Modeling and Analysis of a Regenerative Braking System with a Battery-Supercapacitor Energy Storage

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***Abstract*— Regenerative braking technology is crucial for electric vehicle applications. Where, the motor is used as a generator to charge the vehicle's battery. However, the regenerated energy is not fully returned to the battery. Some power losses are experienced in between such as losses in the motor's armature and switching losses. The motor drive system described in this paper has an energy storage system comprised of a supercapacitor module and a lithium ion battery connected through a DC/DC converter to a dc motor. This allows efficient, high power transfer under regenerative braking and acceleration. Managing the power flow through the DC/DC converter and therefore the supercapacitor voltage is a key control parameter that affects the efficiency of the overall system.**

Keywords—DC Motor; DC-DC converter; Regenerative Braking; Supercapacitor; PWM; Energy harvesting; modeling; simulation

I. INTRODUCTION

Interest in regenerative braking is growing drastically nowadays; as the market is slowly transitioning to electric vehicles instead of using traditional vehicles that run on fossil fuel. Regenerative braking (RB) utilizes the kinetic energy generated by the motor during a brake process. Usually, in traditional vehicles, all of this energy is lost in the form of heat energy due to friction losses. In RB, the motor acts as a generator and the kinetic energy is harvested by applying the proper switching schemes to the driver switches. This harvested energy can be used to charge the vehicle's battery, stored in a supercapacitor or both. In literature, car batteries are used to drive the system. [1][4] A hybrid energy storage system can be used to alternate power generation and storage between a supercapacitor and a battery depending on the required power. [2][3] Knowing the parameters of the system is essential to have a clear idea of the amount of energy being harvested as opposed to that being generated. In literature, the maximum amount of current produced in a DC motor while braking is calculated depending on many variables such as the motor speed and input voltage.[5] In this paper, these calculations are confirmed by experimental results of braking an operating DC motor. The harvested energy is stored into a supercapacitor which powers the drive system. The parameters of the DC motor are first identified using experimental techniques. The paper is divided into 3 sections; section *II* explains the theory behind regenerative braking and provides some theoretical analysis of the most harvested current. Section *III* shows experimental results of braking a DC motor to confirm the analysis shown in section *II*. The effect of varying the duty cycle of the braking signal is also studied.

II. REGENERATIVE BRAKING THEORY

A. System Setup

Figure 1 shows the general topology used in electric drives applications, where the mechanical load is typically coupled to a Permanent-Magnet Synchronous Machine supplied by a battery source through an inverter. A supercapacitor module (SC) is used as an auxiliary power source connected through a bi-directional dc-dc converter to the dc-link, thus making it possible to obtain an optimized charge/discharge operation mode.

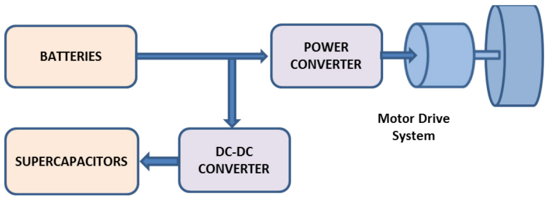

Figure 1: Topology of the Battery-Supercapacitor Energy Storage System

A supercapacitor (V_{sc}) is used to drive the motor in motoring mode. And store the regenerated energy in regenerative braking mode. The motor's rotation is controlled by an H-Bridge. Figure 2 shows the circuit diagram of the system setup. R_{sc} is the internal resistance of the supercapacitor which can be measured using a simple charge-discharge experiment.

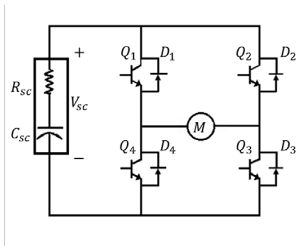

Figure 2: Circuit diagram of the system setup.

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B. Regenerative Braking

In regenerative braking mode, the motor acts as a generator and converts the mechanical energy of the rotating rotor to electrical energy. By applying the suitable switching scheme to the H-Bridge switches, the regenerated energy can be harvested and fed back to the supercapacitor. The idea is to utilize the motor's inductor along with the H-Bridge switches to function as a boost converter that boosts the generated back EMF allowing the current to reverse its direction and flow back to the supercapacitor. [6][7] The operation of the H-Bridge switches can be divided into 3 modes of operation:

1. Driving Mode:

In this mode, Q_1 and Q_3 are switched on. Allowing the current to flow directly from the supercapacitor to the motor terminals to drive the motor in its forward direction. Q_2 and Q_4 by default are always complementary to Q_1 and Q_3 to avoid short circuiting the DC source. To control the motor's speed, switching between $Q_1 - Q_3$ and $Q_2 - Q_4$ is done using pulse width modulation (PWM) signals. Figure 3a shows the direction of current flow in this mode of operation. This mode of operation is ended when a brake command is sent. This break command switches all the switches OFF and the motor runs freely due to its inertia. The current decreases gradually until it reaches zero.

2. Regenerative Braking:

Regenerative braking is achieved by controlling Q_4 only and switching off all of the remaining switches. In this mode, Q_4 is controlled by a separate switching command using a PWM signal. Therefore, it has an ON-time period and OFF-time period.

a. ON-time period: During its ON-time period, Q_4 utilizes the motor's rotation due to its inertia. Where it creates a path for the current to flow in the opposite direction through Q_4 and D_3. During this time interval, the current flows in this closed loop as shown in figure 3b, charging the motor's inductance.

b. OFF-time period: During the OFF-time period, Q_4 does not conduct current, however the current must maintain its direction. Therefore, the current is forced to flow through an alternate path created by the $D_3 - D_1$ and back to the supercapacitor to maintain its direction. In this period, the supercapacitor is charged by the electrical energy generated from the motor's rotation. Regenerative braking is achieved in this mode of operation. Figure 3c shows the current flow during this mode.

C. Analysis of Regenerative Braking

Literature study the maximum amount of current that could be regenerated from braking a DC motor and stored back inside a battery. [5] The same analysis is carried out to study the amount of current regenerated in the supercapacitor.

The source current in the above configuration can be found from power balancing between source and motor. Putting in consideration electrical losses in between. [] The source current can be derived as:

$$i_{source} = \frac{V_{sc} \pm \sqrt{V_{sc}^2 - 4R_{sc}P_e}}{2R_{sc}} \tag{1}$$

Where P_e is the electric machine total input power. To find the maximum amount of current absorbed by the source during the regenerative braking process, the source current i_s is minimized with respect to the controlled armature current i_a.

$$\frac{di_s}{di_a} = 0 \tag{2}$$

$$\frac{d\left(\frac{V_{sc} \pm \sqrt{V_{sc}^2 - 4R_{sc}P_e}}{2R_{sc}}\right)}{di_a} = 0 \tag{3}$$

Since V_{sc} and R_{sc} are constant, therefore the equation is simplified to $\frac{dP_e}{di_a} = 0$.

The electric machine total input power is the power used to run the motor in addition to some electrical power losses in the motor.

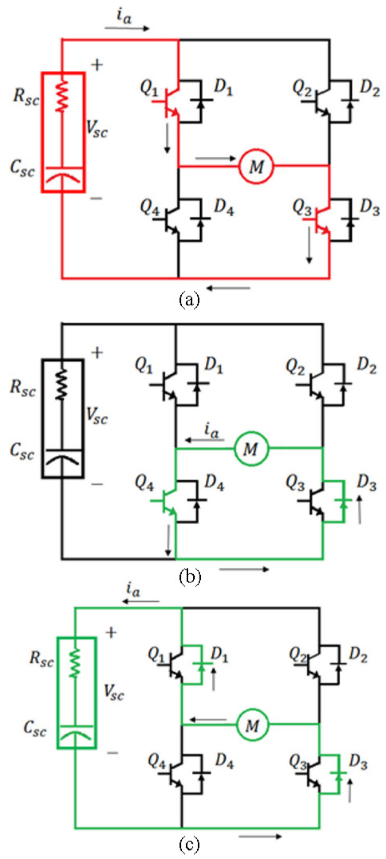

Figure 3: (a) Current flow in driving mode. (b) Current flow during ON-Time period of Q4. (c) Current flow during Off-time period of Q4 (Regenerative mode)

$$P_e = P_{motor} + P_{losses} \quad (4)$$

$$P_e = \tau\omega + i_a^2 R_a \quad (5)$$
$$P_e = K_t i_a \omega + i_a^2 R_a$$

$$\frac{d(K_t i_a \omega + i_a^2 R_a)}{d i_a} = 0 \quad (6)$$

$$K_t \omega + 2 i_a R_a = 0$$
$$i_{a,max} = -\frac{K_t \omega}{2R_a} \quad (7)$$

Substituting in (9) to find the maximum power:

$$P_{e,max} = K_t i_{a,max} \omega + i_{a,max}^2 R_a$$
$$P_{e,max} = -\frac{K_t^2 \omega^2}{2R_a} + \frac{K_t^2 \omega^2 R_a}{4R_a^2} \quad (8)$$
$$P_{e,max} = -\frac{K_t^2 \omega^2}{4R_a}$$

Substituting the maximum power in (5) to find the maximum current absorbed by the source

$$i_{source,max} = \frac{V_{sc} \pm \sqrt{V_{sc}^2 + K_t^2 \omega^2 (\frac{R_{sc}}{R_a})}}{2R_{sc}} \quad (9)$$

From 13, it can be noticed that the maximum current that can be absorbed by the source is dependent of the input voltage, the speed of the motor and the internal resistance of the source and the armature resistance.

III. EXPERIMENTAL TESTS

In this section, experimental results of a regenerative braking process is analyzed to confirm the theory. The supercapacitor's power is also compared to the motor's power to see the efficiency of the braking process. To analyze the results, the DC motor parameters must first be identified.

A. Identification of DC Motor Parameters

Experiments are carried out to identify some of the parameters missing from (1-4). Back EMF constant (K_b), torque constant (K_t) and Inductance (L) can be obtained from the datasheet of the motor. The rest of the parameters have to be identified. To find the armature resistance (R_a), a lockdown test is performed. Where the motor is locked to keep its speed fixed and voltage is supplied. So all of the supplied current is lost in its armature resistance since the motor will not move. The resistance of the motor can be found by measuring the supplied voltage and current. The coulomb friction (τ_c) and motor constant (K_t) can be determined from a steady state experiment. Where the motor is supplied with a step voltage and using some curve fitting techniques, the mentioned parameters can be evaluated. The system's inertia (J) can be evaluated from a deceleration test. The motor is run at constant speed and the supply is cut off. The motor decelerates freely to zero. This response is measured and the inertia is evaluated using curve fitting. Table 1 shows the parameters evaluated.

Table 1: DC Motor parameters.

Parameter	Value
Resistance (R_a)	0.87 ohm
Total inertia (J)	0.00315 Kg.m^2/s^2
Back EMF constant (K_b)	0.055 v
Torque constant (K_t)	0.055 Nm/A
Inductance (L)	0.00174 H
Damping coefficient (B)	$B = 4.741 * 10^{-4}\ Nm/A$
Coulomb friction (τ_c)	$\tau_c = 0.1343$

B. DC Motor Simulation

After identifying the motor parameters, the system is simulated in Simulink/MATLAB environment and the step response of the simulated system is compared to the actual system step input response to confirm the identification process results. From (1-4), the following block diagram in fig. 4 can be constructed to simulate the DC motor.

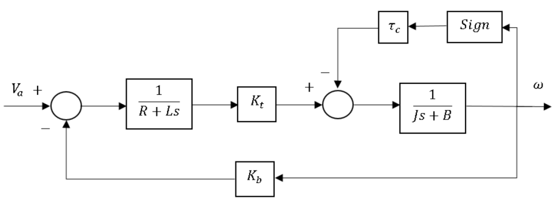

Figure 4: Block diagram of a DC Motor.

The motor is supplied with its rated voltage (V_{rated}) and both responses are compared. The parameters are fine tuned to get better results. Figure 5 shows the actual step response vs simulation step response for both input voltages.

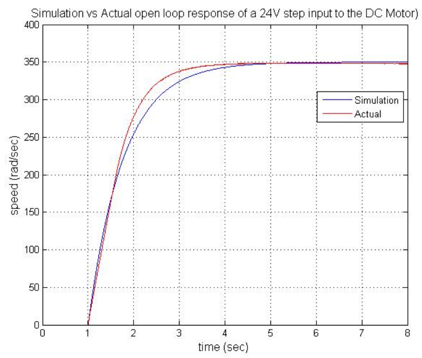

Figure 5: Simulations vs Actual system response.

There is a slight error in the simulation results. This comes to the fact that the used methods are based on approximations and the inertia of the system is not uniformly constant.

C. Analysis of the harvested energy

1) Maximum regenerated current

Using the mentioned setup, the motor is initially powered by the supercapacitor to operate the drive system in driving mode. A break command is sent to the system, which triggers the driver to operate in regenerative braking mode. The current reverses its direction and is absorbed by the supercapacitor. The voltage of the supercapacitor increases and hence the supercapacitor is charged.

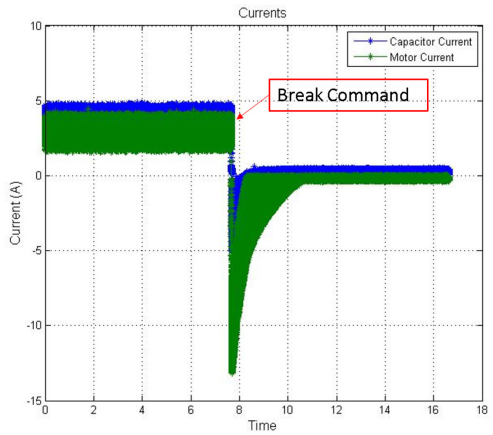

Figure 6: Motor and Capacitor currents during regenerative braking of the DC motor.

Figure 6 shows both of the supercapacitor and motor currents during the entire period. First the supercapacitor is supplying the motor. The capacitor's current is higher than the motor's current due to losses in the switches and the current powering the drive board. Once the brake signal is sent, the direction of the current changes and becomes negative. In this region, the motor is supplying the supercapacitor with energy. It can be seen that the motor current is higher than the capacitor current. Both currents decay to zero as the motor comes to a complete stop.

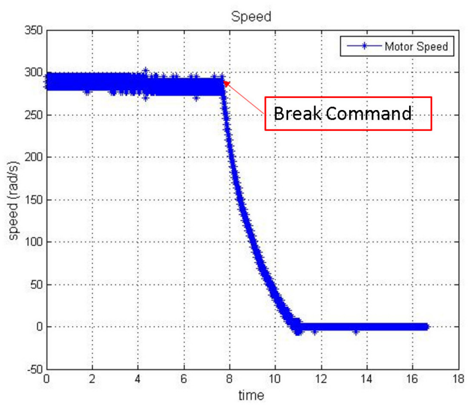

Figure 7: Motor speed in rad/s

Figure 7 shows the speed of the motor in rad/s. The motor is initially running at constant speed. When the break command is received, the motor starts decelerating until it comes to rest. This transient region before coming to rest is due to the motor's inertia. The regenerative braking region is a subset of this period. Where the rotation of the rotor is used to generate electrical energy from its mechanical energy and the motor acts as a generator.

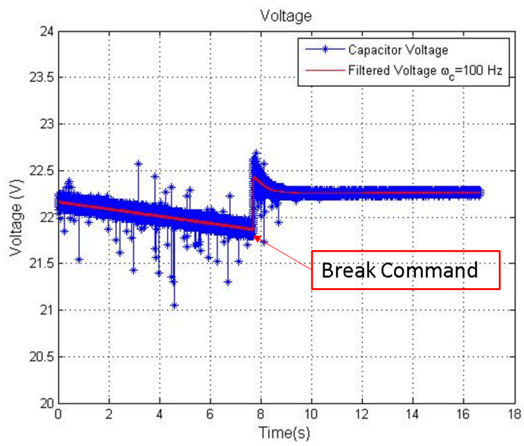

Figure 8: Supercapacitor voltage.

Figure 8 shows the supercapacitor voltage. Initially, the capacitor voltage is dropping as it discharges current to power the motor. On braking, the capacitor voltage increases as current is absorbed by the capacitor. The measured voltage experiences some noise which was eliminated with a simple low pass filter as shown in red. This process was repeated for different capacitor voltages and motor's speed and the maximum regenerated current given by (13). In these experiments, the braking duty cycle is fixed at$d_{braking} = 0.7$. The motor is run at different speeds and the currents are measured. The maximum measured regenerated current was compared to the theoretical maximum current. Table 2 shows the maximum measured current and the theoretical maximum current:

Table 2: Comparison between maximum theoretical and experimental current.

V_{SC} (v)	ω (rad/s)	$i_{s,\ theoretical}$ (A)	$i_{s,\ actual}$ (A)
21	301	-3.56	-3.1602
20.5	295	-3.50	-3.0258
20	282	-3.2741	-2.9352
18.7	257	-2.9157	-2.6644

The maximum measured current never exceeds the maximum theoretical current that was previously derived. Hence, experimental results confirm the previous analysis made in section II.

2) Braking Duty Cycle

The effect of the braking duty cycle is studied to see how much it affects the harvested energy. Different braking commands with different duty cycles are sent and the regenerated current is measured.

Varying the duty cycle of the brake command will change the ON-OFF times of the Q_4 as explained previously in figure 3. Increasing the ON-time period will charge the motor's inductance more. Allowing it to store more energy. This is similar to the operation of a boost converter. However if it is increased too much, this energy will not be fully recovered due to short OFF-time period and will be eventually lost in the switching process. So the duty cycle must be selected carefully. In this section, the recovered energy in the capacitor is compared to the regenerated energy from the motor. The efficiency of the switching scheme is plotted as a function of duty cycle.

The energy of the motor and the energy stored in the supercapacitor during braking are given by:

$$E_{motor} = \frac{1}{2} J \omega_0^2 \tag{10}$$

$$E_{capacitor} = \frac{1}{2} C (\Delta V)^2 \tag{11}$$

Where ω_0 is the initial speed of the motor when the braking process starts. Therefore, the efficiency of the braking process putting into consideration some power losses during switching and due to the motor's internal resistance.

$$\eta = \frac{E_{capacitor}}{E_{motor}} \tag{12}$$

This efficiency is calculated for different braking duty cycles to see the effect of varying the duty cycle during the braking process. The following process was repeated for $d_{brake} = 0.5$ and $d_{brake} = 0.7$. Figures 9-10 show the resulting currents and voltage jump across the capacitor.

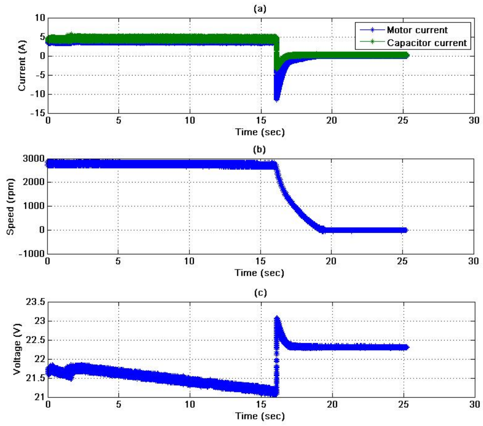

Figure 9: (a) Capacitor and Motor Currents with Brake Command of d=0.7 Fsw = 4 KHz. (b)Motor Speed in RPM. (c) Capacitor Voltage

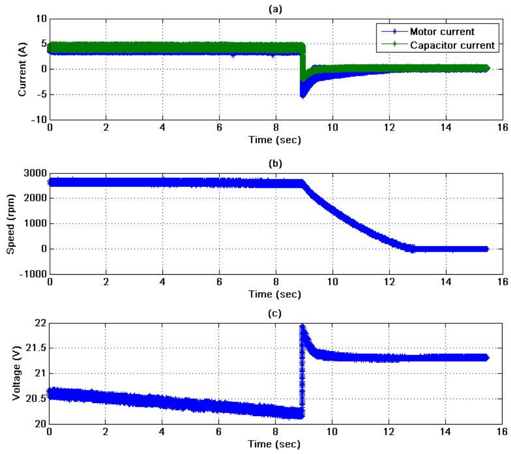

Figure 10: (a) Capacitor and Motor Currents with Brake Command of d=0.5 Fsw = 4 KHz. (b) Motor Speed in RPM. (c) Capacitor Voltage

Table 3 summarizes the results from this experiment and displays the efficiency of energy harvested in each case which can be calculated using (10-12).

Table 3: Efficiency of braking at different duty cycles

d	ω_0 (rad/s)	ΔV (V)	$E_{motor}(J)$	$E_{capacitor}(J)$	η
0.5	276.46	1.17	120.37	69.8139	58%
0.7	289	1.13	131.57	65.1219	49.49%

IV. Conclusion

This paper explained the theory behind regenerative braking. Analysis similar to the literature is carried out to an experimental setup to confirm the hypothesis. Experimental results show that the maximum current absorbed by the capacitor doesn't exceed a certain limit dependent on the supercapacitor's voltage, internal resistances of the system and the motor's speed. The effect of varying the duty cycle is also studied to find the most efficient duty cycle to get the best efficiency in harvesting the regenerated energy.

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