

Fuzzy Logic Controller and Its Application in Brushless DC Motor (BLDC) in Electric Vehicle - A Review

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Abstract— Brushless DC motor (BLDC) is one type of electric motor that is widely used, especially in automotive systems. This motor is widely used as a driving force in electric vehicles. BLDC motor is chosen because it has the characteristics of high efficiency, reliability, and a wide speed range. Besides, BLDC motors require less maintenance and can operate quieter than DC motors. Even though it has many advantages, in its application the use of BLDC motors in electric vehicles is often less than optimal. The use of a conventional control system proportional integral derivative (PID) still has many weaknesses, especially in response to changes in load and track conditions. In this study, a control system was designed to regulate the speed of the BLDC motor, using a combination of Fuzzy and PID methods. Based on the results of the tests that have been done, the Fuzzy-PID control can provide better and more stable performance than using the conventional PI control.

Keywords— Fuzzy Logic, Brushless DC motor (BLDC), proportional integral derivative (PID)

I. INTRODUCTION

The use of electric vehicles in this increasingly modern era is a must. The current transportation system uses more fossil fuels, whose sources are depleting and causing pollution to the environment. The increasing awareness of the environment and attention to fossil fuels in the future has encouraged research on alternative energy sources [1]. One of the results of this research is the development and marketing of electric vehicles for the public. Electric vehicles are an alternative transportation system that is environmentally friendly and reliable in supporting community mobility.

Electric vehicles move by using electrical energy to rotate the motor. Unlike conventional vehicle systems, the driving motor used in electric vehicles is an electric motor. One type of electric motor that is often used is a brushless DC motor (BLDC). BLDC motor is chosen because it has the characteristics of high efficiency, reliability, and a wide speed range [2]. These types of DC motors do not have brushes and commutators, so BLDC motors require less maintenance and can operate quieter than DC motors [3].

BLDC motors move by utilizing 3-phase alternating (AC) electrical energy. To be able to operate, this motor requires a motor drive to control the rotational speed. BLDC motor drives use an inverter for the commutation process in the brush [4]. Unlike conventional DC motors, BLDC motors require electronic commutator switching in the form of a converter for proper operation [5]. In operation, the BLDC motor requires information about the position of the rotor for the correct change in each phase of the inverter [6]. This information can

be obtained with a hall effect sensor attached to the BLDC motor to monitor the position of the rotor.

Even though it has many advantages, in its application the use of BLDC motors in electric vehicles is often less than optimal. Variations in setpoint and dynamic load conditions must be considered in electric vehicles [7]. In conventional control systems, these two aspects cannot be applied in controlling electric vehicles. This makes the electric vehicle system unable to provide maximum performance. To overcome this problem, several studies have been carried out to produce an optimal control system for electric vehicles. One system that is often used is fuzzy logic control. In this paper, there will be a review of several studies that have been carried out regarding the application of fuzzy logic in BLDC motors in electric vehicles.

II. RESEARCH METHODS

A. BLDC motor

BLDC motor is a type of synchronous motor that uses a type of permanent magnet in its rotor. This motor is included in the direct current (DC) motor category, but uses a 3-phase alternating (AC) power source to supply to move the rotor. One of the differences between a BLDC motor and a conventional DC motor lies in the addition of the phase which affects the overall result of the BLDC model [8]. The schematic of a brushless DC motor model can be seen in the following figure [8]:

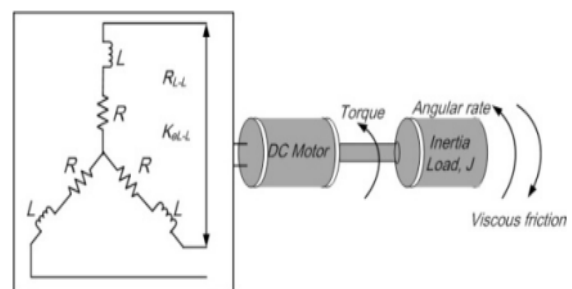


Figure 1. BLDC motor equivalent circuit

The dynamic equation for modeling a BLDC motor can be seen in the following equation [9]:

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = R \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + (L - M) \begin{bmatrix} \frac{di_a}{dt} \\ \frac{di_b}{dt} \\ \frac{di_c}{dt} \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix}$$

Where V_{an} , V_{bn} , and V_{cn} are the voltages of each phase on the stator and R is the stator resistance in each phase. i_a , i_b , and i_c are the phase currents in the stator, M is the mutual inductance and L is the armature inductance. Meanwhile e_a , e_b , and e_c is the back EMF of each phase, which can be calculated using the formula below [9]:

$$\begin{aligned} e_a &= k_e w_e f_a(\theta_e) \\ e_b &= k_e w_e f_b(\theta_e + \frac{2\pi}{3}) \\ e_c &= k_e w_e f_c(\theta_e + \frac{4\pi}{3}) \end{aligned}$$

The mathematical model of the BLDC motor used in this study can be observed in table 1.

TABLE 1. BLDC MOTOR MODEL

Parameter	Nilai
Motor Power (Watt)	2 kW
Resistance Equivalent (R)	0.045
Resistance Equivalent (L)	6.85e-3
Constant voltage (Vp L-L)	65.48
Moment of Inertia (J)	0.0008
Back EMF flat area (derajat)	120
Viscous dampung	0.001
Number of Pole	12

B. Basic Fuzzy Logic

Fuzzy logic is a branch of Artificial Intelligence (AI) that has been used since 1965 until now. Fuzzy is still chosen because of its reliability to solve complex and nonlinear problems, its flexibility to various problems and can be combined with other control methods to produce a more optimal system [10] [2]. Fuzzy logic uses basic rules to produce fuzzy output, namely the IF-THEN rule, where IF is the antecedent and THEN is the consequence [11]. In the fuzzy method, there are 4 main components, namely [2]:

1. Fuzzification

Fuzzification is a stage to change the input from crisp (definite) variables to fuzzy variables based on the membership function and determine the degree of each crisp input to the fuzzy set [10]. The input membership function in this study can be observed in table 2:

TABLE 2. INPUT MEMBERSHIP FUNCTIONS

Membership Function	Notation
Positive Big	PB
Positive Medium	PM
Positive Small	PS

Zero Environ	ZE
Negative Small	NS
Negative Medium	NM
Negative Big	NB

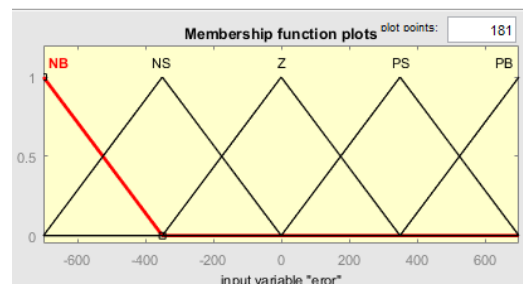


Figure 2. Input error membership function

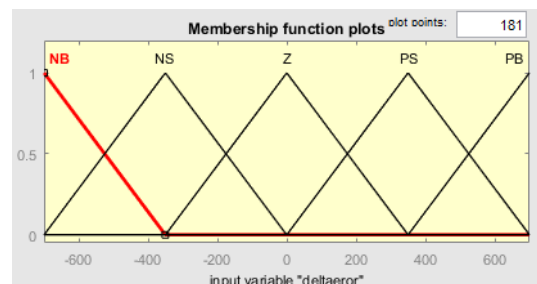


Figure 3. Input delta error membership function

2. Fuzzy Inference.

Fuzzy Inference System (FIS) contains a set of rules used for decision making. This sequence is the result of a combination of the input membership function, which produces several rules as in the following table:

TABLE 3. FUZZY RULES

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

3. De-Fuzzification

Defuzzification produces control decisions to set the best non-fuzzy output value that represents the control decision from different rules [10]. To calculate the crisp thickness value, the center of area (COA) method is used with the following formula [10]:

$$\Delta C_N = \frac{\sum_{i=1}^m \mu(C_{emi}) \Delta C_{emi}}{\sum_{i=1}^m \mu(\Delta C_{emi})}$$

Where μ is the total number of rules, $\mu (\Delta C_{emi})$ is the membership class for rule I, and ΔC_{emi} is the singleton position in rule-i.

C. PID Control

PID control is composed of 3 main parameters, namely proportional (P), integral (I), and derivative (D) [12]. PID control has the characteristics of increasing the rise time, reducing the steady-state error, and reducing oscillations [7]. The block diagram of the PID control can be seen in the following figure:

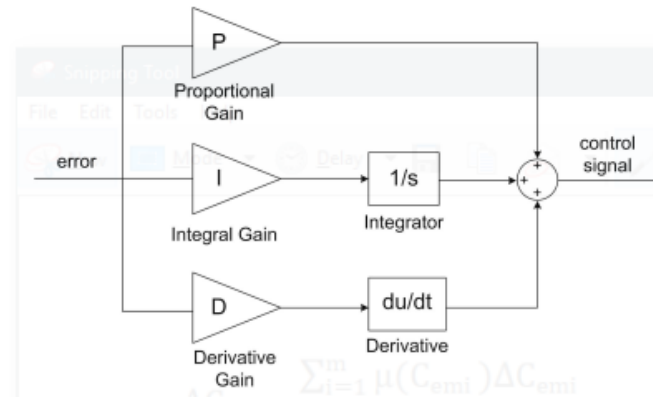


Figure 4. PID control block diagram

Parameters P, I, D connected in parallel will produce PID control. The transfer functions of the PID control are as follows:

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

Where K_p is proportional gain, K_d is derivative gain and K_i is integral gain.

D. Fuzzy Application on BLDC Motors

To increase the reliability of the electric vehicle system, several studies have been carried out by designing an electric vehicle control system. One of the most developed control methods is fuzzy logic. The research was conducted by designing a fuzzy-based control system that is implemented in electric vehicles. The fuzzy control system is also combined with several other methods to increase the efficiency, performance, and accuracy of the system to produce a more optimal electric vehicle. Some of these studies can be seen in the table below:

Method	Ref	Scope	Result
Fuzzy logic with self-tuning	[13]	Adaptive control design for better performance under non-linearity and uncertainty parameters. This	The motor speed is set at a value of 3200 rpm. The proposed system has good tracking capabilities and fast response times when compared to

Method	Ref	Scope	Result
		study combines the ANN and PSO methods to produce the Membership Function parameters of Fuzzy Logic. Tests are carried out on variations in the load and giving interference to the system. The load ranges are 0.25, 0.5, 0.75 and 1 N.	conventional schemes. Then the resulting steady-state error is very low compared to the PI and FLC methods.
Fuzzy Sliding Mode Control (FSMC)	[14]	FSMC design with applications in electro-mechanical braking (EMB)	FSMC provides superior performance, better adaptation to road variations, and shorter braking distances, compared to using PID controllers and traditional control methods.
	[15]	FSMC design for speed control on hybrid bikes with Real-Time Monitoring.	FSMC can provide good speed and torque efficiency and performance in predetermined terrain conditions.
	[16]	The BLDC motor speed control design uses FSMC combined with PI control to reduce overshoot.	The system is designed to run well, where speed fluctuation can be reduced by FSMC. Rise time and settling time can also be reduced from 23 ms to 4 ms using FSMC and 3% overshoot can be eliminated by PI control.
	[17]	Hybrid Fuzzy Sliding Mode (FSMC) design to control the speed	The proposed FSMC can overcome the chattering of the

Method	Ref	Scope	Result
		of the BLDC motor drive. The BLDC motor used has a voltage of 300V with a speed of 392.7 rps. Tests are carried out using MATLAB / Simulink.	SMC control. The test results with this method provide several advantages, namely an enlarged stator current and no torque fluctuation.
<i>Coactive Neuro-Fuzzy Inference System (CANFIS) based on rotor position control</i>	[18]	The design of the CANFIS control system is based on rotor position control to obtain the dynamic response of the BLDC motor with the proposed controller, which is measured for the standard sinusoidal reference input.	<ul style="list-style-type: none"> • (Simulation) The system can solve the problem of non-linearity and uncertainty when the reference input of the BLDC motor changes and ensures a fast and accurate response for steady-state performance • (Hardware) The proposed system can achieve favorable tracking performance without delay phenomena in the control process.
PWM-Based Harmonic Elimination Selection	[5]	The losses minimization enhancement technique uses fuzzy logic for the BLDC motor drive system	The suitability of the proposed control is well demonstrated through the simulation and experimental results on a 350 W BLDC motor.
PID parameters tuned by fuzzy logic	[7]	The design of the BLDC motor speed control system based on PAM (Pulse Amplitude Modulation) with the PID-Fuzzy algorithm to improve the	PID-Fuzzy can improve the performance of the BLDC motor speed at various set points and dynamic load conditions.

Method	Ref	Scope	Result
		reliability of electric vehicles in steady-state response and dynamic loads.	
	[19]	The system design and design of BLDC motor speed control using the Fuzzy-PID method uses soft computing techniques. Fuzzy is used to produce PID parameters (Kp, Ki, and Kd). This control system uses 3 Hall-effect sensors with a chip power of 5V.	The proposed Fuzzy-PID control system can produce the desired output when compared to the usual PID control. The proposed system is proven to be efficient, high resilience, and easy to implement in sensor applications.
	[20]	The design of a BLDC motor speed control system using online self-tuning fuzzy PID. The type of motor drive used is an Outer-rotor brushless DC motor.	The proposed system can produce an overshoot of 1.5% and an error of speed of 3 r / min compared to conventional PID with an overshoot of 3% and an error of 6 r / min. The system can adjust PID parameters in real-time, reducing overshoot and increasing dynamic performance.
	[21]	The design of the BLDC motor speed control system uses the fuzzy-PID method based on vector control. Using a BLDC motor with a number of poles 1, $R = 2.875 \Omega$, $L_d = L_q = 0.835e^{-3} H$, $J = 0.8e^{-3} kg.m^3$	The proposed fuzzy-PID control system can provide a good BLDC motor performance. The test was carried out by providing a variation of the set points of 5000 rpm and 3000 rpm. This system can reduce overshoot,

Method	Ref	Scope	Result
		and a DC voltage of 300V.	stabilization time and increase the robustness of the control system.
- Mamdani's Fuzzy Inference Method	[11]	Fuzzy Logic-based BLDC motor control technique for battery optimization on electric buses.	The proposed method yields better effectiveness and dynamic performance on the battery than the system without this method.
Fuzzy Logic Controller (FLC)	[10]	Fuzzy control system design for multi-phase induction machine (MIM) drives supplied by FLC-based cascaded hybrid multi-level inverters (CHMI).	<ul style="list-style-type: none"> • FLC is capable of providing excellent sine output voltages. • FLC provides better performance and higher durability than PI controllers.
	[6]	Speed control system and ripple minimization of sensorless PMSBLDC motor drives using FLC. The test is carried out by providing load variations. The test results were compared with the PSO tuned PI method for analysis.	Fuzzy control provides better dynamic response results than PI control based on the parameters of rising time, settling time, and overshoot. PMSBLDC uses fuzzy control providing high starting torque with minimal torque ripple. Fuzzy control produces a better speed control system and ripple minimization than using PSO tuned PI control.
	[9]	Design and build a BLDC motor drive with fuzzy control as a speed regulator. Using the STM32F4	The drive motor circuit can produce 3-phase currents with a difference of 120° in each phase. Simulation and

Method	Ref	Scope	Result
		microcontroller, the system is designed for regenerative braking applications in electric vehicles.	testing on the hardware gave a good match for the results. This circuit can work properly and can adjust the motor speed at the specified value.
Fuzzy PID supervised online ANFIS	[22]	The design of the BLDC motor speed control system uses the Fuzzy + PID ANFIS method. Tests are carried out under constant load conditions, load variations, and speed variations.	The proposed control system has better performance than some of the methods tested, under all test conditions.
Bat Algorithm Optimized Fuzzy Proportional Derivative	[23]	BLDC motor speed control system design with simulation using MATLAB / Simulink and Simpower system tools. The optimization results are then compared with several other methods to obtain the best control results.	The proposed control system provides a drastic improvement in measuring performance and better noise compensation than other methods. The system is also able to eliminate uncertain problems that occur in load and speed variations.
Fuzzy PI Controller	[24]	4 switch converter design for BLDC motor drives using Fuzzy control with PI control parameters. The test is carried out at constant velocity and variation in speed.	PI control gives a high overshoot and steady-state error. The use of fuzzy control can reduce steady-state errors and provide a fast BLDC drive response. The combination of PI and fuzzy control produces a system that has a high level

Method	Ref	Scope	Result
			of accuracy and precision.
Hybrid Fuzzy-PID Controller	[8]	Design and analysis of the speed control performance of the PMSBLDC motor using a combination of Fuzzy PID control. The proposed system is then compared with conventional PID control under steady-state and dynamic operating conditions with various set points of speed.	The performance of conventional PID and Hybrid Fuzzy-PID is analyzed based on several parameters. The simulation results show that the Fuzzy-PID hybrid control parameters can be tuned automatically to obtain the desired response. Fuzzy-PID hybrid control provides better performance than conventional PID control, in terms of dynamic response, short settling time, rise time, and no steady-state error.
PSO + Fuzzy Logic Controller (FLC)	[25]	BLDC motor speed control system design with PSO-Fuzzy method to improve the speed performance and efficiency of the BLDC motor. Testing is done through simulation using MATLAB / Simulink.	The combination of PSO and Fuzzy can provide better performance compared to conventional / PI methods. PSO is used to generate parameters. Fuzzy control pod is used to control the output of the electric motor. The use of this method can increase the speed of the motor and reduce the error to a very small degree.
Fuzzy adaptive PID Controller	[26]	Design and implementation of speed-current double closed-loop on permanent	The motor speed setpoint is set to be 300 rpm. The proposed control method can

Method	Ref	Scope	Result
		magnet BLDC (PMSBLDC) motors using PID adaptive fuzzy control. The test is done by giving disturbance to the system in the form of loading at the 6th second which is then analyzed the response of the system.	increase the effectiveness of the system, where this control can be a solution to several problems that are difficult to overcome with conventional methods. The system response is very good for sudden loading compared to the conventional PID method.
Interval Type-2 Fuzzy Logic based PID Controller (IT2FLPIDC)	[27]	BLDC motor adaptive speed control system design uses fuzzy interval type-2 logic based on PID control (IT2FLPIDC) to improve the performance and accuracy of the BLDC motor. Tests were carried out using MATLAB / Simulink software.	The proposed system design can work well. IT2FLPIDC can solve problems of uncertainty and variations in working conditions. The test results of the proposed system were then compared with the PID and Type-1 methods, and the results showed that IT2FLPIDC provided superior performance and response compared to the two methods.
Variable Universe Fuzzy Adaptive PID Control System	[28]	The design of the BLDC motor speed control system uses PID adaptive universal variable control. The test is carried out on MATLAB / Simulink with a series of double closed-loop speed regulations which then performs	The test results with the proposed system can provide a faster response speed and a good level of precision. The applied PSO uses 100 populations and 50 iterations, providing optimal parameters. Variable universe

Method	Ref	Scope	Result
		performance analysis. The PSO algorithm is then applied to identify the optimal scaling factor.	fuzzy adaptive PID control system can reduce overshoot better when compared to conventional PID and Fuzzy PID methods. This system also provides good and stable dynamic performance.

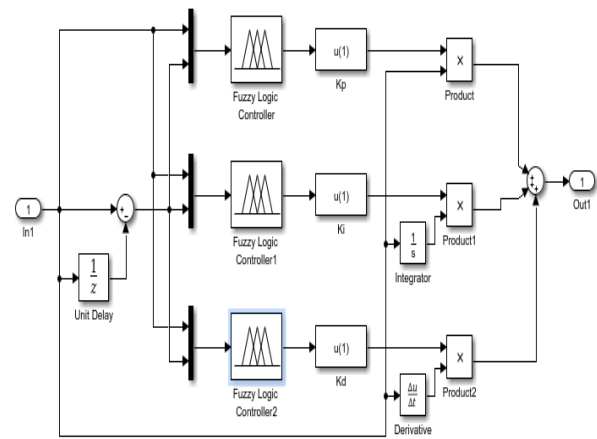


Figure 6. Fuzzy-PID block diagram

Fuzzy block diagram for each output (K_p , K_i , and K_d):

1. Membership function for K_p

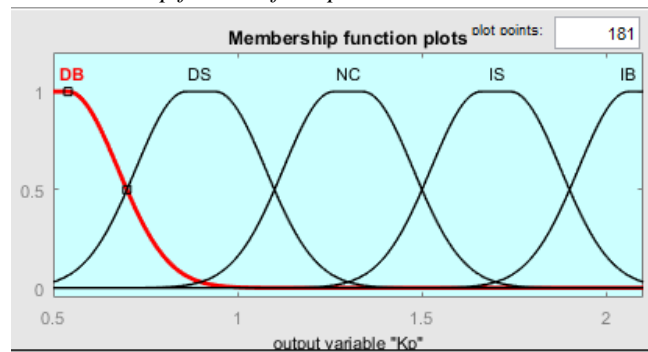


Figure 7. K_p output membership function

2. Membership function for K_i

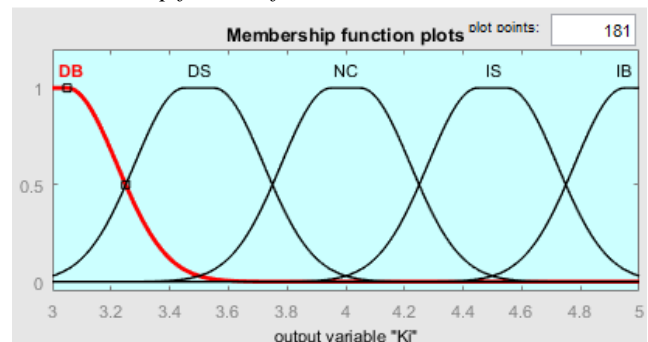


Figure 8. Output membership function K_i

3. Membership function for K_d

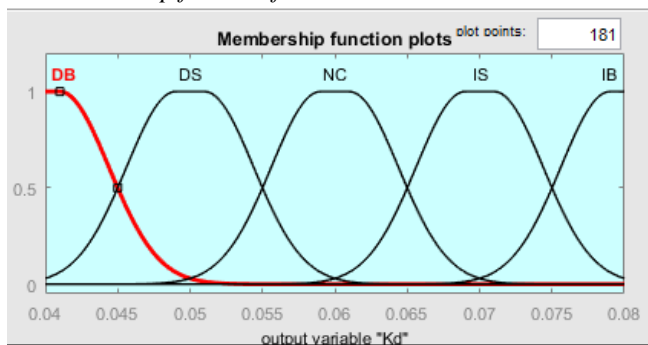


Figure 9. Output membership function K_d

E. Fuzzy-PID based BLDC Motor Speed Control

This research was conducted using MATLAB / Simulink software. The plant of this circuit is a 48V 1kW brushless DC motor with a maximum speed of 700 rpm. The design of the series of this project is as shown below.

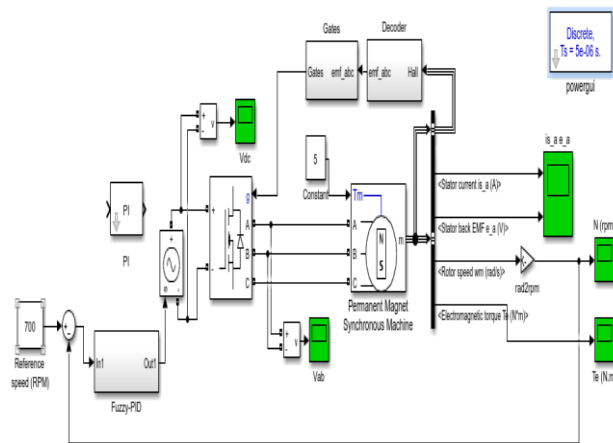


Figure 5. The proposed Fuzzy-PID control circuit

In this circuit, 3 Fuzzy Logic Control blocks are used, each of which has the same input, namely error, and delta-error. While the output of each fuzzy block is K_p , K_i , and K_d . This output is then processed using the PID control to regulate the output voltage from the power source that supplies the BLDC motor. The block diagram of the Fuzzy-PID control can be seen in the following figure:

III. SIMULATION RESULT

The simulation is carried out by providing a speed setpoint input of 650 rpm. The simulation was carried out by bending 2 methods, namely Fuzzy-PID Logic and the conventional Pi method which was carried out for 1 second. The simulation results can be seen in the following graph:

A. Simulation with Fuzzy-PID control

1. Rotor Speed

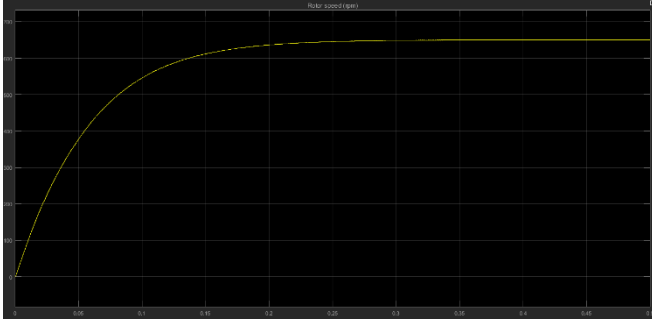


Figure 10. Speed response with Fuzzy-PID

2. Electromagnetic Torque

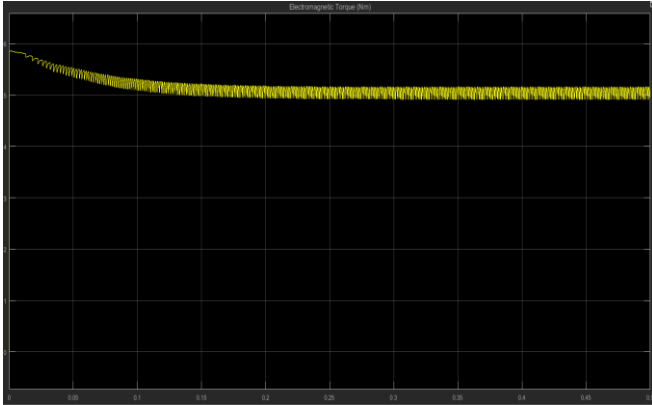


Figure 11. Motor torque with Fuzzy-PID

3. Stator current and back EMF

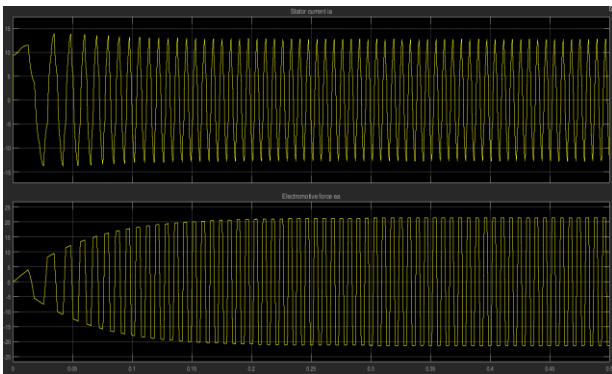


Figure 12. Stator current and EMF with Fuzzy-PID

B. Simulation with PI control ($I = 16.61$ and $P = 0.13$)

1. Rotor Speed

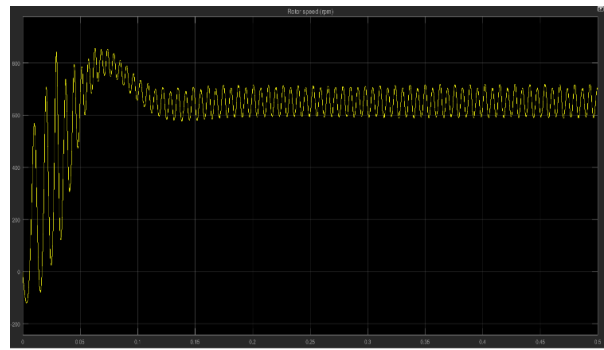


Figure 13. Speed response with PI

2. Electromagnetic Torque

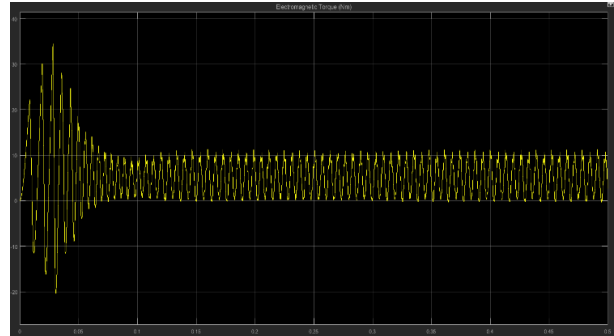


Figure 14. Motor torque with PI

3. Stator Current and back EMF

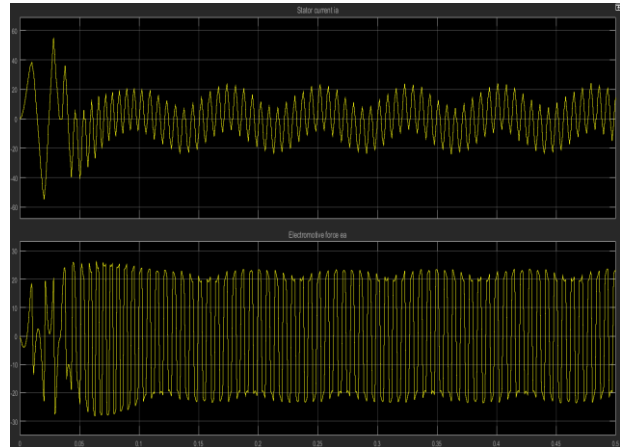


Figure 15. Stator current and EMF with PI

IV. CONCLUSION

Based on the review of 23 papers that have been conducted, several control systems are obtained that combine the fuzzy method with other methods to control the speed of a BLDC motor on an electric vehicle. This combination is intended to obtain an optimal, effective and reliable BLDC motor control system. Of the several proposed methods, the combined method that has the highest usage quantity is the fuzzy-PID method. Fuzzy-PID is considered to provide good control performance, which has many advantages such as: reducing overshoot, minimizing speed errors, increasing control precision. Seeing this fact, in this study, the author has tested the BLDC motor speed control system using the fuzzy-PID method.

From the test results, it can be observed that the Fuzzy-PID control can provide a good response to reach the desired set point. By using the Fuzzy-PID method, steady-state speed can be achieved at 0.3 seconds without significant overshoot and fluctuation. While the conventional PI method can reach a steady-state point at 0.2 seconds but with very high fluctuations and experiencing overshoot up to 830 V.

For electromagnetic torque, using the Fuzzy-PID method produces a stable torque graph, where the torque decreases with the increase in speed of the motor. The torque reaches a constant point at 5 Nm when the motor reaches a steady-state speed. Meanwhile, the PI method provides an unstable graph of torque with a high enough fluctuation and an overshoot of up to 35 Nm before the steady-state speed is reached.

The current and reverse voltage resulting from the use of Fuzzy-PID is quite stable during the motor operation. Meanwhile, if you use the PI method, there are fluctuations in the current and reverse voltage EMF on the stator. This resulted in system instability and resulted in a lot of losses.

Based on the results of the tests that have been done, the Fuzzy-PID control can provide better and more stable performance than using the conventional PI control. The use of Fuzzy-PID control can reduce speed fluctuation and torque stability so that the BLDC motor can operate more efficiently and reliably.

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