Design and Performance Analysis of Brushless Direct Current (BLDC) Motor Controller for Electric Scooter

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Abstract. Electric vehicle is an alternative to substitute internal combustion engine when fuel availability is difficult to obtain. Electric energy can be obtained from renewable energy and non-renewable energy. Electric vehicles like electric scooters consist of many parts. The parts used in an electric scooter have requirements such as reliability, safety, good performance, and high efficiency. Brushless direct current (BLDC) motor controller is one of the main components in the electric scooter. This paper presents a design and performance test of the BLDC motor controller. The controller uses PID current control with six step commutation in a trapezoidal control. The motor current ripple is eliminated by using a digital isolator. Tests were carried out using an Eddy Current Dynamometer. The results show that the current ripple is successfully reduced which makes the controller suitable for electric scooter applications.

1. Introduction
A feedback controller of a brushless direct current (BLDC) motor usually incorporates hall effect sensors, back electromotive force (BEMF) signals, and current sensors. The quality of the controller is affected by the accuracy in measuring the feedback signals. Ripple current may occur, but how much the ripple current can be tolerated. This ripple current issue is important so that the motor can be rotated properly. Ripple currents can cause a rough motor response. Factors causing the current ripple are the error reading of the current sensor, load variations in the motor, switching frequency and inductive interference.

A current measurement method compensated the offset and scaling errors separately [1]. This study used two current measurements in phases A and phase C. Current measurement error consists of noise on hall sensors, filter circuits, and analog to digital converters [2]. Errors occur periodically so that they can be removed by a high pass filter. Ripple torque can be reduced by using a low switching frequency or constant switching frequency [3,4]. The optimal switching is calculated at each switching cycle to satisfy the minimum ripple based on the torque slope equations. Three-phase inverters use switching frequency limited around 0.5–1 kHz to minimize torque ripple [4]. This depends on the design of electric motor. There are many other methods to reduce the current ripple [5–9].

In this paper, a new current control is proposed which minimizes ripple current measurement using digital isolator. This method is effective to reduce the inductive effects of a power circuit. The high voltage ground is separated from the ground of the microcontroller so that the high voltage does not
affect the performance of the microcontroller. ADUM 1200 can be used to separate the ground. This paper is organized as follows. The issues arising in a proportional, integral, derivative (PID) current control technique are described in Section II. Design of a BLDC motor controller in an electric scooter application is presented in Section III. The implementation and evaluation of this control strategy are presented in Sections IV. Finally, the paper conclusion is in Section V.

2. PID Current Control Method

The current control technique consists of two controls (cascade control) as illustrated in Figure 1. The first level control is speed control which uses the hall effect sensor as speed feedback. A speed reference is obtained from the throttle position sensor. Speed error is the difference between the speed reference and the present speed which is then compensated with the PID control technique so that it generates a reference current ($I_{s_{\text{ref}}}$). The second level control is the current control technique that uses the current sensor in phase as feedback. Current error that occurs will be compensated with the PID control. The PID current control will produce duty cycle and frequency values that will be used in Pulse Width Modulation (PWM). Next go to the commutation logic with the hall sensor feedback. The Hall sensor will also provide the position information of the rotor angle so that the commutation can be determined. Commutation logic can be realized in a PWM signal to activate the gate driver on the 3-phase inverter so that each phase becomes in an appropriate supply.

![Figure 1. Current Control of BLDC Motor](image)

A model of a BLDC motor fed by a three phase inverter can be shown in Figure 2. The inverter consists of 3 half bridge MOSFETs as a switching phase A, B and C. Each switch Q1, Q2, Q3, Q4, Q5 and Q6 will be activated by the gate driver. Commutation logic of each switch is shown in Figure 3.
One electrical cycle consists of six-step commutations while one mechanical cycle will be composed of several electrical cycles. The amount depends on the configuration of pole pairs magnet mounted on the motor. Figure 3 shows an example of six-step commutation obtained from experiments. The hall sensor signals H1, H2, and H3 are plotted at the upper side. The commutation logic can be observed from the switching signals of Q1, Q2, Q3, Q4, and Q6. The soft PWM scheme is used where the high leg of a certain positive phase is switched in PWM mode while the lower leg of the companion negative phase is kept ON. Notice that the low leg of the same positive phase is switched in the opposite PWM mode using the PWM complementer. We name it as PWM mode of type (Hp-PWM, Ln-ON, Lp-inverted PWM), where subscripts p and n denote positive and negative phases of the motor.

This type of commutation, which uses PWM type of (Hp-PWM, Ln-ON, Lp-inverted PWM), has a smaller torque ripple compared to (High-ON, Low-PWM) or (High-PWM, Low-PWM) [11]. The results in figure 3 can be summarized as six-step commutation logic according to table 1.
Table 1. Truth Table of Six Step Commutation of a BLDC Motor Controller

| Step | Signal Hall Effect Sensor | Phase A | Phase B | Phase C |
|------|---------------------------|---------|---------|---------|
|      | H1 | H2 | H3 | Q1 | Q2 | Q3 | Q4 | Q5 | Q6 |
| 1    | 1  | 0  | 1  | Open | Closed | PWM | PWM inverted | Open | Open |
| 2    | 1  | 0  | 0  | Open | Closed | Open | Open | PWM | PWM inverted |
| 3    | 1  | 1  | 0  | Open | Open | Open | Closed | PWM | PWM inverted |
| 4    | 0  | 1  | 0  | PWM | PWM inverted | Open | Closed | Open | Open |
| 5    | 0  | 1  | 1  | PWM | PWM inverted | Open | Open | Open | Closed |
| 6    | 0  | 0  | 1  | Open | Open | PWM | PWM inverted | Open | Closed |

This paper uses a 5 KW BLDC Motor operating at 100VDC. The parameter values of the BLDC motor are listed in table 2.

Table 2. Parameter values of the BLDC motor [12]

| Parameter                              | Unit    | Value  |
|----------------------------------------|---------|--------|
| Resistance \((R)\)                    | mΩ      | 8.005  |
| Inductance \((L)\)                    | µH      | 158.485|
| BEMF Constant \((k_e)\)               | Volt/krpm | 16.915|
| Torque Constant \((k_t)\)             | N.m/A   | 0.1616 |
| Time Constant \((\tau_m)\)            | s       | 0.1791 |
| Friction Constant \((B)\)             | N.m.s   | 0.0280 |
| Moment of Inertia \((J)\)             | Kg.m²   | 0.0356 |

3. Design of BLDC Motor Controller

The BLDC motor controller in this paper is illustrated by a block diagram in figure 4. An important point to consider in designing a 3-phase inverter is that HV must be isolated with a microcontroller supply. This is done to avoid spike interference in the HV which can cause a microcontroller reset. Digital isolator ADUM1200 is used. HV sensing uses optical operational amplifiers to measure battery voltage and BEMF. Other sensors such as hall effect sensors and current sensors in phase A and C also use galvanic isolation.

![Figure 4. Diagram of the BLDC Motor Controller](image-url)
Overlapping PWM is needed to ensure that PWM channels high and low sides do not meet. To really protect, certain value of dead time is added. Gate drivers use modules from the manufacturer so that gate driver optimization has been done well by the manufacturer. It is hoped that the failure mode on MOSFETs can be avoided. Isolation can also be done by separating between boards, both the controller board, gate driver board, and the 3-phase inverter board. The designed controller is shown in figure 5.

![Controller module](image1.png)

**Figure 5. BLDC Motor Controller**

4. **Result and Analysis**

The BLDC motor controller performance was tested using an Eddy Current Dynamometer as shown in figure 6. The dynamometer can be used to determine power, torque, and speed (rpm). The signal measurement is done using an oscilloscope.

![Experiment Set-up](image2.png)

**Figure 6. Experiment Set-up**

4.1 **Signal Measurement**

Figure 7 shows the hall effect sensor and BEMF signals. BEMF signals are trapezoidal so that this control technique is called trapezoidal control. A signal was found in the fault hall sensor, which was on the red circle. The signal does not directly affect the commutation logic because the signal does not reach the digital input level to be low. But of course the problem needs to be formulated a solution. BEMF signals on blue circle marking can cause switching losses that need to be eliminated. In general the signal is in accordance with the BLDC motor drive theory.
Figure 7. Measurement of Hall Sensor and Back Electro Motive Force (BEMF)

Figure 8 shows the comparison of current signals of the motor phase A using a digital isolator and not using a digital isolator. Design without a digital isolator can cause ripple current which can lead to compensation calculation errors on the PID controller. The ripple also affects the ripple torque so that the motor rotation is not smooth. Whereas current using digital isolator has less current ripple compared to not using digital isolator. The author suggests that the BLDC motor controller should be completely isolated so that external interference from the motor does not directly affect the system control.

Figure 8. Ripple Current Elimination Using Digital Isolator

Figure 9 shows current measurements results of each phase. Part a is the phase A current at a full speed condition while part b measures the current during start-up. By observing these results, we confirm that the shape of the current signal is in accordance with the BLDC motor drive theory. An interesting thing that needs to be discussed is that the phase current at start-up is very large. This requires that the MOSFET 3-phase inverter can handle large currents, further increasing production costs.
4.2 Performance Test Results

Figure 10 shows the BLDC motor controller performance testing results. The testing was done by rotating the motor until it reached the maximum rotation speed without any load, then new load was added in stages until the motor rotation was unable to resist the dynamometer load. The results indicate that the controller can operate at 5000 Watt instantaneously with the torque reaching 60 N.m at the speed of 1000 rpm. This BLDC motor controller can be applied to electric scooters.

5. Conclusion

We have designed and tested the 5 kW BLDC motor controller using a PID current control with trapezoidal commutation technique. The ripple current in the BLDC motor was reduced by a digital isolator. Performance test results indicate that the controller is suitable for electric scooter applications.

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