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Design and Implementation of 3 Phase Inverter for Brushless DC Motor Using Six-Step Commutation Method with Ripple Suppression

***Abstract**. Along with the times, the application of renewable energy is increasingly being used, one of which is in the field of transportation. There are many means of transportation that use modern motors, such as switch reluctance motors and brushless DC (Direct Current) motors. BLDC motors or brushless DC motors have low mechanical losses because they do not use brushes like conventional dc motors. Because the brushless dc motor uses permanent magnets, a sensor is needed to determine the back-emf, apart from that for switching settings on BLDC motors using a three-phase inverter. In setting the output voltage on the three-phase inverter, it will produce a Pulse Width Modulation (PWM) output signal which will form 120° commutation. The excitation current of a brushless dc motor which is controlled electronically based on position feedback can produce ripple-free torque, however, if the motor is brushless dc. Therefore, this research will discuss the design of a three-phase inverter for BLDC motors using the six-step commutation method with ripple suppression to making prototypes using locally available materials.*

Streszczenie**. Z biegiem czasu coraz częściej stosuje się energię odnawialną, z których jedna znajduje się w dziedzinie transportu. Istnieje wiele środków transportu, które wykorzystują nowoczesne silniki, takie jak silniki reluktancyjne przełączników i bezszczotkowe silniki prądu stałego (DC). Silniki BLDC lub bezszczotkowe silniki prądu stałego mają niskie straty mechaniczne, ponieważ nie używają szczotek, jak konwencjonalne silniki prądu stałego. Ponieważ bezszczotkowy silnik prądu stałego wykorzystuje magnesy trwałe, potrzebny jest czujnik do określenia siły wstecznej, poza tym do przełączania ustawień silników BLDC za pomocą falownika trójfazowego. Ustawiając napięcie wyjściowe na falowniku trójfazowym, wytworzy on sygnał wyjściowy z modulacją szerokości impulsu (PWM), który utworzy komutację 120°. Prąd wzbudzenia bezszczotkowego silnika prądu stałego, który jest sterowany elektronicznie na podstawie sprzężenia zwrotnego położenia, może jednak wytwarzać moment obrotowy bez tętnień, jeśli silnik jest bezszczotkowy prądu stałego. Dlatego w niniejszych badaniach zostanie omówiony projekt trójfazowego falownika do silników BLDC z wykorzystaniem sześciostopniowej metody komutacji z tłumieniem tętnień do wykonania prototypów z wykorzystaniem lokalnie dostępnych materiałów.* (Projekt i realizacja 3-fazowego falownika do bezszczotkowego silnika prądu stałego z wykorzystaniem sześciostopniowej metody komutacji z tłumieniem tętnień***)

Keywords: Inverter, BLDC, Six-Step Commutation, Ripple Suppression
Słowa kluczowe: przekształtnik, BLDC, komutacja sześciostopniowa

Introduction

The use of conventional vehicles that still use fossil fuels causes a lot of sustainable pollution, this can cause damage to the ecosystem. In this era where humans depend on the existence of fossil fuels, due to easy processing and a lot of things related to electric power. Fossil fuels occur from the formation and decomposition over millions of years which gradually solidify which produces energy for coal, oil, and gas. The use of fossil fuels in Indonesia is of course a separate focus, this is because Indonesians use private vehicles that require refined petroleum. Meanwhile, the large number of vehicles can result in reduced world oil supplies, increased pollution in the form of toxins (free radicals), global warming, extreme climate change, and pollution of the soil and water environment.

Technological advances also provide solutions in reducing the effects of using fossil fuels, one of which is transportation that uses renewable energy (EBT). There are already quite a lot of transportation using modern motors, including motor switch reluctance and Brushless DC (BLDC) (Y. Chandra Wibowo & S. Riyadi, 2019) . BLDC motors are often used in the industrial world, based on the type of brushless dc motor there are two kinds, namely permanent magnet synchronous motor (PMSM) and permanent magnet synchronous brushless dc (PMBLDC). The use of BLDC motors has the advantages of simple design and the ability to operate at high speeds. Therefore, this BLDC motor is quite widely used in electric motors because it considers the efficiency given.

BLDC motor rotation regulation requires back-emf to be used as a reference in PWM generation. Because BLDC motors have permanent magnets to produce a magnetic field in the stator, they use alternating current to generate an electromagnetic field and create a north and south pole. Apart from that, the efficiency of the BLDC motor is used through power regulation using a three-phase inverter (A. Mohammad et al., 2016). The inverter itself is a power circuit that can convert direct current or voltage (DC) into alternating current or voltage (AC). The three phase inverter is designed in hardware as a supply to the motor which can drive the motor by generating an electromagnetic field. In the design of the inverter using a microcontroller to be able to generate phase changes or switching. The microcontroller will generate a PWM signal which will later be sent to the driving driver. In some cases of using BLDC motors there are also losses that can affect power efficiency, one of which is the loss of conduction power when a phase change process is carried out by the mosfet while the diode depends on the phase current and switching frequency (Y. K. Lee & J. K. Kim, 2019).

Therefore this conduction can result in ripples in the output signal, so that the received power is not as expected which will affect the stability of the rotational speed of the BLDC motor.

The study of a three-phase inverter for regulating phase change in BLDC motors that uses permanent magnets so that it can provide the expected input from the motor. This is done by knowing the position of the rotor using a hall sensor, after knowing the position of the rotor then through the inverter microcontroller program will be able to produce current or voltage as expected, apart from that when the speed is high then there must be a component that can reduce the ripple. Therefore, this research examines the use of a three-phase inverter on a BLDC motor using the six-step commutation method with PWM settings to regulate the commutation and ripple suppression which can suppress the ripples from the BLDC motor. This BLDC motor controller design will be further developed for BLDC controllers on electric buses.

Basic theory

A. Motor Brushless DC (BLDC)

BLDC Motor (Brushless DC) or often known as Permanent Magnet Synchronous Motor. BLDC motors require a certain direct (DC) power source, but BLDC motors require a 3-phase alternating current (AC) input. So there is a controller that converts direct current into alternating current with a phase difference of 120°. In a BLDC motor there is an equivalent circuit in which each phase passes through a 3-phase voltage source (v) which then contains a current (i), the current flows through an inductor (L) and a resistor (R). as shown in Figure 2.2 below (D. D. Hanselman, 2006).

There are 2 types of stator coils, namely sinusoidal and trapezoidal. Both types are categorized based on the back-emf (Back Electromotive Force) signal. The back-emf signal is the feedback voltage generated by the BLDC motor winding. Based on the above circuit, the following equation is obtained:

(1) $$v = Ri + L\frac{di}{dt} + e$$

where : v : Fasa Tegangan; i : Fasa arus; e : Tegangan *Back-emf;* vL : Induksi; R : Resistansi.

The BLDC motor controller produces three-phase output so that there is a u-phase, v-phase, and w-phase. Then it can be calculated for the inter-phase (D. D. Hanselman, 2006).

(2) $$v_{uv} = R(i_u - i_v) + L\frac{d(i_u - i_v)}{dt} + e_u - e_v$$

(3) $$v_{vw} = R(i_v - i_w) + L\frac{d(i_v - i_w)}{dt} + e_v - e_w$$

(4) $$v_{wu} = R(i_w - i_u) + L\frac{d(i_w - i_u)}{dt} + e_w - e_u$$

In a 3-phase BLDC motor, the equivalent circuit on the stator side is as follows:

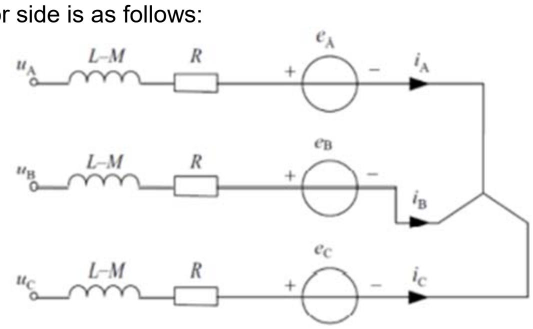

Fig 1. BLDC motor equivalent circuit

In this equivalent circuit, the current law applies:

(5) $$i_A + i_B + i_C = 0$$

Then the equation can be simplified to:

(6) $$u_A - Ri_A + (L - M)\frac{di_A}{dt} + e_A$$

So the equation of the phase voltage matrix on each BLDC motor stator coil is as follows:

(7) $$\begin{bmatrix} u_A \\ u_A \\ u_A \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_A \\ i_A \\ i_A \end{bmatrix} = \begin{bmatrix} L-M & 0 & 0 \\ 0 & L-M & 0 \\ 0 & 0 & L-M \end{bmatrix} \frac{d}{dx} \begin{bmatrix} i_A \\ i_A \\ i_A \end{bmatrix} + \begin{bmatrix} e_A \\ e_A \\ e_A \end{bmatrix}$$

B. BLDC Motor Control System Part

To control the BLDC motor, a control system is needed that can regulate the rotational speed of the BLDC motor, several components used in the control system such as MOSFET and optocoupler.

MOSFET is one type of FET (Field Effect Transistor) which is much different from JFET (Junction Field Effect) and IGBT (Insulated Gate Bipolar Transistor). MOSFET has three conductor legs, namely the first leg (top end) is called the drain, the second leg (lower end) is called the source, and the third leg (middle) is called the gate. Gates usually have 1 or 2 legs. On both the left and right sides there are semiconductor implants of different types of materials. The terminals of the two sides of the implant are connected to each other internally and are called gates. What distinguishes MOSFETs from other FETs lies in the gate, because the gate on the MOSFET is isolated by metal oxide materials. The gate itself is made of metal such as aluminum. Therefore, this field-effect transistor is called a metal oxide semiconductor (J. Linggarjati, 2004).

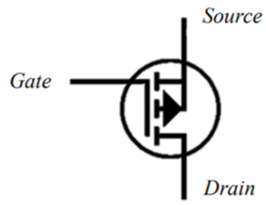

Fig 2. MOSFET Circuit

The graph of the MOSFET I_D characteristics as a function of V_{DS} with parameter V_{GS} is shown in Figure 2. In the MOSFET there are three operations, namely the cut-off, linear, and saturation regions. In the cut-off region, the gate voltage is smaller than the threshold voltage, so no channel is formed, and current cannot flow ($I_D = 0$). In the linear region, initially the gate is energized until a channel is formed, and current cannot flow from source to drain or current will flow from drain to source. Furthermore, the line will act as a resistance, so that the drain current (I_D) will be proportional to the drain voltage. Here is the I_D equation.

(8) $$I_D(SAT) = \frac{K_n}{2}(V_{GS} - V_{Tn})^2$$

The purpose of knowing the drain characteristics so that the MOSFET that will be used can be known for its reliability related to the current and voltage capabilities of the MOSFET, especially at the voltage tested V_DS is the same as the datasheet. These characteristics can provide information about the emptying and filling electrons in the MOSFET. In addition, in the BLDC motor controller there is also a driver (optocoupler) as a microcontroller safety.

In general, a driver system (optocoupler) is used to connect a control system that works on small voltages and currents with a power system that works on a large voltage and current rating, where these two systems have different grounding levels (floating) so that the three-phase inverter topology it is absolutely necessary to have a driver or an isolation system between the microcontroller and the MOSFET (F.D. Rumagit, 2012). Judging from the physical usability of the optocoupler, it can take various forms. If it is only used to isolate the voltage level or data on the transmitter and receiver side, then this optocoupler is usually made in solid form (there is no space between the LED and the photodiode). So that the electrical signal at the input and output will be isolated. In other words, this optocoupler is used as an IC type option. (F.D. Rumagit, 2012).

C. BLDC Motor Control System

A BLDC motor that uses a three-phase input in order to generate a magnetic field on the BLDC motor so that it can drive the BLDC motor. The feedback from the 3-phase system is for reading the rotor position. Therefore an inverter is needed to convert DC current to AC and a 3-phase current feedback reading system is needed.

In general, an inverter is a power electronic equipment that functions to convert direct voltage (DC) into alternating voltage (AC). For BLDC, a 3-phase inverter is required which consists of 6 switching components. The following is the arrangement of the components of a 3-phase inverter switching. (F. Fürst, 2015).

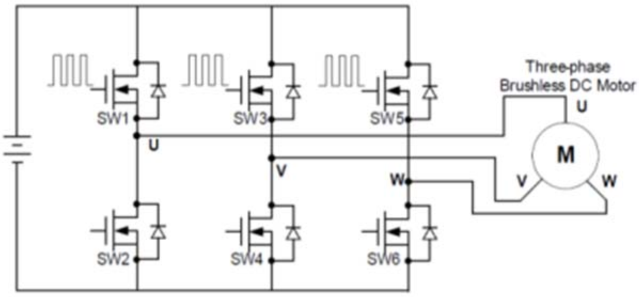

Fig 3. 3 Phase Inverter Circuit

There are 2 types of operating modes of this type of inverter, namely 60° conduction mode and 120° conduction mode. In order to rotate, only two BLDC motor stator coils are active each step and one other coil is off or not electrified. By using the 60° mode, a phase change will be obtained, a 3-phase inverter with a 60° conduction mode allows each switching component to conduct 60° to form different conduction pairs including U, V, W, -U, -V, and -W or can be called six-step commutation. To control the duration of each ON Pulse Width Modulation (PWM) switch. Three-phase balanced output voltages obtained from PWM switching with triangular waves are compared with three sinusoidal control voltages which have a commutation shift of 60° per phase. Each switch in the inverter gets a duty cycle ratio from the PWM switching, and this duty cycle ratio controls if the switch is opened or closed (F. Fürst, 2015).

In making the switching of a 3-phase inverter, a reference is needed to determine the switching logic. Then a back-emf detector is needed. In controlling the BLDC motor, it is necessary to have the right timing of commutation changes so that the BLDC motor can be controlled with constant speed and torque. If the timing of the commutation changes is not correct, the BLDC motor will slip. As a result of the slip is not constant speed and torque. This can be seen especially when the motor rotates at high speed. When a slip occurs, the motor speed will tend to decrease and there is a possibility that the motor will stop rotating. To determine the timing of commutation changes, there is a sensorless method. The sensorless method is carried out by detecting back-emf and zero crossing in the motor phase experiencing floating conditions (C. L. Xia, 2012).

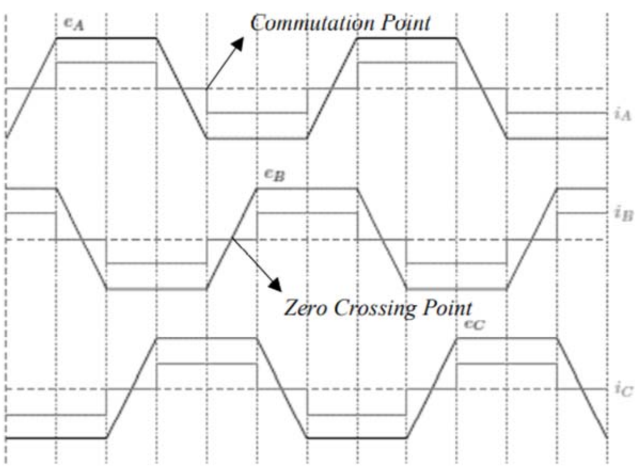

Fig 4. Commutation Wave

D. Six-Step Commutation

The six-step method is the method most often used in commercial BLDC control. This happens because this method is simple so it is easy to implement. This method is called the six-step method because in order to be able to create a trapezoid or square wave consisting of 6 parts, namely 2 positive parts, 2 negative parts, and 2 floating parts. Each part is a 60° sinusoidal wave. The floating condition in this algorithm is the condition when the sinusoidal waves intersect at point 0 (Dharmawan, 2009).

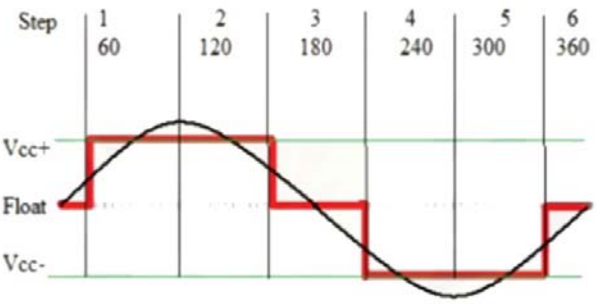

Fig 5. Determination of the Six-Step Method

To form a trapezoidal wave or 3-phase squere wave, a six-step algorithm is used, each of which differs by 1 step (60 degrees) from one algorithm to another.

This method is widely used because it is relatively easy, but in its determination it is necessary to program the microcontroller to produce a PWM signal which will result in switching. Because the switching allows the inverter to generate a 3-phase (AC) wave, previously to generate a PWM signal as a MOSFET trigger requires the following logic:

TABLE I LOGIC SIX-STEP COMMUTATION

Back EMF			Fasa		
A	B	C	A	B	C
1	-1	0	+	-	Float
1	0	-1	+	Float	-
0	1	-1	Float	+	-
-1	1	0	-	+	Float
-1	0	1	-	Float	+
0	-1	1	Float	-	+

E. Ripple Suppression

The BLDC motor also has ripple which is a disturbance, the disturbance generated from the controller is the result of the phase change process. This is because the current in the stator coil cannot change so fast because the inductance, the difference in the level of rise and fall of current during the commutation process affects the electric torque.

In this case the resistance is an important component, to obtain a constant torque result the commutation must be faster than the steady state voltage, even higher than VDC at medium or high speeds. As we know, increasing the voltage can not increase the speed range, but also suppress the torque ripple. The working resistance relationship is explained by the mathematical model (Chen et al., 2007).

(9) $$f_C = \frac{1}{2\pi RC}$$

By determining the resistance and capacitor can reduce the ripple that occurs in the BLDC motor. The low-filter circuit is as follows:

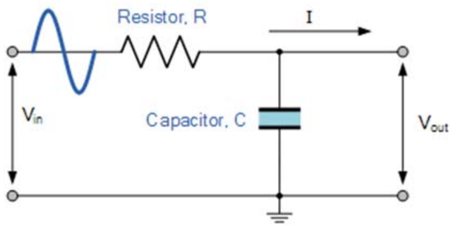

Fig 6. Filter Circuit

Simulation and Implementation

A. BLDC Motor Used

For the need for a 3-phase inverter control design for a BLDC motor, it is necessary to have a specification or rating of the BLDC motor that will be used. In accordance with the datasheet listed on the Readytosky RS-2212 920 kV motor, it can be determined the parameters needed in the design of this research. Specifications of the Readytosky RS-2212 920 kV motor. The capacity of the BLDC motor in this study has a maximum input voltage of 12 volts and a maximum current of 15 amperes. At no-load conditions, the BLDC motor can rotate up to 11,040 Rpm.

TABLE II.
BLDC MOTOR SPECIFICATION

Size :	22 x 12 mm
KV :	920 RPM/V
Max Power :	190 W
No Load Current :	0,6 A / 12 V
Max Current :	15 A
Weight	53 g
Shaft Diameter :	4 mm
Shaft Length :	49 mm
Battery :	2S-3S Li-Po
Poles :	14
Rotor Rotation :	CW/CCW

B. Selection of 3 Phase Inverter

The BLDC motor also has ripple which is a disturbance, the disturbance generated from the controller is the result of the phase change process. This is because the current in the stator coil cannot change so fast because the inductance, the difference in the level of rise and fall of current during the commutation process affects the electric torque.

In determining the inverter component to be used, parameters are needed to determine it, the MOSFET calculation is seen from the motor current and voltage drain source.

(10) $$I_{motor} = \frac{P_{motor}}{V_{motor}}$$

(11) $$V_{DS} = \left(\frac{1}{1-D}\right) V_{in}$$

By using the above calculations it can be determined which MOSFET can be used. While the determination of resistance by:

(12) $$\frac{V_{MAX}}{R} \leq i_f$$

Apart from the resistor, the diode which functions as a reverse diode. It is used to block the current coming from the BLDC motor, so that the control circuit remains safe. In the selection using the current reference by:

(13) $$I_f = \frac{V_{MAX}}{R}$$

The other component is a capacitor, using a capacitor that meets the specifications can provide better performance.

(14) $$C \geq \frac{2\left[2Q_G + \frac{I_{QBS}}{f} + Q_{LS} + \frac{I_{CBS}}{f}\right]}{V_{CC} - V_f - V_{LS} - V_{Min}}$$

Based on calculations using the above equation, the components that will be used are obtained as follows.

TABLE II. COMPONENTS USED

Components	Nilai
DC Supply	12 V
Microcontroller	Arduino Uno
Driver Inverter	IR2104
MOSFET	IRF3205
Diode	1N4148
C_1	$10\ \mu F$
C_2	$2{,}2\ \mu F$
R_1	$100\ \Omega$
R_2	$33\ k\Omega$
R_3	$10\ k\Omega$
C_3	$50\ \mu F$
R_4	$100\ \Omega$
BLDC Motor	RS-2212 920 kV

C. Circuit Simulation

The entire system in this study consists of several blocks, including a power supply for 12 volt supply, ATMega328, an inverter driver connected to the inverter, ripple suppression connected to the inverter output, a BLDC motor as a load, and a back-emf detector to determine commutation. The overall illustration can be seen from the block diagram below.

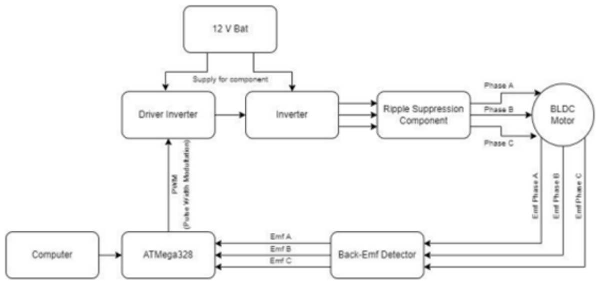

Fig 7. Control Circuit System Schematic

From the schematic above, it can be seen that several important components in the 3-phase inverter control system for BLDC motors are good. As for the modeling of the system circuit is as follows:

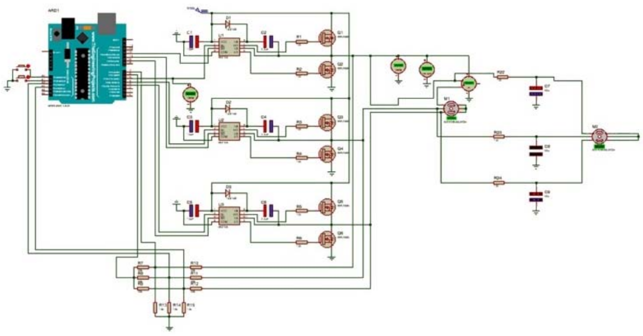

Fig 8. 3 Phase Inverter Control Modeling

Modeling is done to see the results of the simulation of the tool before making the tool, in the above modeling there are several modeling components both from the controller that uses the ATMega328 microcontroller because it is easy to program and widely marketed. In order to control the motor speed.

D. Six-Step Commutation Design

E. Figure 9 shows the flow chart after detecting the back-emf signal which will be converted into a switching signal (gating signal), namely the signal that regulates the ON and OFF MOSFET. This back-emf signal reading becomes a logic that determines switching between MOSFETs is to use the six-step commutation method. By dividing it into six parts as shown in Figure 9, a PWM generator program can be made to perform the switching.

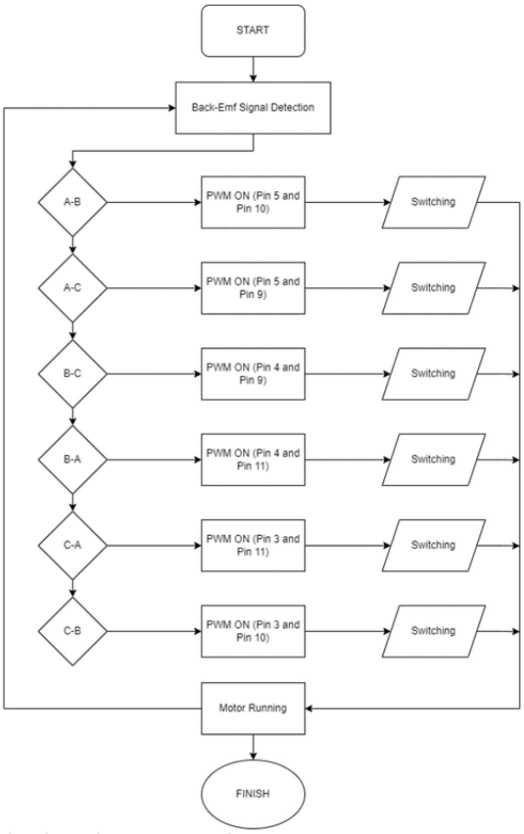

Fig 9. Six-Step Commutation Switching Logic

F. Prototype Design

The design of the prototype is done by designing on the eagle to print the PCB and then making the full tool. The following is a form of implementation of the tools used.

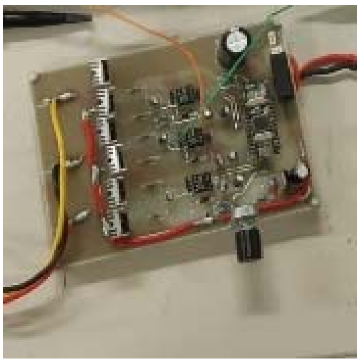

Fig 10. Tool Implementation

Results and Discussion

This section discusses the results of the simulation and implementation of the tool as well as the analysis of the test.

A. 3 Phase Inverter Simulation Results

The 3-phase inverter for BLDC motors with the modeling described above can be tested using the Proteus 8 software, to see the waves and the voltage and current generated from the simulations carried out. PWM generation into 6 parts (3 high side and 3 low side), in this test we get the phase difference between the high and low side as shown below.

In the simulation test above, the phase difference between the high and low sides is obtained, this is in accordance with the plan. On the low side and high side, the period in one wave is 50 ms.

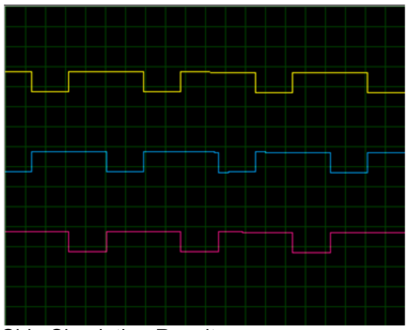

Fig 11. Low Side Simulation Results

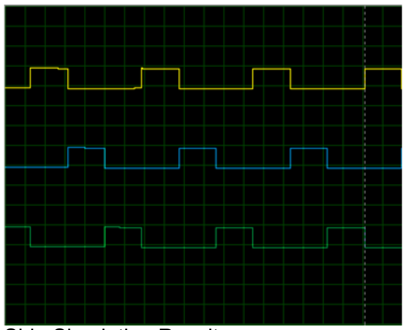

Fig 12. High Side Simulation Results

In the simulation model above, there are also back-emf readings, the back-emf detected by this comparator circuit will be used as a reference to determine the 6 commutation models (six-step commutation). The feedback from the motor is in the form of a trapezoidal signal which will be used for modeling logic for commutation using six-step. The signal form of the back-emf is shown in Figure 13 below.

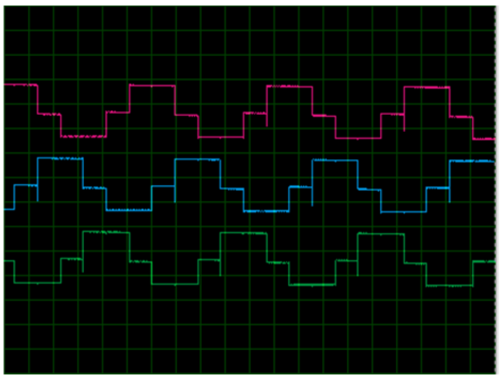

Fig 13. Back-Emf Simulation Results

B. 3 Phase Inverter Simulation Results

In testing the implementation of the tool, several stages were carried out, first testing whether the MOSFET driver was working properly. This is done because the IR2104 driver has bootstrap properties, namely increasing the high side voltage. The results of this test are as follows.

Based on the above test, it can be seen that the difference in the resulting voltage, a microcontroller that uses ATMega328 is only able to produce a voltage of 5 Volts, while the 3-phase inverter circuit requires a 12 Volt supply. Therefore, this MOSFET driver can increase the voltage generated from the microcontroller to be the same as or close to the supply from a DC source.

Then testing is also carried out to see the magnitude of the switching frequency generated by the microcontroller, then data collection is carried out and obtained as follows.

Fig 14. Comparison of Microcontroller and IR2104 . High Side Signals

TABLE III. . COMPARISON OF ANALOG AND SWITCHING FREQUENCY

Analog Variation Value	Frequency (Hz)
0	0
10	200,5
20	424,7
30	631,3
40	942,7
50	1102
60	1211
70	1304
80	1375
90	1420
100	1495

Based on the results above, it can be seen that the frequency generated from the microcontroller analog variation can produce up to 1495 Hz. After that, a test was carried out to see the switching of Voltage Gate Source (VGS) and Voltage Drain Source (VDS).

Based on the waveform from the picture above, it can be seen that when the gate of the MOSFET is high, the drain-source switch will conduct so that current flows and causes the voltage to be low. However, when the gate of the MOSFET is low, the switch will be open, so the current will not flow and the voltage on the drain-source is high. From the picture, it can be seen that the voltage from the gate-source is 11.6 Volts and on the drain-source side is 12 V (according to the DC supply. In this condition there is still a voltage spike, this is due to the use of components that are not ideal during implementation.

After the test is carried out, a test is carried out to see the back-emf waveform of the motor.

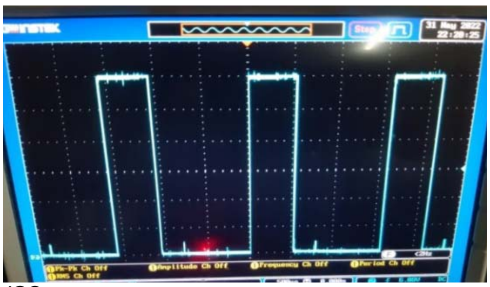

Fig 15. VGS wave

Fig 16. VDS wave

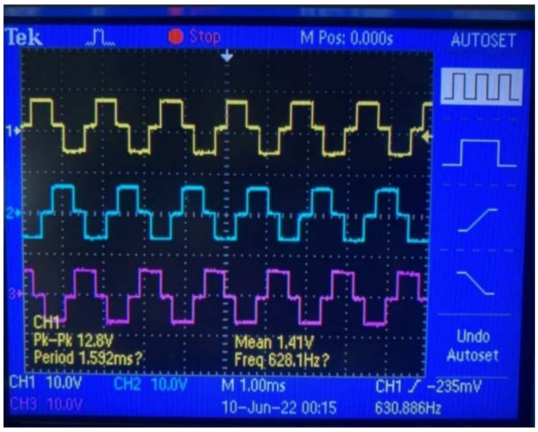

Fig 17. Back-Emf wave

From Figure 17 is the back-emf waveform that emerged from the implementation of the tool, from this trapezoidal waveform it can be analyzed that by determining the six-step commutation, it divides the part into 6 parts with a 60° phase. There are conditions when commutation occurs and there is a zero crossing condition according to the plan, from the data it is in accordance with the simulation results and the expected waveform is appropriate.

In this test, the purpose of this test is to see how the designed ripple suppression works well. In this test, an oscilloscope checks the 3-phase inverter control device so that the voltage graph can be seen. Here are the results of testing the tool:

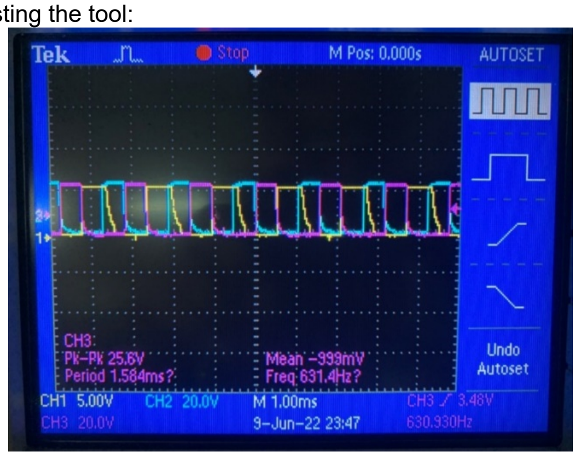

Fig 18. 3-Phase Wave Without Ripple Suppression

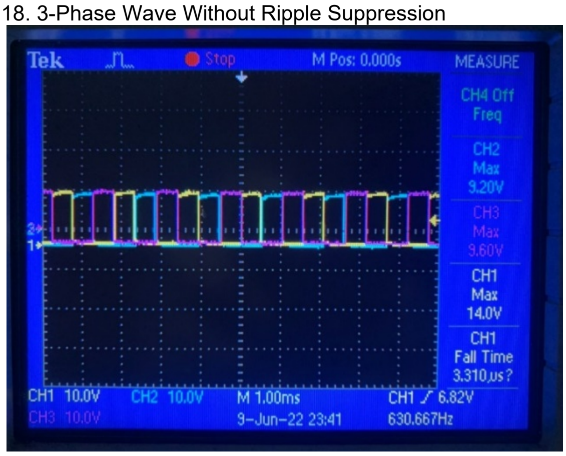

Fig 19. 3-Phase Wave With Ripple Suppression

Based on the above test, it can be seen that the change after using ripple suppression is by looking at the graph where previously there was a decrease in disturbance in each phase. This is due to the use of capacitors and resistors which are filters to reduce interference, based on the test results, ripple suppression has worked as expected.

Then tested for 3-phase inverter control for BLDC motors with and without ripple suppression. The first is a test without ripple suppression.

TABLE IV. TEST DATA WITHOUT RIPPLE SUPPRESSION

Frequency (Hz)	P_{in} (W)	P_{out} (W)	N (rpm)	η
0	0	0	0	0 %
200,5	2,9503	0,9291	1029	31 %
424,7	4,821	1,9682	2576	40 %
631,3	5,5521	2,8662	3922	51 %
942,7	6,9812	3,6589	5207	52 %
1102	7,8829	4,2011	6278	53 %
1211	8,7375	4,8171	7407	55 %
1304	9,4281	5,8967	8892	62 %
1375	9,5272	6,3486	9855	66 %
1420	11,1901	7,8992	10221	70 %
1495	12,2487	8,8562	10988	72 %

Based on the test results above, it can be concluded that the highest efficiency occurs when the frequency is 1495 Hz, which is 72%, while the lowest efficiency is at a frequency of 200.5 Hz, which is 34%. With the average efficiency of 3 phase inverter control is 56%.

Next is a test for a 3-phase inverter using a 1045 propeller load and ripple suppression, the results are as follows:

TABLE V. TEST RESULTS WITH RIPPLE SUPPRESSION AND PROPELLER LOAD 1045

Frequency (Hz)	P_{in} (W)	P_{out} (W)	N (rpm)	η	Torque (Nm)
0	0	0	0	0	0
100,7	35,986	15,871	775	44 %	0,139
221,3	43,719	21,476	1082	49 %	0,135
401,5	54,816	30,100	2142	54 %	0,095
432,6	67,771	37,819	2771	55 %	0,093
483,5	70,812	39,987	3001	56 %	0,090
551,6	77,012	45,117	3547	58 %	0,086
599,2	79,996	49,120	4097	61 %	0,081
621,6	86,987	57,918	4959	66 %	0,079
671,9	90,369	60,712	5188	67 %	0,079
696,3	100,61	65,881	5690	65 %	0,079

Based on the test results, it can be concluded that the highest efficiency occurs when the frequency is 671.9 Hz, which is 67%, and the lowest efficiency occurs at a frequency of 100.7 Hz, which is 44%. While the average efficiency obtained in this test is 57%, while the largest torque is 0.139 Nm. In this test a decrease in the resulting frequency occurs because of the influence of the back-emf voltage which is also low, so that the microcontroller can only produce a small frequency as well.

According to the above test results, it can be concluded that the use of ripple suppression also affects the motor torque and the total efficiency of the 3-phase inverter control, when using ripple suppression, the speed is higher and the torque is smaller.

Conclusion

From the results of the simulation and testing of the 3-Phase Inverter Control tool for BLDC motors with the Six-Step Commutation Method with Ripple Suppression, the following conclusions can be drawn:

1. Implementation of a 3-phase inverter control system for BLDC motors with the six-step commutation method by adjusting the PWM frequency, the greater the PWM frequency, the greater the efficiency and rotational speed.
2. The switch is used to adjust the MOSFET switching to generate a 3-phase waveform.
3. The back-emf wave from the motor is used to set the 6-step commutation logic as a reference for microcontroller programming.
4. The use of ripple suppression affects 3-phase waves, by reducing the ripple caused by changing one phase to 3 phases.
5. Implementation of a 3-phase inverter control system for BLDC motors without ripple suppression and load obtained an average efficiency of 55%.
6. Implementation of a 3-phase inverter control system for BLDC motors with no-load ripple suppression obtained an average efficiency of 56%.
7. Implementation of a 3-phase inverter control system for a loaded BLDC motor without ripple suppression obtained an average efficiency of 56%.
8. Implementation of a 3-phase inverter control system for a loaded BLDC motor without ripple suppression obtained an average efficiency of 57%.
9. Comparison when the system is loaded and without load shows that the more the load, the lower the speed. Loading also causes the PWM frequency to decrease.
10. The use of ripple suppression on a loaded BLDC motor can affect the speed and torque generated.

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REFERENCES

[1] A. Mohammad, M. A. Abedin, & M. Z. R. Khan. (2016). *Implementation of a three phase inverter for BLDC motor drive*.

[2] C. C, & S. Jeevananthan. (2012). *Generalized Procedure for BLDC Motor Design and Substation in MagNet 7.1.1 Software*.

[3] C. L. Xia. (2012). *Permanent Magnet Brushless DC Motor Drives and Controls*.

[4] Chen, W., Xia, C., & Xue, M. (2007). *A Torque Ripple Suppression Circuit for Brushless DC Motors based on Power DC/DC Converters*.

[5] D. D. Hanselman. (2006). *Electrical and Mechanical Relationships*.

[6] Dharmawan, A. (2009). *Pengendali Motor DC Brushless dengan Metode PWM Sinusoidal Menggunakan ATMega 16*.

[7] F. Fürst. (2015). *Design of a 48 V three-phase inverter For automotive applications*.

[8] F.D. Rumagit. (2012). *Perancangan Sistem Switching 16 Lampu Secara Nirkabel Menggunakan Remote Control*.

[9] J. Linggarjati. (2004). *PADA PENGENDALI ELEKTRONIKA MOTOR BLDC PEMBAHASAN Karakteristik Mosfet*.

[10] J. Zhao, & Y. Y. July. (2014). *Brushless DC Motor Fundamentals Application Note*.

[11] Prokop L., & Chalupa L. (2005). *3-Phase BLDC Motor Control with Sensorless Back EMF Zero Crossing Detection Using 56F80x*.

[12] Y. Chandra Wibowo, & S. Riyadi. (2019). *ANALISA PEMBEBANAN PADA MOTOR BRUSHLESS DC (BLDC)*.

[13] Y. K. Lee, & J. K. Kim. (2019). *Power efficiency analysis of a three-phase inverter for a BLDC motor drive with varying speeds and load torques*.

[14] Y. Lai, S. Member, F. Shyu, & Y. Chang. (2004). *Novel Loss Reduction Pulsewidth Modulation Technique for Brushless dc Motor Drives Fed by MOSFET Inverter*.