2019 International Symposium on Electrical and Electronics Engineering

Conference program book
October 10 – 12, 2019
Ho Chi Minh City, Vietnam

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Analysis and Design of BLDC Motor Control in Regenerative Braking

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***Abstract*—Brushless DC motor is suitable to be implemented in electric vehicles for it can develop high torque and is capable to do regenerative braking. During the motor is running, back electromotive force is generated with its magnitudes lower than the DC-link. To make the motor current can flow into the battery in regenerative braking mode, a bidirectional converter with boosting function capability is required. Standard three-phase converter can be controlled to provide such requirements. In this paper, a simple control strategy for a BLDC converter to operate under regenerative braking is proposed. it is capable to be operated in lower speed due to its boosting chopping concept. To verify the analysis, simulations and experimental works were done. They show the effectiveness of the proposed control strategy.**

Keywords—regenerative braking, brushless DC motor, boost, converter, electric vehicle

I. INTRODUCTION

Applications of electric drives for electric vehicles require motors which have high torque and capability to be operated in regenerative braking. A brushless direct current (BLDC) motor can be a solution for it has such requirements. With permanent magnets embedded on its rotor and phase winding on its stator, high torque can be developed. While a BLDC motor is running, back electromotive force (BEMF) is generated and its magnitude is always lower than the DC-link voltage. Regenerative braking can be done if the kinetic energy of the rotor is capable to be converted into electric energy then transferred it into the battery to prolong the distance for electric vehicle [1]-[3]. Some methods have been developed by many researches to implement regenerative braking for BLDC motors.

Rotor position information of three hall sensors can be used as a reference angle to turn the switches on and off in the converter. At any instant time, two switches are operating to provide PWM (pulse width modulation) pattern for regenerative braking [4], [5]. Operation in four quadrant modes including motoring and braking was also proposed by using simple hardware in control circuit [6]. The control strategies can also implement fuzzy logic [7], [8] or combine some methods. Advanced regenerative control can utilize traditional proportional integral derivative (PID) and fuzzy logic for distribution of braking force although complexity will arise [9]. Regarding to capacitor size, current limitation based method is also implemented. Such a control method will keep the voltage on the capacitor to avoid the damage caused by oversize pumping-up voltage [10]. Commonly, regenerative braking is focused to save more energy.

To do an optimal regenerative braking, a proper angles for switches to turn on and off must be determined, operation using fewer switches is also more preferable. A simple design of BLDC motor control in regenerative braking is proposed in this paper. Due to the phases that have highest and lowest BEMF, the lower switch of the converter will be operated in PWM mode to obtain boost chopping operation. To anticipate the change of phase voltage waveforms during boost chopping, the angles between the rotor position information and the instant position for the highest phase voltages will be determined. Simulation and experimental works were also conducted to verify the analysis.

II. BRUSHLESS DIRECT CURRENT GENERATOR

Due to Faraday's law of induction, voltage can be induced across the terminals of the coils under any change of magnetic field. When e, N and Φ are induction voltage or electromotive force (EMF), number of turns and linkage flux, then a relationship can be derived as

$$e = N\frac{d}{dt}\Phi \tag{1}$$

A BLDC machine has a rotor with permanent magnets and windings on its stator. If the rotor is rotated then the stator winding will be subjected by the magnetic field with changing magnitude then the voltage will be induced in the stator winding. Operating a BLDC machine in braking region requires the understanding of such a concept. The kinetic energy of the electric vehicle will rotate the BLDC machine so the machine acts as a generator. Under such speed, the induced voltage generated on the stator winding has magnitude that is lower than the DC-link voltage of the inverter. Operating the BLDC machine in regenerative braking under such condition is impossible for there will be no current can flow to the DC-link.

A block diagram of the system contain BLDC machine operated as a generator is depicted in Fig.1. Kinetic energy of a running electric vehicle is used to rotate the generator. The output voltage of the phase stator windings of the BLDC machine is shown in Fig.3.

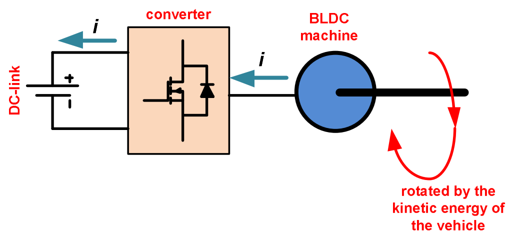

Fig. 1. Block diagram of a BLDC machine under regenerative braking

When the power flow from the BLDC machine to the DC-link, the converter operates as a rectifier. Under condition where there are no switches turning on, the output voltage can be regarded as an output of three phase diode rectifier.

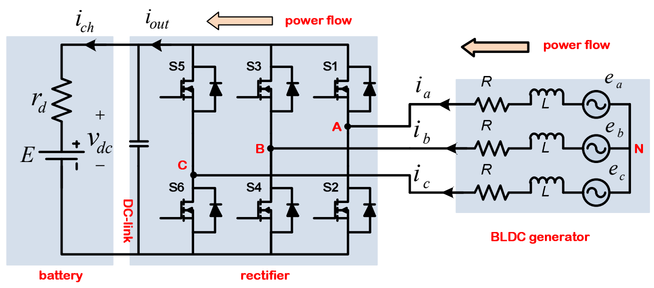

Fig. 2. Equivalent circuit of a BLDC machine in regenerative braking

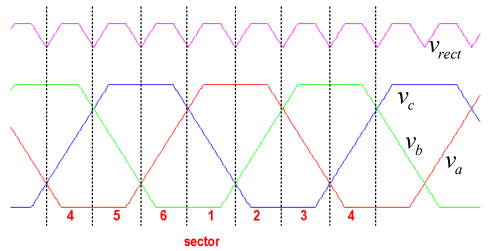

Fig. 3. The voltage waveforms of the phase winding of a BLDC generator and the rectified output voltage

In order to make power flow into the DC-link, the output voltage of the converter must be greater than the voltage of a battery connected to the DC-link. A concept based on DC-DC boost converter (chopper) can be adopted to achieve the required condition. Two mode of operation for boost chopper must be formed, the first mode is storing energy in the inductor (phase winding) and the second mode is transferring energy to the load side (DC-link). Phase windings which have maximum and minimum BEMF must be used as the source for the boost chopper, an equivalent circuit when phase-A and phase-B windings have highest and lowest BEMF for the first mode of boost chopper is depicted in Fig.4 (sector-1). This is implemented by turning on the lower switch of the phase winding with highest BEMF (S_2), so the two phase winding (phase-A and phase-B) will be connected through switch S_2 and diode D_4. By neglecting the phase resistances, simplified circuit can be redrawn in Fig.5.

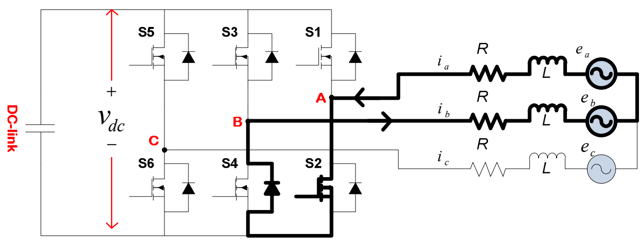

Fig. 4. The current path of a BLDC machine under regenerative braking when va>vc>vb and storing energy in the winding

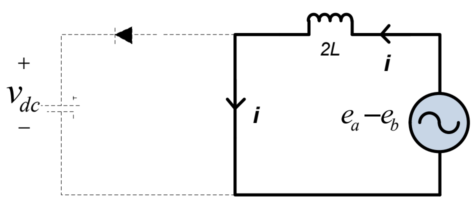

Fig. 5. Equivalent circuit of a BLDC generator when va>vc>vb under storing energy in the winding

Based on the above circuit, equations related to instant voltage and current can be derived as the following

$$e_a - e_b = v_L$$

$$e_a - e_b = 2L\frac{di_a}{dt}$$

$$\Delta i_a = \frac{e_a - e_b}{2L} t_{on} \tag{2}$$

where e_a, e_b, v_L, i_a, Δi_a are BEMF of phase-A, BEMF of phase-B, inductor voltage, phase-A current and fluctuation of phase-A current. After energy has been stored in the inductor, then the second operation mode of boost chopper is formed by turning off all the switches, all the energy will be transferred into the DC-link. The equivalent circuit is depicted in Fig.6 and its simplified circuit is shown in Fig.7. Under this mode, the sum of voltage from the inductor and BEMF equals to the voltage of the DC-link (V_{dc}). Equations related to such condition are expressed as the following

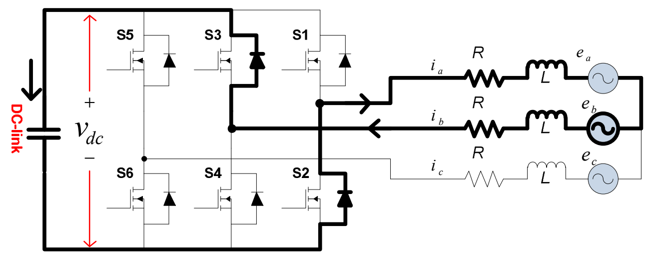

Fig. 6. The current path of a BLDC machine under regenerative braking when va>vc>vb and transferring energy to the DC-link

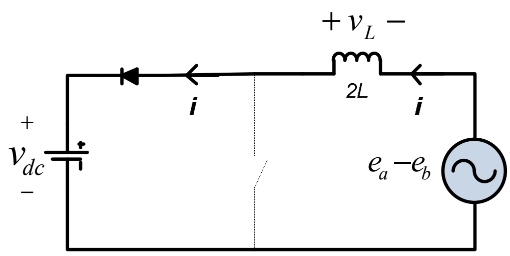

Fig. 7. Equivalent circuit of a BLDC generator when va>vc>vb under transferring energy to the DC-link

$$(e_a - e_b) + v_L = V_{dc}$$

$$2L\frac{di_a}{dt} = V_{dc} - (e_a - e_b)$$

$$\Delta i_a = \frac{V_{dc} - (e_a - e_b)}{2L} t_{off} \tag{3}$$

Substituting (2) into (3) resulting the output voltage of the converter which acts as a rectifier (V_{dc}). This voltage is a function of duty cycle (d)

$$V_{dc} = \frac{1}{1-d}\left(e_a - e_b\right) \tag{4}$$

When the internal resistance and voltage of the battery are r_d and E, the charging current of the battery (I_{ch}) is stated as

$$I_{ch} = \frac{V_{dc} - E}{r_d} \tag{5}$$

III. Control Strategy in Regenerative Braking

A proper operation for regenerative braking of the BLDC motor is determined by the magnitude of DC-link voltage as the output of boost converter. This voltage must be higher than the battery voltage. Referring to boost chopping concept and Fig.3, intervals where the proper switch must turn on and off are depicted in Table-1. Considering under section-1, boosting mode can be implemented by operating switch S_2 in PWM pattern.

TABLE I. Conducting Switches and Diodes in Every Sector

Sector	PWM operated switch	Diodes
#1	S2	D1-D4
#2	S2	D1-D6
#3	S4	D3-D6
#4	S4	D3-D2
#5	S6	D5-D2
#6	S6	D5-D4

In sector-1 and sector-2, the phase-A BEMF has the highest magnitude so the lower switch of leg-A (S_2) must turn on and off but lower diodes of different leg will conduct, it depends on the phase with lowest BEMF. The other sectors can adopt the same manner as used in sector-1 and sector-2. To understand the concept of the proposed control strategy, the position of the phase voltages with respect to the one signal of hall sensor must be considered as depicted in Fig.8.

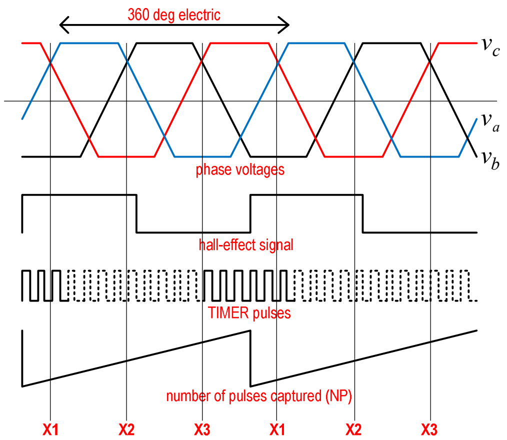

Fig. 8. Determination of the pulse number to excite the lower switches in boost chopping mode

The core of the control circuit utilize a digital signal controller that is implemented by dsPIC30F microcontroller. By activating TIMER, counting pulses will be generated. If the signal of the hall sensor is used as the input signal for input capture (IC) function, then the content of TIMER register is captured at every rising edge of the hall sensor signal. The difference between the contents of the current and the previous captured values is the number of pulses between adjacent input capture events (NP). Based on NP, the above sectors will be determined. The interval for the lower switches of phase-A, phase-B and phase-C to turn on and off in PWM pattern can be expressed as

$$S_2 \rightarrow \text{on-off} \;\Rightarrow X_1 \leq NP \leq X_2 \tag{6}$$

$$S_4 \rightarrow \text{on-off} \;\Rightarrow X_2 \leq NP \leq X_3 \tag{7}$$

$$S_6 \rightarrow \text{on-off} \;\Rightarrow (X_1 \geq NP) \cup (X_3 \leq NP) \tag{8}$$

Combining (6)-(8) with the PWM pattern will produce the PWM waveforms for the lower switches as shown in Fig.9. The flowchart of the proposed control strategy for BLDC in regenerative braking mode is presented in Fig.10 and Fig.11.

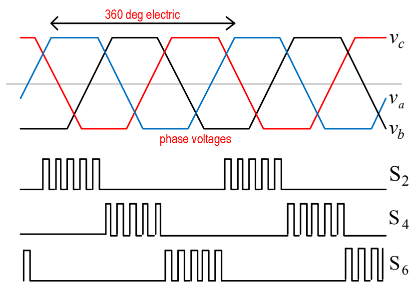

Fig. 9. PWM pulses generated for the lower switches in boost chopping mode

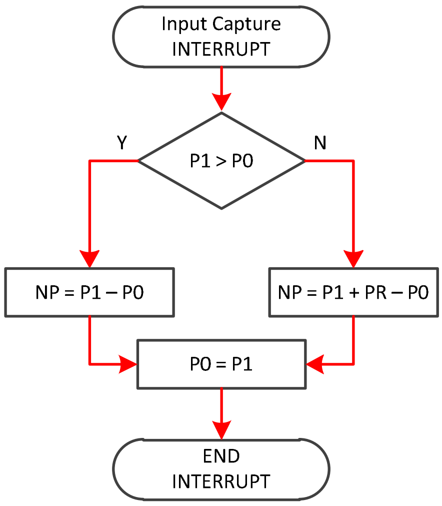

Fig. 10. The flowchart to calculate the number of pulses between two adjacent input capture events

Number of pulses captured between two adjacent events can be determined by using P_1 (content of TIMER2 register captured in current event) and P_0 (content of TIMER2 register captured in previous event). When two events are separated by TIMER overflow event, then the number of TIMER2 period must be inserted.

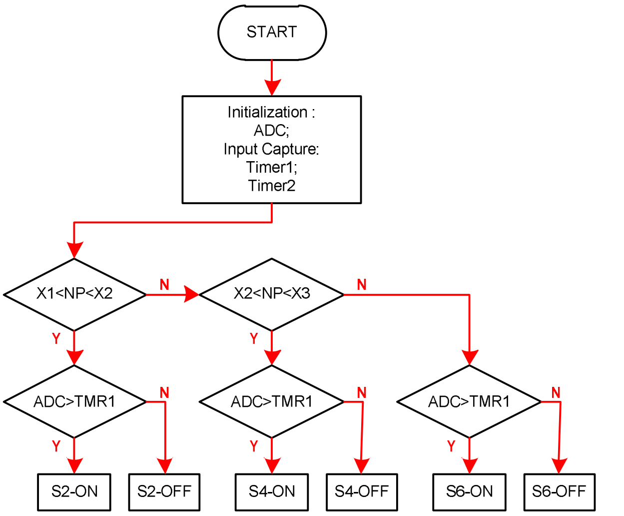

Fig. 11. The flowchart to generate the switching patterns for the lower switches of the converter in regenerative braking

IV. Results and Discussion

To support the analysis, simulations were conducted by using PSIM. The circuit used in the simulation works is based on Fig.2 and the control algorithm implement the flowcharts depicted in Fig.9 and Fig.10. A battery with 48 V and 0.5 Ohm internal resistance which is connected to 200 uF DC-link capacitor is used in the simulation. Waveforms of phase voltage, diode current and charging current are depicted in Fig.12. For the capacitor is too small, the charging current is discontinuous. The comparison of the charging current and the motor speed under different duty cycle are presented in Fig.13 and Fig.14. Under greater duty cycle, the charging current will be higher then it results in lower motor speed because the braking force is greater.

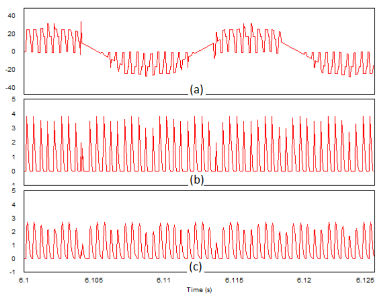

Fig. 12. Simulation results under d = 0.3 (a) phase-A voltage (b) diode current (c) charging current to the battery

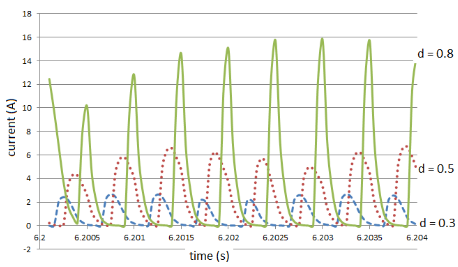

Fig. 13. Simulation results of the charging current comparison with different duty cycle for regenerative braking

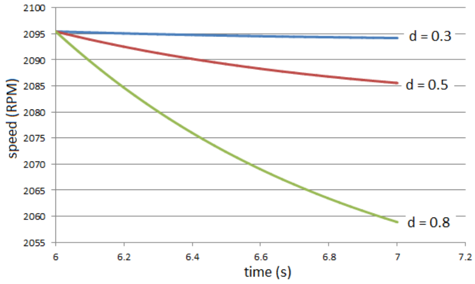

Fig. 14. Simulation results of the motor speed comparison with different duty cycle for regenerative braking

Finally the prototype for experimental works was designed to verify the simulations. The 50W BLDC motor and 12 V battery were implemented for the prototype. The lower switch of phase-A will generate PWM patterns in the interval when the phase voltage has the highest magnitude (Fig.16). The waveforms of the phase voltage, diode current and charging current can be seen in Fig.17. When the motor runs at 2180 RPM, operating regenerative braking under different duty cycle results in different charging currents. The higher charging current can be obtained with greater duty cycle (Fig.18). These will affect the motor speed (Fig.19).

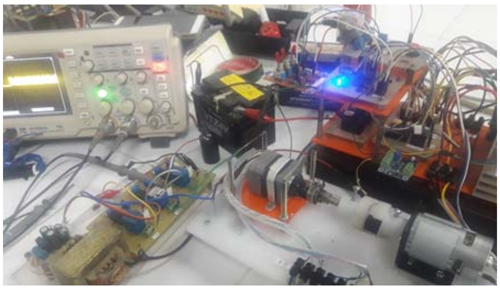

Fig. 15. The prototype for experimental works

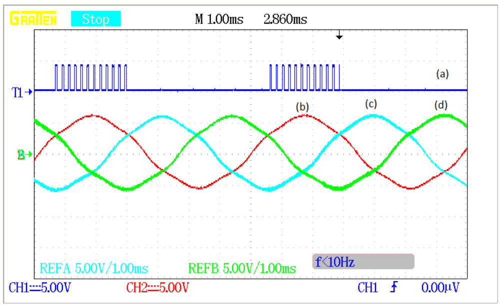

Fig. 16. Experimental results under d = 0.3 (a) switching signal for lower switch of phase-A (b) phase-A voltage (c) phase-B voltage (d) phase-C voltage

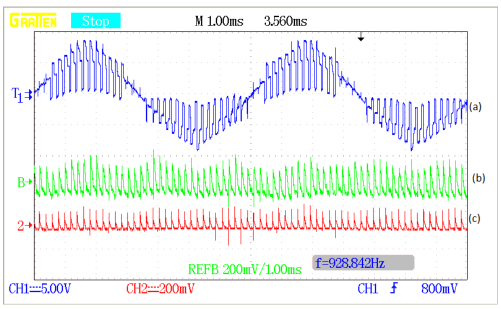

Fig. 17. Experimental results under d = 0.3 (a) phase-A voltage (b) diode current (c) charging current to the battery

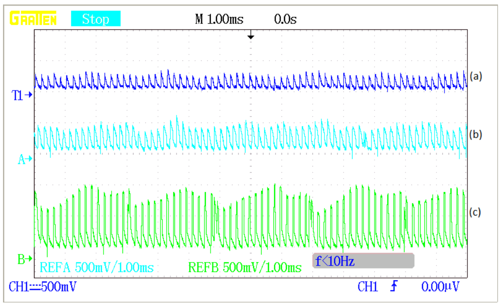

Fig. 18. Experimental results of charging current to the battery under 2180 RPM with different duty cycle (a) d = 0.3 (b) d = 0.5 (c) d = 0.8

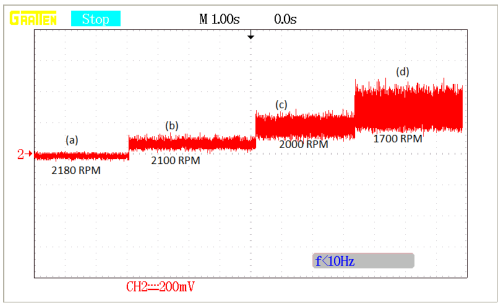

Fig. 19. Experimental results of charging current under different duty cycle with 2180 RPM (a) d = 0 (b) d = 0.3 (c) d = 0.5 (d) d = 0.8

When regenerative braking is operated under lower speed, then the BEMF is also smaller. To keep the charging current flowing into the battery, greater duty cycle is required. Operating the regenerative braking with 0.5 duty cycle results in different charging currents. The motor which runs at lower speed will have smaller charging current (Fig.20).

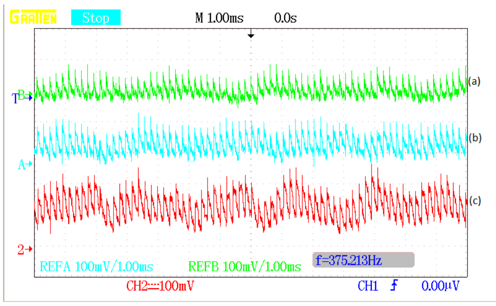

Fig. 20. Experimental results of charging current under different speed with d = 0.5 (a) 1600 RPM (b) 1900 RPM (c) 2180 RPM

To obtain better performance in regenerative braking, information about the phases with highest voltage magnitude is very important. This requirement is used to choose the lower switch that must be turned on. During switching process, the waveforms of the phase voltages will be changed so problems will appear if direct detection of the phase voltages are used. By determining the angles between the phase voltage waveforms related to one hall sensor pulse, the above problem can be anticipated.

V. Conclusion

Operation of a BLDC motor in regenerative braking by adopting boost chopping concept has been presented. The strategy is able to boost the BEMF generated by the BLDC motor under lower speed. A simple control strategy by activating the lower switches of the converter due to their highest BEMF is described. To anticipate the problems related to deformation of the phase voltage waveforms, the angles between the phase voltages and one of the hall sensor information are first determined. Such information is used to choose the switches in the converter to be turned on and off with PWM patterns. The simulation and experimental works show the effectiveness of the proposed control strategy.

Acknowledgment

This work was supported by Directorate of Research and Community Service, Directorate General of Research Strengthening and Development, The Ministry of Research, Technology and Higher Education, Republic of Indonesia 2019.

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Analysis and Design of BLDC Motor Control in Regenerative Braking

at The 2019 International Symposium on Electrical and Electronics Engineering
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General Chair