Single-Stage Step up/down Driver for Permanent-Magnet Synchronous Machines

T R Chen, Y L Juan, C Y Huang and C T Kuo

Department of Electrical Engineering National Changhua University of Education, No. 2, Shi-Da Road, Changhua City, Taiwan.

yljuan0815@cc.ncue.edu.tw

Abstract. The two-stage circuit composed of a step up/down dc converter and a three-phase voltage source inverter is usually adopted as the electric vehicle's motor driver. The conventional topology is more complicated. Additional power loss resulted from twice power conversion would also cause lower efficiency. A single-stage step up/down Permanent-Magnet Synchronous Motor driver for Brushless DC (BLDC) Motor is proposed in this study. The number components and circuit complexity are reduced. The low frequency six-step square-wave control is used to reduce the switching losses. In the proposed topology, only one active switch is gated with a high frequency PWM signal for adjusting the rotation speed. The rotor position signals are fed back to calculate the motor speed for digital close-loop control in a MCU. A 600W prototype circuit is constructed to drive a BLDC motor with rated speed 3000 rpm, and can control the speed of six sections.

1. Introduction

Due to the high environmental awareness in recent years, green energy development has become a national policy focus. Electric locomotives replace chemical energy with electric energy, which can to an extent reduce energy consumption and environmental pollution, leading to rapid electric locomotive development. Commercially available electric locomotives are generally equipped with a brushless DC motor as the core drive. Due to its simple control, high efficiency, high energy density, variable speeds, low electromagnetic interference features, fixed magnetism, and ease in rotor location determination, without problems such as “carbon brush wear” commonly seen in traditional DC motors, it has gradually become a mainstream household appliance. Therefore, this paper is intended to use a DC brushless motor as the drive target.

The motor drive of common electric locomotives is a two-stage structure containing a step up/down converter and a three-phase converter. Literatures have shown that buck-boost converters and Ćuk converters are buck-boost power converters widely applied in brushless DC motor drives at present[1]. The buck-boost converter features the advantages of a stable output voltage and motor speed control completed by means of simple pulse width modulation[2]. However, it also has the drawback of the backend three-phase converter switch requiring higher switch frequency control in order to increase motor speed, which results in increased switch loss and reduced overall performance[3].

Since Zeta converters features having the same output and input voltage polarity and irreversibility as well as a moderate capacitor voltage resistance demand, compared to buck-boost converters of Ćuk converters, Zeta converters are relatively suitable for applications in circuits with battery or input voltage fluctuations. At the same time, Zeta converters also achieve motor speed control through the same method used for Ćuk converter. Moreover, the drive circuit was applied in the motor drive of electric locomotives in this study. For the input part, four series lead-acid batteries were often used, giving rise to greater voltage fluctuations. Hence, a Zeta converter was selected in this study as the buck-boost conversion circuit[4-8].

In this study, the traditional step up/down power converter, combined with the three-phase converte, underwent improvement to be the main circuit framework, while the motor speed was controlled by pulse width modulation. A motor drive with the input voltage of 48V and speeds controlled at six intervals (500 rpm, 1000 rpm, 1500 rpm, 2000 rpm, 2500 rpm, 3000 rpm) was designed.

2. DC converter and driver design

The overall framework of the motor drive put forth in this paper includes energy storage inductor L_1, buck-boost converter switch Q_0, a three-phase converter consisting of six switches Q_1~Q_6 and link capacitor C. In this paper, MCU was used to control the PWM signals of the buck-boost converter's switch components. Through the feedback brushless DC motor Hall sensor components, phase information was provided and the motor speed computed. Additionally, by adjusting the duty cycle, the converter was controlled to provide the motor with different powers, while the motor was controlled at the required speed. Based on the brushless DC motor's phase information, MCU also facilitated the mode switching of the upper and lower arm of the three-phase full-bridge converter corresponding to the six phase intervals, thus achieving motor electronic commutation.

The input source of the motor drive is supplied by 4 12V lead-acid parallel batteries as the power supply. Fig. 1 shows the single-stage step up/down brushless DC motor driver; Fig. 2 shows the power component on schedule at the time of MCU motor drive. Switch Q_0 uses 20 kHz as the switching frequency; Q_1~Q_6 uses the motor's Hall sensor components to provide phase information and perform low frequency switching. Fig. 3 shows the proposed driver operating waveform.

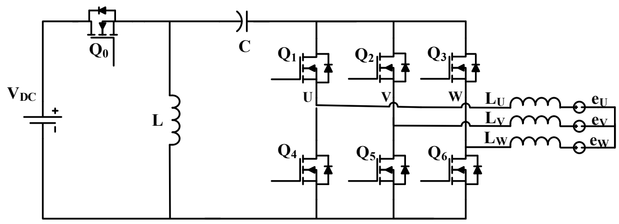

Figure 1. Single-Stage Step up/down BLDC Motor Driver

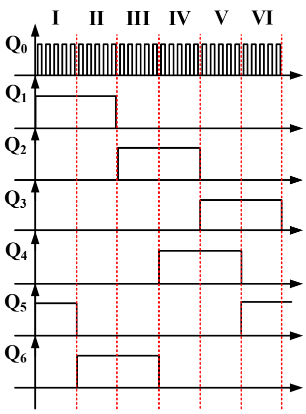

Figure 2. Driver timing

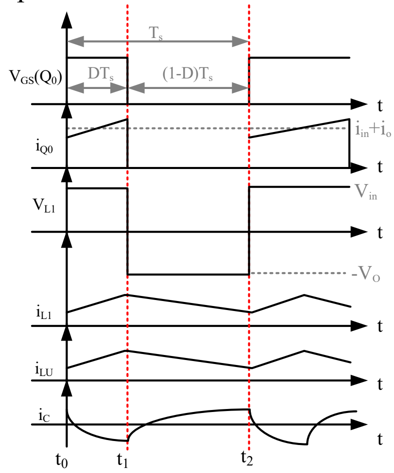

Figure 3. The proposed driver operating waveform

IOP Conf. Series: Earth and Environmental Science **94** (2017) 012098 doi:10.1088/1755-1315/94/1/012098

3. Experimental ruslts

The main target of the circuit, in Fig. 4, proposed in this study is the motor that drives the electric locomotive. Hence, for the input part, 4 12V/22 AH lead-acid series batteries were used and output to the motor end after passing through the converter. In this paper, the drive was loaded to the designed motor loaded platform for testing, and the drive's transient and steady state waveforms and efficiency values measured were presented to verify the system feasibility.

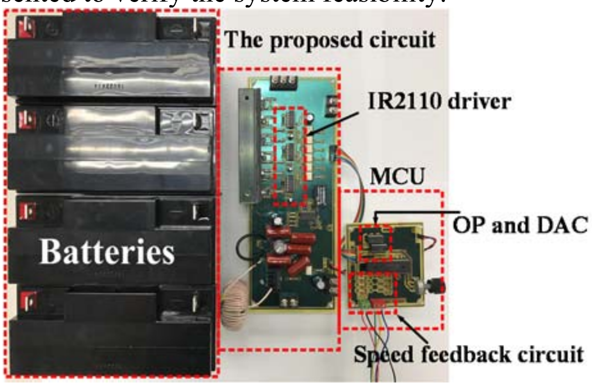

Figure 4. System physical circuit

Fig. 5 and Fig. 6 show the waveform of the brushless DC motor drive with the output power of 50W. In Fig. 6, CHI is the V_{GS} waveform of switch Q_0 , with switching at 20 kHz. By changing the duty cycle of Q_0, the size of power transmitted to the motor can be modulated, thereby changing the motor speed. CH2 is the V_{DS} waveform of switch Q_0; CH3 is the input current of the drive; CH4 is the voltage waveform of link capacitor C. Fig. 7 shows the waveform of the commutation signals, and the phase voltage and current of the brushless DC motor drive with the output power of 50 W. CH1 is the V_{GS} voltage waveform of switch Q1; CH2 is the V_{GS} voltage waveform of switch Q_5;CH3 is the voltage waveform flowing into Phase UV of the motor; CH4 is the current flowing into Phase U of the motor.

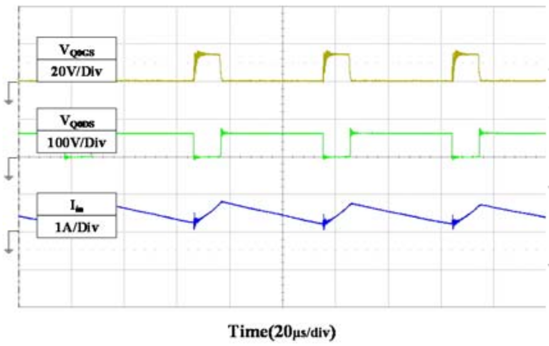

Figure 5. Step up/down converter main switch action waveform

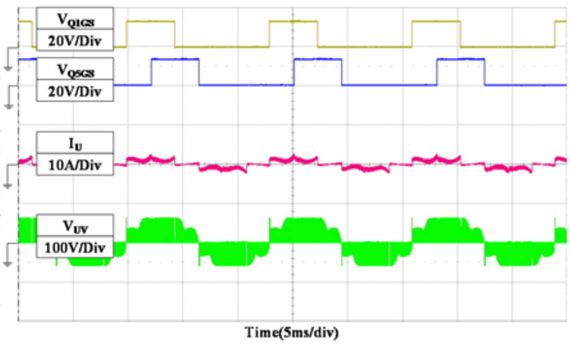

Figure 6. Commutation signal and phase voltage and current waveform

Fig. 7 shows the speed follow curve of the speed closed loop control in this study. CH1 (green line) is the speed command; CH2 (red line) is the motor's actual speed outputted through the digital/analog conversion circuit; CH3 is the motor's Hall sensor signal. The speed feedback circuit transmits the rotary location outputted by the Hall sensor component to the microcontroller where speed computing is carried out. The microcontroller then performs closed-loop speed control through PI computing of the duty cycle and made observations through the digital/analog transposition circuit. Fig. 8 show the replacement waveform of the motor drive. When the motor is instantaneously loaded, the motor speed begins to drop, at which time the speed closed loop controller's speed error value increases. After adjusting the PI controller, the duty cycle ratio of the power switch will increase in order to overcome the sudden increase in the load torque and maintaining the motor speed at the command speed value.

As shown in Fig. 8, the motor drive in this paper remained unaffected by external loads, and the speed was stably controlled.

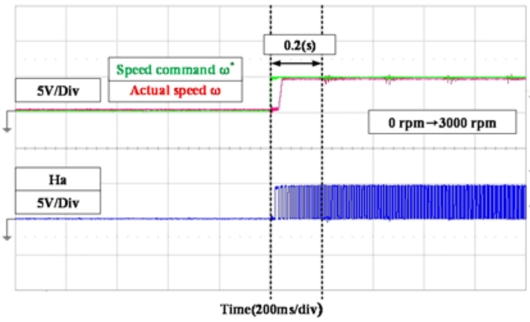

Figure 7. Speed followed curve

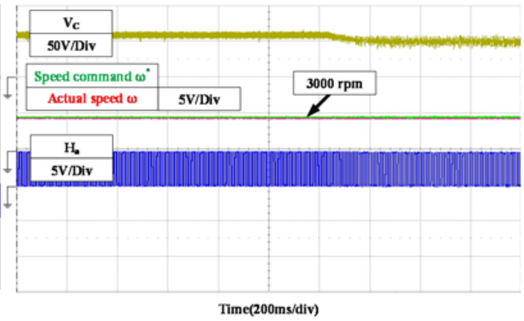

Figure 8. Fixed speed from no load to half load

4. Conclusion

This study is intended to improve the two-stage brushless DC motor drive structure of a traditional step up/down converter, coupled with a three-phase converter, which were integrated to develop a new type of single-level buck-boost brushless DC motor drive. The drive can provide energy to the three-phase inverter circuit to operate by adjusting the duty cycle of the buck-boost drive circuit's main switch, thereby accommodating the closed-loop motor speed control needs, namely, easy control and low switch loss. For the circuit part, a traditional Zeta converter was used, which was combined with a three-phase converter to actually complete a single-stage brushless DC motor driver. A 600W prototype circuit is constructed to drive a BLDC motor with rated speed 3000 rpm, and can control the speed of six sections (500 rpm~3000 rpm).

Acknowledgments

This paper was supported by the Ministry of Science and Technology under Grant MOST 103-2221-E-018-013-MY2 and MOST 105-2221-E-018-014-MY3.

References

[1] Kokawalage H, Ransara S; Madawala U K and Liu T H 2015 Buck converter based model for a brushless DC motor drive without a DC link capacitor *IET on Power Electronics* vol 8 chapter 4 pp 628–635

[2] Xu Y, Wei Y, Wang B and Zou J 2016 A Novel Inverter Topology for Brushless DC Motor Drive to Shorten Commutation Time *IEEE Trans. on Industrial Electronics* vol 63 chapter 2 pp 796–807

[3] Kokawalage H, Ransara S and Madawala U K 2015 A Torque Ripple Compensation Technique for a Low-Cost Brushless DC Motor Drive *IEEE Trans. on Industrial Electronics* vol 62 chapter 10 pp 6171–6182

[4] Chen H C and Huang H H 2013 Design of buck-type current source inverter fed brushless DC motor drive and its application to position sensorless control with square-wave current *IET on Power Applications* vol 7 chapter 5 pp 416–426

[5] Masmoudi M, Badsi B E and Masmoudi A 2014 Direct Torque Control of Brushless DC Motor Drives With Improved Reliability *IEEE Trans. on Industry Applications* vol 50 chapter 6 pp 3744–3753

[6] Cui C, Liu G and Wang K 2015 A Novel Drive Method for High-Speed Brushless DC Motor Operating in a Wide Range *IEEE Trans. on Power Electronics* vol 30 chapter 9 pp 4998–5008

[7] Singh P K, Singh B and Bist V 2016 Brushless DC motor drive with power factor regulation using Landsman converter *IET on Power Electronics* vol 9 chapter 5 pp 900–910

[8] Bist V and Singh B 2014 Reduced sensor configuration of brushless DC motor drive using a power factor correction-based modified-zeta converter *IET on Power Electronics* vol 7 chapter 9 pp 2322–2335