Design and Implementation of an Efficient Regenerative Braking System for a PMSM Drive

Peter K. Abraham  
Department of Electrical Engineering  
National Institute of Technology  
Calicut, India

Dr. S. Ashok  
Department of Electrical Engineering  
National Institute of Technology  
Calicut, India

Abstract - This paper proposes an efficient regenerative braking system for a PMSM Drive which is very much suitable for electric and hybrid vehicles. The proposed method is such that the mechanical energy associated with the PMSM at the time of braking is used to charge an ultra-capacitor. This regenerative system converts the mechanical energy into electric energy only by using a buck converter hence this method is very efficient and cheap. The recovered energy can be used to meet the electrical demands of the vehicle.

Vehicles and hybrid vehicles. Kinetic energy associated with the vehicle at the time of braking can be recovered to energy storage devices instead of being wasted as heat. So regenerative braking is a key technology to extend the driving range.

II. REGENERATIVE BRAKING OF PMSM

When a conventional vehicle applies its brakes the energy stored in the vehicle is converted to heat due to the friction between the wheels and brake pads. The air stream will carry away this heat. The total amount of energy lost in this way depends on the intensity and periodicity of the brakes application. Regenerative braking refers to a process in which a portion of the kinetic energy of the vehicle is stored by a short term storage system during the braking process.

At present most electric drives for electric trams work with dc machines or induction machines. The efficiency of dc machine is very low and only grid connected/battery connected system can extract braking energy from the induction motor powered electric vehicles because the induction motor requires reactive power to operate as generator. Therefore complicated circuit is required. But reactive power is not required for PMSM to operate in the generator mode, because it has already permanent magnet inside the motor to produce the required flux. Hence with a simple buck converter the kinetic energy stored in the vehicle can be converted into electrical energy. Thus compared to induction motor, regenerative braking in PMSM can be implemented more effectively and less costly. Some of the advantages of the regenerative braking system are
1) Improved fuel economy,
2) Reduction in emissions,
3) Improved performance,
4) Reduction in engine and brake wear.
5) The stop time decreases greatly by this electrical braking.
6) Low resource occupancy for the control.

Figure 1 summarizes the basic scheme of Vector Controlled PMSM with regenerative braking.

III. OPERATING PRINCIPLE OF PMSM DRIVE WITH REGENERATIVE BRAKING
The operation of the vector controlled PMSM drive with regenerative braking is classified into two modes which include the operation during motoring and operation during braking.

A) Operation during Motoring
Fig. 2 shows the motoring mode. In this mode switch \( S_1 \) is permanently closed and the PMSM will operate in vector controlled mode as motor.

B) Operation during Braking
Fig. 3 shows the braking mode. In this mode switch \( S_1 \) is permanently open and the rotational energy associated with the PMSM will be used to charge a super capacitor through a constant current buck converter. The braking time can be adjusted by varying the capacitor charging current.

IV. IMPLEMENTATION OF REGENERATIVE BRAKING SYSTEM
The details of the PMSM used in this experiment are given

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Power</td>
<td>1.07kW</td>
</tr>
<tr>
<td>DC Bus voltage</td>
<td>300V</td>
</tr>
<tr>
<td>Stator current</td>
<td>16A peak</td>
</tr>
</tbody>
</table>
A) Design of the Flywheel

Time to achieve the full speed at rated voltage = 5sec

Maximum angular speed, \( \omega = \frac{2\pi \times 4000}{60} = 418.66 \text{ rad/sec} \)

Maximum torque of the motor = 3.6Nm.

The torque equation of the motor \( T = J \frac{d\omega}{dt} + B\omega \) ------ (1)

From(1) the required MI of the flywheel \( J = 0.0414823 \text{ Kg-m}^2 \)

But \( J = \frac{1}{2} mR^2 = 0.0414823 \text{ Kg-m}^2 \)

The radius of the flywheel with a mass of 3kg is 0.166m

Hence a radius of 15cm is selected.

Moment of Inertia of the flywheel = \( \frac{1}{2} \times 3 \times (0.15)^2 = 0.03375 \text{ Kg-m}^2 \)

Maximum KE stored in the flywheel at 4000rpm = \( (\frac{1}{2})^*\times 0.03375 \times (2 \times \pi \times 4000/60)^2 = 3000 \text{ J} \)

B) Design of the storage Capacitor (Neglecting all losses)

Maximum KE stored in the flywheel = 3000J

Energy to be stored in the capacitor = 3000J

ie (\( \frac{1}{2} \))CV^2 = 3000J

Select a super capacitor with 2.5V

The capacitance required = 960F

The capacitor selected is 2.5V, 2000F.

To limit the capacitor current a 0.5Ω resistor is connected in series with the capacitor.

C) Design of constant current Buck converter

A buck converter is required to charge the capacitor in constant current mode. When the capacitor is getting charged the input voltage (DC bus voltage) will decrease. But for effective charging the output current shall be constant. Figure 4 shows the basic scheme of a constant output current buck converter for charging the super capacitor.

D) Design of the buck converter Filter circuit.

1) Inductor

The inductor is designed for the minimum duty ratio of 0.008 and a ripple current of 2A.

\[ L = \frac{V_{max} D_{min}}{\Delta I_f} = \frac{300}{0.008} = 0.008H = 8\text{mH} \]

Hence a 10mH inductor is selected.

2) Capacitor

The capacitor is designed for the minimum duty ratio of 0.008 and a ripple voltage of 0.5V and a maximum charging current of 50A

\[ C = \frac{1-D}{\Delta V_{ref}} = \frac{50 \times 0.008}{0.5 \times 5 \times 10^5} = 53.3\mu F \approx 100\mu F \]

Hence a 100μF capacitor is selected.

V. MATHEMATICAL MODEL OF BRAKING CIRCUIT WITH THE GIVEN PMSM AND FLY WHEEL.

a) General expression for reference current for required brake time.

The Energy stored in the flywheel at any speed
\[ E = \frac{1}{2} J \omega^2 \]
\[ = 1.712 \times 10^{-4} \text{ N}^2 \]  \hspace{1cm} \text{---------}(2)

In constant current mode Energy stored in the capacitor
\[ = \frac{1}{2} \left( \frac{(lt)^2}{C} \right) \]  \hspace{1cm} \text{---------}(3)

During energy transfer (Neglecting PMSM losses and switching losses)
\[ \frac{(1/2)J^2\omega^2}{2} = \frac{1}{2} \left( \frac{(lt)^2}{C} \right) + I^2 R t \]  \hspace{1cm} \text{---------}(4)
\[ 1.8487 \times 10^{-4} \text{ N}^2 = \frac{1}{2} \left( \frac{(lt)^2}{C} \right) + I^2 R t \]
\[ I_{\text{ef}} = 0.01359 \left( \frac{N}{\sqrt{\frac{t^2}{2C} + Rt}} \right) \]  \hspace{1cm} \text{---------}(5)

b) Expression for voltage at the DC bus of the given PMSM during Braking
Consider eqn.(4)
\[ \frac{(1/2)J^2\omega^2}{2} = \frac{1}{2} \left( \frac{(lt)^2}{C} \right) + I^2 R t \]

Differentiate both sides wrt time
\[ J_0 \frac{d\omega}{dt} = \frac{1}{C} I + I^2 R \]  \hspace{1cm} \text{---------}(6)

Voltage at the DC side bus of the given PMSM in braking mode, \( V = k \omega \), \( k=0.72 \)  \hspace{1cm} \text{---------}(7)

Therefore \( \frac{dV}{dt} = k \frac{d\omega}{dt} = k \frac{d\omega}{dt} \)  \hspace{1cm} \text{---------}(8)

Substitute eqn.(7) in (5)
\[ \frac{J_0 \omega}{k} \frac{dV}{dt} = \frac{1}{C} I + I^2 R \]
\[ \frac{dV}{dt} = \frac{k}{J_0} \left( \frac{1}{C} I + I^2 R \right) \]  \hspace{1cm} \text{---------}(9)

But, \( \omega = \frac{V}{k} \) Therefore \( \frac{dV}{dt} = \frac{k^2 R}{IV} \left( \frac{1}{C} I + R \right) \)

The waveforms are shown below.

A) Speed - 4000rpm, braking time - 10s

B) Speed - 1500rpm, braking time - 10s

Let \( C=2000F, R=0.5\Omega, k = 0.72 \), \( J=0.03375 \)
\[ V(t) = 5.5431 \left( \sqrt{\frac{t^2}{4000} + \frac{t^2}{2}} \right) \]  \hspace{1cm} \text{---------}(11)

VI. SIMULINK MODEL OF REGENERATIVE BRAKING

Fig. 9.1 shows the simulation model of regenerative braking system, ie a constant current buck converter charged from a decreasing voltage.

VII. SIMULATION RESULT

According to the proposed constant current buck converter the simulation model, run in Matlab with a 2000F, 2.5V ultra capacitor for different braking times and speeds.

The waveforms are shown below.

A) Speed - 4000rpm, braking time - 10s

B) Speed - 1500rpm, braking time - 10s
**VIII  EXPERIMENTAL SET UP**

The experimental set up is shown below.

**IX  EXPERIMENTAL RESULT**

The Vector controlled PMSM with an efficient regenerative braking system were tested successfully with the hardware mentioned earlier and the performance were monitored and is as expected. The results were tabulated for various conditions. PMSM speed and capacitor current waveform at 1500rpm is shown below.

A) Speed curve for normal stopping

![Speed curve for normal stopping](image)

B) Speed curve for 10S Braking time.

![Speed curve for 10S Braking time](image)

C) Capacitor current for 10S braking time.

![Capacitor current for 10S braking time](image)

**X. CONCLUSION**

The paper proposes an efficient regenerative braking system for a vector controlled PMSM drive and explain how the kinetic energy associated with the moving vehicle is converted into electrical energy that can be used to charge an ultra capacitor. The proposed method converts the mechanical energy into electric energy only by using a buck converter. Hence this method is very efficient and cheap. Therefore more investigations are required in this area. Finally experimental results with a 1.07kW PMSM are given to analyse the effectiveness of the proposed method.

**XI. REFERENCES**


