Dynamics and Limits of Electrical Braking

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Abstract

Conversion between electrical energy and mechanical energy is done by electrical machines. It is possible to use most of the electrical machines as motor or generator and also it is easy to switch between these states. This phenomenon makes them preferable in any dynamic application. Due to fast torque response, ease of control and efficiency; brushless DC machines (BLDC) are widely used in applications those need both acceleration and deceleration in operation, i.e. electric propulsion. This paper investigates features and scope of using a BLDC as a motor/generator.

1. Introduction

Any moving or rotating system eventually stops if no accelerating power is applied and a friction force is affecting. Actually, this is conversion of kinetic energy on the system, seen in Eq.1.1(a) for translational moving body, Eq.1.1(b) rotational moving body, to heat energy(m: mass of translational body, ϑ: linear velocity, I: moment of inertia around rotational axis, ω: angular speed).

$$E_{translational} = \frac{m \cdot \vartheta^2}{2} \qquad (1.1.a)$$

$$E_{rotational} = \frac{I \cdot \omega^2}{2} \qquad (1.1.b)$$

If a moving or rotating body is requested to be stopped quickly, braking systems are utilized. In this case, system frictions are trivial and braking power can be used to define amount of deceleration. New translational or rotational energy can be found subtracting E_{brake} calculated in Eq.1.2 from relevant energy and new velocity or angular speed can be easily found using Eq.1.1.

$$E_{brake} = \int_{t_0}^{t_1} P_{brake} \cdot dt \qquad (1.2)$$

Braking force affecting on the system also defines stopping time. If E_{brake} is equal to $E_{translational}$ or $E_{rotational}$, system stops and $t_{stopping}=t_1-t_0$. To be able to design a braking system, one must basically know maximum speed and mass of the system and requested stopping time as input.

Since the above mentioned systems are decelerated by friction, difference kinetic energy is turned into heat energy and (needed to be) dissipated. In systems driven by electric machines, it is possible to decelerate the system by means of electrical braking. In this case, generated electrical energy can be stored in batteries, given back to power lines or turned into heat in resistors, etc. Possibility to regain this energy is an important input to those who design efficient dynamic systems. This phenomenon is widely used in electric and hybrid electric vehicles [1-4]. For example, battery powered electric vehicles regenerate electric from braking energy to store on their batteries or trains use braking energy to support line and supply another accelerating train connected to line.

However, electrical braking has its own limitations and vehicles with electric drives cannot be braked safely and efficiently only by electrical means. This requires introduction of mechanical (generally hydraulic) braking systems. Blending of mechanical and electrical braking is a tough issue that the engineers and researchers are putting great effort to define the best way to control braking and optimize solutions. The solutions include various methods from optimal control to soft control [5, 6].

In this paper, braking characteristics of brushless DC (BLDC) machines, which are widely used on light electric vehicle applications, are studied and limitations of electric braking is investigated. An experimental rotational system is built to see theoretical features on a physical system. Several deceleration tests are realized and effects of various components are seen.

2. Characteristics of a Brushless DC Machine (BLDC)

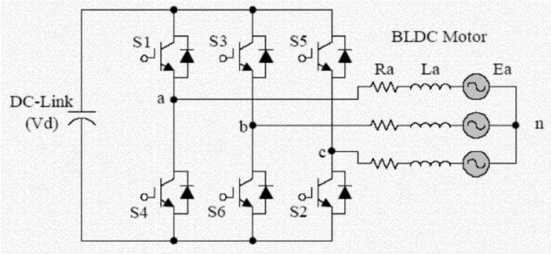

Fig. 2.1 Equivalent circuit of BLDC motor [7]

BLDC is very similar to conventional DC machine. But unlike conventional DC machine, BLDC does not have slip-ring for commutation; instead, electronic commutation is realized. The position of rotor and stator is followed by Hall Effect sensors or encoders and relevant windings are triggered. Similar to conventional DC machine, there is a correlation between armature voltage and speed, current and torque as seen in Eq.2.1(a) and (b), where k_e and k_i are speed and torque coefficients and related with design of the machine, ε is back EMF and *i* is armature current.

$$\omega = k_e \cdot \varepsilon \qquad (2.1.a)$$

$$T = k_t \cdot i \qquad (2.1.b)$$

A BLDC machine can be operated as both motor and generator. The basic difference for these operation modes is direction of armature current. If the armature current direction is into the BLDC machine, it operates as a motor and if the current direction is out of the BLDC machine then it operates as a generator. A simple equivalent circuit is given in Fig.2.1.

a. Motor Operation

BLDC motor is supplied by 3 phase AC voltage and rotor position is very important to apply the proper phase to motor's stator. Because of these reasons BLDC motors usually driven by a 3 phase inverter. Hall effect sensors are used to determine rotor position data in BLDC motors with sensors. Sensor signals are processed by the driver circuit to turn on the proper switch. Although driving a BLDC motor is more complicated and difficult compared to a conventional DC motor, the electrical model and operation principle is the same with the conventional DC motor. The voltage equation of BLDC motor is in Eq. 2.2 and the electrical energy that converted to mechanical power is in Eq. 2.3 where V is armature voltage R is armature resistance, L is armature inductance and P is input electrical power. For motor operation armature current's direction is into the motor and by assuming that direction is positive, the electrical power is positive and the power flow is from armature to the shaft.

$$V = R \cdot i + L \cdot \frac{di}{dt} + \varepsilon \qquad (2.2)$$

$$P = V \cdot i \qquad (2.3)$$

The relation between mechanical speed and output toque can be inferred by using Eq. 2.1.a, Eq. 2.1.b. There is a linear relationship between mechanical torque and speed. A BLDC motor rotates its maximum speed for no load condition and can be loaded its nominal torque value safely. Exceeding rated torque value forces the motor to operate in discontinuous torque region.

A BLDC can be driven by PWM signal simply. PWM signals are generated by hall sensor data. In Fig. 2.2, the hall sensor output signals, back EMF voltages, phase currents and output torque for BLDC motor is given.

b. Generator Operation

A BLDC machine also can be operated as a generator. During generator operation, the armature current changes its direction and the current starts flow from the armature to DC-link. Inverter's switches are kept open and armature current completes its path by body diodes of inverter switches and inverter operates in 3 phase uncontrolled rectifier mode. Armature voltage and current waveforms are given in Fig. 2.3.

For generator operation voltage equation changes, since back EMF voltage is greater than armature voltage. This also explains the reason of current direction change. The sign of armature current becomes negative.

$$V = \varepsilon - R \cdot i - L \cdot \frac{di}{dt} \qquad (2.4)$$

$$P = -V \cdot i \qquad (2.5)$$

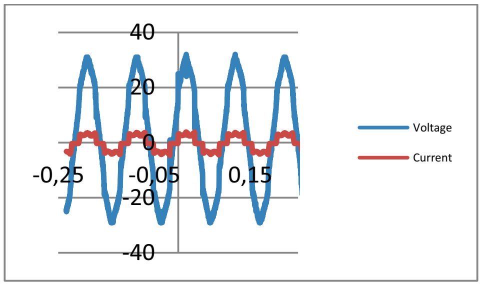

Fig. 2.2 BLDC motor operation armature voltage and current

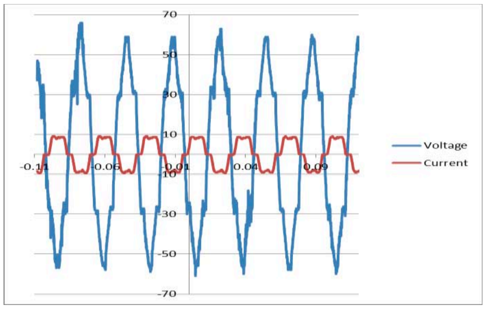

Fig. 2.3 BLDC generator operation armature voltage and current

As it is seen in Eq. 2.5 the power has a negative sign which means the power flow is from machine shaft to armature windings. By using a battery or a battery group this energy can be stored easily which is a common method used for regenerative braking.

3. Types and Limitations of Electrical Braking

Systems with electrical drive can be electrically braked in 3 ways:

a. Regenerative Braking

The main idea is to save the energy. In regenerative braking, kinetic energy of the moving or rotating system is turned back into electrical energy. For battery powered systems, like electrical vehicles, regenerated energy is saved on the batteries. For line-fed systems, it can be sent back to the line to feed another motor connected to the line.

Regenerative braking needs generator operation of electric machine. In this respect, current and voltage is reversed with respect to each other. Voltage is positive to motion but current is from the system to the source, which is the opposite of what happens in motor mode.

For a system with battery power and BLDC machine, steady state braking torque through regenerative braking can be seen below. In this equation, E_a is back-EMF for braking, V_{batt} is battery voltage, I_{Brake} is braking current, R_{batt} is battery internal resistance, R_{pp} is phase-to-phase resistance of the electrical machine and RSC represents semiconductor voltage drop.

$$E_a - V_{batt} = I_{Brake} \cdot (R_{batt} + R_{PP} + R_{SC}) \quad (3.1.a)$$

$$T = k_t \cdot I_{Brake} = k_t \cdot \frac{E_a - V_{batt}}{R_{batt} + R_{PP} + R_{SC}} \quad (3.1.b)$$

From equation above; to realize a desired braking time (or desired braking torque, which is proportional to stopping time) basically, there must be a difference between generated EMF and battery voltage as in equation below.

$$E_a > V_{batt} + (R_{batt} + R_{PP} + R_{SC}) \cdot I_{Brake} \quad (3.2)$$

From this equation, one limitation of a regenerative braking system can be seen that; naturally, system would never have enough speed to overtake battery voltage; thus, a voltage boosting is required during braking.

Another limitation of this system occurs when the batteries are full. Even if the system has a boost capability, if the batteries would not accept any more energy, they would start acting as resistors and eventually heat up, burn or blow.

Since batteries are electrochemical machines, they have a reaction time and this time is generally related with amount of energy that is taken or given. When I_{brake} exceeds charging current limits of a battery pack, amount of braking is limited to amount of current that can be safely stored on.

b. Dynamic Braking

Dynamic braking is similar to regenerative braking, but instead of storing energy, it is dissipated on a resistance. Steady state braking torque of a dynamic braking system can be seen below. In this equation, R_{brake} represents dynamic braking resistance.

$$E_a = I_{Brake} \cdot (R_{brake} + R_{PP} + R_{SC}) \quad (3.3.a)$$

$$T = k_t \cdot I_{Brake} = k_t \cdot \frac{E_a}{R_{brake} + R_{PP} + R_{SC}} \quad (3.3.b)$$

Dynamic braking can be applied in any speed, regardless of boosting. But, a limitation occurs when speed of the system is relatively low and required braking torque is high. Even if the system is short circuited (R_{brake} is zero), heavy systems or systems with high moment of inertia cannot be stopped quickly.

c. Plugging

Plugging is a method, which is used in heavy systems with very high inertia and should be stopped quickly. Different from the previous electrical braking systems, both voltage and current are reversed in plugging (by reversing phase sequence), resulting consumption of energy to stop the system [8]. Technically, it is driving the electrical machine, opposite to movement. In plug braking, back EMF and line voltage is in the same direction, resulting very high braking current and torque.

$$V_{plug} + E_a = I_{Brake} \cdot (R_{PP} + R_{SC}) \quad (3.4.a)$$

$$T = k_t \cdot I_{Brake} = k_t \cdot \frac{V_{plug} + E_a}{R_{PP} + R_{SC}} \quad (3.4.b)$$

While designing a system with plug braking, one should consider high current would be flowing on electronic components and all of the active components should be sized and cooled accordingly. Also, since this system consumes energy to brake, it would be costly to operate. So, this type of braking should be used with other electrical braking methods. It is suggested that, three methods can be blended to efficiently and quickly stop at relatively slower system speeds.

4. Experimental Investigation of Braking Characteristics

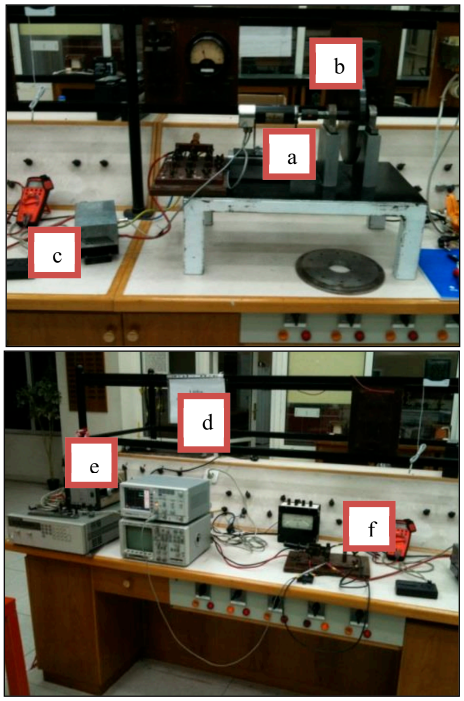

Fig. 4.1 Experimental Setup

To be able to investigate breaking characteristics, an experimental setup is designed. The setup consists of following components and can be seen in Figure 4.1:

i. Maxon EC60 BLDC (Figure 4.1-a)
ii. A metal disk as inertia and coupling (Figure 4.1 –b)
iii. Motor driver (Figure 4.1 –c)
iv. Oscilloscope (Figure 4.1 –d)
v. Power Supply (Figure 4.1 –e)
vi. Resistance and other switchgear (Figure 4.1 –f)

Using this setup, following experiments were done to see breaking characteristics. Unless specified otherwise, source voltage is 36V's and motor speed is around 2200min^{-1}.

a. Acceleration → 0-2200min^{-1}

When 36V is applied, time is measured (t=40s) to reach maximum speed and load current (Ia=2A) is observed.

b. Coasting to Zero → 2200-0min^{-1}

After reaching maximum speed of 2200min-1, power circuit is opened to see coasting to zero speed time is observed and found t=145s. According to this, Figure 4.2 shows open circuit voltage (goes down to 14V due to that observation can be done on input side of the motor driver and a filter capacitor is present there).

c. Braking with Resistor (22Ω - 8Ω - 5Ω) and Short Circuit → 2200-0min^{-1}

Switch is used to brake motor over several resistors. Also, motor is short circuited to stop the system. In all the experiments, stopping times and braking currents are measured and using those values, internal resistance of motor and switch is found as follows:

R_{ext}=22Ω → I_{max}= 1.2A, $t_{stopping}$=93s
R_{ext}=8Ω → I_{max}= 2.33A, $t_{stopping}$=75s
R_{ext}=5Ω → I_{max}= 2.6A, $t_{stopping}$=58s
R_{ext}=0Ω → I_{max}= 25A, $t_{stopping}$=17s

22Ω and 5Ω braking results are seen in Figure 4.3. To be able to have a full model of braking, internal resistance of motor (PP) and switch (S) is calculated from short circuit experiment. According to this:

$$E_{max} = I_{max} \cdot R_{PP+S}$$
$$36V = 25A \cdot R_{PP+S}$$
$$R_{PP+S} = 1.44\Omega$$

Catalog of the motor indicates internal resistance as 1.12Ω and adding resistance of the switch, calculated value is plausible. Using this value, braking resistance values, including resistances of all other components (driver etc.), are as follows:

$$E_{max} = 36V = I_{max}(R_{brake} + R_{PP+S} + R_{other})$$
$$36V = 2.7(5 + 1.44 + R_{other}) \quad \rightarrow \quad R_{other\_1} = 6.89\Omega$$
$$36V = 2.33(8 + 1.44 + R_{other}) \quad \rightarrow \quad R_{other\_2} = 6.56\Omega$$
$$36V = 1.2(22 + 1.44 + R_{other}) \quad \rightarrow \quad R_{other\_3} = 6.01\Omega$$

Mean value is taken as; R_{other} = 6.5Ω. So, braking resistances for the experiments above are recalculated as;

R_{ext}=22Ω→R_{brake}=22+6.5+1.44=29.94Ω, I_{max}=1.2A, $t_{stopping}$=93s
R_{ext}=8Ω → R_{brake}=8+6.5+1.44=15.94Ω, I_{max}=2.33A, $t_{stopping}$=75s
R_{ext}=5Ω → R_{brake}=5+6.5+1.44=12.94Ω, I_{max}=2.6A, $t_{stopping}$=58s
R_{ext}=0Ω → R_{brake}=1.44Ω, I_{max}=25A, $t_{stopping}$=17s

These values show that, maximum braking current is not directly proportional to stopping time. This is because of the EMF, reduces with speed, causing braking current (and torque) to reduce. Using the values above, curve fitting is done and Figure 4.4, showing relevance between max. braking current and stopping time is obtained. This also supports limitations of dynamic braking mentioned in section 3.b.

$$E_{max} = 36V = I_{max}(R_{brake} + R_{PP+S} + R_{other})$$
$$36V = 2.7(5 + 1.44 + R_{other}) \qquad R_{other\_1} = 6.89\Omega$$
$$36V = 2.33(8 + 1.44 + R_{other}) \qquad R_{other\_2} = 6.56\Omega$$
$$36V = 1.2(22 + 1.44 + R_{other}) \qquad R_{other\_3} = 6.01\Omega$$

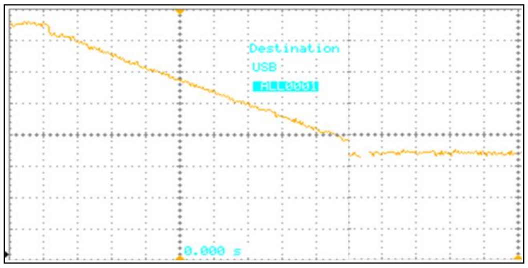

Fig. 4.2 Open Circuit Deceleration (t-E , 10s/grid, Max. 36V, Min. 14V)

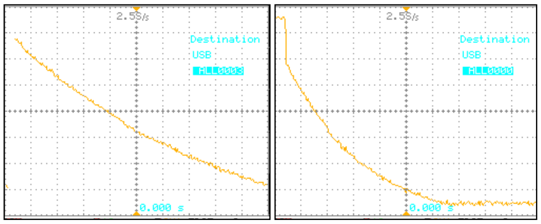

Fig. 4.3 22Ω and 5Ω Stopping (t-E, 10s/grid, Max. 36V, Min. 0V)

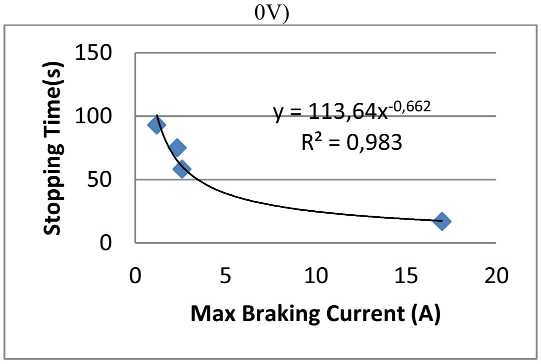

Fig. 4.4 Max Braking Current vs. Stopping Time

d. Low Speed Braking → 300-0min-^{1}

In the previous experiment, it is seen that system would not stop quickly in low speeds, because voltage to ensure adequate braking current is not induced. This renders dynamic or regenerative braking insignificant in lower speeds. Thus, 3 more experiments are done to see low speed braking performance of open circuit (OC), short circuit (SC) and plug braking performances. In these experiments, armature voltage is 4.6V and the relevant speed is 300min^{-1}.

i. Stopping time in OC: 25s
ii. Stopping time in SC: 10s
iii. Stopping time in 36V Plug Brake: 3.5s

e. Regenerative Braking

Lastly, an experiment was performed to observe regenerative braking characteristic. To perform this experiment, 36V battery pack is used to receive the braking energy and as a voltage source. BLDC motor was operated as a generator. Armature voltage decreases while the motor speed decreases so, for low speed values it is not possible to charge the batteries directly. There should be a converter that increases the armature voltage to desired values and this process can be done simply by a boost converter. An equivalent circuit for this experiment is given in Fig. 4.5.

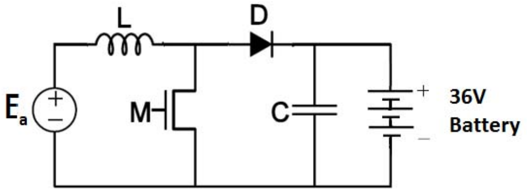

Fig.4.5 Regenerative braking equivalent circuit

Experiment has been performed at 1000 min^{-1} for no load condition and for different duty ratios and results are given in Fig. 4.6.

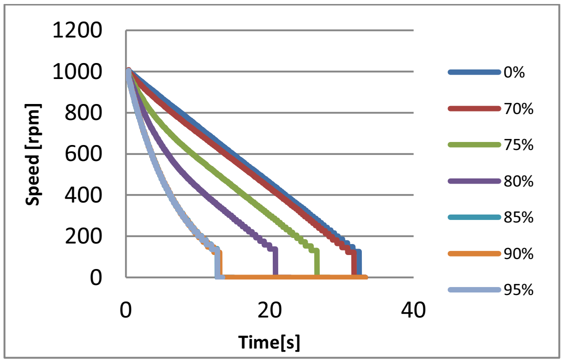

Fig. 4.6 Regenerative braking experiment results

As it is seen from the experiment results regenerative braking is remarkable for certain duty ratios. For the duty ratio 70%, boost operation is not succeeded and as a result regenerative braking is not possible for this value. For the duty ratios 75-90% boost operation is successful and regenerative braking can be observed clearly. The braking time for 95% duty ratio is almost equal to %90 percent. Thus, 90% can be assumed for upper limit for regenerative braking for this case. During the experiment, battery open circuit voltage is around 38.7V. During braking, armature voltage of the BLDC at 1000min^{-1} is around 15.3V. This is why duty cycle values bigger than (~3.3 times boost) working mode is meaningful to brake the system since at least 2.5-3 times boost is required to achieve enough voltage levels to charge batteries.

5. Conclusions

In this paper, dynamics of electrical braking is investigated. It is seen that, the three possible braking strategies have limitations. Regenerative braking is useless if the system could not induce enough voltage. If the batteries are full, it is not possible to brake. For dynamic braking, even if the system is short circuited, there would be a resistance, sometimes not low enough to create adequate breaking torque or in other words; current. In slower speeds, amount of electrical braking becomes insignificant and it is not possible to quickly stop a slowly running system with regenerative or dynamic braking. Plug braking is difficult to utilize since it produces high currents and consumes energy, but to be able to achieve a total coverage of slowing down with electric braking, blending of regenerative/dynamic and plug braking is necessary.

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