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

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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.

Keywords: Regenerative braking, Super capacitor, Permenant magnet synchronous motor (PMSM), Vector Control, V/F Control.

I. Introduction

In recent years, because of global environmental pollution and oil crisis, most developed countries are trying to reduce the use of fossil fuel as a source of energy. Hence green energy industry is getting more and more attention. At present most electric drives for electric trams work with induction motors or DC motors. But the demands for improved energy savings combined with precision operation has increasingly led engineers to specify permanent magnet synchronous motors (PMSM). This is because the PMSM has many features like high efficiency, compactness, smooth torque, high torque to inertia ratio, high pull out torque, higher power factor, good heat dissipation, good overloading capability, rapid dynamic response, simple modelling and control, low noise and maintenance free operation. Another advantage of PMSMs is that they typically have a wider speed range than AC induction motors. As a general rule PMSMs are rated for 20:1 speed range without feedback (open loop) or 2000:1 closed loop (with encoder). Depends upon the supply frequency the motor runs at constant speed at any torque up to the motor's operating limit. Therefore PMSM are suitable for high accuracy, fixed speed drives. Regenerative braking is an advantage to electric 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 performace,

4)Reduction in engine and brake wear.

5)The stop time decrease 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.

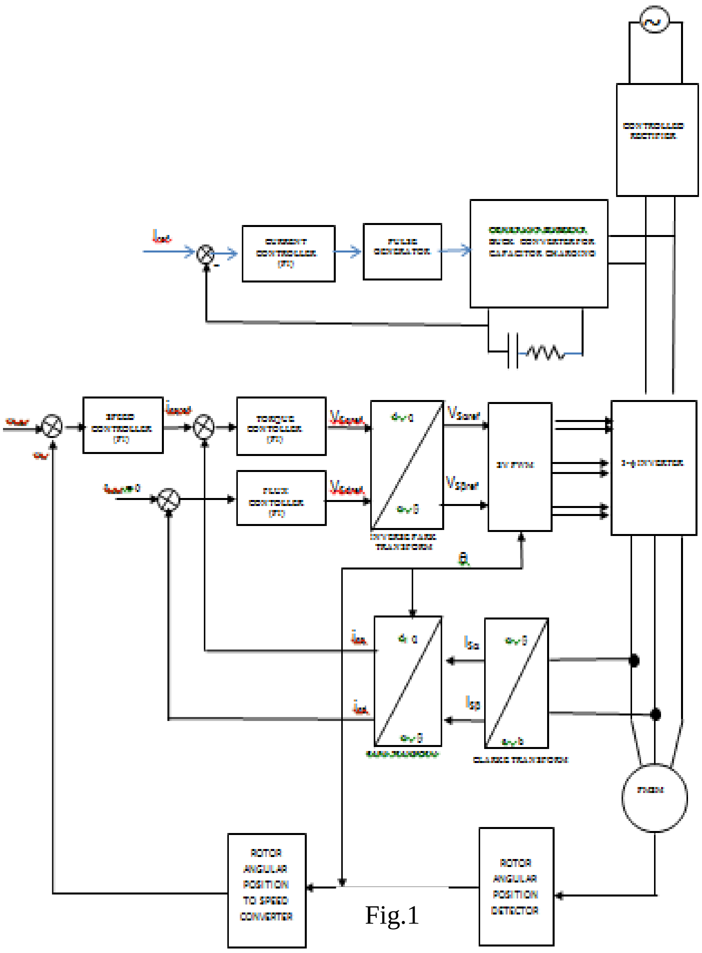


Fig.1

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 permenantly closed and the PMSM will operate in vector controlled mode as motor.

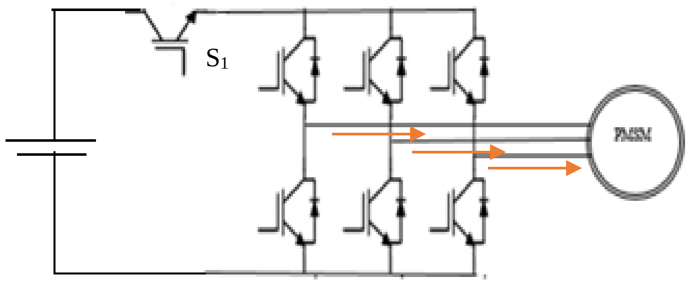


Fig.2

B)Operation during Braking

Fig. 3 shows the braking mode. In this mode switch S_1 is permenantly open and the rotational energy associated with the PMSM will used to charge a super capacitor through a constant current buck converter.The braking time can be ad0justed by varying the capacitor charging current.

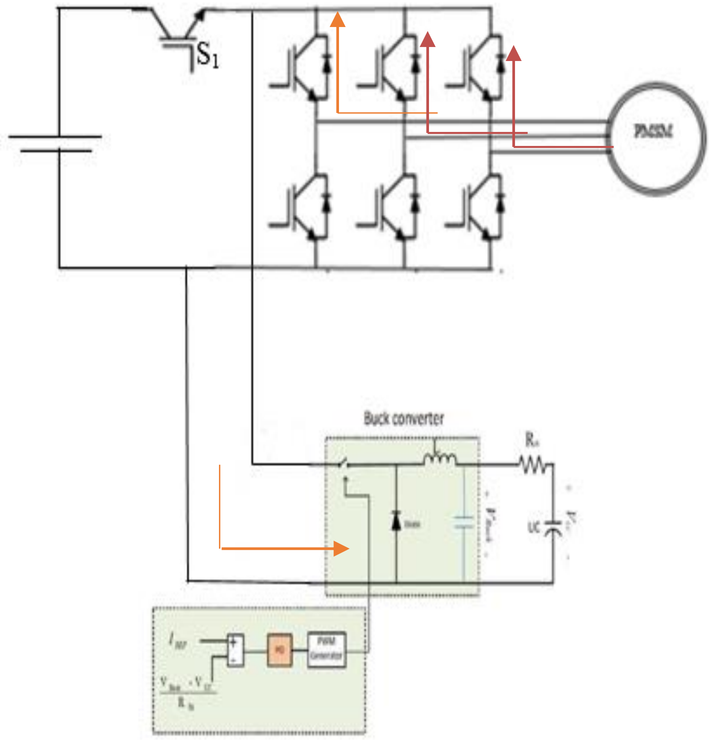


Fig.3

IV. IMPLEMENTATION OF REGENERATIVE BRAKING SYSTEM

The details of the PMSM used in this experiment are given

Rated Power	1.07kW
DC Bus voltage	300V
Stator current	16A peak

Rated speed	4000rpm
Rated torque	3.6N-m
Number of poles	4
Stator resistance	1.0Ω
D-axis inductance	0.009Ω
Q-axis inductance	0.024Ω
Permanent magnetic flux	0.123Wb
Moment of Inertia(J)	0.000629Kg-m^2

A)Design of the Fly wheel

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

Maximum angular speed, ω = $\frac{2*\pi*4000}{60}$ = 418.66 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 fly wheel J =0.0414823Kg-m^2

But J = $\frac{1}{2}mR^2$ = 0.0414823 Kg-m^2

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

Hence a radious of 15cm is selected.

Moment of Inertia of the fly wheel

= (½)* 3* (0.15)^2 = 0.03375 Kg-m^2

Maximum KE stored in the flywheel at 4000rpm

= (1/2)*J*ω^2 = (½)*0.03375*(2* π *4000/60)^2 = 3000 J

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

Maximum KE stored in the fly wheel = 3000J

Energy to be stored in the capacitor = 3000J

ie (½)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.

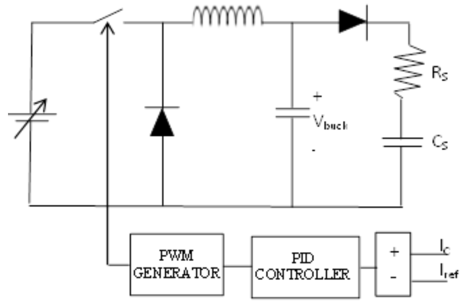


Fig.4

The frequency of the pulse	-	15kHz
Maximum buck input voltage	-	300V
Minimum buck input voltage	-	2.5V
Minimum buck output voltage	-	0V (In fully discharged condition)
Maximum buck output voltage	-	2.5V
Maximum Duty ratio	-	1.0V
Minimum duty ratio	-	0.008

Duty ratio has to be varied from 1 to 0.008

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.

$L = \frac{V_{imax}D_{min}}{\Delta i_L f} =$ = 0.008H= 8mH

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

$C = \frac{I_0 D}{\Delta V_0 f} = \frac{50*0.008}{0.5*15*10^3}$ = 53.3μF ≈ 100μF

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

$E = (1/2)*J*\omega^2$

$= 1.712*10^{-4}\ N^2$ -------(2)

In constant current mode Energy stored in the capacitor

$$= \frac{1}{2}\left(\frac{(It)^2}{C}\right)$$ -------(3)

During energy transfer(Neglecting PMSM losses and switching losses)

$$(1/2)*J*\omega^2 = \frac{1}{2}\left(\frac{(It)^2}{C}\right) + I^2Rt.$$ -------(4)

$$1.8487*10^{-4}\ N^2 = \frac{1}{2}\left(\frac{(It)^2}{C}\right) + I^2 R t$$

$$\mathbf{I_{ref} = 0.01359\left(\frac{N}{\sqrt{\frac{t^2}{2C} + Rt}}\right)}$$ -------(5)

b)Expression for voltage at the DC bus of the given PMSM during Braking

Consider eqn.(4)

$$(1/2)*J*\omega^2 = \frac{1}{2}\left(\frac{(It)^2}{C}\right) + I^2Rt.$$

Differentiate both side wrt time

$$J\omega\frac{d\omega}{dt} = \frac{I^2}{C}t + I^2R$$ -------(6)

Voltage at the DC side bus of the given PMSM in braking mode, $V = k\omega$, (k=0.72) -------(7)

Therefore $\frac{dV}{dt} = k\frac{d\omega}{dt} = k\frac{d\omega}{dt}$ -------(8)

Substitute eqn.(7) in (5)

$$\frac{J\omega}{k}\frac{dV}{dt} = \frac{I^2}{C}t + I^2R$$

$$\frac{dV}{dt} = \frac{k}{J\omega}\left(\frac{I^2}{C}t + I^2R\right)$$ -------(9)

$$= \frac{kI^2}{J\omega}\left(\frac{t}{C} + R\right)$$

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

$$V\frac{dV}{dt} = \frac{k^2I^2}{J}\left(\frac{t}{C} + R\right)$$

$$VdV = \frac{k^2I^2}{J}\left(\frac{t}{C} + R\right)dt$$

On integration we get

$$\int_0^V VdV = \int_0^t \frac{k^2I^2}{J}\left(\frac{t}{C} + R\right)dt$$

$$V = \sqrt{\frac{2k^2I^2}{J}\left(\frac{t^2}{2C} + Rt\right)}$$ -------(10)

Therefore the DC bus voltage at any instant of braking

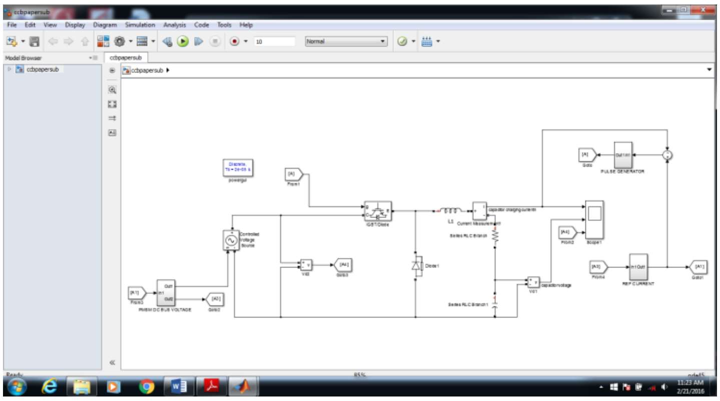
$$V(t) = V - \sqrt{\frac{2k^2I^2}{J}\left(\frac{t^2}{2C} + Rt\right)}$$

Let C =2000F, R=0.5Ω , k = 0.72 , J=0.03375

$$\mathbf{V(t) = V - 5.543I\sqrt{\left(\frac{t^2}{4000} + \frac{t}{2}\right)}}$$ --------(11)

VI. SIMULINK MODEL OF REGENERATIVE BRAKING

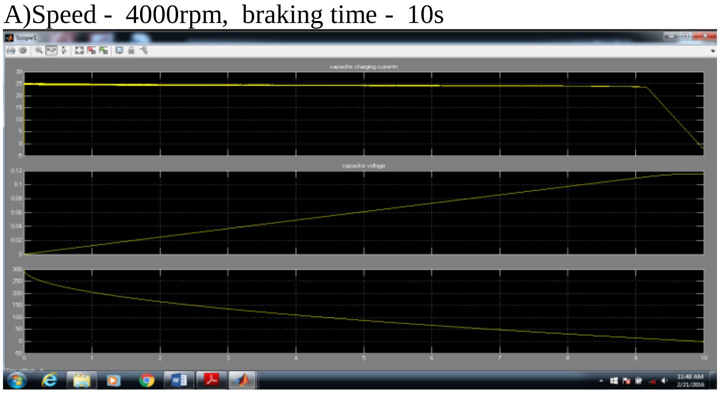
Fig. 9.1 shows the simulation model of regenerative braking system, ie a constant current buck converter charged from a decreasing voltage.



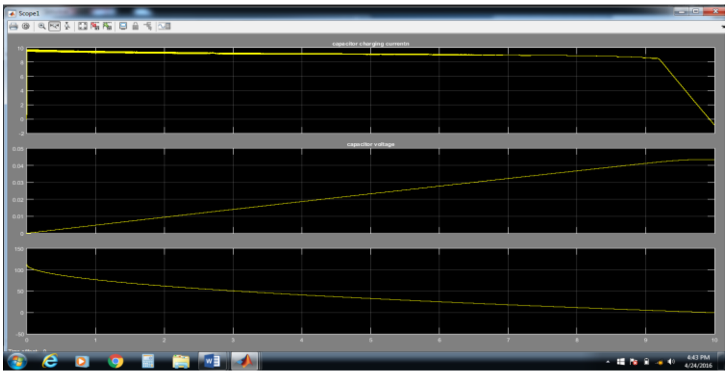
VII. SIMULATION RESULT

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



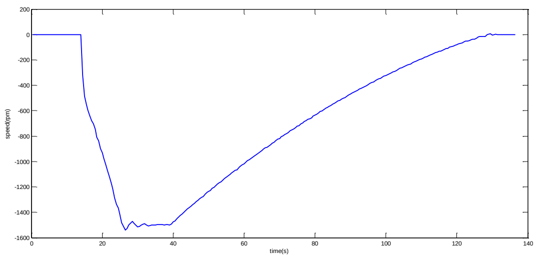
VIII EXPERIMENTAL SET UP

The experimental set up is shown below.

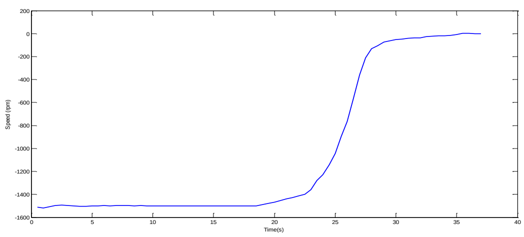
IX EXPERIMENTAL RESULT

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

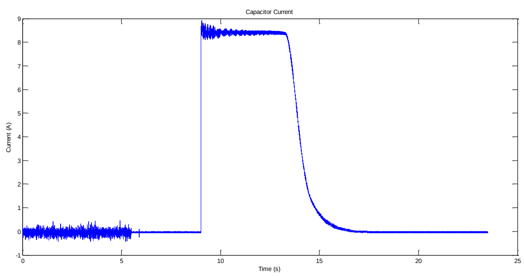
A)Speed curve for normal stopping



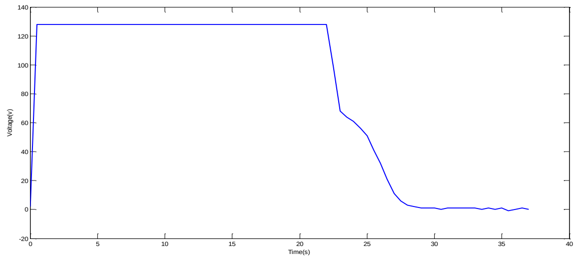
B)Speed curve for 10S Braking time.



C)Capacitor current for 10S braking time.



C)DC bus voltage at the time of regeneration.



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 metod 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

[1] Mrs. S S Kulkarni, A G Thosar Mathematical Modeling and Simulation of Permanent Magnet Synchronous Machine International Journal of Electronics and Electrical Engineering Vol. 1, No. 2, June 2013

[2] Květoslav Belda, Mathematical Modelling and Predictive Control of Permanent Magnet Synchronous Motor Drives. Transactions on Electrical Engineering, Vol. 2 (2013), No. 4.

[3] Kiran Boby, Prof.Acy M Kottalil, N.P.Ananthamoorthy. Mathematical Modelling of PMSM Vector Control System Based on SVPWM with PI Controller Using MATLAB. International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering Vol. 2, Issue 1, January 2013

[4] Tzu-Yu Liu1, Cheng-Hu Chen2, Wen-Chun Chi1 ,and Ming-Yang Cheng Study on the Current Control Loop of PMSM Based on Sinusoidal Commutation IEEE PEDS 2011, Singapore, 5 - 8 December 2011

[5] ZHANG Kangkang, LI Jianqiu, OUYANG Minggao Dept. of Automotive Engineering, Tsinghua Universtiy Beijing, 100084, China.Electric Braking Performance Analysis of PMSM for Electric Vehicle Applications. 2011 International Conference on Electronic & Mechanical Engineering and Information Technology