Four Quadrant Operation and Control of Three Phase BLDC Motor without Loss of Power

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Abstract- **Brushless DC motors are extensively being used in wide spectrum of applications including aerospace, automation, computers, military, household appliances and traction because of their properties such as compact size, higher efficiency and longer lifespan. There is a need for an efficient control strategy for these motors. The control of BLDC motor in four quadrants is very crucial. In this paper, BLDC motor is controlled in all the four quadrants, without any wastage of power. During regenerative braking period, power generated is being stored in the chargeable battery. This concept is important where there is frequent reversal of direction of rotation of motor is needed. MATLAB/SIMULINK software is used to carry out the above investigation**.

Keywords-**Brushless Direct Current Motor;Proportional Integrator (PI); Hall Sensor;Regenerative Mode.**

I. INTRODUCTION

Brushless DC motor has a rotor made of permanent magnets and a stator with windings. It is essentially a DC motor turned in and out. In this motor, brushes and commutator have been eliminated which require periodical maintenance and the windings are connected to the control electronics. The control electronics replace the function of the commutator and also helps in the energizationof the proper winding. The mechanical commutation is replaced by electroniccommutation.The motor will easily start and stop because of its less inertia [1]. The Brushless DC motor is widely used in domestic and Industrialapplication due to overweighing merits of this motor such as less noisy, more reliable, more efficient, etc. There is continuing trend to propose an improved control strategies to enhance the performance of the motor. BLDC motor is reliable, noiseless and has high efficiency, high power factor and high torque. It plays a vital role in Automotive, Aerospace, Consumer, and Medical and instrumentation [2].

This paper proposes speed control of BLDC motor over four quadrants with minimum loss of power, and when the braking command isreceived by the motor, the motor does not goes to Stand Still Position.The kinetic energy wasted as heat have been conserved as electrical energy in a chargeable battery and used to drive the motor in case of interruption of main supply. PI controller is employed to achieve desired speed and the absolute position of rotor can be known from Hall Effect sensors [3]. Four quadrant operationsof BLDC motor can be used in small power application including rotation of spindles, embroidery machines, washing machine, fans and large power application including industry, electric locomotive and in satellite.

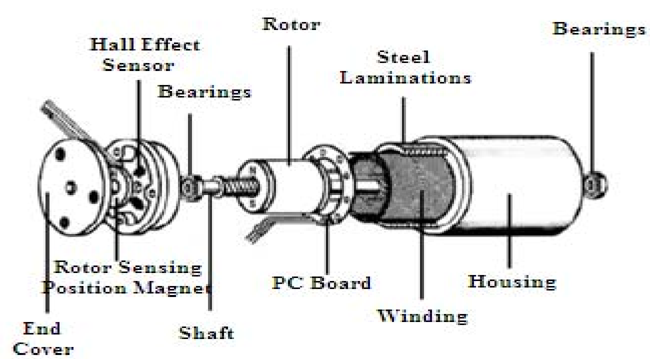

Fig. 1.Cross sectional view of BLDC motor with hall sensors

This paper is organized as follows: Section IIdescribes the three phaseBLDC motor and mathematical modeling of BLDC.Section III describes the four quadrant operation of the three phase BLDC motor and its features. The controller PI and its features are explained in Section IV. In section V, the simulation results are presented. Section VI concludes the proposed work.

II. DYNAMIC MODELLING OF BLDCMOTOR

A. BLDC Motor

BLDC motors are, in fact, a type of permanent magnet synchronous motors, which consists of a rotor made of permanent magnet and a wound stator. Here the electromagnetic field is created by permanent magnets in the rotor. The brushless motors are controlled using a three phase voltage source inverter. For the proper commutation of power electronic devices in the inverter

978-1- 5090-4967- 7/17/$31.00 © 2017 IEEE

bridge, motor require rotor position sensors. The power electronic devices are commutated sequentially at every 60 degrees based on the rotor position [4]. The problems associated with the brushes and the commutatorarrangement like sparking and wearing caneliminated by electronic commutation.This will make the BLDC motor more rugged compared to a dc motor. The drive system of brush less dc motor consist of four main parts Power converter, permanent magnet brushless DC Motor (BLDCM), sensors and control algorithm. The power converter transforms power from the source to the BLDCM, which in turn converts electrical energy to mechanical energy [5].

B. Mathematical model

BLDC motor can be modeled in the 3-phase ABC variables which consist of two parts. One is an electrical part which calculates electromagnetic torque and current of the motor. The other is a mechanical part, which generates revolution of the motor. Fig. 2. shows the mathematical model of BLDC motor.

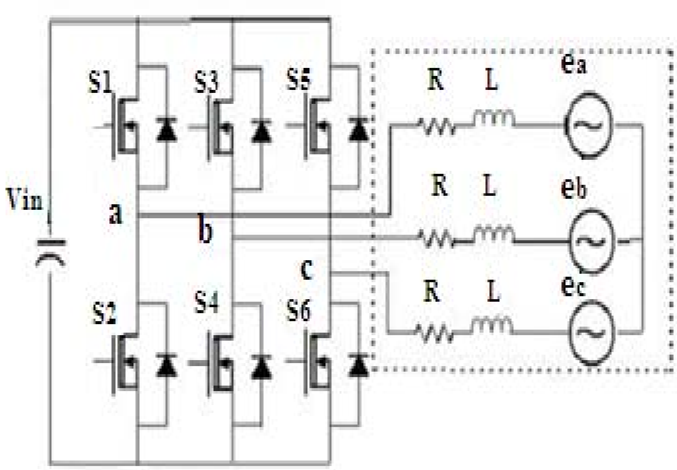

Fig. 2.Mathematical model of BLDC motor

Using KVL, the voltage equation from Fig. 2.can be expressed as follows:

$$V_a = R_s i_a + L\frac{di_a}{dt} + M\frac{di_b}{dt} + M\frac{di_c}{dt} + e_a \qquad (1)$$

$$V_b = R_s i_b + L\frac{di_b}{dt} + M\frac{di_a}{dt} + M\frac{di_c}{dt} + e_b \quad (2)$$

$$V_c = R_s i_c + L\frac{di_c}{dt} + M\frac{di_a}{dt} + M\frac{di_b}{dt} + e_c \ (3)$$

where,
L represents per phase armature self-inductance [H],
$R_S$represents per phase armature resistance [Ω],
Va ,Vb, and Vc indicates per phase terminal voltage [V],
ia ,ib and ic represents the motor input current [A],
ea, eb and ec indicates the motor back-EMF developed [V].
M represents the armature mutual-inductance [H].

In matrix form,

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L & M & M \\ M & L & M \\ M & M & L \end{bmatrix} p \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (4)$$

For a balanced system,
$i_a + i_b + i_c = 0$ (5)
Rearranging (1) and substituting (5),

$$V_a = R_s i_a + L\frac{di_a}{dt} + M\frac{d(i_b + i_c)}{dt} + e_a$$

$$Va = R_s i_a + L\frac{di_a}{dt} - M\frac{di_a}{dt} + e_a$$

$$V_a = R_s i_a + (L - M)\frac{di_a}{dt} + e_a$$

Let L-M = LS

$$V_a = R_s i_a + L_s\frac{di_a}{dt} + e_a \quad (6)$$

Similarly, equations (2) and (3) can be written as
$V_b = R_s i_b + L_s\frac{di_b}{dt} + e_b$ (7)

$V_c = R_s i_c + L_s\frac{di_c}{dt} + e_c$(8)

Eqn. (4) becomes

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + L_S p \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} (9)$$

In case of three phase BLDC motor, we can represent the back emf as a function of rotor position and it is clear that back EMF of each phase has 120 degree shift in phase angle [6].

Hence the equation for each phase of back emf can be written as:

$$e_a = k_a f(\theta)\omega_r (10)$$

$$e_b = k_b f\left(\theta - \frac{2\pi}{3}\right)\omega_r \ (11)$$

$$e_c = k_c f\left(\theta + \frac{2\pi}{3}\right)\omega_r \quad (12)$$

where,
k_a, k_b, k_cdenotes per phase back EMF constant [V/rad.s-1],
Θ represents electrical rotor angle [rad],
$\omega_r$represents rotor speed [rad.s-1].

Total electrical torque developed,

$$T_e = T_a + T_b + T_c \qquad (13)$$

where,
Te denotes total torque output [Nm].

The expression for electrical rotor angle can be represented by multiplying the mechanical rotor angle with the number of pole pair's P:

$$\Theta_e = \frac{P}{2}\Theta_m \qquad (14)$$

Mechanical part of BLDC motor is represented as follows:

$$T_e - T_l = J\frac{dw}{dt} + Bw \qquad (15)$$

where,
Tl denotes load torque [Nm],
J denotes of rotor and coupled shaft [kgm2],
B represents the Friction constant [Nms.rad-1].

III. FOUR QUADRANT OPERATION OF BLDCMOTOR

When an electric machine is required to operate as both a motorand a generator, and also in forward and reverse directions, it is said to beoperating in the four quadrant modes of operation [7]. There is a need of four quadrant controller when a motor is designed forautomotive applications which must run in both forward and reverse directions andwhich must provide regenerative braking in both directions.

There are four possible modes or quadrants of operation using a BLDC Motor which is depicted in Fig. 3. In speed versus torque characteristics, Quadrant I is forward speed and forward torque. Here the torque is propelling the motor in the forward direction. Conversely, Quadrant III is reverse speed and reverse torque. Now the motor is "motoring" in the reverse direction, spinning backwards with the reverse torque.

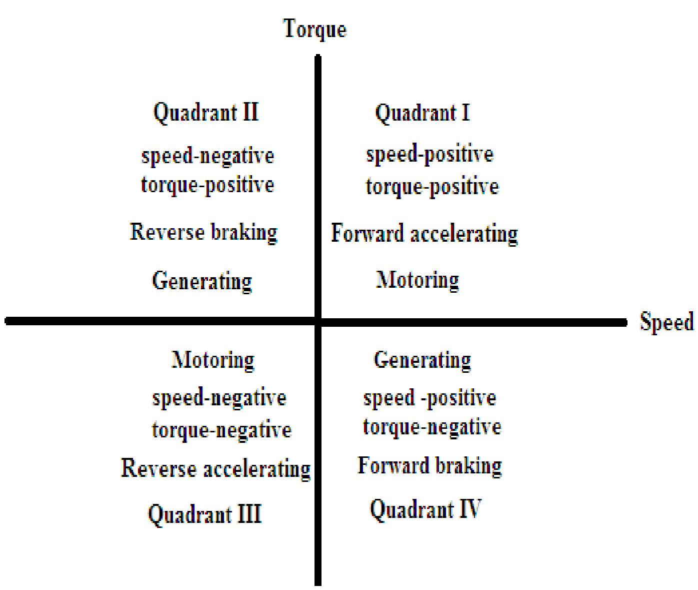

Fig. 3.Four quadrants of operation

Quadrant II is where the motor is spinning in the forward direction,but torque is being applied in opposite direction. Torque is being used to "brake" themotor, and the motor is now generating power as a result. Finally, QuadrantIV is exactly the opposite. The motor is spinning in the reverse direction, butthe torque is being applied in the opposite direction. Again, torque is beingapplied to attempt to slow the motor and change its direction to forward again.As a result, power is being generated by the motor [8].

When BLDC motor is operating in the first and third-quadrant, the supplied voltage is greater than the back emfwhich is forward motoring and reverse motoring modesrespectively, but the direction of current flow differs. Whenthe motor operates in the second and fourth quadrant thevalue of the back emf generated by the motor should begreater than the supplied voltage which are the forwardbraking and reverse braking modes of operation respectively,here again the direction of current flow is reversed [9].

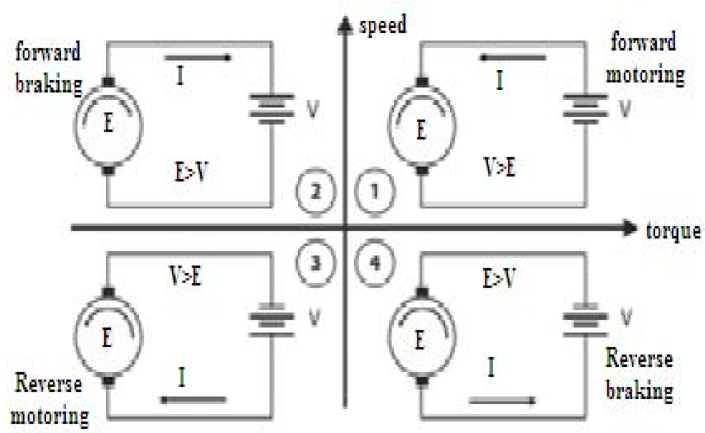

Fig. 4. Modes of operation in BLDC motor

Initially the motor is being rotated in clockwise direction,but when the speed reversal command is obtained, the control goes into theclockwise regeneration mode, which brings the rotor to the standstill position.Instead of waiting for the absolute standstill position, continuous energizationof the main phase is attempted. This rapidly slows down the rotor to astandstill position. Therefore, there is a necessity for determining the instantwhen the rotor of the machine is ideally positioned for reversal. Hall sensorsare used to ascertain the rotor position[10].

IV. CONTROLLER

The block diagram of the proposed drive system is presented in Fig. 5. The three-phase inverter is supplied from a DC source. The voltage source inverter circuit is coupled to the brushless dc motor using normally closed contacts. During motoring operation, the PWM pulses provide the appropriate switching sequence to the three phase inverter. The switching circuit (relay circuit) is coupled to the BLDC motor. Whenever the motor is operating in the regenerative mode, the normally open contacts of the switching circuit get closed. Thereby the generated voltage gets rectified and the energy gets stored in the chargeable battery [11].

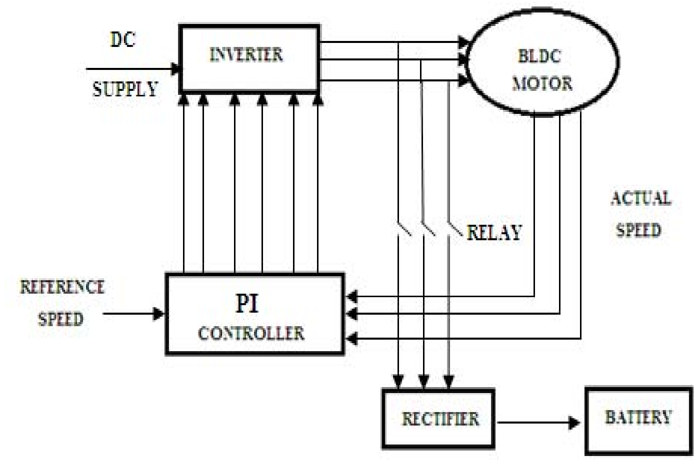

Fig. 5.Block Diagram of Proposed drive system

PI controller is chosen due to its simple structure and there is no difficulty in design. Conventional PI controller is used as a speed controller for recovering the actual motorspeed to the reference. The reference and the measured speed are the input signals to the PI controller. The $K_p$and $K_i$values of the controller are determined by trial and error method for set speed. The proportional (P) term of the controller is formed by multiplying the error signal by a P gain, causing the PI controller to produce a controlresponse which is a function of the error magnitude [12]. As the error signal becomes larger, the P term of the controller becomes larger to provide more correction. The effect of the P term tends to reduce the overall error as time goes by. However the P term has less effect as the error approaches zero. In most systems, the error of the controlled parameter gets very close to zero but does not converge. The result is a small remaining steady state error. The integral (I) term of the controller is used to eliminate small steady state errors. Integral term has the effects of accumulation, memorization and delay, which enables PI controller to remove static error. This accumulated error signal is multiplied by a gain factor I and becomes the output term I of the PI controller. Inorder to achieve the desired steady state response of the speed in the proposed system the PI controller is used.

V.SIMULATION RESULTS

This section deals with the results obtained from the developed Simulink model. The load torque is applied at different instants and the performance variables are observed. The load torque is varied and the response of the machine is observed, as it operates in all the four quadrants. Simulink model of the proposed system is shown in the fig. 6.The simulation is carried out for a time of 3 s and the discrete power GUI mode is adopted. Load torque at different instant is shown in the fig. 7.

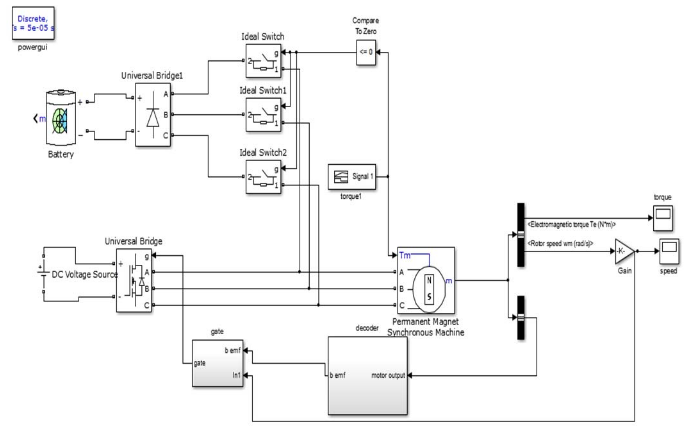

Fig. 6.Matlabsimulink model with PI controller

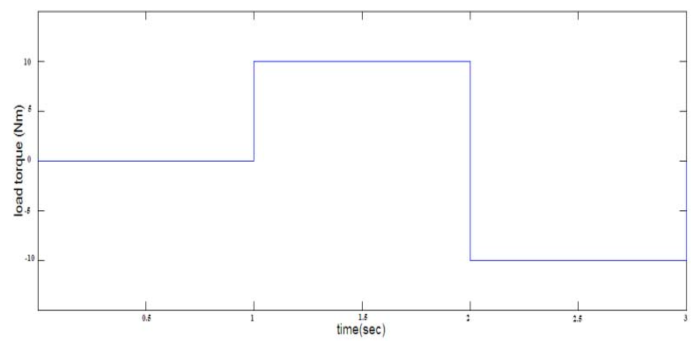

Fig. 7. Applied load torque

The back emfproduced for the proposed system is trapezoidal in nature.In case of sensorless system the back emf serves as the means of rotor position sensing. In motoring mode,back emf is less than the supply voltage andin braking mode, back emf is greater than supply voltage. Fig. 8-10 shows the three phase back emf.

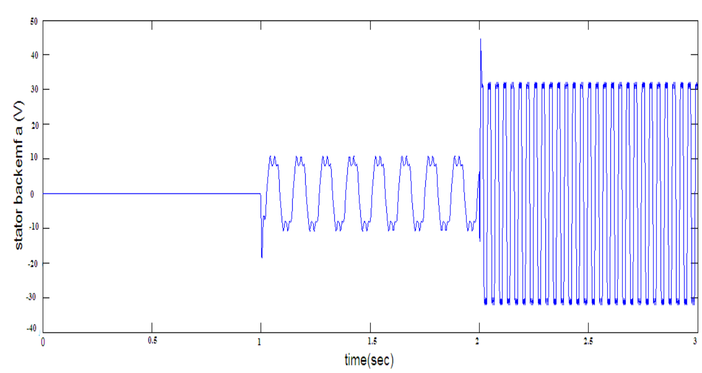

Fig. 8. Stator backemf of phase a

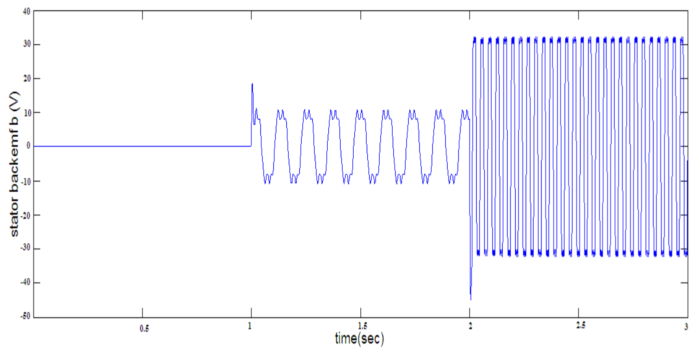

Fig. 9. Stator backemf of phase b

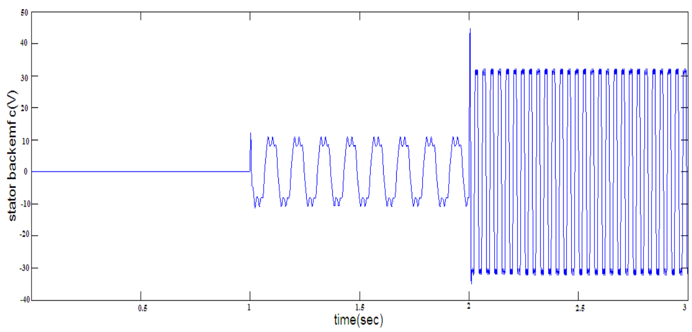

Fig. 10. Stator back emf of phase c

The stator currents of the three phases have spikes at some instant which implies there is a change in thespeed of the BLDC motor.Three phase stator current is shown in the fig. 11-13.Fig. 14. Show the speed of the motor.

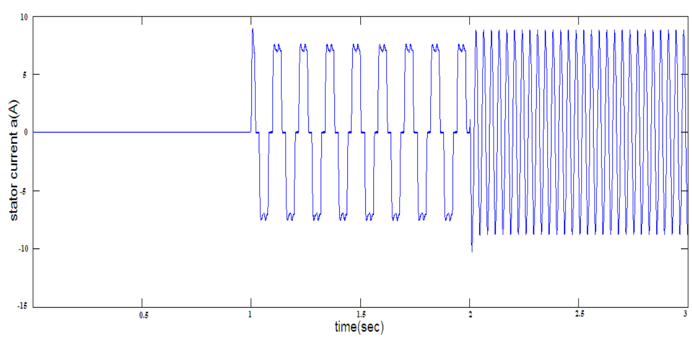

Fig. 11. Stator current of phase a

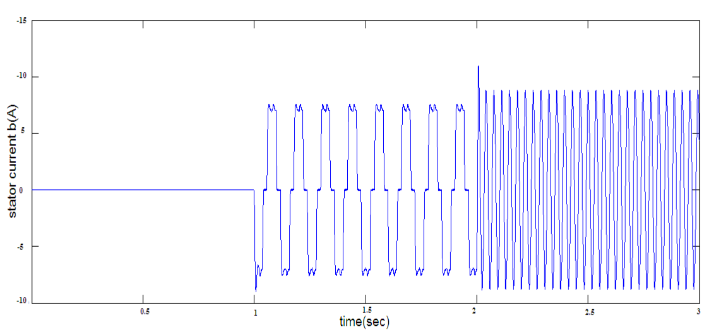

Fig. 12. Stator current of phase b

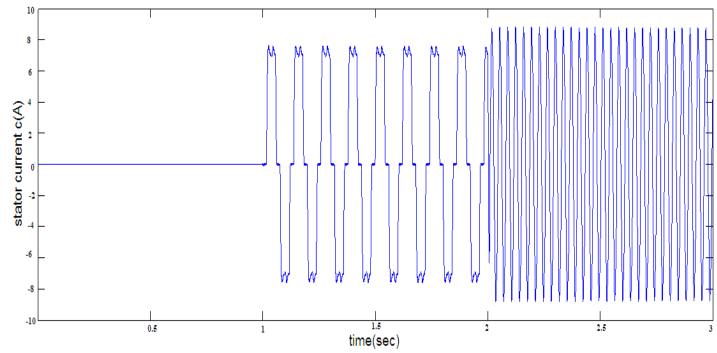

Fig. 13. Stator current of phase c

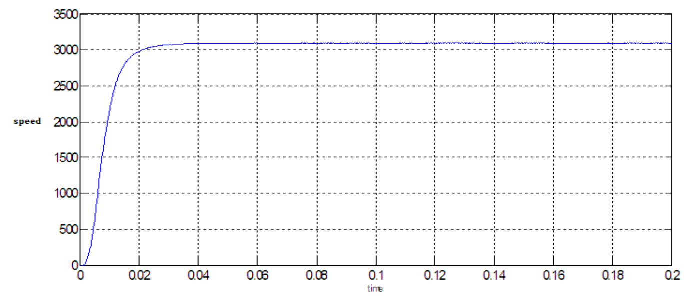

Fig. 14. Speed

During regenerative braking mode, energy is stored in the battery. In case of interruption of power supply, this energy can be utilized.The battery has charging current and voltage. Battery charging voltage is shown in the fig. 15.Fig. 16. shows the state of charge of the battery.

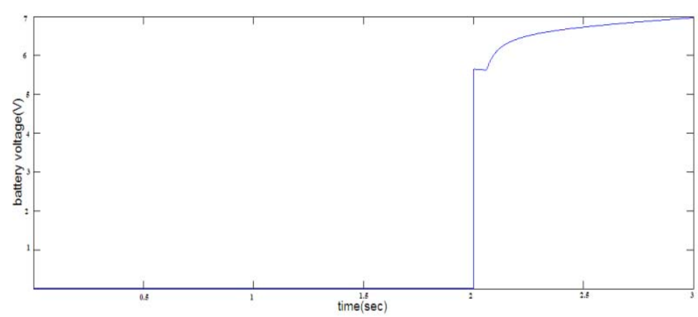

Fig. 15. Battery voltage during regenerative mode

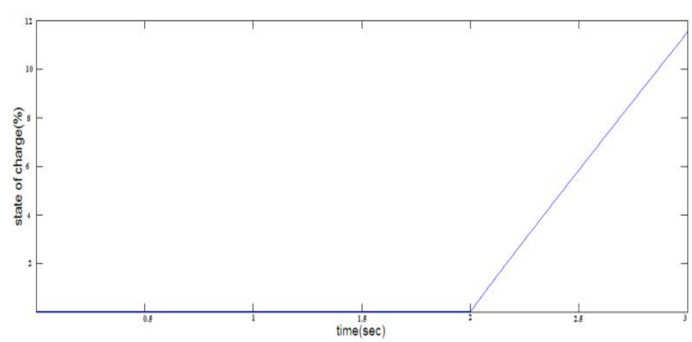

Fig. 16. Battery state of charge

VI. CONCLUSION

The speed control of four quadrant operation of three phase BLDC motor has been done without any loss of power using Matlab/Simulink. Battery is charged during regenerative mode of operation by using conventional PI controller. Closed loop speed control is carried out and simulation results are presented. During the regenerative mode, the generated voltage can be returned to the supply mains which will result in considerable saving of power. This concept is used in applications like rotation of spindles, embroidery machines and electric vehicles where there is frequent reversal of direction of rotation of themotor.

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