21028_Invincibles 5.0_Energy Regeneration System Report

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1. INTRODUCTION

In the context of improving and advancement of Electrical Vehicle (EV) the need to improve overall efficiency of the vehicle we opted to implement the regenerative braking system (RBS).The RBS will be used to convert the heat that have been lost during braking into electrical energy during braking. The technique considered to be the most practical is 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.

2. CONCEPT AND TECHNICAL FEATURES

The bidirectional VSI is used as the sole converter to operate a brushless direct-current (BLDC) motor during braking mode.

2.1 BLDC MOTOR

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

2.2. Bidirectional VSI

A bidirectional VSI works in two directions; delivering the power from the battery to motor during acceleration, and reversely from the motor to battery during 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 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, whereas the lower-part switches (low-side, S_4-S_6-S_2) are continuously ON. 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. 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. CALCULATION AND ANALYSIS

3.1 CALCULATION

Assuming that the vehicle moves with maximum velocity:

Regenerative Event from the graph = 0.75 – 1.25 (0.55)

The kinetic energy of the vehicle in the graph from 0.75 to 1.25 regenerative events at the time of brake application is:

$$KE = ½mv^2$$

M= mass of the vehicle= 270kg

V= velocity of the vehicle= 11.78 m/s²

KE= 0.5×270× 11.78^2=18,733.734 J

Work done for the Regeneration on the battery is:

$$W = V\times q = V \times I \times T$$

W = 55.53×20×0.5 =555.3 J

Efficiency of regeneration, ŋ% = $w_{battery}/w_{K.E}$

= 0.029641 = 2.964 %

3.2 ANALYSIS

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. 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 set point 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 48VDC with the internal resistance of 1.5 ohms.

3.2.1 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. 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 S4 is conducting, a closed circuit is formed by e_{ab}, R_a+R_b, and L_a+L_b. 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**.

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.

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

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,

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

The relationship between the effective current I_a and I_o is given by $\sqrt{(3/2)}$, which represents the coefficient of the DC effective current with respect to the AC current.

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

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

$$W_r = V_s.I_L.\mathrm{T} \tag{8}$$

3.2.2 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. 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. 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.

The equation for the armature current is expressed as follows.

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

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

$$i_a\ (1 - 2\mathrm{D}) = i_b \tag{10}$$

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

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

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 $\sqrt{(3/2)}$, which represents the coefficient of the DC effective current with respect to the AC current.

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

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. COST OF PRODUCT

The products required for this are already included in the Electrical Drivetrain of our vehicle

i.e. KTC BLDC Motor, KTC BLDC Controller, Battery.

No additional cost is required to implement this Regenerative Braking System (RBS)

Therefore, Total Cost of Product for RBS system is

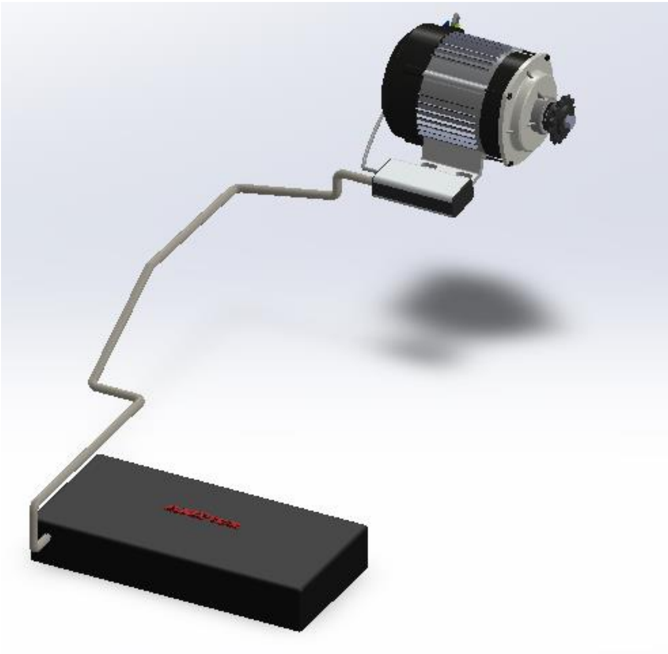
(Cost of KTC BLDC Motor) + (Cost of KTC BLDC Controller) + (Cost of Battery) = 3106 + 1994+ 26500 =31600 (Rs)

5. RESULT & CONCLUSION

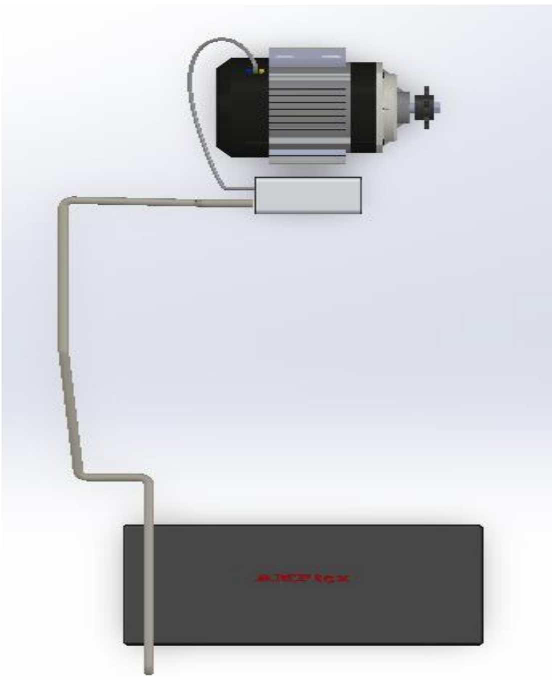
The analysis on two methods of regenerative braking, i.e. regenerative-plugging mode and regenerative mode, brings into conclusions that for the same braking current and speed, the first mode results in higher charging capacity than the second one, which means better efficiency. Apart from that, the 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.
Using bidirectional switch we achieved regenerative breaking with an efficiency of 2.964 %

APPENDIX –1: DESIGN VIEWS AND PHOTOGRAPHS

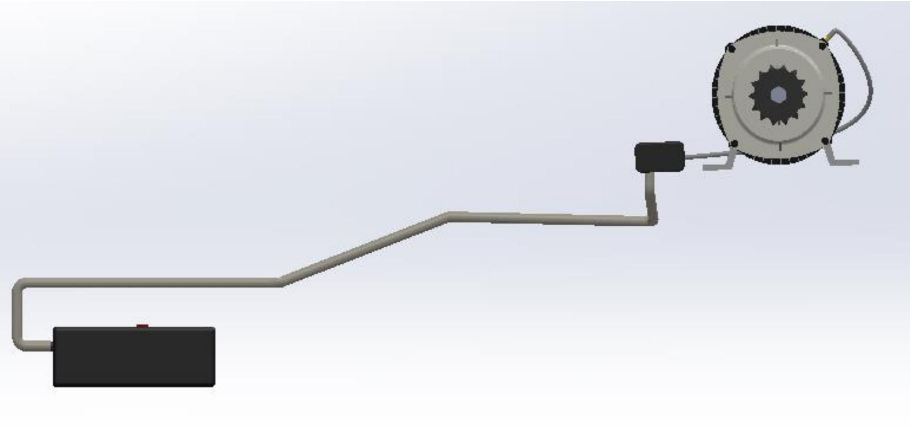
CONCEPT AND TECHNICAL FEATURES



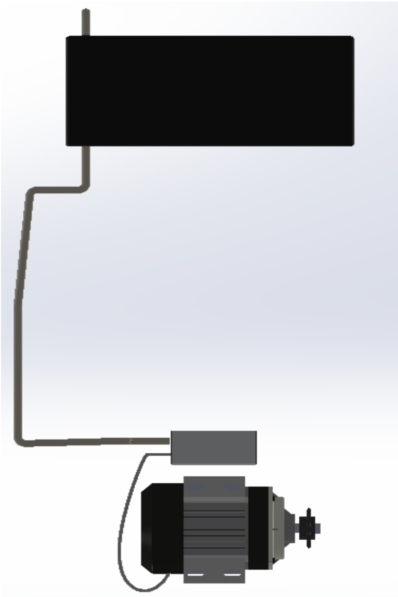
ISOMETRIC VIEW OF RBS SYSTEM



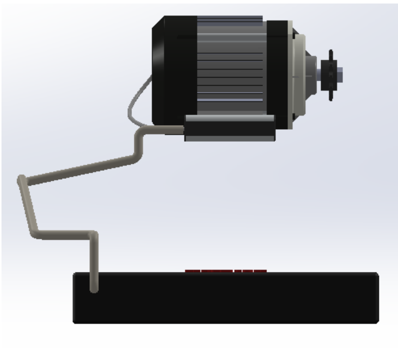
TOP VIEW



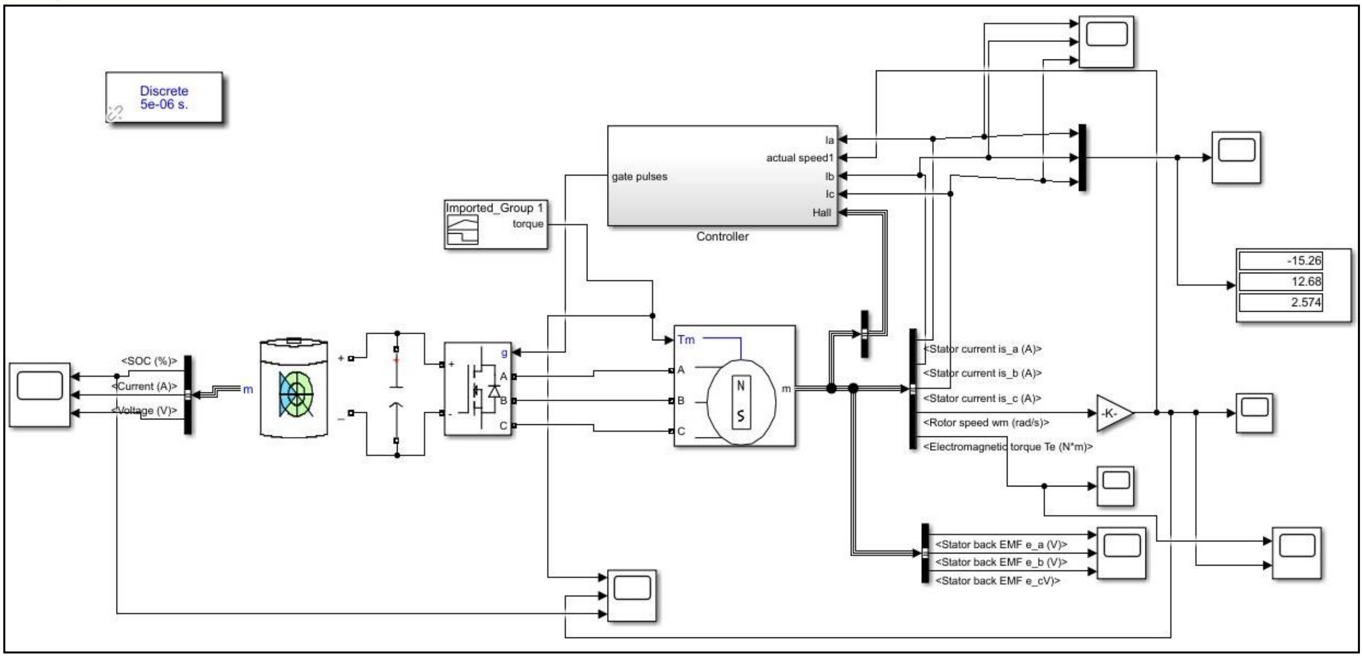
SIDE VIEW



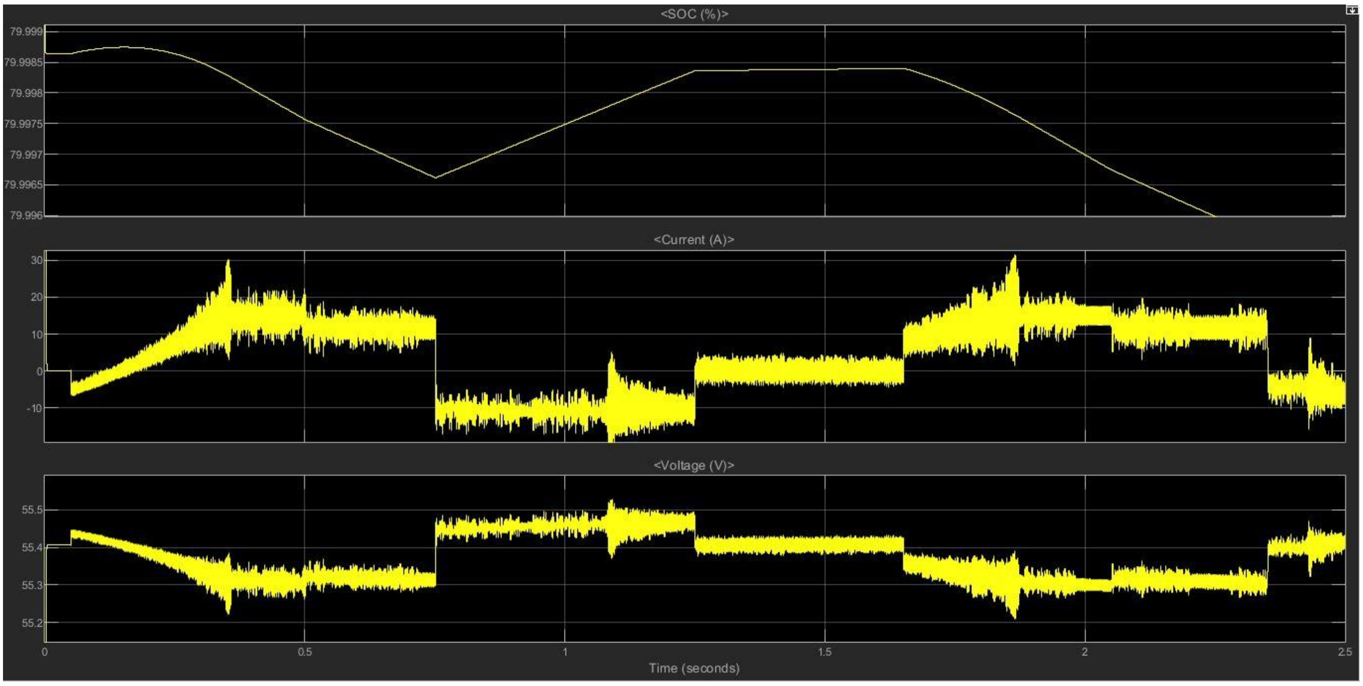
BOTTOM VIEW



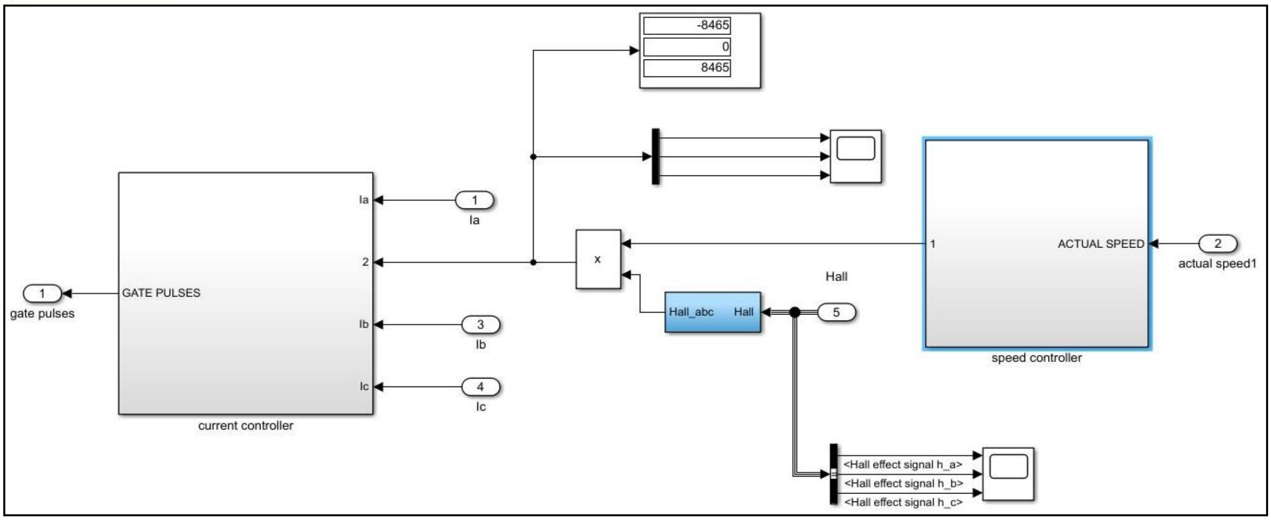
FRONT VIEW



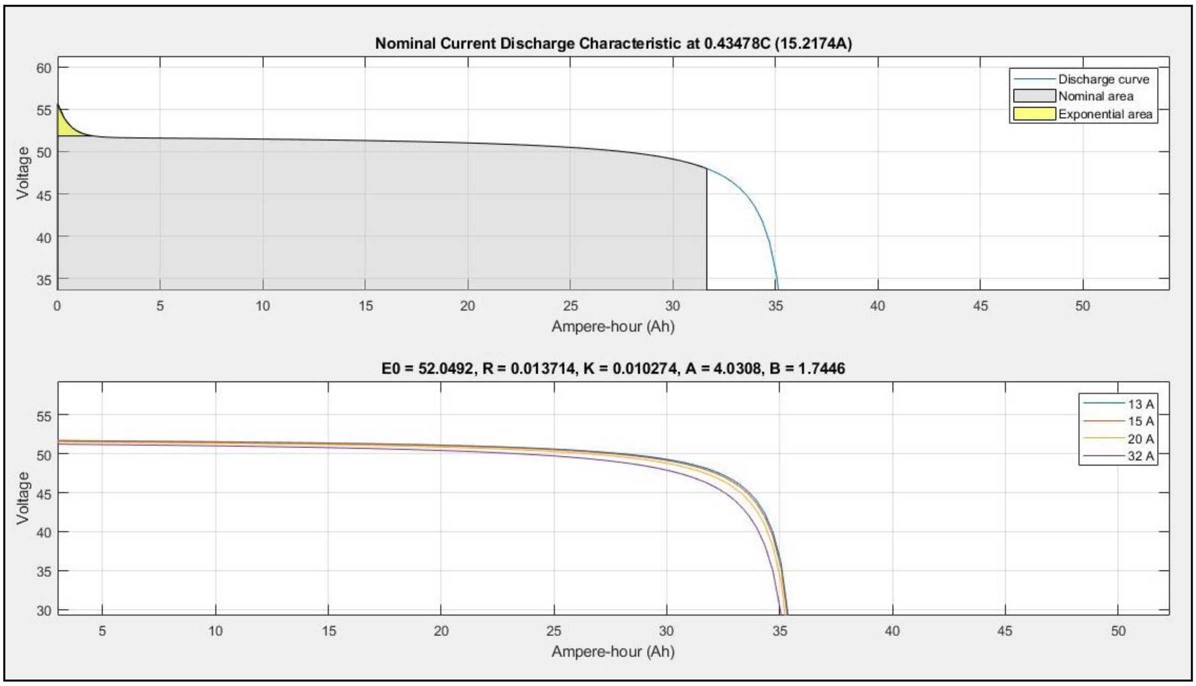
CIRCUIT DIAGRAM OF THE RBS SYSTEM



SOC, V, I GRAPH



CONTROLLER DIAGRAM



BATER DISCHARGE GRAPH

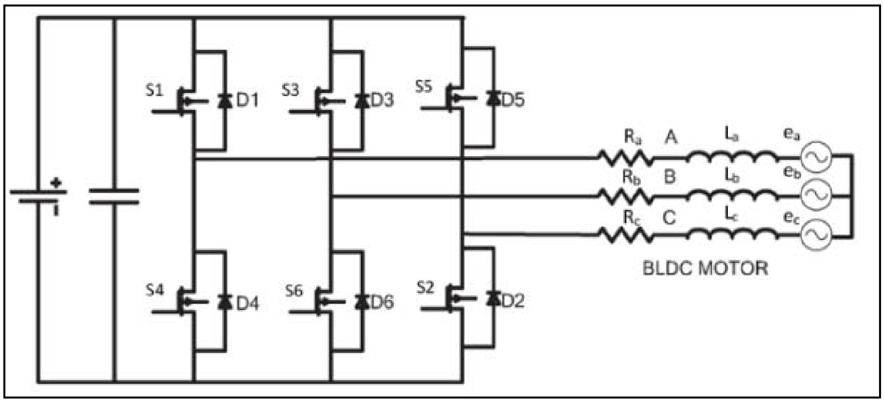


Fig.1. The equivalent circuit of a BLDC motor being supplied through a VSI

CALCULATION AND ANALYSIS

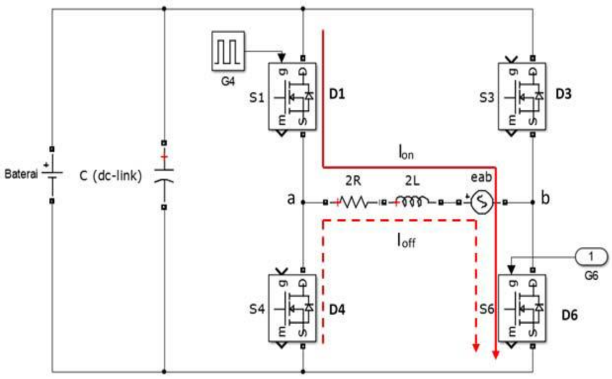


Fig.2. The flowing-current direction during the acceleration mode (State I)

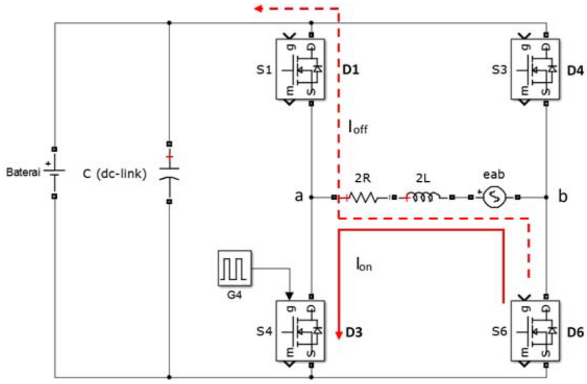


Fig.3. The flowing-current direction during the regenerative mode (State I)

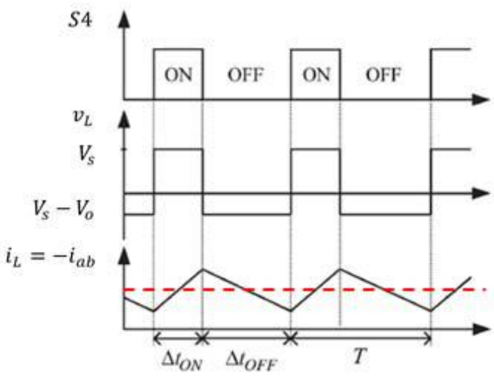


Fig.4. The form of switching signal, voltage and current curves under the regenerative braking mode

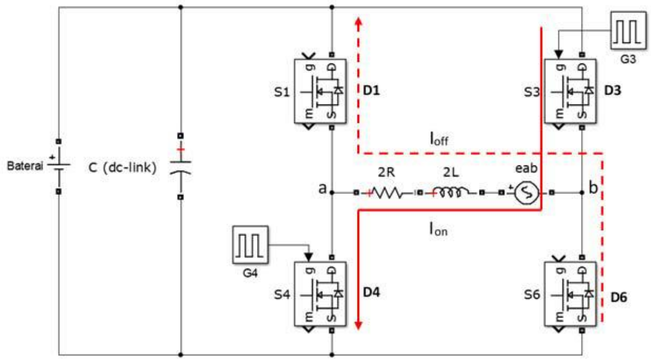


Fig.5. The flowing current direction during the regenerative plugging mode (State I)

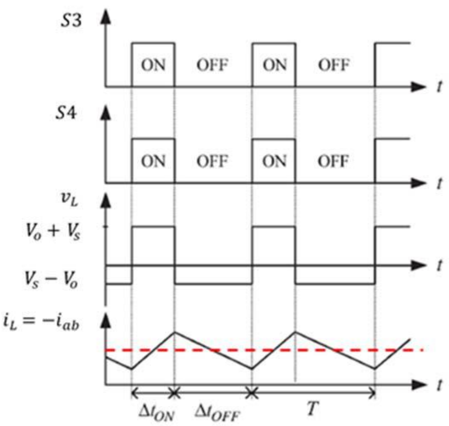


Fig.6. The form of switching signal, voltage, and current curves under the regenerative-plugging mode for the continuous conduction mode (CCM)

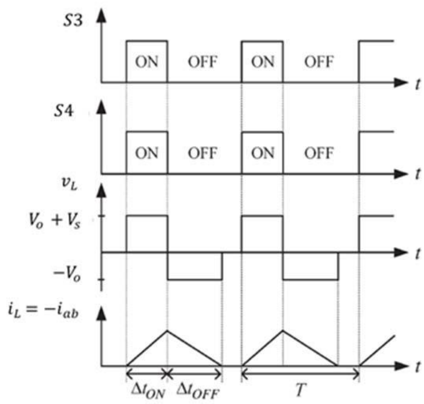


Fig.7. The form of switching signal, voltage, and current curves under the regenerative-plugging mode for the discontinuous conduction mode (DCM)