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Implementation of modified trapezoidal commutation scheme for speed control of 1 kW BLDC motor

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Abstract

The commutation process in brushless DC (BLDC) motors is done electrically and depends on the rotor position feedback. The Six-Step method is the most commonly used method in BLDC control, as it is easy to implement. However, this method has a high root mean square (RMS) current. On the other hand, a perfect sinusoidal commutation method is very complicated. Therefore, this research proposes a simple modified scheme of trapezoidal commutation circuits that can produce sinusoidal BLDC output voltage. This circuit can still responsively control the speed of the BLDC motor. This scheme uses 2 Arduinos. Pulse width modulation (PWM) signal from Arduino2 is then combined with hall signals from Arduino1, resulting in six outputs which are modified electrical commutation signals. This commutation signal is used as a MOSFET controller in a 3-phase inverter to produce a sinusoidal waveform. The average efficiency obtained when implementing the commutation is 75 % at low and high speeds.

Keywords: BLDC; modified trapezoidal commutation; motor speed control; sinusoidal waveform.

I. Introduction

Permanent magnet synchronous motors (PMSM) are widely used among AC motors due to their advantageous features. BLDC is one type of permanent magnet motor that has advantages including low inertia, fast response, power density, and high reliability. Thus, this motor is widely applied to electric vehicles, computers, and medical equipment [1]. BLDC with non-sinusoidal (more-trapezoidal) back-EMF waveforms is an established technology suitable for the growing electrification market. The commutation process in BLDC motors is performed electrically and depends on the rotor position feedback. The position of the rotor in a BLDC is known with a hall sensor divided into six position sectors with 60° intervals [2]. Although using 3-phase current, BLDC motors are not AC motors because the BLDC motor current source comes from 1 DC source which is converted into a 3-phase AC voltage using an inverter circuit. This 3-phase inverter is a substitute for brushes on the motor. This inverter is also used as a BLDC motor speed control by adjusting the duty cycle on each switch component such as metal oxide semiconductor field effect transistor (MOSFET).

In general, there are two methods of controlling BLDC motors, namely the sinusoidal method and the trapezoidal/six-step method. The sinusoidal BLDC motor control method has smaller RMS current and losses than the six-step method [3], so it has high efficiency. However, a perfect sinusoidal signal is very complicated to generate and requires a lot of microcontroller resources. Meanwhile, the Six-Step method is the most commonly used method in BLDC control. This is because it is simple and easy to implement. However, this method has the disadvantage of high root mean square (RMS) current. This can occur because the PWM used in

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Figure 1. 1 kW 48 V BLDC

this method is a square PWM with a certain frequency, creating a trapezoidal or square AC wave. The result of a square or trapezoidal wave is the generation of harmonic waves. Although the instantaneous torque produced is smooth, there are torque ripples caused by induction that occur during current switching [4]. This torque ripple is an obstacle in adopting BLDC motors for high-performance applications and good speed response.

Several modifications of the trapezoidal method have been carried out to drive and regulate the speed of BLDC motors. Some modifications are made digitally by adding a control box before the PWM enters the inverter. The digital PWM control technique is based on a comparison of the speed reference and the actual speed value. In research [5], the H-PWM and L-PWM methods are carried out by adjusting the switching frequency so that the utility voltage can change and result in a change in the maximum speed range of the BLDC motor. Similar to research [4] which made changes to the input voltage and conduction period to be able to drive a BLDC motor with high efficiency. This method requires reliable sensors and microprocessors. Modified trapezoidal commutation is also performed with the pulse amplitude modulation (PAM) technique. The PAM method proves superior to the PWM technique in terms of efficiency and performance. However, this type of implementation is more complex and can be done if the motor is supplied by a DC converter [6][7]. The modified form of the trapezoidal method carried out in this study was based on instructions from research [8][9][10]. The switching signal is produced by multiplying the PWM modification signal with the hall sensor excitation signal on positive signals only. This can provide improvements to the torque ripple which is a deficiency in the trapezoidal computing method. This carrier modulation is the most common technique for the inverter of modern digital motor drives [11]. The multiplication of the two signals is done using a logic gate [12]. The use of logic gates for these modifications provides reliability and provides stable performance with lower complexity. This method can produce an inverter output wave that is close to a sinusoidal wave which has not been shown in research [9]. Therefore, this research will apply the same switching concept but use different components to control the speed of a 1 kW BLDC motor which will be applied to an electric car.

II. Materials and Methods

A. Word BLDC motor drives system

A BLDC motor has three stator windings and a rotor permanent magnet. A BLDC motor has mainly two operating states: conduction state and commutation state. In the conduction state with the selected rotor position, two phases are conducted. In the case of the commutation state which is a transient area that converts current conduction into to next one and at that time three phases will be conducted [13]. It is called 2-phase conduction mode because there are only 2 active phases, while the other 1 phase is float [14]. The floating condition in this algorithm is the condition when the sinusoidal wave intersects at point 0. The BLDC used is a QS 48V 1000w type BLDC as shown in Figure 1 and Table 1.

The rotor position is given by a hall effect sensor which is placed inside the motor and accurately provides commutation information to the inverter circuit [15]. The information is in the form of high and low signals based on the position of the north and south poles. The inverter uses 6 MOSFETs or IGBTs that require an ignition signal or pulse. This power circuit can activate the coil at the right time so that the motor can move. Therefore, the switching sequence must be controlled correctly so that the current can flow to the correct phase.

There are two types of operating modes of this type of inverter, 120° conduction mode and 180° conduction mode. The 180° mode has drawn more current as expected because three windings are energized at all times [16]. In order to rotate, the BLDC motor stator coil is given a 3-phase AC voltage, in each step of which only two coils are active and one other coil is off. So that at each step, only two switches are allowed to be active alternately. therefore, the mode used is mode 120°. A 3-phase inverter with a 120° conduction mode allows each switching component to be conduction conducted for 120° with different conduction pairs [17]. There are six sequences of switching times so the

Table 1.
Paramater BLDC

Parameter	Value
Motor type	BLDC motor hub with permanent magnet
Motorcycle design	double axle with 10 inches rims
Rim size	10 x 2.15 inches, hub width: 7.3 cm
Motorcycle version	30H 1000 W
Rated power	1000 W
Rated voltage	48 V
Magnet height	30 mm
Polar pair	23 pairs (46 pieces straight magnets)
Speed	50 km/h – 75 km/h

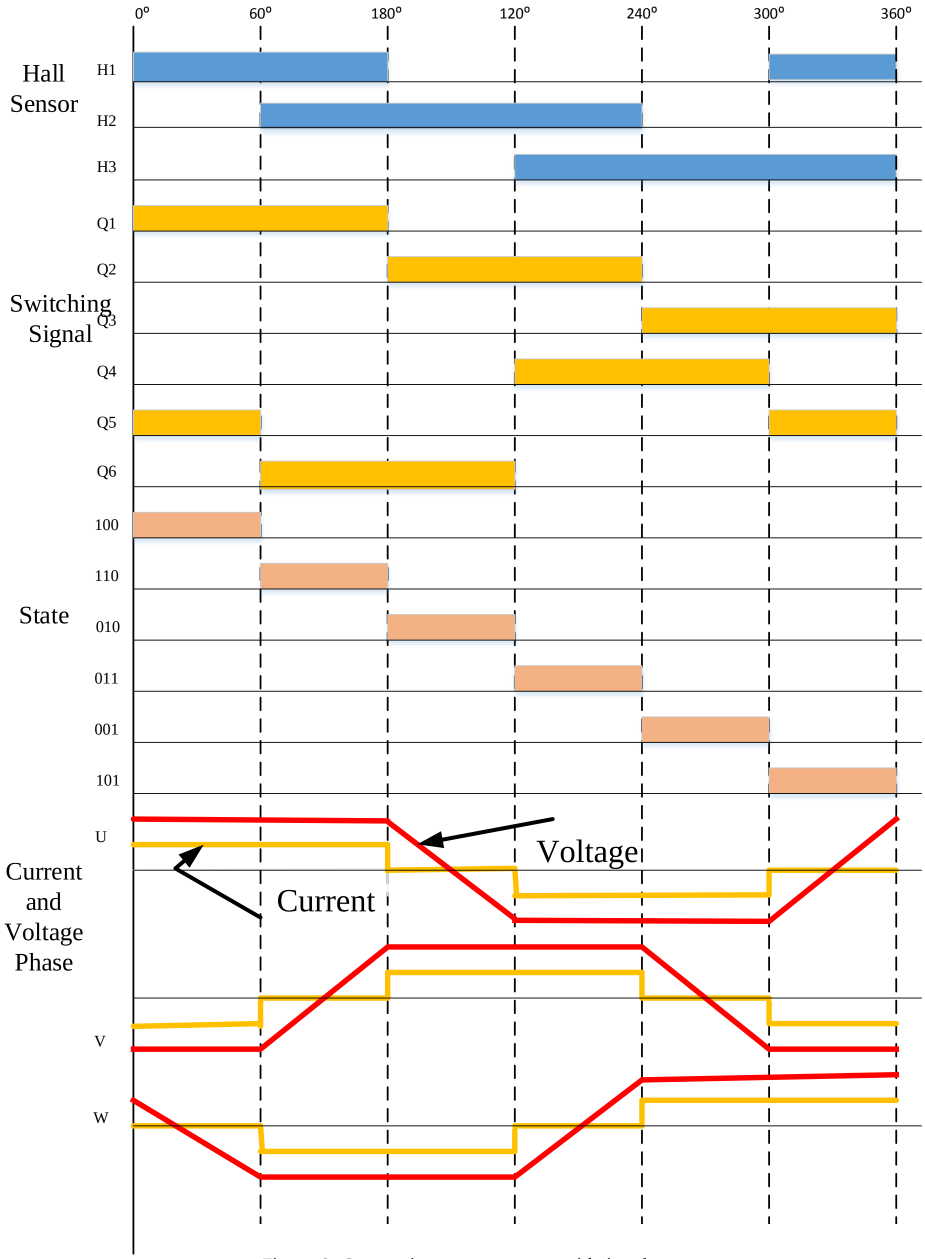


Figure 2. Generation process trapezoid signal

trapezoidal method is also called the six-steps method. To form a trapezoidal wave or a 3-phase square wave as shown in Figure 2, three six-step algorithms are used, each of which differs by one step (60 degrees) from one algorithm to another [18]. The formation of phase U, phase V, and phase W through the reading of hall sensor H1, sensor H2, and sensor H3 through codes 1 and 0. Q1, Q2, Q3 made up the upper legs, and Q4, Q5, Q6 comprised the corresponding lower legs in the inverter circuit. The switching order was used to assign numbers to the switches. Q1 was switched ON first, followed by Q5, then Q6 was triggered ON after Q5 [19]. The first part consists of Q1 and Q5 which are active, then the U phase will be high because it gets a positive voltage supply, the V phase will be low because it gets a negative voltage supply and the W phase will be floating because the MOSFET is not active. Changes in conditions in the 3-phase inverter based on hall effect sensors can be seen in Table 2.

B. Modified Trapezoidal Commutation

Basically, BLDC uses a 3-phase current that has a sinusoidal shape. Thus, this modification scheme aims to create a sinusoidal inverter output wave from a simple trapezoidal commutation base circuit. The sinusoidal wave is generated from a modified electrical commutation signal. The positive signal on

Table 2.
Comparison change signal on 3 phases inverter

Hall Effect Sensors			3-Phase Inverters		
H1	H2	H3	U	V	W
0	0	1	Low	Floats	High
1	0	1	High	Floats	Low
1	0	0	High	Low	Floats
1	1	0	Low	High	Floats
0	1	0	Floats	High	Low
0	1	1	Floats	Low	High

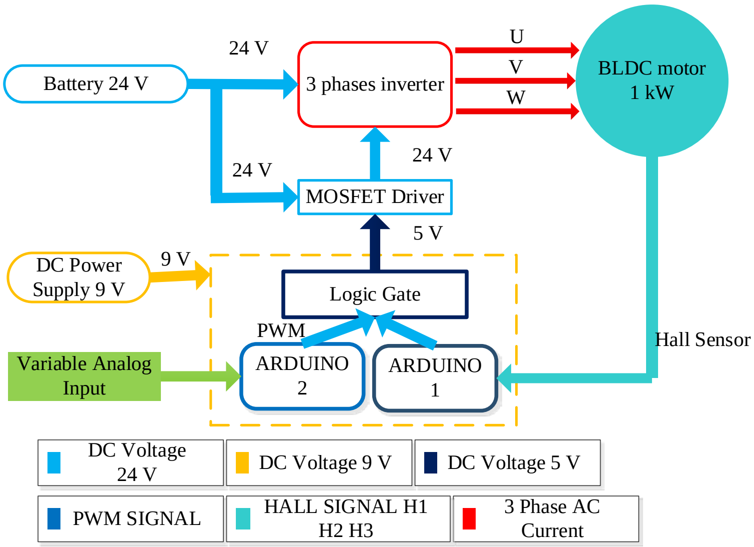


Figure 3. Block diagram of trapezoidal commutation modification scheme

the modified electrical commutation is formed from a combination of a square signal and a PWM signal so as to produce a trapezoidal wave in which there is a PWM signal. This modification is also intended so that controlling the speed of the BLDC motor is still easy to do.

The PWM square signal consists of six parts, namely two positive parts, two negative parts, and two floating parts, each of which is 60° [20]. The modification scheme of the trapezoidal commutation circuit is composed of two Arduinos as shown in Figure 3. The two Arduinos consist of Arduino1 which is used as a hall signal generator that resembles the output of a 1 kW BLDC motor and Aduino2 which is used as an electric commutation signal generator. in Arduino2 there is a potentiometer as a variable speed input. The potentiometer provides an analog input signal to determine the width of the PWM duty cycle generated by Arduino. This PWM signal is then combined with three hall signals output from Arduino1 using a logic gate, resulting in six outputs which are electrically commutated signals. The shape of the hall signal is shown in Figure 4 and the shape of the electrical commutation signal is shown in Figure 5.

Figure 4 shows an image of the hall signal simulation at the Arduino1 output. There are three outputs on Arduino1 called Hall1 (H1), Hall2 (H2), and Hall3 (H3), these outputs have the same period but different phases. This phase difference indicates that there is a magnetic field in the coil that is active alternately. The hall signal form is a square signal consisting of a high signal and a low signal. In BLDC motors, a high signal means the sensor detects a magnet and a low signal means the sensor does not detect a magnet.

Figure 5 is the Arduino2 output waveform as a commutation signal. Arduino2 functions as a decoder with three hall signals input from ARDUINO1 into six output signals namely Q1, Q2, Q3, Q4, Q5, and Q6. The form of this commutation signal is divided into positive signals (Q1, Q3, and Q5) and negative signals (Q2, Q4, Q6). The negative signal is in the form of a square signal, as seen in Figure 5 section Q2. while the positive signal seen in Figure 5 section Q1, is formed from a combination of a square signal and a PWM signal. A positive signal that has a

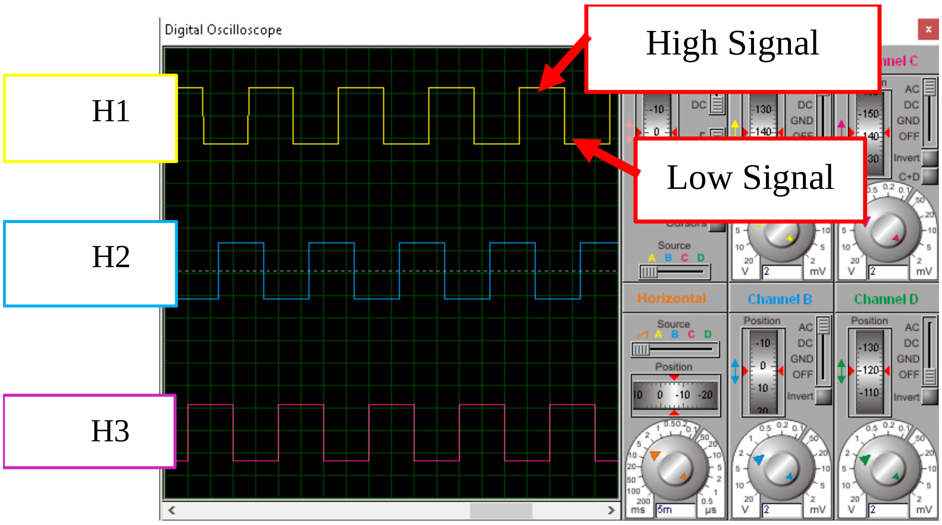


Figure 4. Hall signal at arduino1 output

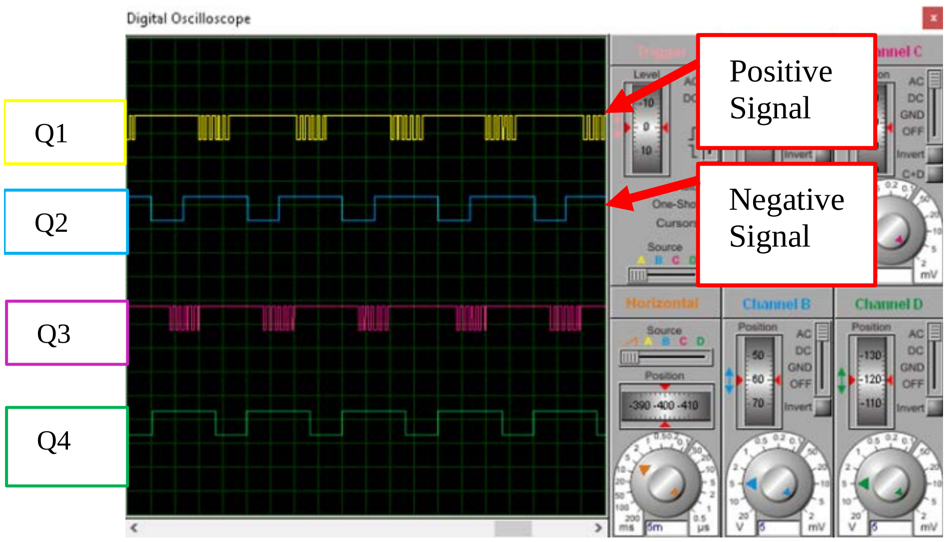


Figure 5. The commutation signal generated by the Arduino2

square shape with a PWM inside is the proposed method according to the paper [8]. Meanwhile, negative signals remain in the form of square signals only. Modifications to the commutation signal are simulated as shown in Figure 6 to produce a BLDC output signal that is close to sinusoidal. Figure 7 is the output waveform of a 3-phase inverter resulting from simulation in the Ni Multisim software. Each phase has three conditions, namely high, low, and float. This condition is determined from the commutation process in the MOSFET in the 3-phase inverter. The high condition is the condition when the active MOSFET supplies positive voltage. The low condition is when the active MOSFET supplies negative voltage, and the float condition is when the MOSFET is not active. at each step, 1 phase is in high condition, 1 phase is in low condition and the rest are in float condition. This happens at each step so that the BLDC motor can rotate. Changes in conditions in the 3-phase inverter based on the hall effect sensor can be seen in Table 2.

III. Results and Discussions

The proposed method is a modification of the trapezoidal computing method with a very simple algorithm because it uses logic gates. This component was chosen because this method is applied to BLDC motor drives in electric vehicles, so a speed control system is needed whose algorithm is

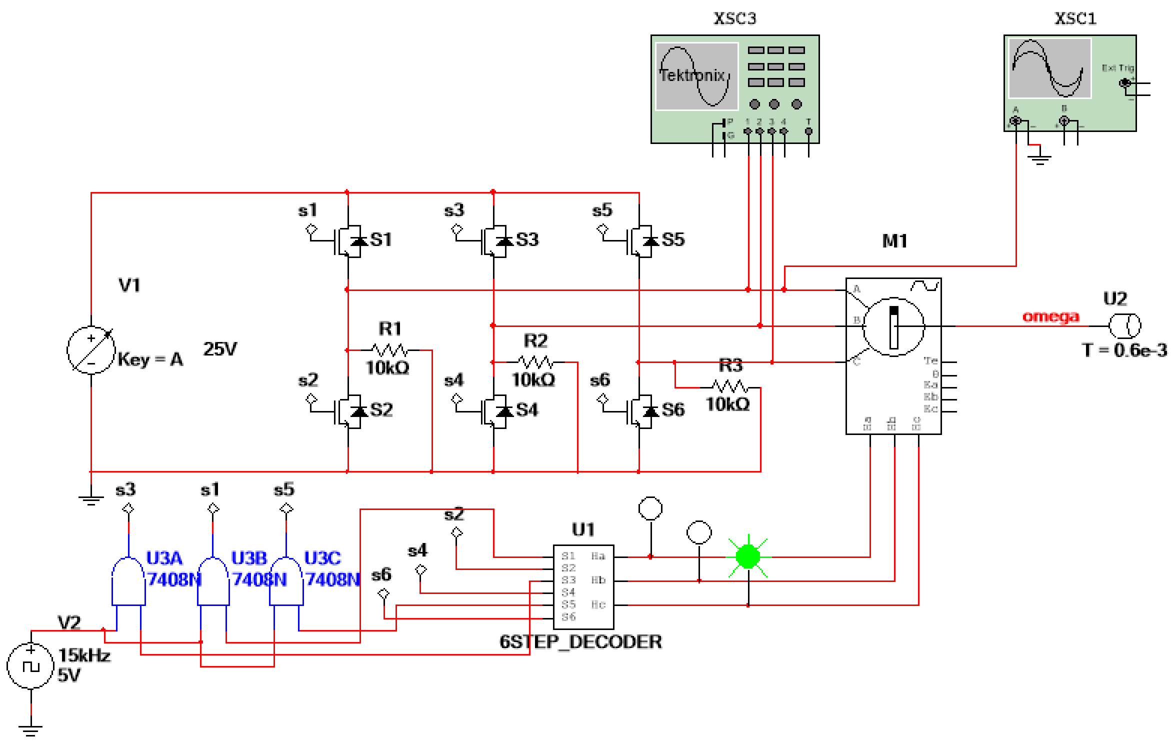


Figure 6. Simulation of modification methods on commutation signals

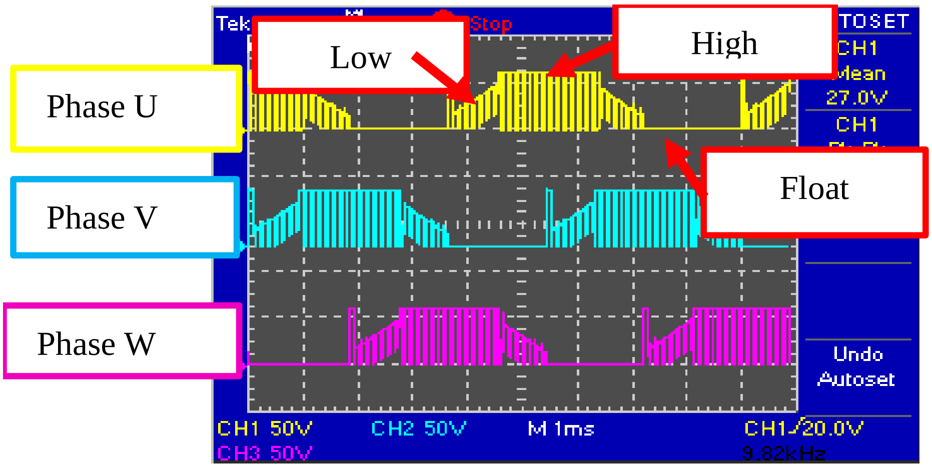


Figure 7. Phase inverter output signal

simple but stable and provides a good response. There is a pedal to determine the rotation speed of the BLDC motor. The gas pedal in Figure 8 functions like a potentiometer providing analog input to the Arduino2. Next, the input is processed by a program to produce a PWM signal with the appropriate duty cycle value. The duty cycle value has a range of 0 – 100 % depending on the pressure applied to the gas pedal. The greater the pressure applied, the duty cycle value approaches 100 %. It can be seen in Figure 9 part (a) that when the duty cycle value is 20 %, the low signal is greater than the high signal, and in Figure 9 part (b) when the duty cycle value is 50 %, the high signal and low signal have the same rise time.

The logic gates used are AND gates and NOT gates. The AND gate Integrated Circuit (IC) is used to combine the PWM signal from ARDUINO2 with the box signal from ARDUINO1 to produce positive switching signals (Q1, Q3, and Q5). Then the signal enters the NOT gate to be reversed so that it produces a square-shaped positive commutation

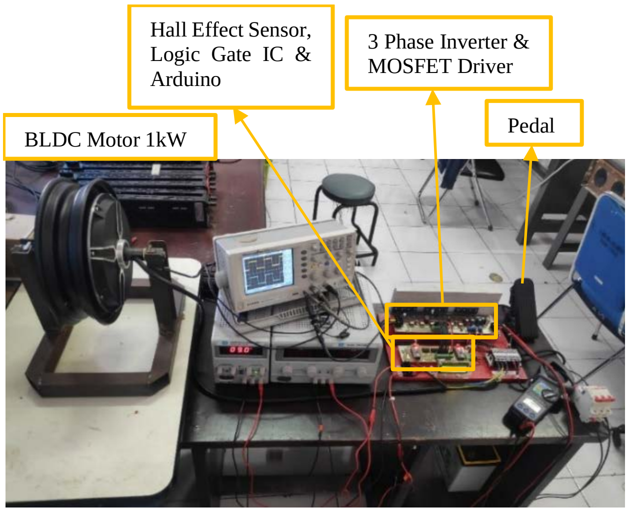
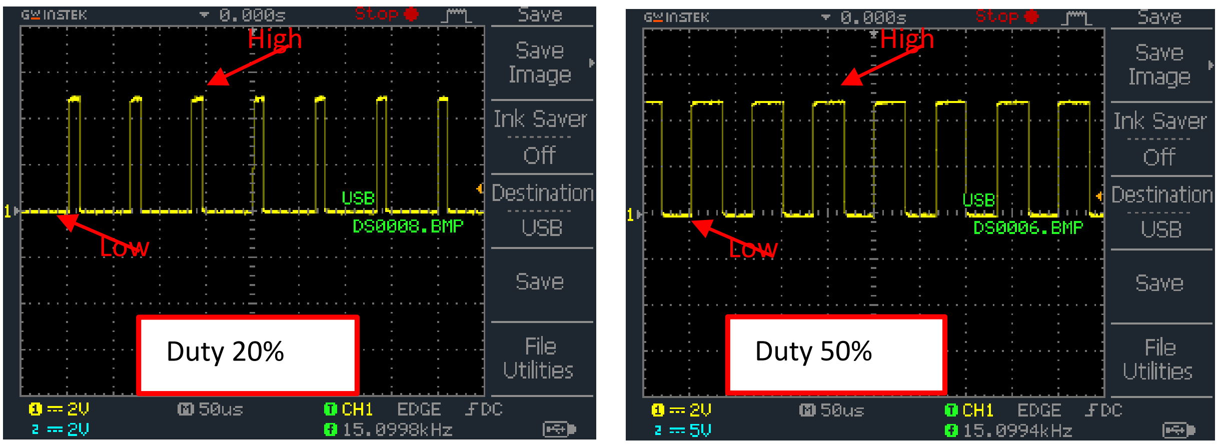
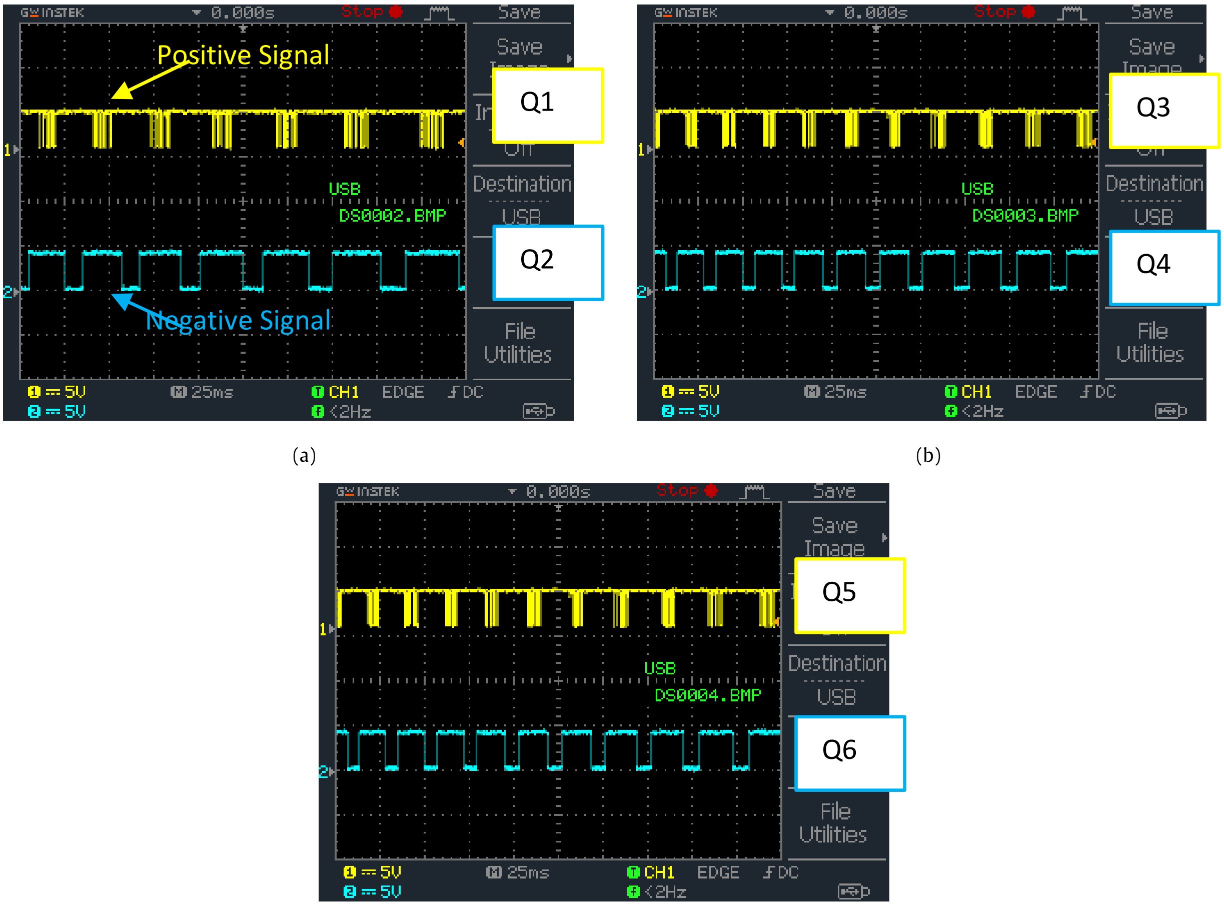


Figure 8. Experimental setup for commutation strategies



(a) (b)

Figure 9. PWM signal with duty: (a) 20 %; (b) 50 %



(a) (b)

(c)

Figure 10. Commutation signal generated by MOSFET driver: (a) Q2; (b) Q4; (c) Q6

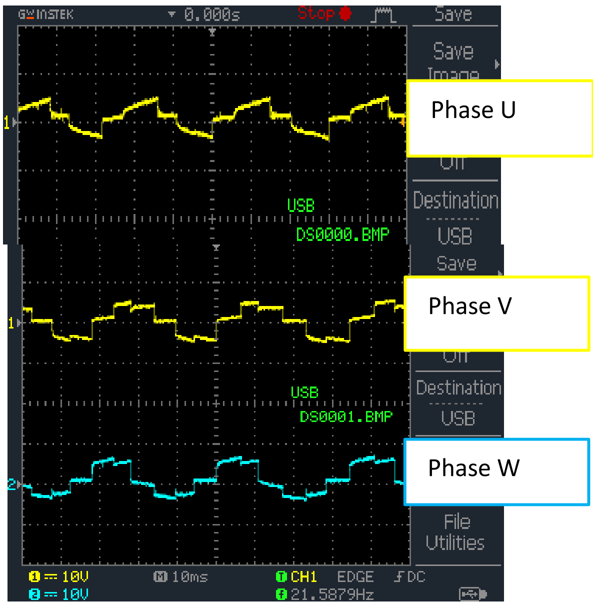


Figure 11. Output signal of 3-phase inverter

signal with PWM in it. Meanwhile, the shape of the negative signal (Q2, Q4, Q6) is a regular square signal. These two forms of signals are paired signals as in Figure 10 (a), (b), and (c), but do not experience high conditions at the same time. In the test carried out at the IC gate output, the signal produced had a voltage of 5 V and then the voltage of the signal was increased at the output of the MOSFET driver. This signal is used in the electrical switching process as a determinant of MOSFET scheduling changes in the 3-phase inverter.

In the end, the inverter output signal resulting from the proposed trapezoidal modification circuit can resemble a sinusoidal shape. Figure 11 shows the signal output form of a 3-phase inverter consisting of the U phase, V phase, and W phase. This signal is produced from the switching process that occurs in the 3-phase inverter. The signal form for

Table 3.
Motor speed measurement based on duty cycle

Duty Cycle	Motor Speed (rpm)	P_{in} (Watt)	P_{Out} (Watt)	Cos φ	Eff. (%)
20 %	443	46.6	67.2	0.5	75.1
30 %	807	127.7	170.9	0.5	70.9
40 %	1216	235.6	292.7	0.6	73.3
50 %	1671	372.1	435.0	0.7	80.7
60 %	2285	540.5	657.0	0.7	85.1
70 %	2528	596.3	737.8	0.7	89.1
80 %	2679	825.0	857.5	0.7	75.9

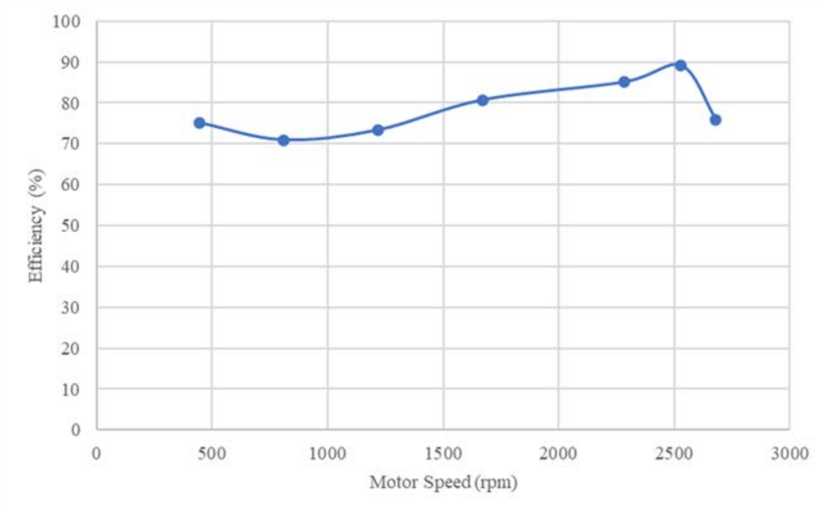


Figure 12. The efficiency profile depends on the motor speed

Table 4.
Current and voltage parameters of battery input and inverter output table caption

Duty Cycle	Battery (DC)		3-Phase Inverter (AC)					
	V_{Batt} (V)	I_{Batt} (A)	V_{UV} (V)	V_{UW} (V)	V_{VW} (V)	I_u (A)	I_v (A)	I_w (A)
20 %	24.5	1.9	4.4	4.3	4.4	15.4	15.4	15.4
30 %	24.1	5.3	7	6.9	6.9	24.7	24.7	24.7
40 %	23.8	9.9	8.9	8.9	8.8	33	33.1	33.1
50 %	23.4	15.9	11.3	11.3	11.2	38.6	38.7	38.6
60 %	23	23.5	14.1	14	14.1	46.7	46.7	46.7
70 %	22.5	26.5	14.9	14.9	14.9	49.5	49.5	49.5
80 %	22	37.5	14.7	14.8	14.8	58	58.1	58.1

each phase has three conditions, namely high, float, and low, resulting in a signal shape resembling a sinusoidal wave.

Table 3 shows that apart from the resulting signal being nearly sinusoidal, the circuit created can regulate the BLDC speed based on the pressure applied to the pedal. Even though the inverter output signal is approaching sinusoidal, the trapezoidal commutation character is still visible, namely torque ripple occurs at low speeds and gets better at high speeds. So, the maximum efficiency of 89.1 % is obtained at a speed of 2528 rpm as seen in Figure 12. The efficiency value increases with increasing speed and will reach the maximum value at nominal rpm.

The efficiency of the BLDC motor's performance is also influenced by the input power of the 48 V 45 Ah battery. The faster the rotation is produced, the greater the current released by the battery. Details of the battery and inverter voltage and current parameter values are shown in Table 4. In Figure 13, the higher the duty cycle sent by the commutation signal, the inverter will respond by providing a higher inverter output voltage and current. So the BLDC motor can spin faster.

Even though the performance of the proposed circuit can be used as a drive and speed control for BLDC motors, the resulting efficiency is not very high. One of the causes is a change in the waveform of the positive signal output in the MOSFET driver circuit. The voltage value increases from 5 V to 15 V which is used to drive the gate on the MOSFET so that an electrical commutation process occurs. However, the positive signals on the input and output sides are different, as shown in Figure 14. This is due to the dead time that occurs in the trigger signal as shown in Figure 15.

Dead time is the movement between trigger signals, which in Figure 15 shows the movement between trigger signals Q1 and Q3. In this signal form, the dead time that occurs is 300 μs. The problem that occurs due to this dead time is a delay

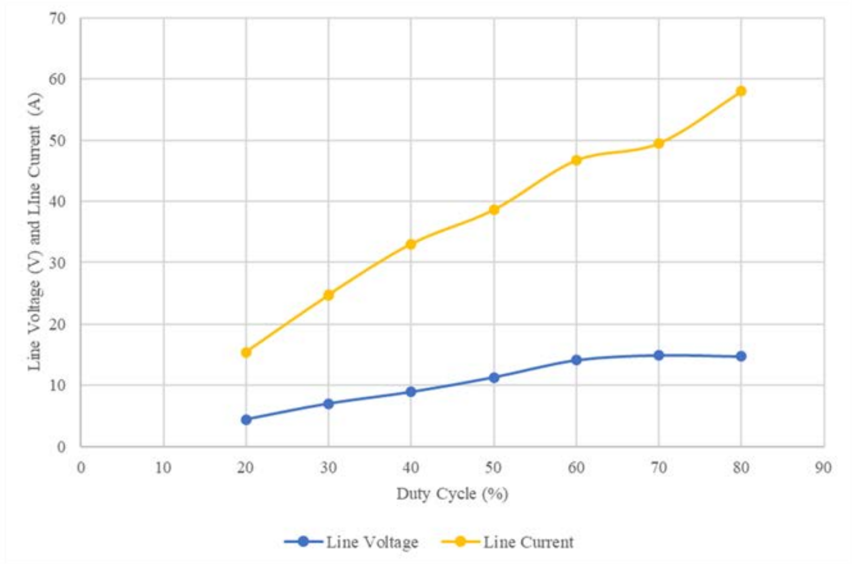


Figure 13. Comparison of line voltage and current to duty cycle

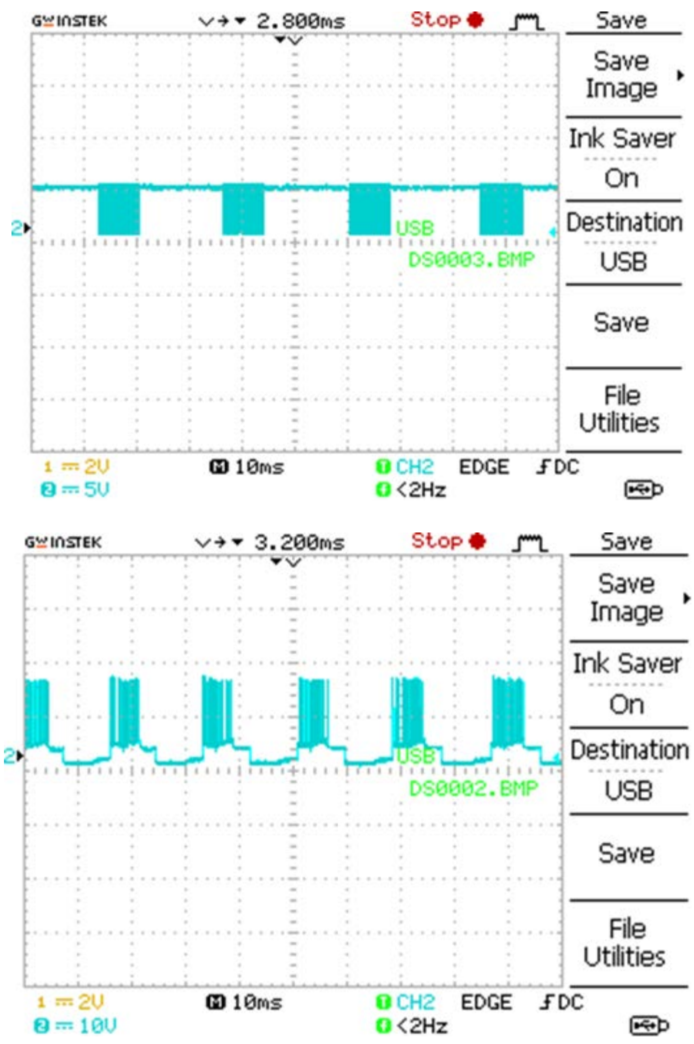


Figure 14. MOSFET driver signal waveform: (top) input and signal; (bottom) output on the MOSFET driver

in the switching process on the MOSFET, where there is not enough voltage to drive the MOSFET. The availability of this voltage is influenced by the process of charging the bootstrap capacitor at the output of the optocoupler so that the bootstrap capacitor is empty before the gate signal on the high MOSFET is triggered. This causes the MOSFET to not work optimally, which is indicated by the current reading being very high and the MOSFET getting hot faster.

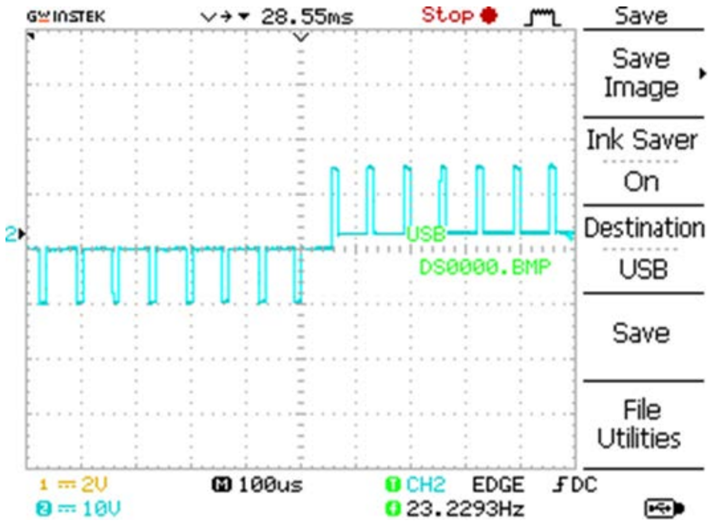


Figure 15. Dead time on the trigger signal

IV. Conclusion

The commutation circuit scheme by providing switching on the positive part and flat on the negative part using logic gates and minimal algorithms can produce a modified trapezoidal signal. By adding a PWM signal to the positive commutation signal, the inverter output waveform can be nearly sinusoidal. So, modifying the scheme of a simple trapezoidal switching signal generator circuit can produce an inverter output signal that is close to sinusoidal. Apart from the simple circuit, this scheme can still provide a good response in controlling the speed of the BLDC motor. Speed fluctuations can be set based on the duty cycle provided by the commutation signal. The highest efficiency is 89.1 % at a speed of 2528 rpm. However, the dead time on the trigger signal cannot be resolved, thus affecting the process of charging the bootstrap capacitor at the output of the optocoupler. This causes the MOSFET to not work optimally, which is indicated by the current reading being very high and the MOSFET getting hot faster.

Declarations

Author contribution

All authors contributed equally as the main contributors to this paper. All authors read and approved the final paper.

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Competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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