -1.688%. But the PID can't reach the steady state within that time range. While PID-Fuzzy shows rise time of 98.526 ms, overshoot of -0.326% at set point 100 rpm and rise time of 115.795 ms, overshoot of -0.211% at set point 700 rpm. The PID-fuzzy can reach the steady state on that time range with load.

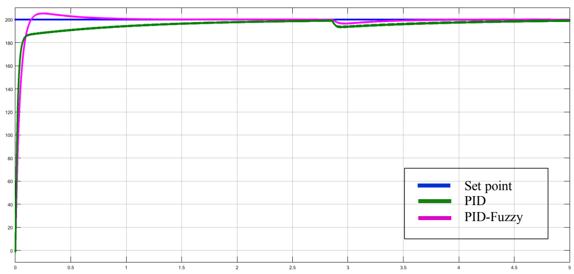

Fig. 15. Speed Response of 700 rpm with no load

Fig. 15 shows the output response of the PID-Fuzzy and conventional PID at the set point of 200 rpm with disturbance. The disturbance was suddenly given at time of 2.8 second. The result shows that PID can reach the steady state condition at the settling time of 4.7 second. Meanwhile, PID-Fuzzy can reach the steady state condition at the settling time of 3.6 second.

To compare system performance on conventional PID and PID-Fuzzy, measurement of speed response performance on brushless DC motor is shown in Table 4. Where tr is Rise Time (ms), ts is Settling Time (s), and Mp is Overshoot (%).

TABLE IV. PERFORMANCE RESULT BETWEEN CONVENTIONAL PID AND PID-FUZZY

Controller	Set point	No load			With load		
		tr	ts	Mp	tr	ts	Mp
PID	100	34.48	-	-1.75	36.44	-	-1.45
	200	34.53	-	-1.75	36.49	-	-1.45
	400	35.02	-	-1.74	36.80	-	-1.62
	600	35.12	-	-1.74	79.26	-	-1.68
	700	35.37	-	-1.74	80.68	-	-1.68
PID-Fuzzy	100	66	0.23	9.78	98.52	1.71	-0.32
	200	67	0.23	9.65	99.10	1.71	-0.31
	400	69.32	0.23	7.44	112.19	1.99	-0.23
	600	68.54	0.23	7.44	115.10	1.99	-0.21
	700	68.76	0.23	7.44	115.79	1.99	-0.21

V. CONCLUSION

The simulation of speed control brushless DC motor has been presented. The simulation result show that the PID parameters tuned by fuzzy logic can improve the performance of brushless DC motor speed in varied set point and dynamic load conditions. PID-Fuzzy produces better performance than conventional PID. PID-Fuzzy indicates that the response can reach steady state condition faster than conventional PID on dynamic load and varied set point in electric vehicle. This research is the first step of the implementation. So, in the future this research will be reference to be continued in implementation.

ACKNOWLEDGMENT

The authors thank to the research group of Electric Drive Laboratory, Electronics Engineering Polytechnic Institute of Surabaya (EEPIS), for all the support and guidance.

REFERENCES

[1] H.X. Wu, S.K. Cheng, and S.M. Cui. “A Controller of Brushless DC Motor for Electric Vehicle,” 12th Symposium on Electromagnetic Launch Technology, 2004.

[2] R. Khandiban and R. Arulmozhiyal. “An Intelligent Speed Controller for Brushless DC Motor,” Industrial Electronics and Application (ICIEA), 2014.

[3] R. Khandiban and R. Arulmozhiyal. “Design of Adaptive Fuzzy PID Controller for Speed control of BLDC Motor,” International Journal of Soft Computing and Engineering (IJSCE), 2012.

[4] R. Ahmed, C-S. Marcel J, and R. Ofoli. Abdul, “DSP-Based Laboratory Implementation of Hybrid Fuzzy-PID Controller Using Generic Optimization for High-Performance Motor Drives,” IEEE Transactions on Industry Applications, Vol.44 No.6, November/December 2008.

[5] R. Shanmugasundram, M. Zakariah and N. Yadainah. “Implementation and Performance Analysis of Digital Controllers for Brushless DC Motor Drives,” IEEE/ASME Transactions on Mechatronics.

[6] N.K. Bapayya and R.K. Venkata, “Performance Evaluation of Hybrid Fuzzy PI Speed Controller for Brushless DC Motor for Electric Vehicle Application,” Conference on Power, Control, Communication, and Computational Technologies for Sustainable Growth (PCCCTGS), 2015.

[7] K. Zdenko and B. Stjepan “Fuzzy Controller Design Theory and Applications,” © 2006 by Taylor & Francis Group.

[8] J.X. Shen, Z.Q. Zhu, D. Howe, and J.M. Buckley, “Fuzzy Logic Speed Control and Current-Harmonic Reduction in Permanent-Magnet Brushless AC Drives,” IEEE Proc.-Electr. Power appl., vol. 152, no. 3, pp. 437-446, 2005.

[9] R. Krishnan, “Electric Motor Drives : Modeling, Analysis, and Control,” Prentice Hall, 2001, pp. 577-580.

[10] Xia. Chang-liang, “Permanent Magnet Brushless DC Motor Drives and Controls,” Wiley, 2012, pp. 33-39.

[11] K. T. Vamsee and Sonjanya. I.L.B, “Speed Performance of a BLDC Motor Employing PWM/PAM Control Techniques,” International Journal of Application or Innovation in Engineering & Management (IJAIEM), Volume 5, Issue 5, May 2016.

[12] F. Indra, P. Era, and A.W. Novie, “Fuzzy Gain Scheduling of PID (FGS-PID) for Speed Control Three Phase Induction Motor Based on Indirect Field Oriented Control (IFOC),” EMITTER International Journal of Engineering Technology, Vol. 4, No. 2, December 2016.

[13] A. Johnson. Michael and H.Moradi. Mohammad, “PID Control : New Identification And Design Method,” Springer.

[14] C. Wn-Jer, and H. Feng-Ling, “Mamdani and Takagi-Sugeno Fuzzy Controller Design for Ship Fin Stabilizing System,” Fuzzy System and Knowledge Discovery (FSKD), 2015.

[15] S. Alexandra-lulia, P. Stefan, P. Radu-Emil, D. Caludia-Adina, and R. Mircea-Bogdan, “Takagi-Sugeno Fuzzy Control Solution for BLDC Drives,” Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM), 2012.