International Electrical Engineering Journal (IEEJ)
Vol. 3 (2012) No. 2, pp. 784-790
ISSN 2078-2365

Different Braking Techniques Employed to a Brushless DC Motor Drive used in Locomotives

M.Rakesh, P.V.R.L. Narasimham
Department of EEE., Gudlavalleru Engineering College, Gudlavalleru-521356, A.P, India

***Abstract*— Brushless Direct current (BLDC) motors are gaining attention these days in many applications because of their simplicity in its control and high power density. Due to their usage many advances are taking place in field of automobiles in general and locomotives in particular. To have an effective control over the locomotive it is desirable to have control over starting, running and braking of a bldc drive. This paper mainly describes about different types of braking that can be applied to a bldc drive used in locomotives. Various braking methods are introduced and described. The braking of bldc motor is simulated in MATLAB/Simulink. The simulation results are presented and comparative study is made.**

Key words: **BLDC drive, braking methods, locomotives, Matlab/Simulink.**

I. INTRODUCTION

Brushless Direct current (BLDC) motors are one of the motor types rapidly gaining popularity in industry such as appliances, automotives, aerospace, consumer, medical, industrial automation equipment and instrumentation. Recent trend in automobile industry is using these BLDC motors as electric vehicles as these are energy efficient and pollutant free. Simulation studies indicate that a 15% longer driving range is possible for an electric vehicle with PM brushless motor drive systems compared with induction types.

As the name implies, BLDC motors do not use brushes for commutation; instead they are electronically commutated. In BLDC motor since the back emf is non sinusoidal, the inductance do not vary sinusoidally in the abc frame and it does not seem advantageous to transform the equations to d-q frame since inductances will not be constant after transformation [5].

The braking of BLDC motors is quite easier as these machines employ a permanent magnet as its rotor. The braking methods of a BLDC motor are similar to that of a direct current machine. This paper deals with different types of braking applicable to a BLDC drive. The performance of locomotive is examined for dynamic braking, plugging and regenerative braking and simulation results are presented.

II. MATHEMATICAL MODELING OF BLDC MOTOR

In modeling a BLDC motor, abc phase variable model is preferred to d-q axis model as the mutual inductance between stator and rotor is non-sinusoidal[1]. The mathematical modeling is done in abc phase variable model and is expressed in state-space form.

Following assumptions are made in modeling the BLDC motor[10].

- The motor is not saturated.
- Stator resistances of all the windings are equal and self and mutual inductances are constant.
- The power semiconductor devices are ideal.

The voltage equations of the three phase stator windings are

$$\begin{pmatrix} v_a \\ v_b \\ v_c \end{pmatrix} = \begin{pmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{pmatrix} \begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} + p \begin{pmatrix} L & M & M \\ M & L & M \\ M & M & L \end{pmatrix} \begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} + \begin{pmatrix} e_a \\ e_b \\ e_c \end{pmatrix} \quad (1)$$

The generated electro-magnetic torque equation is

$$T_e = (e_a i_a + e_b i_b + e_c i_c)/\omega_m \quad (2)$$

The equation of motion is

$$p\omega_m = (T_e - T_l - B\omega_m)/J \quad (3)$$

These voltage equations are transformed to state-space form and are arranged as follows:

$$p \begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} = \begin{pmatrix} -R/L & 0 & 0 \\ 0 & -R/L & 0 \\ 0 & 0 & -R/L \end{pmatrix} \begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} + \begin{pmatrix} 1/L & 0 & 0 \\ 0 & 1/L & 0 \\ 0 & 0 & 1/L \end{pmatrix} \begin{pmatrix} v_a \\ v_b \\ v_c \end{pmatrix} \quad (4)$$

Where

v_a, v_b, v_c are the voltages of the three phases a,b and c in volts

R is resistance of each phase of motor in ohms

i_a, i_b, i_c are the currents of the three phases a,b and c in amperes.

p is the derivative

International Electrical Engineering Journal (IEEJ)
Vol. 3 (2012) No. 2, pp. 784-790
ISSN 2078-2365

L is self inductance of each phase of motor in henrys

M is mutual inductance between respective phases in henrys

e_a, e_b, e_c are the back emfs of the three phases a,b and c in volts

T_e is the electromagnetic torque in Newton meters

ω_m is the mechanical speed of the motor in radians per second

T_l is load torque in Newton meters

B is damping constant in newtons per radian per second

J is inertia of rotor in $kg - m^2$

L is difference of self and mutual inductances in henrys

The modeling of the machine during motoring operation is presented above and is modified for different braking operations.

III. BRAKING AND TYPES OF BRAKING

In locomotives, precise control over stopping of machine is important along with start. In such a case to stop the machine quickly and accurately, braking methods are useful. Braking is nothing but stopping the machine at a desired position. Ideal braking is bringing the machine to rest in no time.

Braking of locomotive can be done as electric braking or mechanical braking. In mechanical braking the motion is restricted by the friction applied by mechanical brakes which is preferred during low speeds. In electric braking the motor works as a generator developing a negative torque which restricts the motion. The purpose of electrical braking is to restrict the motion of the machine as quick as possible. Electric braking cannot replace the ordinary mechanical brakes, as the vehicle cannot be held stationary by it. In locomotives, for the braking to be done perfectly and smoothly, electric braking in conjugation with mechanical braking is used. This is done by applying electrical braking to slow down the locomotive to a lower speed and then mechanical brakes are applied.

During electric braking the motor torque will reverse and the machine will work as a generator, absorbing mechanical energy from load and converting it into electrical energy. The mechanical energy is obtained from the load either from the energy stored in the inertia of the motor load system or from the active load torque when the locomotive is moving down gradient. Electrical braking reduces the wear of the brake shoes and gives higher rate of braking retardation, thus brings the vehicle quickly to rest and shortens the running time to a considerable extent.

Braking action can be achieved by generating a torque of opposite polarity (braking torque) to that of motoring torque which opposes the motion. If the input current is in phase with back emf, motoring torque is developed otherwise if the input current is in out of phase with back emf then braking torque is developed.

The electro magnetic torque developed in phase 'a' is

$$T_{ea} = (e_a * i_a)/\omega_r \qquad (5)$$

Braking during forward motoring is called forward braking while it is in reverse rotation is called reverse braking. In Speed-Torque plane, forward braking will result in second quadrant operation where as reverse braking results in fourth quadrant operation.

Figure.1. is a basic bldc motor drive used in locomotives.

a three phase inverter is used for exciting the three phase bldc motor. For the motor control, Commutation logic and control block takes the rotor position, torque command and current feed back as inputs for switching the gate drives of the switches.

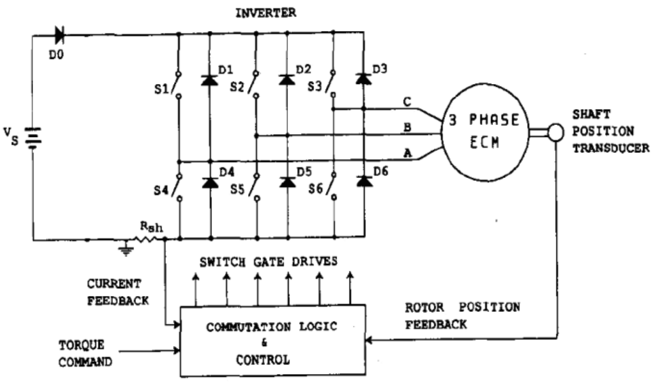


Figure.1 Basic BLDC Motor drive during normal operation

Electric braking to above drive can be implemented in three ways namely Dynamic Braking, Plugging and Regenerative Braking.

A. DYNAMIC BRAKING

Dynamic braking is bringing the machine to rest position by dissipating the kinetic energy possessed by the rotor of motor in the form of heat energy through some external resistance.

This braking can be implemented by disconnecting the power supply to windings and short circuiting them. The short circuited windings carrying higher magnitudes of current will damage the windings. To limit the short circuit current flowing in these windings, an external resistance R is connected in series with the windings. This resistance is used to limit current and is called braking resistance. Thus, the power generated in the three stator windings during

International Electrical Engineering Journal (IEEJ)
Vol. 3 (2012) No. 2, pp. 784-790
ISSN 2078-2365

braking is wasted in the external resistance.

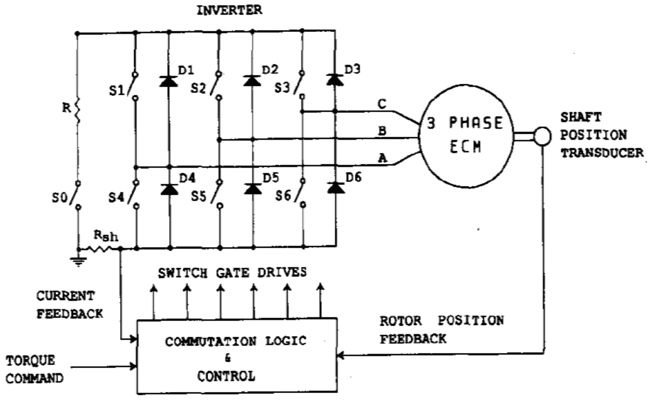


Figure.2 Circuit configuration of bldc motor drive during dynamic braking

Fig.2 is an implementation of dynamic braking to the drive in fig.1. The generated power is dissipated in the resistor R through the fed back diodes. When fast braking is desired, that is in order to keep the braking torque at a fixed value the resistance has to be decreased with time. This is done by controlling switch *So* [4].

The equation of speed during normal operation is

$$\omega = (V/K) - (R*T)/K^2 \qquad (6)$$

For dynamic braking V=0, then the speed equation becomes

$$\omega = -(R*T)/K^2 \qquad (7)$$

Here R is the resistance of winding after insertion of braking resistance. So during dynamic braking the speed-torque relation is in the form of a straight line which passes through the origin with a negative slope of $-R/K^2$.

B. PLUGGING

Plugging is a method of braking obtained by reversing the applied supply voltage, so that the input voltage assists the back emf in forcing armature current in reverse direction. This reversed current will have impact on torque, thus producing deceleration. Plugging provides faster braking response because braking torque is high as the magnitude of current during this braking is high. Even though plugging provides faster braking response it is highly in-efficient because in addition to generated power, the power supplied by the source is also wasted in resistances and plugging increases the inverter rating also. Plugging can be implemented to the drive in figure.1 by reversing the voltage (by high speed switches) and a braking resistance is connected just as in dynamic braking.

The speed equation now becomes

$$\omega = (-V/K) - (R*T)/K^2 \qquad (8)$$

So plugging provides torque at zero speed. when reverse voltage is applied for stopping the locomotive the supply must be disconnected at the instant where speed is close to zero. Otherwise it will rotate in reverse direction (reverse motoring takes place).

The speed-torque relation is of the form of a straight line with a negative intercept. Thus the speed-torque plot during plugging doesn't pass through origin, it is a straight line having a slope of $-R/K^2$ and having a negative intercept of $-V/K$.

C. REGENERATIVE BRAKING

In regenerative braking, instead of wasting the power in external resistance the power generated during retardation is fed back towards the source i.e., the motor works as a generator developing a negative torque which opposes the motion and the generated energy is supplied to the source.

For the generated energy to be supplied to the source two conditions should be satisfied

i) back emf should be greater than supply voltage (E > V) for all speeds

ii) Current has to reverse its direction

For the above two conditions to be satisfied, increase the back emf so that it is greater than the supply voltage. In order to increase the back emf, increase the speed. The speed increases when the locomotive is moving down the gradient or by increasing the field flux. But increasing the field flux beyond rated is not possible as the permanent magnets are used in field system. So, for a source of fixed voltage of rated value regenerative braking is possible only for speeds higher than rated value and for a variable voltage source it is possible for below rated speeds also.

During regeneration if the generated power is not absorbed by the load, it will be supplied to the line and the line voltage will rise to dangerous values leading to insulation break down. Hence regenerative braking should be used only when there are loads connected to absorb regenerated power.

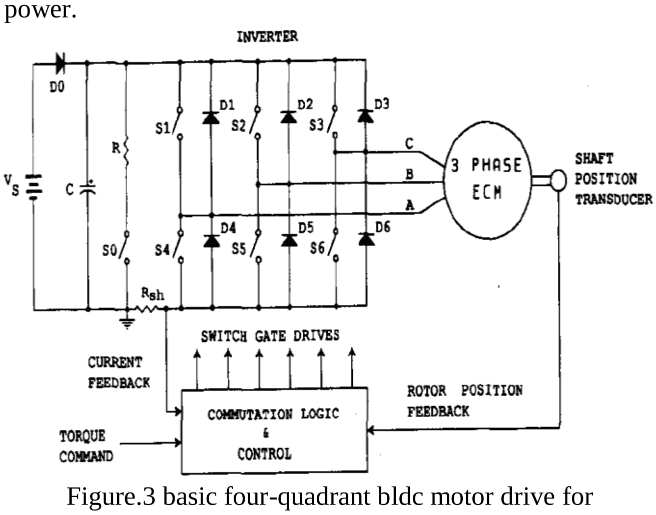


Figure.3 basic four-quadrant bldc motor drive for regeneration

Figure.3 shows a basic four-quadrant electronically commutated motor drive which provides regenerative braking. During regeneration the capacitor *C* stores the energy recovered from the load through the feed back diodes

International Electrical Engineering Journal (IEEJ)
Vol. 3 (2012) No. 2, pp. 784-790
ISSN 2078-2365

across the switches. To limit the capacitor *C* voltage to a safer value Switch *S0* is used to dissipate the excess energy through the resistor.

The speed equation during regeneration becomes

$$\omega = (V/K) - (R*T)/K^2 \qquad (9)$$

The above equation is of the form of a straight line with a positive intercept. As we keep on decreasing the voltage with reference to back emf, the voltage becomes zero finally. Thus the speed equation becomes

$$\omega = (V/K) + (R*T)/K^2 \qquad (10)$$

So during regenerative braking the speed-torque relation is in the form of a straight line which passes through the origin with a slope of R/K^2.

IV. SIMULATION RESULTS

The locomotive system is developed using the motor parameters listed in below table:

Voltage V_{dc},(volts)	200	Torque constant K_t(Nm/A)	0.66
No of Poles, 2P	4	Rotor inertia J(kg-m²)	0.79
Winding resistance R_s(Ω)	1.4	Noload Speed N_{nl}(rpm)	5400
Winding inductance Ls(mH)	8.90	Stalling Torque T_{stall}, (Nm)	8

In my model, initially the machine is started as a motor and is subjected to braking after the locomotive reaches a steady speed. Three different types of brakings are performed in MATLAB / SIMULINK.

A. DYNAMIC BRAKING

During simulation, machine is allowed to attain a steady speed initially and after that at 0.05sec dynamic braking is applied. The simulation results are obtained.

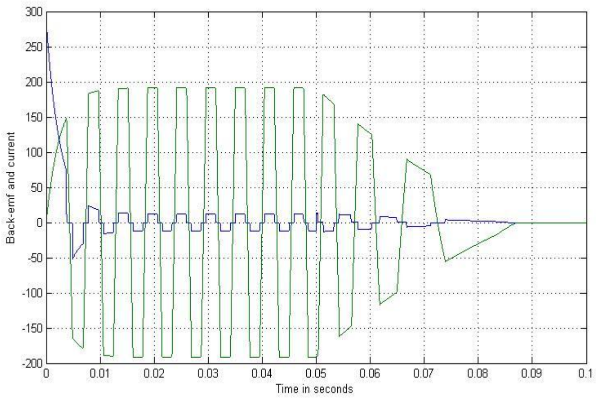


Figure.4 Current and Back emf waveforms during dynamic braking

Figure.4 shows the variation of current and back emf waveforms from motoring to dynamic braking. Here a reversal in current is observed (at 0.05 sec) but not in back emf, this produces negative torque called braking torque. The magnitude of current during braking will decide the braking time and it exists till the kinetic energy possessed by rotor is dissipated completely. This current has to be restricted in order to protect the circuitry from damage. To limit the current we can use fixed or variable resistance, but variable resistance is employed in order to decrease the braking time.

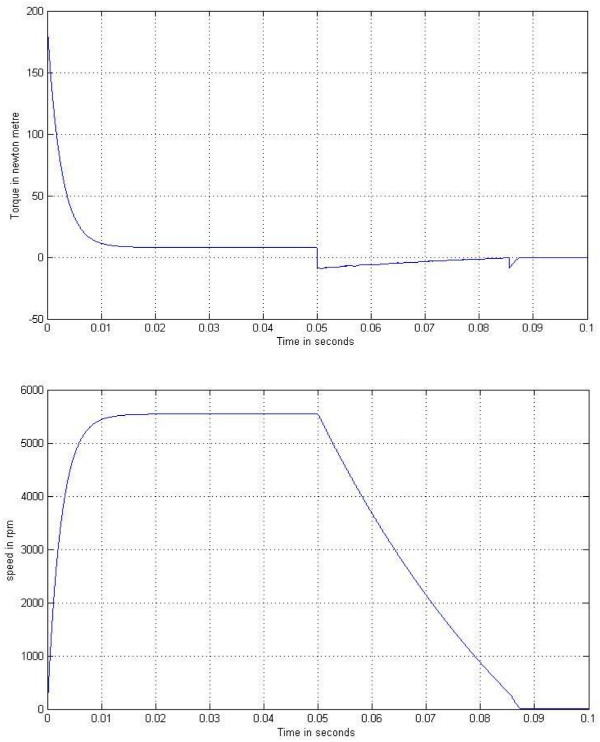
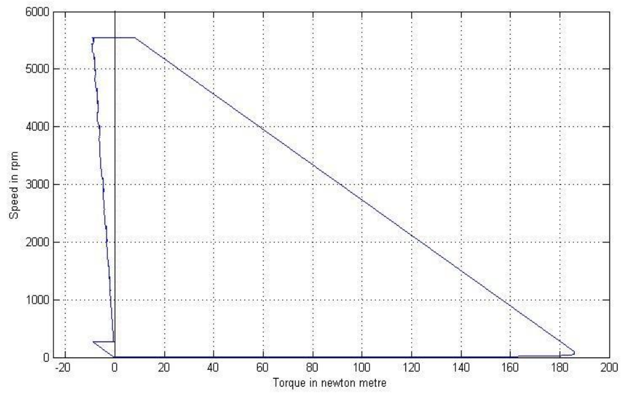


Figure.5 a) Torque and b) Speed waveforms during dynamic braking

Initially the vehicle attained a steady speed in 0.03sec during motoring. At time t =0.05sec, the dynamic brake is applied which developed a negative torque that opposed the motion and tended the locomotive to rest. The time taken by the locomotive to reach zero speed is 37.5 milliseconds.



International Electrical Engineering Journal (IEEJ)
Vol. 3 (2012) No. 2, pp. 784-790
ISSN 2078-2365

Figure.6 Speed-Torque plot of locomotive from motoring to dynamic braking

When Dynamic brake is applied, the operating point has shifted to second quadrant with same magnitude of speed. Speed can't be changed abruptly but the torque maintains the same magnitude but with opposite in sign (negative torque) as shown in figure.6. This negative torque means the negative power; i.e. power generated which is dissipated in the braking resistance. The locomotive stops when the operating point is origin.

B. PLUGGING

During simulation, machine is allowed to attain a steady speed initially and after that at 0.05sec reverse voltage is applied to stop the vehicle. The simulation results are obtained. Figure.7 shows the variations in current and back emf waveforms from motoring to braking

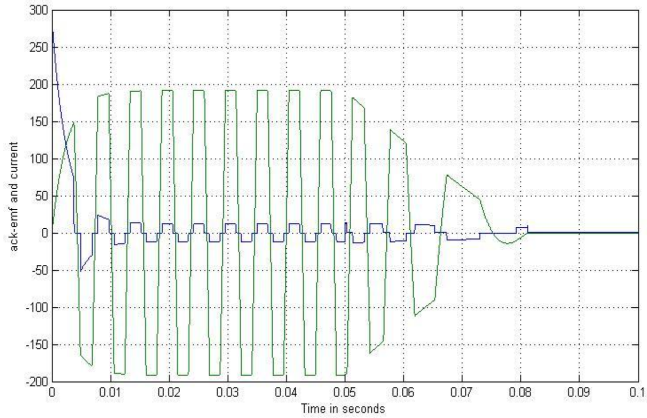


Figure.7 Current and Back emf waveforms during plugging

At a time of 0.05sec, when plugging is applied current has changed its direction. In this case of braking, the magnitude of current has increased to 2.67 times to that of steady value with out braking resistance. Figure.8 shows the waveforms of torque and speed during plugging. With out braking resistance, the braking torque has increased with respect to current, and it also increased by 2.7 times to that of steady value in magnitude but with a negative sign. So to incorporate plugging the inverter has to be redesigned and proper care is to be taken for the windings to with stand this much of current.

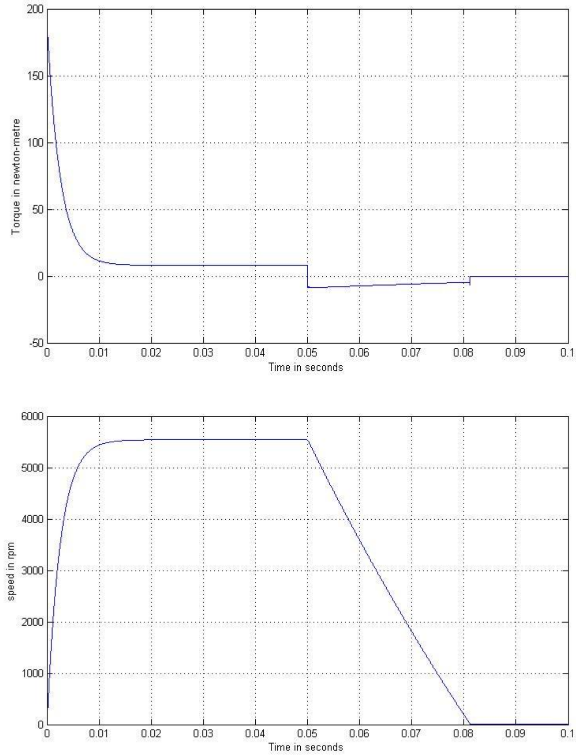


Figure.8 a) Torque b) Speed waveforms during plugging

In plugging, time taken by the locomotive to reach zero speed is 31.2 milliseconds (figure.8), which is 37.5 milliseconds in case of dynamic braking for the same machine. So plugging gives quick response compared to dynamic braking.

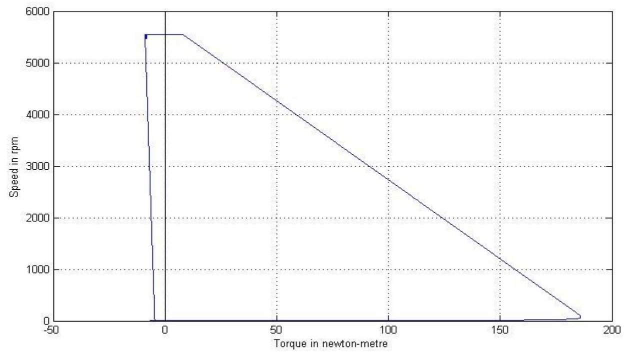


Figure.9 Speed-Torque plot of locomotive from motoring to braking for plugging

When plugging is applied for the machine operating in first quadrant the operating point has shifted to second quadrant with same magnitude of speed but with a change in the magnitude of torque with an opposite sign (negative torque). The path of the curve is a straight line as shown in figure.9. When speed is zero there does torque exists. So mechanical

International Electrical Engineering Journal (IEEJ)
Vol. 3 (2012) No. 2, pp. 784-790
ISSN 2078-2365

brakes are applied at that instant to prevent reverse motoring.

C. REGENERATIVE BRAKING

During simulation, at 0.05sec to stop the locomotive regenerative braking is applied. The simulation results are shown. Figure.10 shows the variations in current and back emf waveforms from motoring to braking during regeneration.

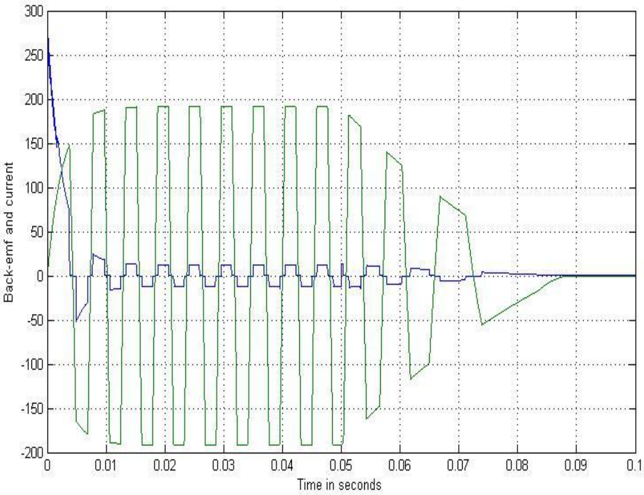
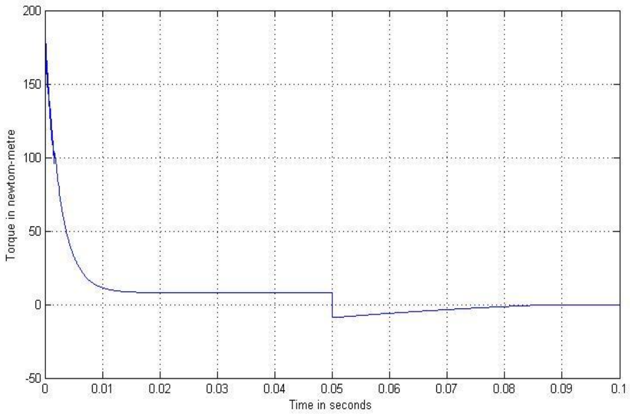


Figure.10 Current and Back emf waveforms during regenerative braking

In this braking, in order to keep the magnitude of current with in the bounds proper care has to be taken in varying voltage. Figure.11 shows the torque and speed waveforms during regenerative braking.



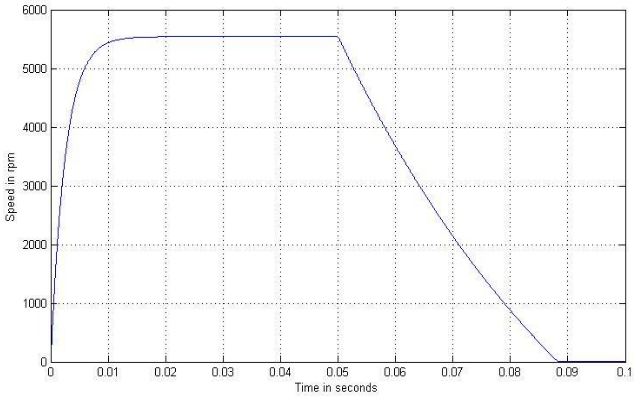


Figure.11 a)Torque b) Speed waveforms during regenerative braking

The time taken by the machine to reach zero speed is 38.3 milliseconds (figure.11), which is almost same during dynamic braking. This time interval is the time for which regeneration took place. Till 0.05seconds, the three windings of the machine had consumed the power and after that instant the power has become negative because the three windings are generating power which is fed to an external load.

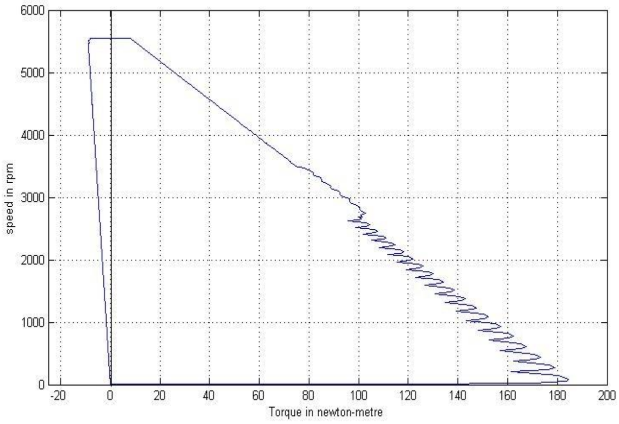


Figure.12 Speed-Torque plot of locomotive from motoring to regenerative braking

The speed-torque plot of the machine during its operation from motoring to regeneration is shown in figure.12. When Regenerative braking is applied, the power generated is delivered to an external load and the operating point has shifted to second quadrant, this quadrant is called Forward regeneration. The locomotive stops regeneration when the operating point tends to origin.

V. CONCLUSION

From the simulation results analysis of the three brakings,

i) Regenerative braking is more useful as no power is wasted but this process is costlier as this requires some external circuitry for regeneration.

ii) Dynamic braking can be used where stopping the machine is important not wasted power i.e., where economy is a factor.
iii) Plugging is the most in-efficient method as this will damage the windings, though this gives faster braking to incorporate this the inverter has to be redesigned. Power supplied by the source is wasted along with the power generated.

Hence regenerative braking is preferred in locomotives. For consumers using bldc motor drive regenerative braking is suggested, if they can afford the extra cost for the regenerative circuitry else dynamic braking is preferred.

REFERENCES

[1] P.Pillay and R.Krishnan, "Modeling, simulation and analysis of permanent-magnet motor drives, part-II: the brushless DC motor drives," IEEE Trans. on Industry Applications, vol. 25, pp.274-279, March/April1989.
[2] T. Jahns, R. C. Bccerra, and M. Ehsani, "lntcgrated current regulation for a brushless ECM drive," IEEE Trans. Pother(-Iron., vol. 6, no. I, pp. 118-126, Jan. 1991.
[3] Roger C.Becerra, "Four-Quadrant Brushless ECM Drive with Integrated Current Regulation," IEEE Trans. on Industry Applications, vol. 28, No.4, July/August 1992.
[4] Gopal K Dubey "Fundamentals of Electrical Drives", Narosa Publishing House, New Delhi, Second Edn, 2001, Chapter 7, pp271-277
[5] Pragasan Pillay and R.Krishnan, ''Modelling of permanent magnet motor drives'' IEEE Transactions on industrial electronics, Vol.35, No.4, November 1988.
[6] Krishnan R "motor Drives Modeling, Analysis and Control", Prentice Hall of India, First Edn, 2002.
[7] Pragasan Pillay and R.Krishnan, ''Control Characteristics and Speed Controller Design for a High Performance Permanent Magnet Synchronous Motor Drive'' IEEE Transactions on Power Electronics Vol.5 No.2 April 1990.
[8] P.Pillay and R.Krishnan, "An investigation into the torque behaviour of a brushledd dc motor drive",IEEE Transactions 1988
[9] Pragasan Pillay and R.Krishnan, ''Application characteristics of permanent magnet synchronous and brushless dc motors for servo drives'' IEEE Trans. on Industry Applications, vol. 27, No.5, september/october 1991.
[10] Vinatha U, Swetha Pola, Dr K.P.Vittal, ''Simulation of Four Quadrant Operation & Speed Control of BLDC Motor on MATLAB / SIMULINK''.
[11] Padmaraja yedmale,''Brushless dc motor fundamentals'' Microchip AN885- Microchip technology Inc