Design And Simulation Of 10 kW BLDC Motor Speed Control For Electric Vehicles Using FOC Based On Fuzzy Logic Control

Mochamad Shofwan Rizqulloh
Institut Teknologi Sepuluh Nopember
Department of Electrical Engineering
Surabaya, Indonesia
sh.rizqulloh@gmail.com

Feby Agung Pamuji
Institut Teknologi Sepuluh Nopember
Department of Electrical Engineering
Surabaya, Indonesia
feby@ee.its.ac.id

Heri Suryoatmojo
Institut Teknologi Sepuluh Nopember
Department of Electrical Engineering
Surabaya, Indonesia
suryomgt@ee.its.ac.id

Abstract*— The use of electric vehicles in the current era has begun to spread evenly. Apart from the issue of air pollution produced by Internal Combustion Engine (ICE) vehicles, the ease and practicality of using electric vehicles is the reason why the public is starting to become interested in electric vehicles. Electric vehicle manufacturers are currently choosing BLDC motors for their production vehicles because they are considered suitable for applications that require high power and torque output. However, BLDC motors require more complicated control techniques than other DC motors. The commonly used BLDC motor speed control methods are trapezoidal scalar control and field oriented control. FOC is a type of BLDC motor control with a vector control method which has advantages in terms of efficiency compared to scalar control methods. Many studies on implementing FOC as speed control for BLDC motors, but the research that has been carried out still uses PI control as a basis, where it is known that PI control has shortcomings in the form of complexity in its design. Fuzzy Logic Control is known to be easy to design and reliable in control, so this paper will show the performance of Fuzzy-PI based FOC control as speed control for 10kW BLDC motor in simulation using Simulink program. The simulation results of proposed Fuzzy-PI based FOC method have better response than PI based FOC in terms of starting response with 6.43 times faster rise time, 2.45 times faster settling time, 96.31% lower overshoot value, 26.7% lower steady state error and reliability in overcoming disturbances up to 78.05% lower overshoot value and 2.33 times faster recovery time.

***Keywords*— 10 kw BLDC motor, BLDC motor control, FOC, fuzzy-pi control.**

I. INTRODUCTION

Transportation is an important part of supporting our daily activities. According to Indonesian Central Bureau of Statistics (BPS) data that last updated on 23 February 2023, in Indonesia there over 148 million motorized vehicles[1]. However, the excessive number of motorized vehicles causes problems, namely high levels of air pollutants, this is because motorized vehicles contribute around 70% of air pollutants to the atmospheric air [2]. So many companies producing electric vehicles have emerged in Indonesia as an effort by society to fix this problem.

There are several types of electric motors that can be used for electric vehicles, such as DC motors, induction motors, permanent magnet synchronous motors, and BLDC motors (Brushless DC motors) [3]. It is known that BLDC motors have several advantages, namely BLDC motors have high efficiency, power density and torque density [3], apart from that BLDC motors have easy maintenance and a more compact size [4]. These advantages mentioned make BLDC motors suitable motors for use as electric vehicle drive motors, so they are chosen by many electric vehicle manufacturers [5].

However, BLDC motors are known to have major weaknesses in the form of control methods that are more complicated than other types of DC motors [5]. This is because BLDC motors require switching with the help of power electronic components to keep the BLDC motor rotating [6]. Common methods used for controlling BLDC motors are trapezoidal scalar control and field oriented control (FOC). The FOC method has several advantages over the trapezoidal scalar control method, namely that FOC provides higher efficiency at high speeds [7].

In designing a FOC controller, there are several control methods that can be used. Most used control based for FOC controller currently is PI control because PI control has the advantages of simplicity of structure, ease of implementation and can eliminate steady state errors. However, PI control is known to have disadvantages in the form of producing large rise time, settling time and overshoot [8].

The PI control method can be optimized by adding other control methods to regulate PI control parameters based on load condition so the added control can help reduce its shortcomings. Fuzzy logic control (FLC) and artificial intelligent system are two control methods that can used for this application. The advantage of the FLC method is that it produces values that vary according to the error value so that when applied combined with PI control, the parameters of PI control can be adjusted by Fuzzy control so that the resulting response has a lower rise time, settling time and overshoot than PI control [9][8] and is able to handle non-linear parameters [10].

Research on field oriented control has been carried out for a long time, some of its application is to regulate the speed of induction motors, as was done in [11] in [12]. In [12] research was carried out to examine the speed control of a three-phase induction motor which applied FOC control on a PID control basis. This research method was carried out by simulating the Self Tuning Regulator adaptive PID control model that had been created and then realizing the control model using the AVR Atmega16 Microcontroller. The research results obtained show that after coordinating the system with the motor that is given control, the motor speed is obtained which gradually provides synchronous speed. In [11] an FOC

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application using FLC to control the speed of an induction motor is carried out. The design that has been made is then simulated with several induction motor loading test scenarios to determine the results of the induction motor response. The research results obtained are that the control can regulate the speed of the induction motor so that the value remains constant at the specified speed even under fluctuating load conditions.

Research on BLDC motor speed control has been carried out several times, various control methods have been introduced. BLDC motor speed control is divided into two types, the first is scalar control using the trapezoidal method or 6-step control and vector control using the Direct Torque Control and Field Oriented Control methods.

Research [4] explains the comparison of the performance of BLDC motor speed control using PI and FOC control. The performance dynamics of a brushless DC motor with the help of a PI controller when there is no load, under load, changing the load torque steps at a constant speed. The speed remains almost constant and exactly matches the actual speed. In FOC, the speed curve reaches a constant value in a shorter time compared to the PI controller. Torque ripple is relatively lower in FOC compared to traditional BLDC with PI. FOC is used for fundamentals and there is harmonic reduction. The Sliding Mode Observer (SMO) scheme has been applied to the FOC of the BLCD drive which results in effectively minimizing speed errors and having better speed performance compared to conventional PI controllers. In the FOC sliding mode is used as a damper to maintain the oscillations observed in the PI.

Research [5] examines the application of BLDC motor speed control using FOC control for 120kW motors. This research was carried out applying FOC control to control the id iq independently so that it can achieve the Maximum Torque Per Ampere (MPTA) ratio to minimize current. The FOC method is applied to a 120kW BLDC motor. The reference torque used is 100N.m. and 350N.m. The motor has a ripple of around 51N.m. and a constant/steady state is reached after 5.68 seconds. Meanwhile, at reference torques of 250N.m. and 200N.m., steady state was reached after 7.4 s and 11.6 s respectively. When the torque is higher, the motor response is faster to reach a nominal rotation speed of 3000rpm. In terms of speed control, the speed reference is set to 2000rpm and 2500rpm. Steady state is reached after 2s and 2.18s. However, there is a high torque ripple caused by the difficulty of PI control settings, high load (100N.m.), and BLDC trapezoidal back EMF.

Although research in [4] and [5] has discussed the application of the motor speed control method using FOC, the basis of the FOC used in the study uses PI control. Other research on BLDC motor speed control using vector control with fuzzy logic control was carried out in [13].

In [13], the BLDC motor speed control system which is carried out using DTC-based ANFIS (Direct Torque Control) can maintain the speed value by considering the torque required by the system. ANFIS has the advantage of fewer variables than Fuzzy-PID, so the execution process on the microcontroller is faster and requires less storage memory. When there is an increase in load, speed performance decreases even though there is no significant difference. Although research [13] has applied FLC control to BLDC motor speed control using vector control, the type of control used is DTC which is a different type from FOC control.

From research mentioned above, it shows that in general PI-based FOC has been widely applied and has quite good performance, but it still has shortcomings which, if corrected by applying fuzzy control, will further optimize PI-based FOC. Based on the explanation above, in this research a BLDC motor speed control method is proposed using Fuzzy-PI based FOC. It is hoped that the proposed Fuzzy-PI based FOC control can increase the reliability and efficiency of BLDC motors in terms of speed and torque. This research is carried out using 10 kW BLDC motors that used for ITS electric vehicle project named Multi-purpose Electric vehicle ITS (MEvITS) with load torque scheme based on EV application.

II. METHODS

A. Brushless BLDC Motor

BLDC motors are one type of motor that is widely used for electric vehicle applications because of their suitability for applications that require high torque and output power values [5]. Another advantage is that BLDC motors don't have brushes, so no friction occurs between the rotor and brushes [11]. Due to the absence of friction, BLDC motors have another advantage in the form of lower maintenance costs than conventional DC motors because there are no components that wear out due to friction. The basic components of a BLDC motor include a rotor with permanent magnets, a stator with 3, 4 or more phase windings, a rotor position sensor, and an electronic circuit to regulate the phase of the stator winding [12].

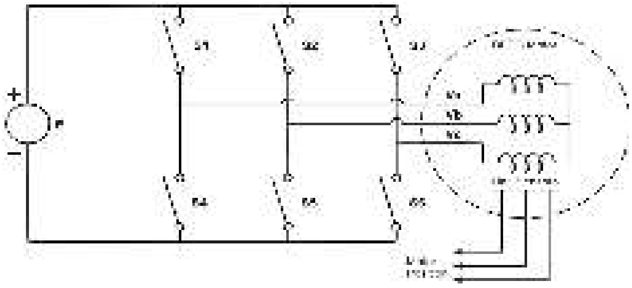


Fig. 1 Simple BLDC Motor Diagram

BLDC motors use a control circuit to replace the function of the commutator by supplying coil energy to the stator in a sequence of commutation steps. This control is connected to the driver which will later supply the BLDC motor according to the required voltage value. In determining the sequence of commutation steps, a rotor position sensor or what is known as a hall sensor is used. Usually, this sequence of commutation steps is separated by 60° or 120° electrical cycles [11].

BLDC motors are operated by energizing one stator winding at a time with a constant DC voltage. When the winding is excited, the stator magnetic field *Bs* will be generated and a torque of τ_{ind} will appear on the rotor with a value shown in equation 1 [12]:

$$\tau_{ind} = kB_R \times B_S \tag{1}$$

Where B_R is the rotor magnetic field which adapts the rotor to the stator magnetic field.

By using Fig.1, when the Va winding remains excited for a long time, the rotor will rotate until the two magnetic fields align and the rotor will stop. Winding Vb will switch on when winding Va is turned off, so that the rotor can continue to have torque in a counterclockwise direction and the rotor will continue to rotate. This process will continue continuously according to the phase winding sequence of the BLDC motor [12].

The BLDC motor specifications that used in the simulation are shown in Table 1.

TABLE 1 BLDC MOTOR SPECIFICATION

No	Specification	Value
1	Power	10 kW
2	Voltage	48 V
3	Efficiency	91%
4	Phase Resistor	38 mΩ
5	Phase Inductor	48 µH
6	Speed	2000-6000 rpm
7	Most Efficient Torque	11.957 N.m.
8	Most Efficient Current	123.658 A
9	Pole	4

The 10 kW BLDC motor data in Table 1 will be used as a data reference for BLDC parameter values in simulation model that provided by the Simulink application. The motor model used for simulation requires Constant Torque Peak ($C\tau\ Peak$) and Flux Linkage (ψ_m) values whose values are calculated using the most efficient point values that provided in Table 1, calculations are carried out using equation:

$$C\tau = \frac{\tau}{I} \tag{2}$$

$$C\tau\ peak = \frac{C\tau}{\sqrt{2}} \tag{3}$$

$$\psi_m = \frac{C\tau\ peak}{2p} \tag{4}$$

Where:

τ = most efficient torque (N.m.)
I = most efficient current (Ampere)
$C\tau$ = constant torque (N.m./A)
$C\tau\ peak$ = peak constant torque (N.m./Apeak)
ψ_m = flux linkage (Weber)
p = pole number

B. *Field Oriented Control*

Field Oriented Control (FOC) or what is known as vector control is the arrangement of the field coils on a BLDC motor where the coupling system is changed to a decoupling system so that the armature current and field current in the motor can be controlled separately, so that torque and flux can also be regulated separately [7]. The block diagram of the Field Oriented Control (FOC) method for BLDC motor plant is shown in Fig. 2.

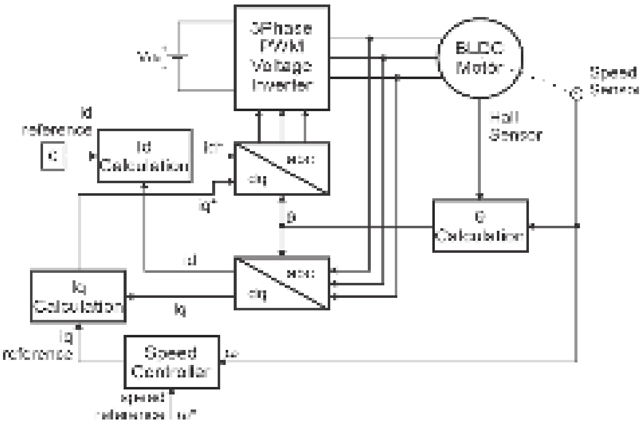


Fig. 2 Block diagram of Field Oriented Control (FOC) method for BLDC Motor.

The FOC designed in this research is intended to control direct and quadrature axis currents (i_d and i_q) to achieve the desired torque value as [5],

$$T_e = \frac{3}{2}\frac{p}{2}[(L_d i_{sd} + \lambda_m)i_{sq} + L_{sq} i_{sq} i_{sd} \tag{5}$$

By controlling i_d and i_q separately will get the maximum torque ratio per ampere to minimize the current at a certain torque to increase the efficiency of the BLDC motor [14].

C. *Proportional Integral Control*

PI control is a control based on Proportional and Integral feedback control. Proportional (P) control is a form of feedback control used in closed loop systems. P control works to minimize fluctuation values but can produce large steady state error values. Integral control (I) is the second form of feedback control used in closed loop systems. Control I is used to eliminate possible differences in values so that the given steady state value can return to the actual setting value [16].

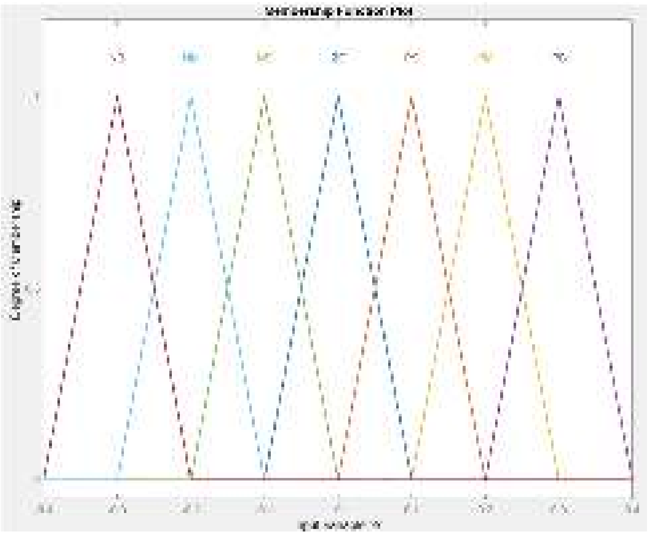
The PI control parameters for the 10 kW BLDC FOC was obtained using trial and error method to make it easier. After trial and error was done, the PI parameter values were obtained for each PI control on the BLDC FOC as shown in Table 2.

TABLE 2 PI PARAMETERS FOR FOC BLDC

No	Controller	Parameters	
		P	***I***
1	Speed	0.003	9
2	Torque (I_q)	0.05	4.5
3	Flux (I_d)	0.05	4.5

D. *Fuzzy Logic Control*

Fuzzy control design is based on the PI parameter values that have previously been obtained. In this simulation, fuzzy logic control is used for regulating correction value to PI control parameters. The designed membership function and rules base used for fuzzy logic control are obtained using trial and error methods, which shown in Fig. 5, Table 3, and Table 4: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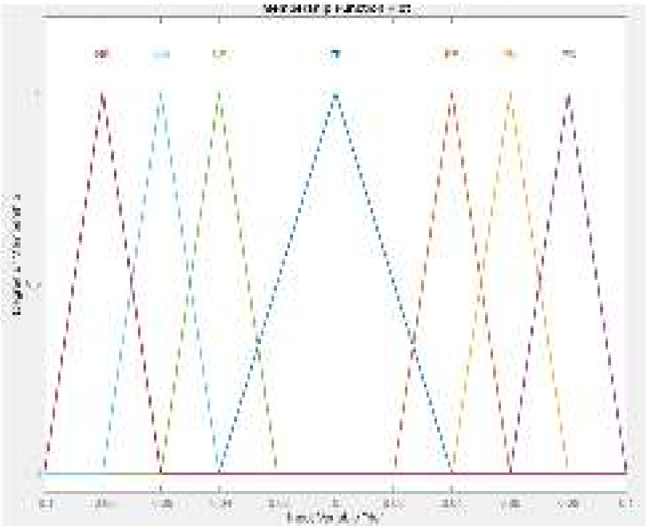
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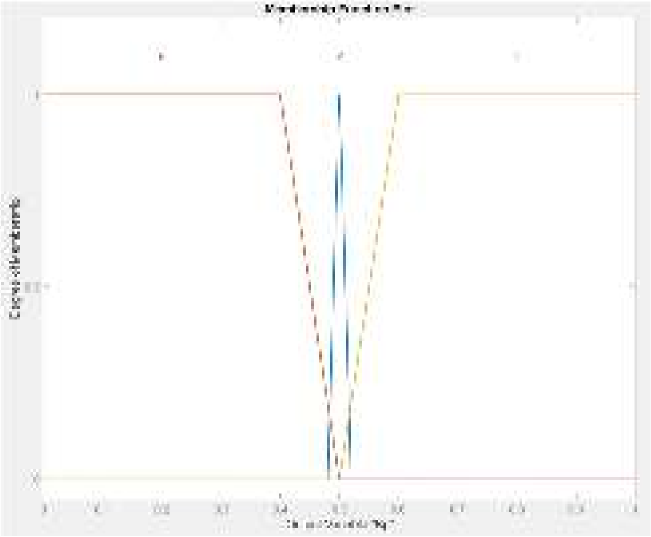
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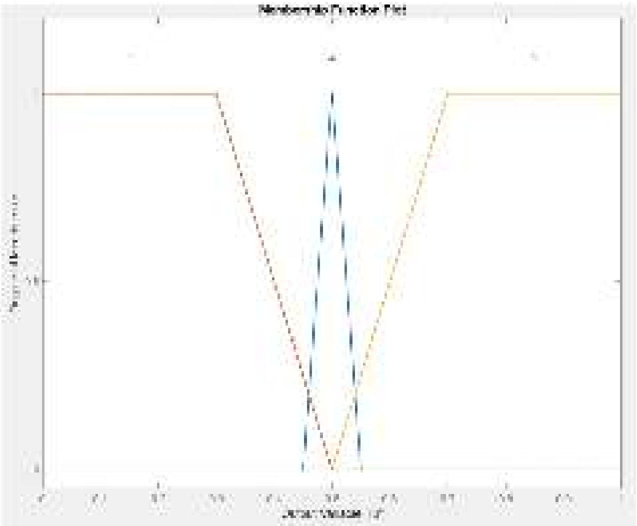
(d)

Fig. 3 Membership function fuzzy, (a) input e, (b) input de, (c) output Kp, (d) output Ki.

TABLE 3 PROPORTIONAL PARAMETER FUZZY CONTROL RULE BASE

e \ de	NB	NM	NS	ZE	PS	PM	PB
NB	P	P	P	P	P	P	P
NM	Z	P	P	P	P	P	Z
NS	N	Z	Z	P	Z	Z	N
ZE	N	N	N	Z	N	N	N
PS	N	Z	Z	P	Z	Z	P
PM	Z	P	P	P	P	P	Z
PB	P	P	P	P	P	P	P

TABLE 4 INTEGRAL PARAMETER FUZZY CONTROL RULE BASE

e \ de	NB	NM	NS	ZE	PS	PM	PB
NB	N	N	N	N	N	N	N
NM	P	Z	Z	Z	Z	Z	P
NS	P	Z	P	N	Z	P	P
ZE	N	P	P	Z	P	P	P
PS	P	Z	P	N	Z	P	N
PM	P	N	Z	N	N	Z	P
PB	N	N	N	N	N	N	N

III. RESULTS AND DISCUSSION

Simulation was carried out with the MEvITS electric vehicle application, the supporting parameters that comply with the MEvITS specifications are shown in the following Table 5.

TABLE 5 ELECTRIC VEHICLE (MEVITS) SPECIFICATION

No	Specification	Value
1	Vehicle Weight	850 kg
2	Weight Capacity	500 kg
3	Wheel Size	R14
4	Tire Profile	185/70
5	Final Gear Ratio	10
6	Gearbox Ratio	3.417

The EV data in Table 5 is the value from the mechanical side of the EV, where calculations need to be carried out to be able to project it to the BLDC motor side. Because MEvITS has 4 wheels, the weight of the load at 1 wheel is.

$$F_{L1w} = \frac{F_{LC}}{4} \tag{10}$$

Where:

F_{L1w} = load weight on 1 wheel (N)
F_{Lc} = MEvITS total load weight (N)

After getting the weight value on 1 wheel, then torque value for the load on the wheel side can be calculated using the equation:

$$\tau_{Lw} = r_w \times F_{L1w} \tag{11}$$

Where:

τ_{Lw} = load torque on 1 wheel (N.m.)
r_w = wheel radius (m)

Then, because the reference for electric vehicles uses a gearbox and gear shaft, it is necessary to carry out 2 levels of calculation by comparing the gears using equation:

$$\frac{\tau_{out}}{\tau_{in}} = \frac{G_{out}}{G_{in}} \tag{12}$$

$$\frac{\tau_{out}}{\tau_{in}} = GR \tag{13}$$

$$\tau_{in} = \tau_{out} \times \frac{1}{GR} \tag{14}$$

So, the values of τ_{Ls} and τ_{Lm} can be written as:

$$\tau_{Ls} = \tau_{Lw} \times \frac{1}{GR_s} \tag{15}$$

$$\tau_{Lm} = \tau_{Ls} \times \frac{1}{GR_{gb}} \tag{16}$$

Where:

τ_{Ls} = load torque on drive shaft (N.m.)
τ_{Lm} = load torque on motor shaft (N.m.)
GR_s = final gear ratio
GR_{gb} = gearbox gear ratio

In addition to the torque equation above, a gear ratio to speed equation is also needed which can be written as:

$$\frac{v_{out}}{v_{in}} = \frac{G_{out}}{G_{in}} \tag{17}$$

$$\frac{v_{out}}{v_{in}} = \frac{1}{GR} \tag{18}$$

$$v_{in} = v_{out} \times GR \tag{19}$$

So, the values of v_s and v_m can be written as:

$$v_s = v_w \times GR_s \tag{20}$$

$$v_m = v_s \times GR_{gb} \tag{21}$$

Where:

v_w = rotational speed on wheel (rpm)
v_s = rotational speed on drive shaft (rpm)
v_m = rotational speed on motor shaft (rpm)
GR_s = final gear ratio
GR_{gb} = gearbox gear ratio

The equation above will then be used to calculate the load torque and speed of the BLDC motor when run with Simulink simulation.

The designed model for simulations performed using the MATLAB Simulink program. The circuit that used for simulation on MATLAB Simulink is shown in Fig. 6.

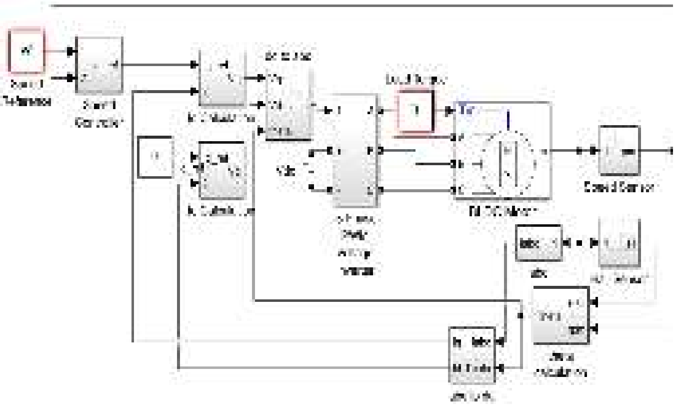

Fig. 4 Field Oriented Control for BLDC Simulink Simulation Model.

The simulation results PI and Fuzzy-PI were then compared and analyzed. Simulations are performed using several variations in load torque and speed references based on data that were given above. Then the simulation results of the BLDC motor speed control model using FOC based on PI and Fuzzy-PI will be compared and analyzed to find out which system has a better response.

A. Simulation with different load torque scheme.

This simulation is performed to obtain the response of the BLDC motor speed control system using PI and Fuzzy-PI based FOC when load torque is changed.

Load torque scheme that used for simulation is shown in Fig. 7:

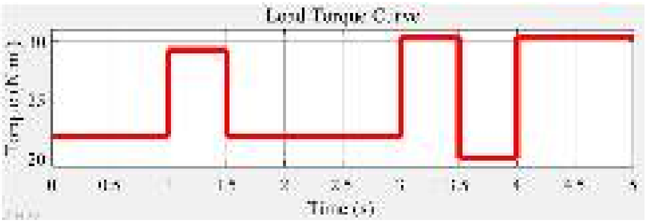

Fig. 5 Load Torque Scheme Curve

After the simulation done running, we obtain the results as follows:

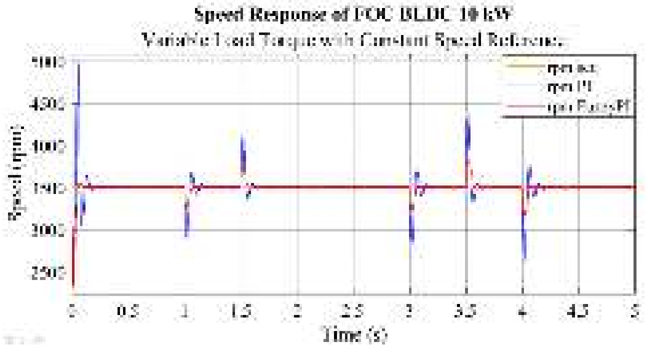

Fig. 6 Speed Response of FOC BLDC 10 kW Motors with Variable Load Torque

From Fig. 8 above we can obtain that by using Fuzzy-PI based FOC control system gives a better starting response than PI control based FOC with detailed explanation as shown at Table 6.

TABLE 6 STARTING SPEED RESPONSE COMPARISON OF PI AND FUZZY-PI BASED FOC

No	Parameters	PI	Fuzzy-PI
1	Rise Time (s)	0.0221	0.0034
2	Settling Time (s)	0.1079	0.0441
3	Overshoot (%)	42.61	1.82
4	Error Steady State	0.57	0.42

From Table 6, we can conclude that by using Fuzzy-PI based FOC for 10 kW BLDC motor gives starting speed response better with 6.43 times faster rise time, 2.45 times faster settling time, 96.31% lower overshoot and 26.7% lower error steady state than PI based FOC. This number if translated to EV behavior is with Fuzzy-PI based FOC, when EV start moving from still condition has better throttle response due to lower rise time and settling time and smoother car movement due to lower overshoot and error steady state value.

Also, from Fig. 8 we obtained Fuzzy-PI based FOC speed response is dropping after reach first set point value, it happens because Fuzzy control provides correction for PI parameter to reduce overshoot that might occur as in PI based FOC speed response curve.

From Fig. 8, we can obtain that when the load torque is changing, by using Fuzzy-PI based FOC control system gives better performance for mitigating error compared to PI-based FOC control with detailed explanation as shown at Table 7.

TABLE 7 SPEED RESPONSE COMPARISON OF PI AND FUZZY-PI BASED FOC WHEN LOAD TORQUE CHANGING

No	Time (s)	Parameters	PI	Fuzzy-PI
1	1	Overshoot (%)	17.58	7.31
		Recovery Time (s)	0.1135	0.0485
2	1.5	Overshoot (%)	17.66	7
		Recovery Time (s)	0.0762	0.0484
3	3	Overshoot (%)	20.26	8.31
		Recovery Time (s)	0.1131	0.0489
4	3.5	Overshoot (%)	24.95	10.4
		Recovery Time (s)	0.0799	0.06
5	4	Overshoot (%)	24.52	9.9
		Recovery Time (s)	0.1169	0.0547

From Table 7, we can conclude that when load torque is changing, by using Fuzzy-PI based FOC for 10 kW BLDC motor gives better speed response with 58.46-61.69% lower overshoot and 1.29-2.32 times faster recovery time compared to PI based FOC. This number if translated to EV behavior is when EV experience changes in the load torque value, with Fuzzy-PI based FOC gives smoother feel and more stable motor speed due to lower overshoot value and faster recovery time.

Other than speed response that described above, both control systems are known to have a torque response as shown in Fig. 9.

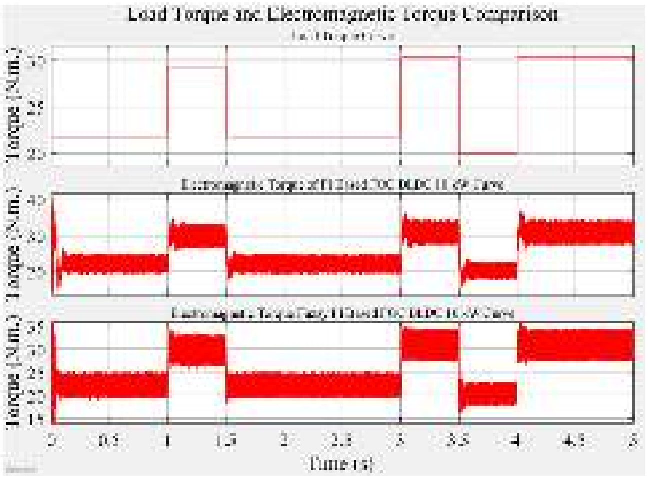

Fig. 7 Load Torque and Electromagnetic Torque Comparison

From the Fig. 9 it is known that either Fuzzy-PI and PI based FOC systems both can provide torque values that suit the needs of the load torque. In starting conditions, the PI-based FOC control system has an initial torque value of 58.8863 N.m. and has a steady state error ranging from ± 14.14-15.67%, while the Fuzzy-PI based FOC control system has an initial torque value of 87.7694 N.m. and has a steady state error ranging ranged ± 13.62-15.74%. From the values mentioned above, it can be concluded that the Fuzzy-PI based FOC control system has a greater initial torque value compared to PI based FOC control, but with the same steady state performance.

B. *Simulation with different speed reference scheme.*

This simulation is performed to obtain the response of the BLDC motor speed control system using PI and Fuzzy-PI based FOC when speed reference is changed.

Speed reference scheme made by determining the speed value based on 10 kW BLDC motor speed specification value range. Speed reference scheme curve that used for simulation is shown in Fig. 10:

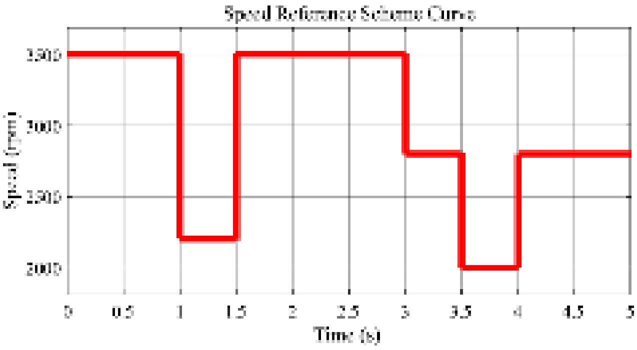

Fig. 8 Speed Reference Scheme Curve

After the simulation done running, we obtain the results as follows:

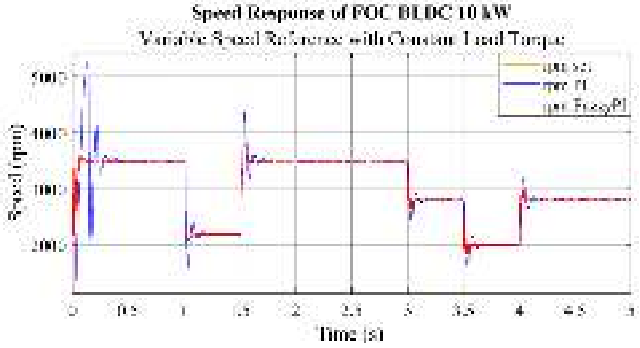

Fig. 9 Speed Response of BLDC Motor with Variable Speed Reference

From Fig. 11, we can obtain that when the speed reference is changing, Fuzzy-PI based FOC control system gives better performance for mitigating error compared to PI-based FOC control with detailed explanation as shown at Table 8.

TABLE 8 SPEED RESPONSE COMPARISON OF PI AND FUZZY-PI BASED FOC WHEN SPEED REFERENCE CHANGING

No	Time (s)	Parameters	PI	Fuzzy-PI
1	1	Overshoot (%)	27.39	6.02
		Recovery Time (s)	0.1335	0.0651
2	1.5	Overshoot (%)	24.65	8.87
		Recovery Time (s)	0.1396	0.0688
3	3	Overshoot (%)	11.94	5
		Recovery Time (s)	0.0898	0.0575
4	3.5	Overshoot (%)	18.77	8.55
		Recovery Time (s)	0.1304	0.0729
5	4	Overshoot (%)	13.77	6.99
		Recovery Time (s)	0.1247	0.0605

From Table 8, we can conclude that when load torque is changing, by using Fuzzy-PI based FOC for 10 kW BLDC motor gives better speed response with 50.81-78.05% lower overshoot and 1.75-2.33 times faster recovery time compared to PI based FOC. This number if translated to EV behavior is when EV experience changes in the speed reference value, with Fuzzy-PI based FOC gives smoother feel and better motor response in changing speed due to lower overshoot value and faster recovery time.

IV. CONCLUSION

Based on the results that obtained before, can be concluded that at starting conditions, FOC control with a Fuzzy-PI basis has a better system response compared to FOC control with a PI basis. When the first 10 kW BLDC motor is operated, the Fuzzy-PI based FOC control has 6.43 times faster rise time, 2.45 times faster settling time, and 96.31% smaller overshoot value and 26.7% lower steady state error when compared with the PI based FOC control.

When the load torque on a 10kW BLDC motor is changing, FOC control with a Fuzzy-PI basis has a better performance on mitigating error compared to FOC control with a PI basis. On a 10 kW BLDC motor when there is a change in load torque, Fuzzy-PI based FOC control has 58.46-61.69% lower overshoot value and 1.29-2.32 times faster recovery time compared to PI based FOC control.

When the speed reference of a 10kW BLDC motor is changing, FOC control with a Fuzzy-PI basis has a better performance on mitigating error compared to FOC control with a PI basis. On a 10 kW BLDC motor when a change in reference speed occurs, Fuzzy-PI based FOC control has 50.81-78.05% lower overshoot value and 1.75-2.33 times faster recovery time compared to PI based FOC control.

This research can be used as reference when applied to real electric vehicles by considering parameters that ignored in this research, Further research also can be done using different control for FOC base such as fuzzy control or artificial intelligence system. By applying tuning methods for determining the parameters of PI control is hoped can give more accurate result since in this research the parameters are determined using trial and error method.

REFERENCES

[1] BPS, "Badan Pusat Statistik," [Online]. Available: https://www.bps.go.id/id/statistics-table/3/VjJ3NGRGa3dkRk5MTlU1bVNFOTVVbmQyVURSTVFUMDkjMw==/jumlah-kendaraan-bermotor-menurut-provinsi-dan-jenis-kendaraan--unit-.html?year=2022.

[2] A. P. Firdaus and L. Sulistyorini, "Kadar SO2 dan Kejadian ISPA di Kota Surabaya menurut Tingkat Pencemaran yang berasal dari Kendaraan Bermotor," in *Simposium I Jaringan Perguruan Tinggi untuk Pembangunan Infrastruktur Indonesia*, Surabaya, 2016.

[3] A. Oktav, "New Trends and Recent Developments in Automotive Engineering," *RESEARCHES ON SCIENCE AND ART IN 21st CENTURY TURKEY,* no. 331, pp. 2976-2987, 2018.

[4] P. K. Sharma and A. S. Sindekar, "Performance Analysis and Comparison of BLDC Motor Drive using PI and FOC," in *International Conference on Global Trends in Signal Processing, Information Computing and Communication*, Jalgaon, 2016.

[5] M. R. Fadli, M. M. Musyasy, J. Furqani and A. Purwadi, "Modelling of Field Orientation Control (FOC) Method in 120 kW Brushless DC Motor (BLDC)," in *6th International Conference on Electric Vehicular Technology (ICEVT)*, Bali, 2019.

[6] C. L. Xia, Permanent Magnet Brushless DC Motor Drives and Controls, Singapore: John Wiley & Sons Singapore Pte. Ltd., 2012.

[7] R. Lokhande and P. Dukre, "Design of FOC Brushless DC (BLDC) Motor Controller," *IJSDR (International Journal of Scientific Development and Research),* vol. 5, no. 9, pp. 466-470, 2020.

[8] F. Suryatini and A. Firasanti, "KENDALI P, PI, DAN PID ANALOG PADA PENGATURAN KECEPATAN MOTOR DC DENGAN PENALAAN ZIEGLER-NICHOLS," *JREC (Journal of Electrical and Electronics),* vol. 6, no. 1, pp. 65-80, 2018.

[9] D. O. Kusputra, "Perbandingan Boost Converter Menggunakan Logika Fuzzy - PID dan Kontroler PID," Universitas Brawijaya, Malang, 2019.

[10] R. Arulmozhiyal and R. Kandiban, "Design of Fuzzy PID controller for Brushless DC motor," in *2012 International Conference on Computer Communication and Informatics*, Coimbatore, 2012.

[11] R. Firmansyah, "Desain Kontrol Motor Induksi 3 Fasa 50 HP Berbasis Fuzzy Logic Control," Universitas Jember, Jember, 2015.

[12] S. Aryza, Z. Lubis and P. Wibowo, "Injeksi Penambahan Field Oriented Control (FOC) dan PID Didalam Kecepatan Motor Induksi Tiga Phasa," in *Seminar Nasional Teknik (SEMNASTEK) UISU*, Medan, 2020.

[13] M. Ridwan, "Rancang Bangun Sistem Kontrol Kecepatan Motor BLDC Menggunakan ANFIS untuk Aplikasi Sepeda Motor Listrik," Institut Teknologi Sepuluh Nopember, Surabaya, 2018.

[14] S. J. Chapman, Electric Machinery Fifth Edition, Melbourne: Mc.Graw-Hill, 2012.

[15] H. C. Wu, M. Y. Wen and C. C. Wong, "Speed Control of BLDC Motors Using Hall Effect Sensors Based on DSP," in *2016 International Conference on System Science and Engineering (ICSSE)*, Taiwan, 2016.

[16] P. Woolf, Chemical Process Dynamics and Controls, Michigan: LibreTexts, 2023.