Bidirectional VSI as a Regenerative-Braking Converter for BLDC Motor – An Analysis on a Plug-in Electric Vehicle Application

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Abstract

The limited distance covered by a plug-in electric vehicle is commonly caused by the limited capacity of its battery. In fact, the energy consumption of the battery can be reduced by recovering the energy wasted during braking using the regenerative braking method. In this way, it brings benefit to increase the battery efficiency while providing vehicle deceleration. Other possible advantages include reducing the maintenance cost because of the wearing out of friction pads and/or brake shoes and providing smoother braking torque. This paper analyzes two methods of regenerative braking, which become the object of many types of research nowadays, using a bidirectional voltage-source inverter. Characteristics of each method and its implementation are presented. Motor torque can be controlled and energy can be recovered to charge the battery just by interchanging the switching order of the inverter.

1. Introduction

The continuously rising of energy saving awareness is one of the reasons why electric vehicles (EV) become the topic of many types of research. Being different from the internal combustion engine (ICE) vehicles, the use of EVs reduces the environmental pollution, which is normally associated with the gas emission, noise, and the dependence on fossil fuels produced and caused by ICEs. ICEs are also more vulnerable to deadly blast and explosion during accidents. Some disadvantages of EVs so far still becoming the focus attention of many researchers are their low efficiency, the engine durability and lifetime, their bulky dimensions, and the number of required components and their related complexity [1]-[3].

A plug-in electric vehicle (PEV) is defined as any motor vehicle which can be recharged from any external source of electricity. One of the PEV's main drawbacks is related to its energy storage, i.e. the battery. The battery's limited capacity makes the distance to be covered or mileage of EVs also limited. One of the ways to increase the usage efficiency of the battery can be taken by implementing a regenerative braking technique. It is achieved by utilizing the kinetic energy of vehicle's wheel movement while decelerating it. Many types of research on regenerative braking methods have been recently developed with the utilization of various converters and other components such as ultracapacitors [4]-[7]. However, the technique being considered to be the most practical is realized by modifying the switching order of bidirectional voltage-source inverters (VSI) so that the energy supposed to be wasted could be recovered to charge the battery [8].

This paper presents the analysis and performance comparison of two simple but effective methods of regenerative braking. A bidirectional VSI is used as the sole converter to operate a brushless direct-current (BLDC) motor during either motoring or braking mode (Fig. 1). Characteristics of each method and its implementation are analyzed as they are very important to determine the optimum operating range of the converter.

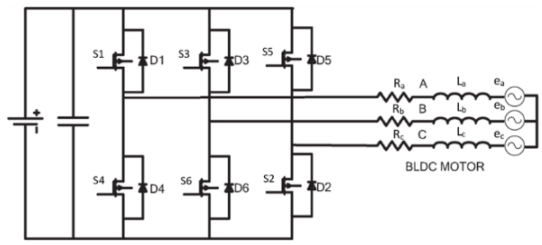

Fig. 1. The equivalent circuit of a BLDC motor being supplied through a VSI

2. Regenerative braking methods

2.1. BLDC motor

BLDC motors are suitable for EVs application due to their good torque-speed characteristics, the wide-range of speed controlling, high dynamic response, high reliability and efficiency, long lifetime (no wearing-out of brushes), silent operation, and high torque-to-motor size ratio [9].

The torque in a BLDC motor can be expressed as [9],

$$T_{\mathrm{em}} = \frac{P_{\mathrm{em}}}{\omega_{\mathrm{r}}} = \frac{3\,\omega_{\mathrm{e}}|\lambda_{\mathrm{m}}||I_{\mathrm{a}}|}{\omega_{\mathrm{r}}} \tag{1}$$

and as $\omega_e = \frac{p}{2}\omega_r$, furthermore

$$T_{\mathrm{em}} = \frac{mp}{2}|\lambda_{\mathrm{m}}||I_{\mathrm{a}}| \tag{2}$$

which means that the electromagnetic torque T_{em} increases proportionally to the armature current increase so that the motor torque can be controlled through its armature current.

2.2. Bidirectional VSI

A bidirectional VSI is working in two directions; delivering the power from the battery to motor during acceleration, and reversely from the motor to battery during regenerative braking. As seen in Fig. 1, the main supply used is a battery, with *R* and *L* represent the resistance and inductance of the armature, whereas e_a, e_b, and e_c, represent the back-emf of the BLDC motor. S_1 to S_6 can be regarded as the power switches of the inverter, while D_1 to D_6 are the freewheeling diodes. The DC-link capacitor between the battery and the inverter is used as a temporary energy storage.

2.3. Motoring Mode of the BLDC Motor

During the BLDC motor functioning in the motoring mode, the upper-part switches (high-side, S_1-S_3-S_5) as shown in Fig. 1 are operated in the pulse-width modulation (PWM) mode with the order determined based on the Hall sensors combination described in Table 1, whereas the lower-part switches (low-side, S_4-S_6-S_2) are continuously ON [8],[10].

Table 1. Commutation timing in the acceleration mode

State	Sensor combination (a,b,c)	S_1	S_3	S_5	S_4	S_6	S_2
I	101	1	0	0	0	1	0
II	100	1	0	0	0	0	1
III	110	0	1	0	0	0	1
IV	010	0	1	0	1	0	0
V	011	0	0	1	1	0	0
VI	001	0	0	1	0	1	0

The flowing-current direction during the State I of the acceleration mode is shown in Fig. 2. In this state, if S_1 and S_6 are conducting, the current I_{on} is flowing from the node *a* to *b* to charge the inductor. When S_1 is off, the inductor will discharge so that the current I_{off} flows from S_6 to D_4 forming a closed circuit.

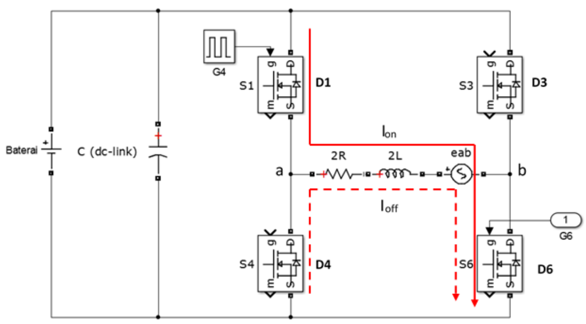

Fig. 2. The flowing-current direction during the acceleration mode (State I)

Due to rotor induction, e_{ab} appears as the motor back-emf. The effective current in the motor winding can be controlled through the duty-cycle of the odd-numbered switches.

3.4. Regenerative Braking Mode of the BLDC Motor

The regenerative braking mode is performed to achieve the deceleration of the BLDC motor. It is accomplished by operating the even-numbered switches with the sequence determined using the Hall sensors combination, as described in [8]-[10]. Different from the commutation timing in the motoring mode presented in Fig. 2, the ON-states are found on the switch S_4 in the states I and II, S_6 in the states II and IV, and S_2 in the states V and VI.

The direction of the flowing current during the State I of the regenerative mode is shown in Fig. 3. In this state, if S_4 is conducting, a closed circuit is formed by e_{ab}, R_a+R_b, and L_a+L_b.

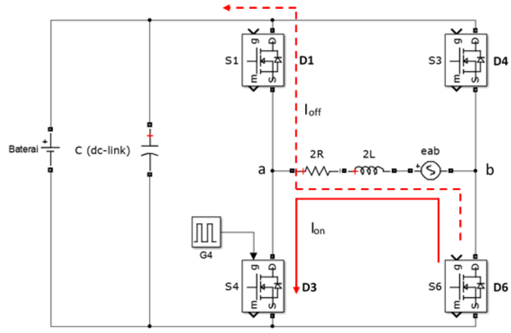

Fig. 3. The flowing-current direction during the regenerative mode (State I)

The current is flowing from the node *b* to *a* (in opposite direction to the current in the acceleration mode). In this state, I_{on} will charge the inductor. When S_4 is off, the inductor will discharge so that I_{off} flows through the freewheeling diode towards the battery for energy regeneration; a similar principle to the operation of a boost-converter circuit. The form of switching signal, voltage and current curves under the regenerative braking mode is given in Fig. 4.

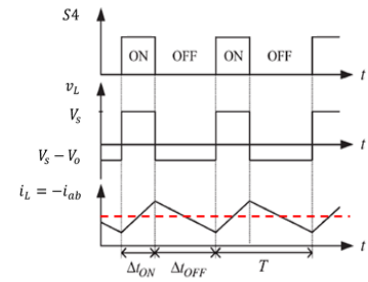

Fig. 4. The form of switching signal, voltage and current curves under the regenerative braking mode

As the total average value of the inductor voltage during one period is zero, the flowing current in the armature can be expressed as follows.

$$i_a = \frac{v_s - V_o(1-D)}{2R} \tag{3}$$

The relationship between the current flowing into the battery and the armature current can be given as follows.

$$i_a(1-D) = i_b \tag{4}$$

If V_o=R_b.i_b, then the armature current can be expressed as follows.

$$i_a = \frac{v_s}{R_b(1-D)^2 + 2R} \tag{5}$$

The peak value of the back-EMF and the effective current $I_{a,rms}$ are given as follows, with 0.7804 as the rms coefficient value of the armature current.

$$V_{s,max} = \sqrt{3}E_{max} = \sqrt{2}V_{emf,L-L}\ ;\ I_a = 0.7804 \times I_{a,max}$$

Finally, the current I_a can be expressed as,

$$I_a = 0.7804 \times \frac{\sqrt{2}V_{emf,L-L}}{R_b(1-D)^2+2R} \quad (6)$$

The relationship between the effective current I_a and I_o is given by √(3⁄2), which represents the coefficient of the DC effective current with respect to the AC current.

$$V_o = \left(\frac{1.35163V_{emf,L-L}}{(1-D)}\right)\left(\frac{1}{1+2R/[R_b(1-D)^2]}\right) \quad (7)$$

The amount of energy to be restored back during one period of time is expressed in (12).

$$W_r = V_s.I_L.T \quad (8)$$

3.5. Regenerative-Plugging Mode of BLDC Motor

This mode combines the plugging method of braking with the regenerative braking to obtain the motor deceleration. It is achieved by performing the conduction on the switches group in the PWM mode using the sequence shown in Table 2, as described in [8]-[10].

Table 2. Commutation timing in the regenerative-plugging mode

State	Sensor combination (a,b,c)	S_1	S_3	S_5	S_4	S_6	S_2
I	101	0	1	0	1	0	0
II	100	0	0	1	1	0	0
III	110	0	0	1	0	1	0
IV	010	1	0	0	0	1	0
V	011	1	0	0	0	0	1
VI	001	0	1	0	0	0	1

In this mode of operation as seen in Fig. 5, if S_3 and S_4 are conducting, the current I_{on} is flowing from the battery passing through the motor winding from the node *b* to *a* in opposite direction to the current in the acceleration mode. In this state I_{on} is charging the inductor. When S_3 and S_4 are off, the inductor will discharge so that I_{off} flows to the battery passing through the freewheeling diodes D_1 and D_6.

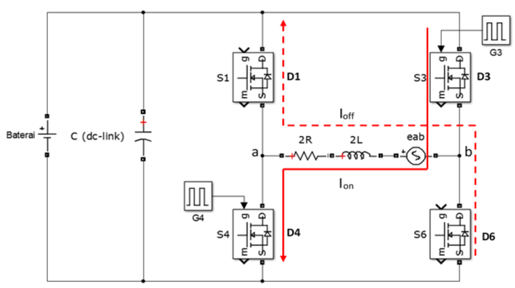

Fig. 5. The flowing current direction during the regenerative-plugging mode (State I)

As both the motor rotation speed and the braking torque are varying, the analysis of the winding current is divided into two conditions, i.e. the continuous conduction mode (CCM) and the discontinuous conduction mode (DCM).

The forms of the switching signal, voltage and current curves under the regenerative-plugging mode are given in Fig. 6 for the continuous conduction mode and in Fig. 7 for the discontinuous conduction mode.

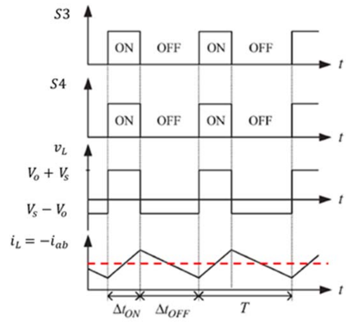

Fig. 6. The form of switching signal, voltage, and current curves under the regenerative-plugging mode for the continuous conduction mode (CCM)

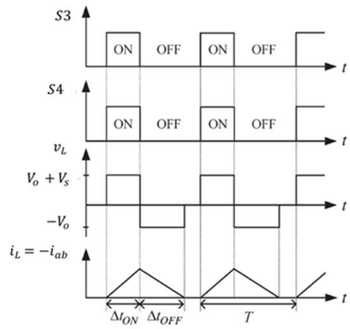

Fig. 7. The form of switching signal, voltage, and current curves under the regenerative-plugging mode for the discontinuous conduction mode (DCM)

The equation for the armature current is expressed as follows.

$$i_a = \frac{v_s - V_o(1-2D)}{2R} \quad (9)$$

The relationship between the current flowing into the battery and the armature current can be given as follows.

$$i_a(1-2D) = i_b \quad (10)$$

If $V_o = R_b.i_b$, the armature current can be given as follows.

$$i_a = \frac{v_s}{R_b(1-2D)^2+2R} \quad (11)$$

Finally, using the same method as in the regenerative mode, the armature current value is obtained.

$$I_a = 0.7804 \times \frac{\sqrt{2}V_{emf,L-L}}{R_b(1-2D)^2+2R} \quad (12)$$

The relationship between the effective current I_a and I_o is given by √(3⁄2), which represents the coefficient of the DC effective current with respect to the AC current.

$$V_o = \left(\frac{1.35163V_{emf,L-L}}{(1-2D)}\right)\left(\frac{1}{1+2R/[R_b(1-2D)^2]}\right) \quad (13)$$

The ratio of Δt_{off} with respect to Δt_{on} can be expressed as follows,

$$\frac{\Delta t_{off}}{\Delta t_{on}} = 1 + \frac{2v_s}{V_o - v_s} \quad (14)$$

Furthermore, the energy being used during the plugging process is given in (15), whereas the energy restored back during the regenerative process is given in (16).

$$W_p = V_o \times I_L \times \Delta t_{on} \quad (15)$$

$$W_r = V_o \times I_L \times \Delta t_{off} \quad (16)$$

The ratio between the energy of the regenerative process to that during the plugging process is expressed in (17).

$$\frac{W_r}{W_p} = \frac{\Delta t_{off}}{\Delta t_{on}} = \frac{1}{D} - 1 = 1 + \frac{2v_s}{V_o - v_s} \quad (17)$$

It implies that for an ideal converter, the energy obtained from the regenerative mode will be higher than that during the plugging process.

The amount of energy to be restored during one period of time is expressed as follows.

$$W_n = V_s \times I_L \times T \quad (18)$$

Finally, the ratio between the energy obtained from the regenerative mode and that from the plugging process is given as follows.

$$\frac{W_r}{W_p} = 1 + \frac{v_s}{V_o} \quad (19)$$

4. Results and Discussion

The analysis of bidirectional VSI performance as regenerative braking converter has been performed through a computer simulation. The observed performance parameters include the gradient of the parameter increase, the optimum working-range of the converter, as well as the resulted regenerative power. The system configuration being used during the simulation is shown in Fig. 8.

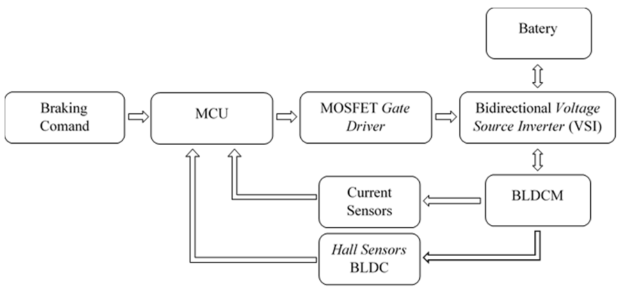

Fig. 8. The system configuration being used in the implementation

In general, the configuration is purposed to maintain the braking current which is flowing in the armature winding at the value determined by the setting point. The microcontroller reads the setpoint value of the braking-current given using a potentiometer and compares it to the actual braking current at the armature. The error between these two current values is used to set the duty-cycle and the braking mode of the VSI. The feedback obtained using the Hall sensors determines the choice of the switches to be activated. The MOSFET gate driver circuit plays the role of buffer between microcontroller and VSI. Under this configuration, current will flow from the battery to motor in the motoring mode and flow back from the motor to the battery in the regenerative mode.

Simulation has been undertaken to know the characteristics of armature current, the output voltage of the converter, and the charging power. During the simulation, the battery was represented using a supply source of $48V_{DC}$ with the internal resistance of 1.5 ohms.

4.1. The Characteristics of Regenerative Braking Mode

The resulted characteristics of the regenerative-braking mode simulation are shown respectively in Fig. 9 – Fig. 10.

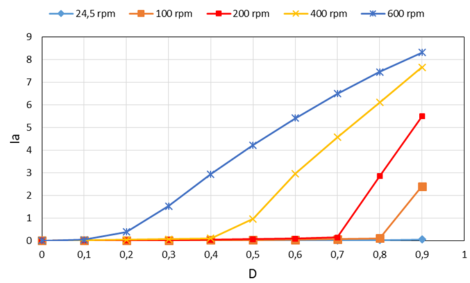

Fig. 9. The armature current characteristics as a function of the duty cycle for various values of rotor speed under regenerative mode

Fig. 9 shows the characteristics of the braking current as a function of the duty cycle for various values of rotor speed. Higher the rotor speed, which means higher the back emf, wider will be the obtained controlling range of duty cycle. The maximum braking current to be achieved will also be higher. As seen, the highest braking current achieved during simulation was 8.3A. The duty cycle was limited up to 90% because beyond that value the braking current was decreasing due to converter saturation.

Being related to the braking current characteristics, the maximum charging voltage increases along with the increase in rotor speed. The highest charging voltage was achieved at 600 rpm with the value of 54.72 volts.

The charging power characteristics as a function of armature current under the regenerative braking mode for various value of rotor speed can be seen in Fig. 10. Power charging increases along with the braking current increase. The maximum power charging will be higher if the rotor speed is higher.

4.2. The Characteristics of Regenerative-Plugging Braking Mode

The characteristics of regenerative-plugging braking mode resulted from the simulation are shown respectively in Fig. 11 – Fig. 12.

Fig. 11 presents the characteristics of armature current as a function of duty cycle for various values of rotor speed under regenerative-plugging mode. Higher the rotor speed, which means higher back emf, the obtained controlling range of duty cycle will also be wider. Under this regenerative-plugging mode, the gradient of current increase is smaller for higher rotor speed. Another remark is that the maximum braking current to be achieved is smaller. The regenerative-plugging mode enables to obtain higher braking current than the regenerative mode for motors with the same specifications.

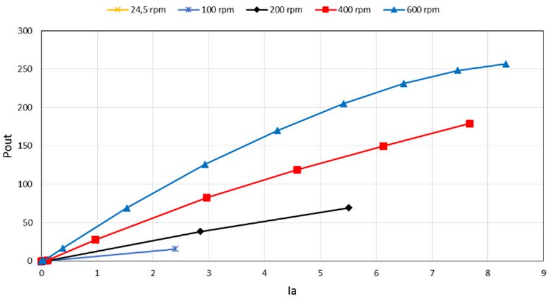

Fig. 10. The charging power characteristics as a function of the armature current for various values of speed under regenerative mode

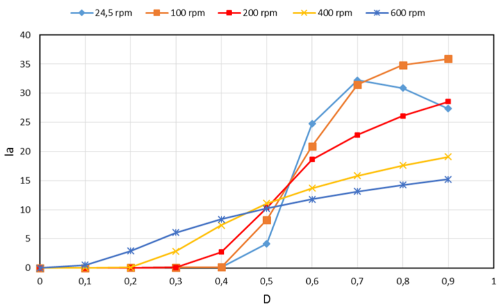

Fig. 11. Characteristic of armature current as a function of duty cycle for various values of rotor speed under regenerative-plugging mode

When an observation was made on the charging voltage characteristics as a function of duty-cycle for various values of rotor speed, it was known that beyond 48V of the voltage across the battery terminals, the current flew into the battery. Oppositely, when the charging voltage is less than 48 V, the battery will send out current.

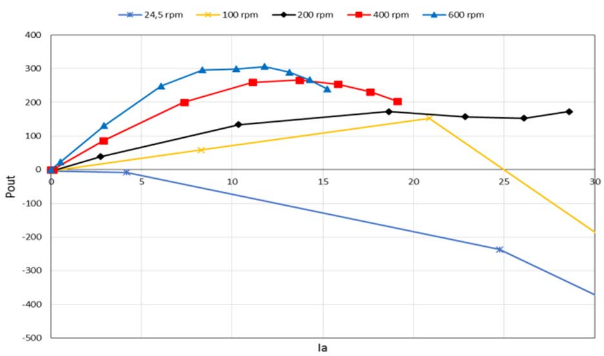

Fig. 12. Characteristic of charging power as a function of duty cycle for various values of rotor speed under regenerative-plugging mode

The charging power characteristics as a function of armature current under the regenerative-plugging mode for various value of rotor speed is presented in Fig. 12. The charging power increases along with the increase of braking current. The maximum power charging will also be higher if the rotor speed is higher.

6. Conclusions

The analysis on two methods of regenerative braking, i.e. regenerative-plugging mode and regenerative mode, brings into conclusions that for the same braking current and speed, the first mode results in higher charging capacity than the second one, which means better efficiency. Apart from that, the first mode also offers wider operation range than the second one, making it suitable for application in vehicles with high inertia, in need of sufficiently high decelerating torque when requiring sudden braking.

7. References

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