2022 International Conference on Electrical Engineering, Computer and Information Technology
University of Jember, Jember, Indonesia, November 22-23 2022

Regenerative Braking Using Fuzzy Logic Control on BLDC Motor Driven Electric Vehicles

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2022 International Conference on Electrical Engineering, Computer and Information Technology (ICEECIT) | 978-1-6654-9352-9/22/$31.00 ©2022 IEEE | DOI: 10.1109/ICEECIT55908.2022.10030473

***Abstract*— The problem that often occurs in electric vehicles is their cruising ability which is limited by the energy stored in the battery. However, there is an opportunity to increase the effectiveness of battery energy, by the braking regenerative. It converts brake energy to electric power and this electric energy then recharges the battery. For this purpose, a voltage regulator is needed so that the power generated during braking has a voltage that can be charged to the battery. In this research, the regulation voltage uses fuzzy logic. The research experiment was carried out on an electric bicycle with a Brushless Direct Current (BLDC) motor. The test results show that at 30 meter track, a braking time of 9.46 seconds, have stopping distance of 20 meters and an efficiency of 92.79%. While in the fastest braking, braking time of 7.43 seconds, the stopping distance is 7.4 meters, and produces efficiency in 97.94%.**

***Keywords*— regenerative braking, bldc motor, fuzzy logic controller**

I. INTRODUCTION

Every year transportation vehicles in Indonesia are increasing, which of course also increases fuel consumption and causes air pollution to increase. Vehicles that do not use fuel oil are needed so as to reduce air pollution. The vehicle is an electric vehicle. Electric vehicle use electric motors with batteries as a source of energy. To increase the efficiency of using battery energy, electric vehicle need a system that can restore wasted energy when braking occurs, which is called regenerative braking. A regenerative braking system is a braking system that converts the system's mechanical energy into electrical energy, which can be stored in the battery and can later be used again [1-2].

Many types of electric motors can be used for electric vehicles. There are DC motors or AC motors. The DC-type motor often used in the manufacture of electric vehicles is Brushless Direct Current (BLDC) motor. BLDC motor is one kind of permanent magnet synchronous motor. It means that the magnetic field generated by the stator and the magnetic field generated by the rotor rotate at the same frequency [2-3].

The problem that often occurs in electric vehicles is the cruising ability that is not optimal, so an energy recycling system is needed to increase battery resource power. Increasing the cruising range of electric cars can be done through the concept of an energy recycling system in electric cars through regenerative braking. Regenerative braking is a braking method that utilizes the generator concept; when the motor rotates without voltage, it will turn into a generator and produce an electromotive force (emf) [1-4].

In this research, the regenerative braking of a BLDC motor for charging the battery is designed using the fuzzy logic controller method. The control is made on the microcontroller. The purpose of the control is so that the voltage generated by the regulated BLDC motor using a 3-phase rectifier and boost converter circuit can charge the battery [5]. This arrangement has the principle, even though the input voltage changes, the output voltage remains at the specified value. So the designed system is based on the output voltage of a BLDC motor in the form of a 3-phase sine, so the system consists of a 3-phase rectifier and a boost converter which is used to increase the voltage..

II. METHOD

A. Converter Spesification

In designing a converter boost converter, calculations are first carried out to find the size of the components that match the desired specifications. The specifications of the desired converted boost in this study are as Table I.

TABLE I. DESIRED CONVERTER BOOST SPECIFICATIONS

Input Voltage	1-10 V
Output Voltage	14 V
Output Current	2 A
Frequency	50 kHz

B. Converter Design

For the schematic design of the boost converter circuit that has been created and simulated as in the following Fig.1.

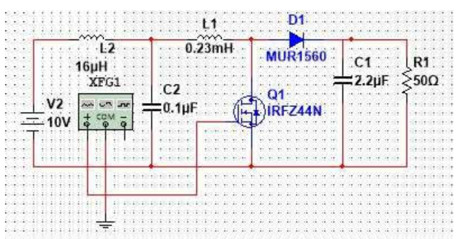

Fig. 1 Boost converter schematic using Multisim

To carry out the determination of the size of the components to be installed on the converter boost must first be carried out calculations. This is so that the boost converter can produce output that is in accordance with the specifications in the previous Table 1. The calculation of the size of the boost converter component is based on the formula contained in the previous.

C. Duty Cycle Calculation

The general formula for calculating the duty cycle on the boost converter that the system can produce an output voltage according to the set point value is equal (1).

$$D = \frac{V_o - V_{in}}{V_o} \qquad (1)$$

The maximum and minimum duty cycle calculations required by the system can be carried out based on the input voltage boost of the converter in Table I. The calculation as follows:

$$D_{max} = \frac{14 - 1}{14} = 0.93 = 93\%$$

$$D_{min} = \frac{14 - 10}{14} = 0.29 = 29\%$$

D. Inductor Calculation

In the boost converter, the determination of the inductance value can be find by the parameters of the ripple current, the switching frequency used, and the minimum operational voltage value on the boost converter. The calculation formula (2) and the calculation is in the below.

$$L = \frac{V_{in}.D.T}{I_{in}.Rippel} \qquad (2)$$

$$L_{min} = \frac{1.0.93.0.02}{2.0.1} = 0.093\ mH$$

$$L_{max} = \frac{10X0.29X0.02}{2.0,1} = 0.29\ mH$$

E. Capacitor Calculation

In the boost converter, determine the value of the capacitor doing the following formula (3) and find C value as shown in below.

$$C = \frac{V_{in}D(1-D)^2T}{V_{in}Rippel} \qquad (3)$$

$$C_{min} = \frac{1.0,93(1-0,93)^2 0,02}{1.0,01} = 0.09114\ uF$$

$$C_{max} = \frac{10.0,29(1-0,29)^2 0,02}{10.0,01} = 2.92\ uF$$

TABLE II. CONVERTER BOOST PARAMETERS

Output Voltage	14 V
Input Voltage	1-10 V
Maximum duty cycle	0,93
Minimum duty cycle	0,29
Switching Frequency	50 kHz
Inductor	0,1 mH
Capacitor	2,2 µF
Power MOSFET	IRFZ44N
Diode	MUR1560

F. Converter Parameter

After determining the components on the boost converter, the value of the parameter in the design of the boost converter can be determined as in the table II.

G. Fuzzy Logic Controller

G.1 Control Block

This Fuzzy Logic Controller implementation uses a direct embedded system in the form of an Arduino UNO microcontroller. The Fuzzy Logic Controller in the boost converter system is systematically designed with calculations that adjust the conditions of the BLDC motor used. There are steps in designing this Fuzzy Logic Controller, which starts from fuzzification which begins with the creation of a fuction membership. Furthermore, in the inference step, namely the process of creating a rule base and then the last step of defuzzification, namely the process of changing the fuzzy logic back to the crisp logic obtained from the whole process.

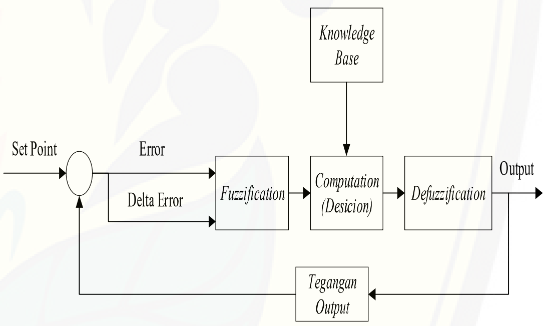

Fig. 2 Fuzzy Logic Control Diagram Block

G.2 Fuzzification

Fuzzification is the initial process of data processing with fuzzy logic. At this stage, the logical input is boldly converted into fuzzy logic to define the rules in the rule base process. The process of calculating errors and delta errors and membership functions uses a predetermined set point voltage of 14 volts. The membership function has 3 memberships including N (Negative), Z (Zero) and P (Positive).

To create the membership function, a set point value of the specified voltage is required, which is 14 V which aims to reference the control of the voltage stabilizer in regenerative braking. The fuzzy logic controller will read the voltage value at the regenerative braking output. Furthermore, the fuzzy logic controller processes the error value or delta error with the previous error value.

G.3 Membership

Membership function error is represented with the FIS editor on MATLAB R2013a as shown in Fig. 3. The determination of the delta error membership set is obtained from the difference between the current error value and the previous error value. For membership function delta errors, namely N (Negative), Z (Zero) and P (Positive) as shown in Fig. 4.

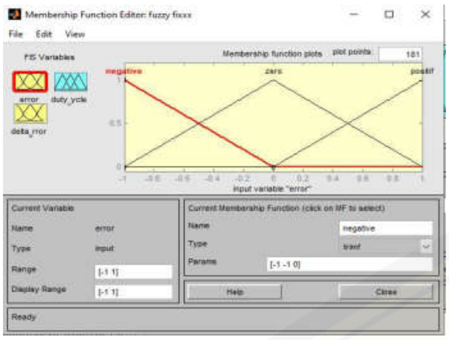

Fig. 3 Membership Function Error on Fuzzy Control Input

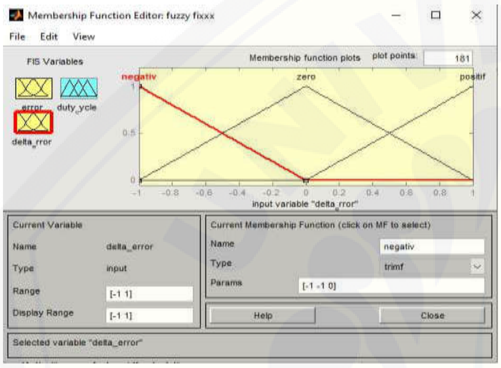

Fig. 4 Membership Function Delta Error

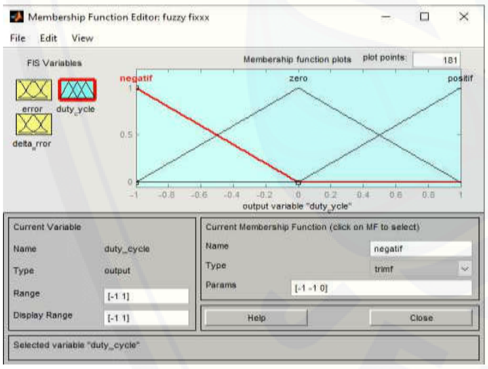

Fig. 5 Membership Function Duty cycle

The output membership function used as a fuzzy logic controller uses a range value from -1 to 1 divided into 3 curves, namely N (Negative), Z (Zero) and P (Positive). The output of this fuzzy inference system is expected to be able to adjust the duty cycle value by increasing or subtracting the PWM value, which is in the range of 255 to 0.

G.4 Inference

Inference is a process of processing decisions obtained from predetermined rules. Table III of determining the rule base in the fuzzy inference system.

TABLE III. RULE BASE PADA FUZZY INFERENCE SYSTEM

ΔE \ E	N	Z	P
N	P	P	N
Z	P	Z	N
P	P	N	N

G.5 Defuzzification

Defuzzification is the process of converting fuzzy logic back into assertive logic. Where the Defuzzification process is carried out based on the degree of membership in the inference process. The method used at this stage is the centroid method, which is the calculation of the moment and the area of implications. Such calculations can be carried out in the following equation:

a. Calculation of moments in each area of implications

$$M = \int \mu D.(z).z\, dz \tag{4}$$

$$M^* = \frac{(M1 + M2 + M3)}{(A1 + A2 + A3)} \tag{5}$$

b. Calculation of the area in each area of implications

$$A = \frac{1}{2}\, x\, a\, x\, t \tag{6}$$

c. Value calculation Z

$$Z = \frac{\int \mu D.(z).z\, dz}{\int \mu D.(z)\, dz} \tag{7}$$

The value of Z that has been obtained from the calculation is used as the output of the PWM value produced by the Fuzzy Logic Controller which aims to increase the voltage on the converter boost.

III. RESULTS AND DISCUSSION

The braking test was carried out in two systems, namely without a control system and with a control system. The uncontrolled condition is carried out to determine the flow of power from the boost converter circuit to the battery when the electric vehicle throttle is removed. This test is carried out by varying the duty cycle value on the Arduino as a PWM generator, then observing changes in the input voltage value, output voltage value, current and power during braking. The duty cycle in the boost converter circuit is varied gradually from 30% to 60%.

The braking test with control system or regenerative braking test is carried out using a fuzzy logic controller, with the duty cycle directly regulated by the Fuzzy Logic Controller based on the output voltage value generated by the electric bicycle.Regenerative Braking Testing without Fuzzy Control.

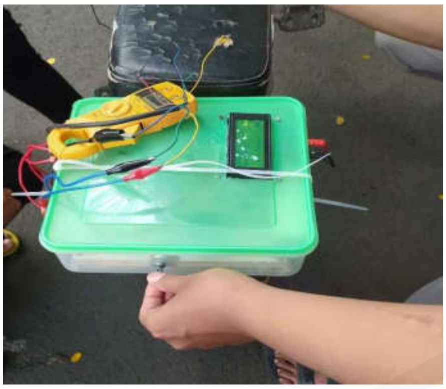

Fig. 6 Regenerative Braking Testing without Fuzzy Logic

The regenerative braking test without fuzzy control is carried out on a straight road, with a distance of 30 meters before braking. After 30 meters braking is done using the potentiometer as the braking level. The duty cycle used varies from 30% to 60% rated in step up to the boost converter circuit. The following is a braking test without using fuzzy logic. The test setup is shown in Fig. 7.

A. Regenerative Braking Testing without Fuzzy Control

This regenerative braking test is carried out with variations in the duty cycle. From the test results it is known that the greater the duty cycle, the shorter the time needed for the motor to stop. This uncontrolled braking shows the effect that sooner or later the motor stops.

TABLE IV. RESULT OF REGENERATIVE BRAKING TESTING WITHOUT CONTROL ON DUTY CYCLE 30%

Time (s)	Stop distance (m)	Vin (V)	Vout (V)	Iin (A)	Iout (A)	Pin (W)	Pout (W)	Vout Baterai (V)	Eficiency (%)
0,75	1,54	14,03	15,00	2,52	2,06	35,36	30,90	12,60	87,40
1,42	2,96	12,08	15,80	3,57	2,08	43,13	32,86	12,60	76,21
2,09	4,38	11,53	15,89	3,12	1,78	35,97	28,28	12,70	78,62
2,76	5,80	10,65	15,24	2,89	1,55	30,78	23,62	12,70	76,75
3,43	7,22	9,93	15,65	2,14	1,26	21,25	19,72	12,70	92,79
4,10	8,64	8,23	13,22	0,66	0,30	5,43	3,97	12,70	73,01
4,77	10,06	7,30	12,94	0,19	0,05	1,39	0,65	12,70	46,65
5,44	11,48	6,83	12,89	0,30	0,08	2,05	1,03	12,70	50,32
6,11	12,90	5,12	12,84	0,00	0,00	0,00	0,00	12,70	0,00
6,78	14,32	4,19	12,84	0,00	0,00	0,00	0,00	12,70	0,00
7,45	15,74	4,26	12,78	0,00	0,00	0,00	0,00	12,70	0,00
8,12	17,16	3,93	12,78	0,00	0,00	0,00	0,00	12,70	0,00
8,79	18,58	2,95	11,86	0,00	0,00	0,00	0,00	12,70	0,00
9,46	20,00	1,30	5,28	0,00	0,00	0,00	0,00	12,70	0,00

A.1 Duty Cycle 30%

Regenerative braking test results without fuzzy control during duty cycle 0.3. The results of regenerative braking testing are shown in table IV.

It can be seen that when the bicycle is in the condition that the bicycle braking and pedal throttle is removed, it can be seen that the output power produced is 30.9 watts with the time needed to stop is 0.75 seconds, stopping distance is 1.54 meters, the input voltage generated from the bike is 14.03 V, the output voltage of 15 V, the output current of 2.06 A, and the efficiency produced by the braking system is 87.397%.

From the results of the braking data, by using a duty cycle of 30% the time required in braking is 9.46 seconds with a stopping distance of 20 meters. From these data, it can be concluded that when braking using a small duty cycle variation, the time required for braking is also getting longer. As well as the efficiency value in braking can be calculated by calculating the value of input power and output power at a duty cycle variation of 30% using the following equation.

$$Pin = Vin.Iin \tag{8}$$

$$Pout = Vout.Iout \tag{9}$$

The calculation of power efficiency is carried out by comparing the value of the output power generated by braking with the input power in braking using the following equation (10).

$$Efficiency = \frac{Pout}{Pin} x\ 100\% \tag{10}$$

From the results of the calculation of power efficiency produced by regenerative braking, it can be seen that this braking system has sufficient efficiency values as shown in the latter column of Table IV.

A.2 Duty Cycle 60%

When the duty cycle given is 60%, it produces a smaller input voltage value generated by the electric bicycle and the shorter the bike stop distance. The results of regenerative braking testing with a duty cycle of 60% are shown in Table V.

TABLE V. RESULT OF REGENERATIVE BRAKING TESTING WITHOUT CONTROL ON DUTY CYCLE 60%

Time (s)	Stop distance (m)	Vin (V)	Vout (V)	Iin (A)	Iout (A)	Pin (W)	Pout (W)	Vout Baterai (V)	Eficiency (%)
0,93	0,92	5,96	13,64	5,65	1,92	33,65	26,19	12,90	77,77
1,88	1,88	4,08	15,15	4,15	0,90	16,93	13,64	13,00	80,53
2,80	2,80	3,83	14,66	3,48	0,59	13,33	8,65	13,00	64,89
3,73	3,72	3,60	14,23	2,13	0,55	8,32	7,83	13,00	94,11
4,65	4,64	3,12	13,88	1,39	0,31	4,34	4,25	13,00	97,94
5,58	5,56	2,95	13,21	1,05	0,14	3,10	1,85	13,00	59,71
6,50	6,48	2,90	13,00	0,40	0,06	1,16	0,73	13,00	62,76
7,43	7,40	1,67	12,78	0,10	0,01	0,17	0,11	13,00	65,81

From Table V can be seen that the value of the input voltage when the bicycle pedal throttle is removed, the input voltage has decreased from a value of 5.96V to 1.67V. It is planned that braking occurs at a time of 0.93 seconds to 7.43 seconds, and the bicycle is in a stopped state with a distance of 7.4 meters. It produces the largest output power of 26.19 watts, while the smallest output power until the bike stops running is 0.11 watts. Resulting in the greatest efficiency of 97.94% and the smallest efficiency of 59.71%.

A.3 Affects Duty Cycle on Deceleration

From the table, it can be found that the duty cycle affects the sooner or later the bike stops. And also affects the value of the input voltage on the bicycle, the greater the duty cycle value, the smaller the input voltage value produced by the bicycle and the shorter the bicycle stop distance. Table VI shown affects duty cycle on deceleration.

From the Table VI, it can be calculated the deceleration produced by the bicycle when braking is carried out. Before calculating the deceleration that occurs on the bike, first calculate the final speed value of the bicycle when braking is carried out. So that the value of the final speed can be obtained using the following equation formula.

$$v = \frac{s}{t} \tag{11}$$

TABLE VI. AFFECTS DUTY CYCLE ON DECELERATION

Duty Cycle (%)	Time (s)	Stop Distance (m)	Initial speed (m/s)	Final speed (m/s)	Deceleration (m/s^2)
0,1%	15,21 s	24,4 m	3,3 m/s	1,604 m/s	-0,112 m/s^2
0,2%	16,19 s	26,8 m	3,3 m/s	1,655 m/s	-0,102 m/s^2
0,3%	9,46 s	20 m	3,3 m/s	2,114 m/s	-0,125 m/s^2
0,4%	11,45 s	17,2 m	3,3 m/s	1,502 m/s	-0,157 m/s^2
0,5%	8,36 s	12,6 m	3,3 m/s	1,507 m/s	-0,214 m/s^2
0,6%	7,76 s	7,4 m	3,3 m/s	0,954 m/s	-0,302 m/s^2

Furthermore, when the initial speed value is known, it is continued to calculate the deceleration experienced by the bicycle when braking is carried out, using the following equation (12).

$$a = \frac{v_2 - v_1}{t} \tag{12}$$

From these data, it can be seen that the bike experienced a slowdown of -1.12 m s2 when given a duty cycle or braking rate of 0.1 with a stopping distance of 24.4 meters, with a final speed of 1,604 m/s. Meanwhile, when given a duty cycle or braking rate of 0.6, the bike experienced a slowdown of -0.302 m s2, with a stopping distance of 7.4 meters, the final speed produced was 0.954 m/s. So it can be concluded that the duty cycle or braking rate affects the deceleration on the bike, the greater the braking rate, the bike will in large deceleration, so that the bike's time used to stop is smaller.

B. Regenerative Braking Testing using Fuzzy Control

In this regenerative braking test, it is carried out using the fuzzy logic controller control. Where the relationship between the output voltage value and the duty cycle to be given is interrelated with each other. This duty cycle is set directly by the Fuzzy Logic Controller based on the output voltage value generated by the bike. In this test, it was carried out on a straight road with a distance of 30 meters.

This test is carried out by means of a bicycle on the pedal with a distance of 30 meters and then braking is carried out, then later the voltage generated from braking will be processed by arduino with a fuzzy logic program, where later when the output voltage reads less than the set point, which is 14V, then later the fuzzy logic controller will respond in the form of adding a duty cycle.

On the other hand, when the read output voltage is more than the voltage of the set point that has been determined, the fuzzy logic controller will respond in the form of a reduction in the duty cycle. The following is a test table of regenerative braking using fuzzy controls.

Regenerative braking testing using fuzzy controls can be seen that when the bicycle pedal is removed and braking is carried out which is activated by the potentio when the starting distance is 30 meters, an input voltage of 10.20 V is obtained, the cycle duty set by fuzzy logic gives a response of 0.27%, braking time for 1.77 seconds, bicycle stop distance of 2.78 meters, produces an output voltage that has been set by fuzzy control of 13.98V, resulting in an output power of 5.45 watts with an efficiency of 84.84%.

TABLE V. CONVERTER BOOST EFFICIENCY TESTING USING FUZZY LOGIC CONTROL WITH A RESISTOR LOAD OF 39Ω

Duty cycle (%)	Stop Distance	Time (s)	Vin (V)	Vout (V)	Iin (A)	Iout (A)	Pin (W)	Pout (W)	Vout Battery	Sfficiency (%)
0,27	2,78	1,77	10,20	13,98	0,63	0,39	6,43	5,45	12,90	84,84
0,33	5,53	3,49	9,12	13,56	0,98	0,49	8,93	6,64	12,90	74,32
0,47	8,28	5,21	7,41	14,02	1,02	0,46	7,55	6,45	13,00	85.37
0,63	11,03	6,93	5,10	13,78	1,57	0,48	8,01	6,61	13,00	82,57
0,74	13,78	8,65	3,83	14,53	2,23	0,53	8,53	7,70	13,00	90,18
0,77	16,53	10,37	3,02	13,53	3,04	0,49	9,18	6,63	13,00	72,18
0,85	19,28	12,09	2,01	13,84	4,55	0,47	9,15	6,50	13,00	71,02

When the input voltage is 3.02 V, fuzzy logic immediately responds in the form of a duty cycle of 0.77% with the resulting output voltage value stable according to the set point regulated by the fuzzy control, resulting in an output power of 6.63 watts with an efficiency of 72.19% this requires a stopping time when braking for 10.37 seconds with a stop distance of 16.53 meters. So from the data of table 4.14, it can be concluded that this fuzzy control is used to stabilize the output voltage of braking, and the duty cycle is set directly by the fuzzy logic controller based on the value of the output voltage generated by the bicycle when braking.

IV. Conclusion

1. The regenerative braking design has been successfully created and has worked as planned. The system is designed by using a three-phase rectifier to adjust the output voltage of the motor, then a boost converter system is designed to increase the voltage from the motor output which is regulated by setting the pulse width (duty cycle generate by Arduino as a PWM generator. The output voltage result of the boost converter is used to charge the battery.
2. Tests without fuzzy control using duty cycle variations for braking rate settings, the fastest braking time was obtained when the duty cycle was 60%, with a braking time of 7.43 seconds, a stopping distance of 7.4 meters, resulting the greatest efficiency of 97.95%, with a total output power generated when braking of 63.23 watts.
3. In the regenerative braking using Fuzzy control works if the bicycle throttle is removed and braking is carried out. The voltage generated from braking will enter the boost converter, then processed by Arduino with a fuzzy logic program, when the output voltage exceeds the set point, the fuzzy controller will respond to decrease the duty cycle.

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