Simulation of Four Quadrant Operation of Sensor less BLDC Motor

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Abstract: *This paper gives a control for three phase Sensor less brushless DC (BLDC) motor in all four quadrant operation. The control system in this paper is capable to detect and identify the rotor position by sensor less method signal. In this paper behaviour of BLDC motor is studied in all four quadrant operations through simulation model. The simulation is carried out for four quadrant operation and during regenerative braking kinetic energy is wasted as heat energy. This paper gives utilization of wasted kinetic energy is converted and stored in battery. The simulation model shows the control for four quadrant operation without sensor. From this paper during regenerative braking instead of wasting kinetic energy can be considerable as saving of power.*
Keywords: *BLDC motor; Four quadrant operation; regenerative braking; Digital controller Introduction*

I.   Introduction

Brushless DC motor has a rotor with permanent magnets and a stator with windings. It is essentially a DC motor turned inside out. The brushes and commutator have been eliminated and the windings are connected to the control electronics. An electronic controller replaces the brush/commutation assembly of the brushed DC motor, which continually switches the phase to the windings to keep the motor turning. The controller performs similar timed power distribution by using a solid-state circuit rather than the brush/commutation system .The motor has less inertia, therefore easier to start and stop. BLDC motors are potentially cleaner, faster, more efficient, less noisy and more reliable. The Brushless DC motor is driven by rectangular or trapezoidal voltage strokes coupled with the given rotor position. The voltage strokes must be properly aligned between the phases, so that the angle between the stator flux and the rotor flux is kept close to 90 to get the maximum developed torque. BLDC   motors is also known as synchronous devices because the magnetic fields of the stator and rotor rotate at the same frequency. The stator comprises steel laminations, slotted axially to accommodate an even number of windings along the inner periphery. The rotor is constructed from permanent magnets with from two-to-eight N-S pole pairs. BLDC motors are used in Automotive, Aerospace, Consumer, Medical, Industrial automation equipments   and instrumentation.
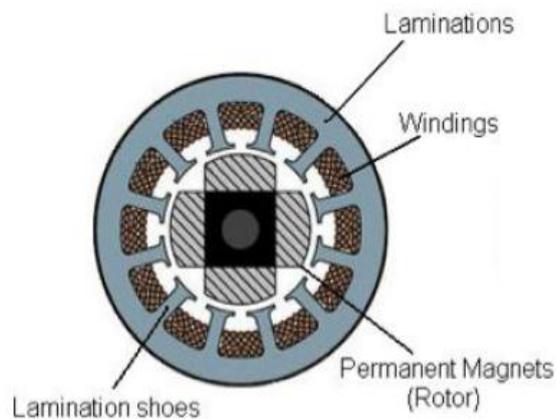
Fig 1 Shows the cross sectional View of BLDC motor

The BLDC motor's electronic commutator sequentially energizes the stator coils generating a rotating electric field that 'drags' the rotor around with it. Efficient operation is achieved by ensuring that the coils are energized at precisely the right time. This paper also deals with the speed control of BLDC motor. Generally the rotor position can be sensed by the hall effect sensor or any other explicit method like zero crossing detection method ,inductance method etc also. Hall sensors work on the hall-effect principle that when a current-carrying conductor is exposed to the magnetic field, charge carriers experience a force based on the voltage developed across the two sides of the conductor. If the direction of the magnetic field is reversed, the voltage developed

will reverse as well. For Hall effect sensors used in BLDC motors, whenever rotor magnetic poles (N or S) pass near the hall sensor, they generate a HIGH or LOW level signal, which can be used to determine the position of the shaft. In a commutation system – one that is based on the position of the motor identified using feedback.

II.   Working Principle And Working

The underlying principles for the working of a BLDC motor are the same as for a brushed DC motor; i.e., internal shaft   position feedback. In case of a brushed DC motor, feedback is implemented using a mechanical commutator and brushes. With a in BLDC motor, it is achieved using multiple feedback sensors. The most commonly used sensors are hall sensors and optical encoders. In a commutation system one that is based on the position of the motor identified using feedback two of the three electrical windings are energized at a time as shown in figure 4.

In figure 4 (A), the GREEN winding labelled "001" is energized as the NORTH pole and the BLUE winding labelled as "010" is energized as the SOUTH pole. Because of this excitation, the SOUTH pole of the rotor aligns with the GREEN winding and the NORTH pole aligns with the RED winding labelled "100". In order to move the rotor, the "RED" and "BLUE" windings are energized in the direction shown in figure 4(B). This causes the RED winding to become the NORTH pole and the BLUE winding to become the SOUTH pole. This shifting of the magnetic field in the stator produces torque because of the development of repulsion (Red winding – NORTH-NORTH alignment) and attraction forces (BLUE winding – NORTH-SOUTH alignment), which moves the rotor in the clockwise direction. This torque is at its maximum when the rotor starts to move, but it reduces as the two fields align to each other. Thus, to preserve the torque or to build up the rotation, the magnetic field generated by stator should keep switching. To catch up with the field generated by the stator, the rotor will keep rotating. Since the magnetic field of the stator and rotor both rotate at the same frequency, they come under the category of synchronous motor. This switching of the stator to build up the rotation is known as commutation. For 3-phase windings, there are 6 steps in the commutation; i.e., 6 unique combinations in which motor windings will be energized.

A. Hall Sensor and Demerits

Most BLDC motors have three Hall Sensors embedded into the stator on the non-driving end of the motor. Whenever the rotor magnetic poles pass near the Hall sensors, they give a high or low signal, indicating the N or S pole is passing near the sensors. Based on the combination of these three Hall sensor signals, the exact sequence of commutation can be determined. Hall sensors are embedded into the stationary part of the motor. Embedding the Hall sensors into the stator is a complex process because any misalignment in these Hall sensors, with respect to the rotor magnets, will generate an error in determination of the rotor position. To simplify the process of mounting the Hall sensors onto the stator, some motors may have the Hall sensor magnets on the rotor, in addition to the main rotor magnets. These are a scaled down replica version of the rotor. Therefore, whenever the rotor rotates, the Hall sensor magnets give the same effect as the main magnets. The Hall sensors are normally mounted on a PC board and fixed to the enclosure cap on the non-driving end. This enables users to adjust the complete assembly of Hall sensors, to align with the rotor magnets, in order to achieve the best performance. Based on the physical position of the Hall sensors, there are two versions of output. The Hall sensors may be at 60° or 120° phase shift to each other. Based on this, the motor manufacturer defines the commutation sequence, which should be followed when controlling the motor. But the sensor has different disadvantages so we go for sensor less methods ,that is it increases the cost , increases the extra connections and extension ,reduces the system reliability and also difficulties provided in the contaminated area .Nowadays many research are doing in the sensor less field .
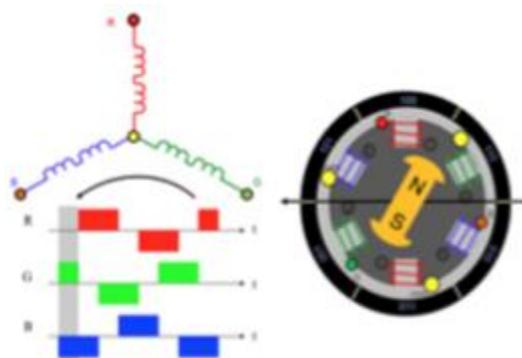
Fig. 1A Phase 1
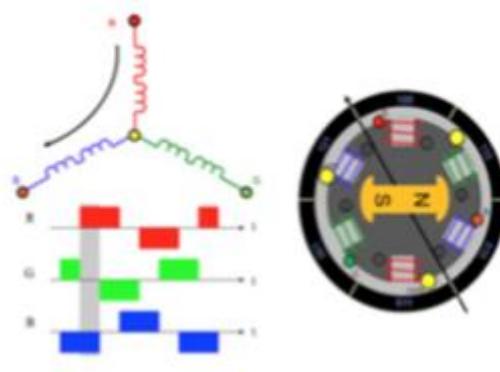
Fig. 2B Phase 2
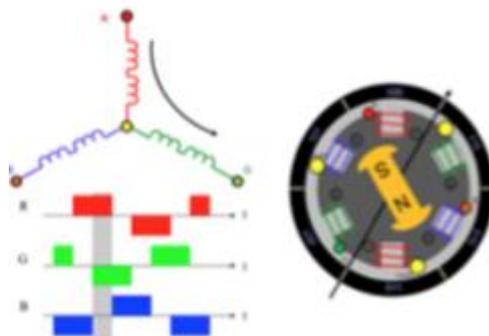
Fig. 3C Phase 3
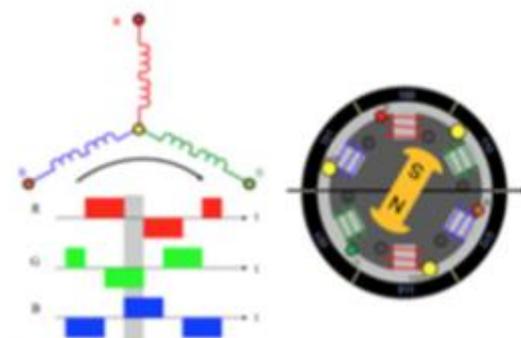
Fig. 4D Phase 4
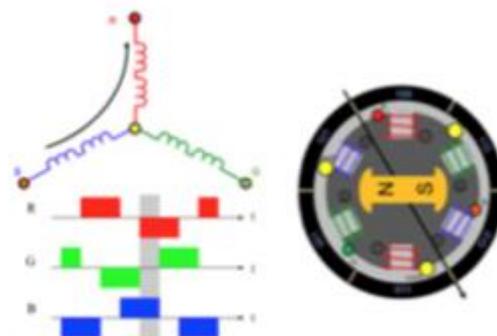
Fig. 5A Phase 5
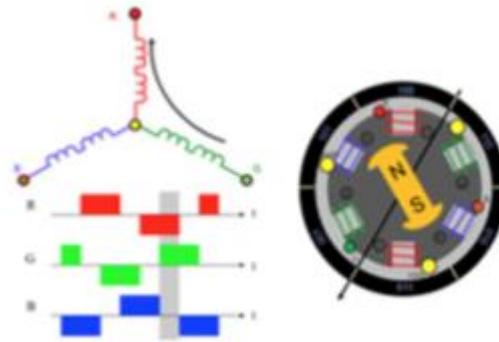
Fig. 6A Phase 6

In this paper the four quadrant operation and regenerative braking achieves of a three phase (star connection) permanent magnet BLDC motor Without Hall sensor ,while we using Zero crossing Detection Method for obtaining the rotor position. The four quadrant operations of brushless DC motor mainly helps in the locomotive of train systems for frequently reversal of command. The proposed digital control of four quadrant operation system performs the following tasks. i.e.

☐ **speed controlling**
☐ **Regenerative braking and**
☐ **Utilize the wasted kinetic energy.**

Fig .3 shows the block diagram of speed controlling of the BLDC Motor. The dspic or pic digital controller is used for control and determines the motor operation for different quadrant and regenerative braking .Generally the which is very advantageous over other controllers, as it combines the calculation capability of Digital Signal Processor and controlling capability of Pic microcontroller, to achieve precise control.
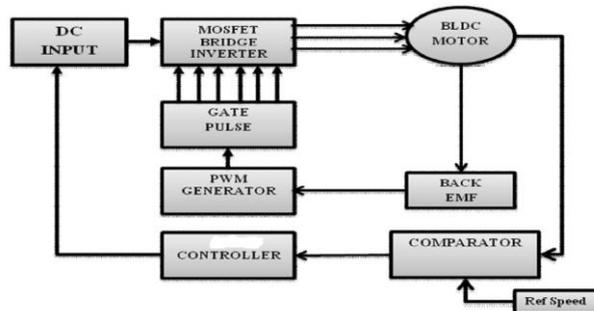
Fig. 7 Speed control of BLDC Motor.

When the regenerative braking is applied normally closed (NC) contacts opens and normally open contacts (NO) contacts closes, hence wasting kinetic heat energy wasted in the motor the back EMF voltage utilized by three phase rectifier circuit to charge the battery. In fact the wasted energy is conserved and saving in regenerative braking operation. The arrangement of schematic diagram as shown in the below figure .3
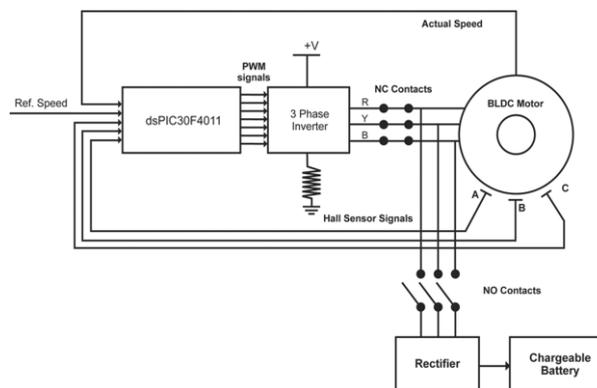
Fig. 4 Schematic Diagram of Proposed BLDC Motor

III.   Four Quadrant Control Operation

There are four possible modes or quadrants of operation using a three phase Brushless DC (BLDC) Motor. In 1st Quadrant positive speed and the torque is positive hence the motor rotates in the forward direction. . In 2nd Quadrant motor is rotating in the forward direction, but torque is being applied in reverse. Reverse Torque is applied to "brake" the motor, and the motor is now generating power. In 3rd Quadrant negative speed and negative torque. In this condition the motor is rotating in reverse direction. in 4th Quadrant exactly the opposite. The motor is rotates in the reverse direction, but the torque is being applied in the forward direction. Again, torque is being applied to attempt to slow the motor and change its direction to forward again. Once again, power is being generated by the motor .In this paper uses the motoring and regenerative mode.
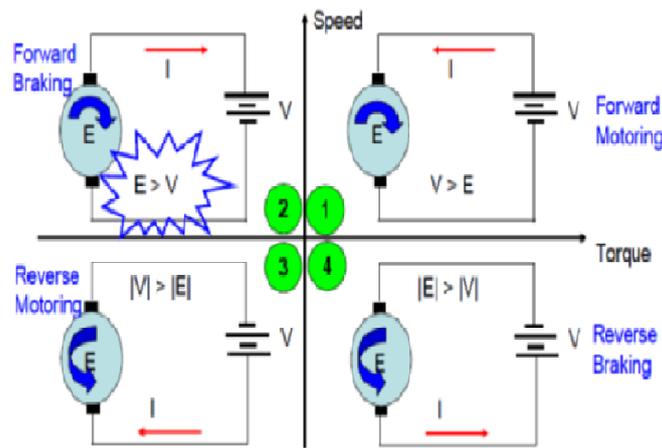
Fig. 5 Four Quadrant Operation Of BLDC Motor

The three phase brushless DC (BLDC) motor is initially made to rotate in forward direction, but when the speed command is given reverse, the control goes into the forward braking mode hence current flows from motor to battery , in this case the rotor comes to the standstill position is term named as forward braking or regenerative braking. Instead of waiting for the absolute standstill position, continuous energization of the main phase is attempted. This rapidly slows down the rotor to a standstill position. Similarly for when the motor rotates in the reverse direction, but when the speed command is given positive, the controller goes into reverse regeneration mode, in this case the current is flows from motor to source.

B. Regenerative Braking

Electrical Braking is mainly two types one is dynamic braking another one is Regenerative braking .BLDC Hub motor used in e-bike applications .Regenerative braking stores energy into the battery ,while increasing the life of motor. During braking(off time) mode or instead of wasting kinetic energy can be considerable as saving of power and also increases the reliability by the elimination of Hall sensor .That is implement in the simulation.

IV.   Mathematical Model

The BDCM has three stator windings and permanent magnets on the rotor. Since both the magnet and the stainless steel retaining sleeves have high resistivity, rotor-induced currents can be neglected. Hence the circuit equations of the three windings in phase variables are

$$\begin{vmatrix} VR \\ VY \\ VB \end{vmatrix} = \begin{vmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{vmatrix} \begin{vmatrix} iR \\ iY \\ iB \end{vmatrix} + \rho \begin{vmatrix} LR & LYR & LBR \\ LYR & LB & LBY \\ LBR & LBY & LY \end{vmatrix} \begin{vmatrix} iR \\ iY \\ iB \end{vmatrix} + \begin{vmatrix} eR \\ eY \\ eB \end{vmatrix} \quad .....(1)$$

Where it has been assumed that the stator resistances of all the windings are equal. The back EMF's eR**,** eY, and eB, have trapezoidal shapes. Assuming further that there is no change in the rotor reluctances with angle, the

LR = LY = LB = L s

LRY=LRB=LBY=M

Hence

$$\begin{vmatrix} VR \\ VY \\ VB \end{vmatrix} = \begin{vmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{vmatrix} \begin{vmatrix} iR \\ iY \\ iB \end{vmatrix} + \rho \begin{vmatrix} Ls & M & M \\ M & Ls & M \\ M & M & Ls \end{vmatrix} \begin{vmatrix} iR \\ iY \\ iB \end{vmatrix} + \begin{vmatrix} eR \\ eY \\ eB \end{vmatrix} \quad ......(2)$$

But iR= iY= IB=0

Assuming constant self and mutual inductance, the voltage equation becomes

$$\begin{bmatrix} VR \\ VY \\ VB \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} iR \\ iY \\ iB \end{bmatrix} + p \begin{bmatrix} Ls-M & 0 & 0 \\ 0 & Ls-M & 0 \\ 0 & 0 & Ls-M \end{bmatrix} \begin{bmatrix} iR \\ iY \\ iB \end{bmatrix} + \begin{bmatrix} eR \\ eY \\ eB \end{bmatrix}$$

In state space form the equation is arranged as

$$\frac{d}{dt} \begin{bmatrix} iR \\ iy \\ iB \end{bmatrix} = -\frac{R}{L} \begin{bmatrix} iR \\ iY \\ iB \end{bmatrix} - \frac{1}{L} \begin{bmatrix} eR \\ eY \\ eB \end{bmatrix} + \frac{1}{L} \begin{bmatrix} VR \\ VY \\ VB \end{bmatrix} \dots \dots (3)$$

The electromagnetic torque is given as

$$Te \equiv (eR\ iR + eY\ iY + eB\ iB)/wr$$

The equation of motion is given as

$$\frac{d\ wr}{dt} = (Te - Tl - Bwr)/J$$

V.   Simulink Model

The source to the BLDC motor is AC supply which is converted to DC through VSI. Here six switch 3 legs inverter is used. MOSFET is used as switch in order to control the speed of the motor. Simulink model can drawn with the help of schematic diagram of the proposed Sensor less BLDC control.
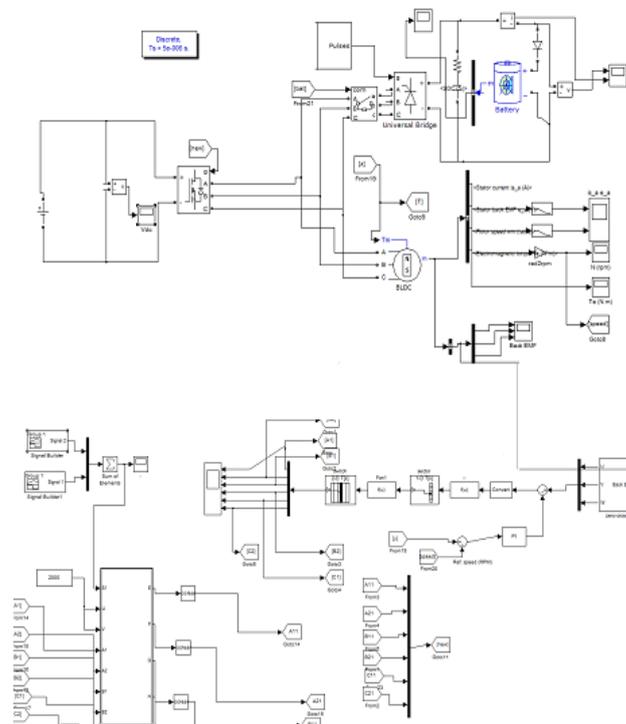
A.   Circuit Description

The simulink model of the BLDC motor is shown in fig.6. Permanent Magnet Synchronous motor with trapezoidal back EMF is modelled as a Brushless DC Motor. A three-phase motor rated 1 kW, 500 Vdc, 2000 rpm is fed by a six step voltage inverter. The inverter is a MOSFET bridge of the SimPowerSystems library. A speed regulator is used to control the DC bus voltage and it is compared with the zero crossing back emf output.. The three-phase output of the inverter are applied to the PMSM block's stator windings. Two control loops are used. The inner loop synchronises the inverter gates signals with the electromotive forces. The outer loop

controls the motor's speed by varying the DC bus voltage. The difference between the required speed and the actual speed is input into the PI controller, which then modulates the duty cycle of the PWM based on the error signal obtained by the difference between the actual speed and required speed. Different type of another MAT Lab Blocks are used like MAT Lab Functions Converter , Signal Builder etc. Signal Builder-Create and generate interchangeable groups of signals whose waveforms are piecewise linear. The Direct Lookup Table (n-D) block uses inputs as zero-based indices into an n-dimensional table. The number of inputs varies with the shape of the output: an element, column, or 2-D matrix. We define a set of output values as the Table data parameter. The first input specifies the zero-based index to the table dimension that is one higher than the output dimensionality. FCn-General expression block. Use "u" as the input variable name. Converter- Convert the input to the data type and scaling of the output. MAT Lab functions are used to create or edit a call back function for those block select it in the call back list. Then enter the MAT Lab CODE that implemented the function in the content pane .In this block represented the duration and condition the forward motoring reveres motoring forward braking reverse braking. The conversion has two possible goals. One goal is to have the Real World Values of the input and the output be equal. The other goal is to have the Stored Integer Values of the input and the output be equal. Overflows and quantization errors can prevent the goal from being fully achieved .In this Simulink Zero cross is a subsystem and conditions for getting the zero position of the rotor signal that is compared with the rotor speed .The Back emf and speed are expressed in the value so we use the convert tool for converting to the signal ,that is the part of the sensor less method. Next sub system is the MAT Lab function the time duration of the quadrant operation is given to this block, as per this coding the controlling of these quadrant is possible that are shown in Wave forms. We set the time duration of quadrant in the signal builder that is forward motoring(0-0.1),reverse braking (0.1-0.2),reverse motoring (0.2-0.4) .Six gate signals are produced to control the on and off period of the switches associated in the power electronic circuit. In this simulation the (rotor position) can be getting from zero crossing subsystem ,that provide the signals as per the condition if the signal is compared to Zero and one and obtained the PWM signal. When the motor runs in the forward motoring at 2000 rpm ,while there is no voltage stored in the battery. But motor runs in braking quadrant while the voltage stored in the battery. Motor runs in the reverse direction while the speed of motor is -2000 rpm. These are clearly shown in the wave .The total harmonic distortion of battery is also obtained.

When the nominal torque is applied, the stator current increases to maintain the nominal speed. The saw tooth waveform is also observed in the electromagnetic torque signal Te. However, the motor's inertia prevents this noise from appearing in the motor's speed waveform. When the motor is in the braking mode or stand still condition while kinetic energy stored to the battery through a rectifier that are shown in the wave form .
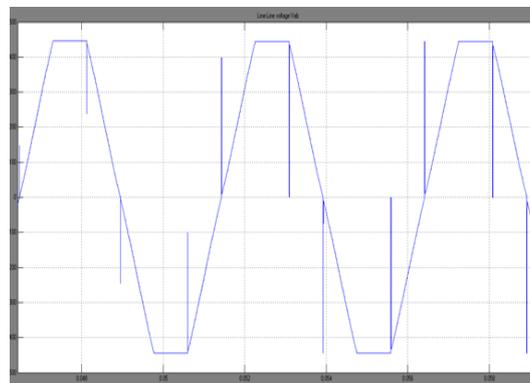
Fig 7: Input of the Motor
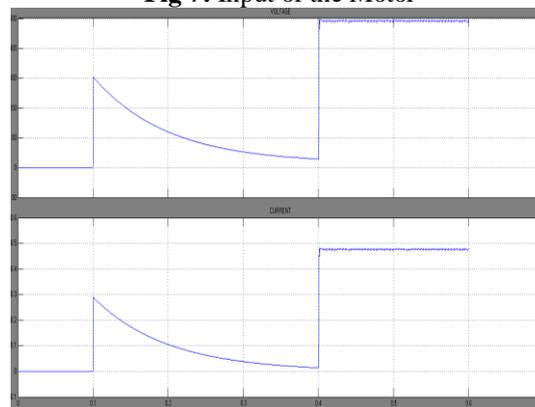
Fig. 8 Output of the Battery
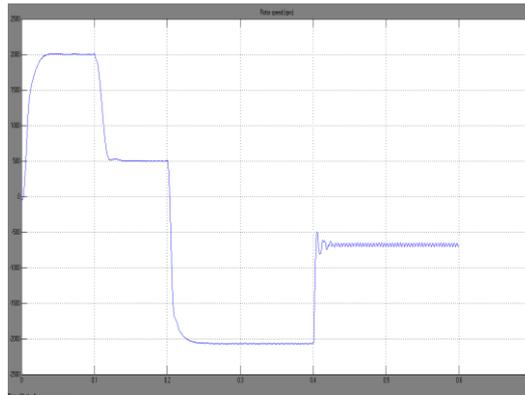
Fig. 9 Rotor speed in all quadrants
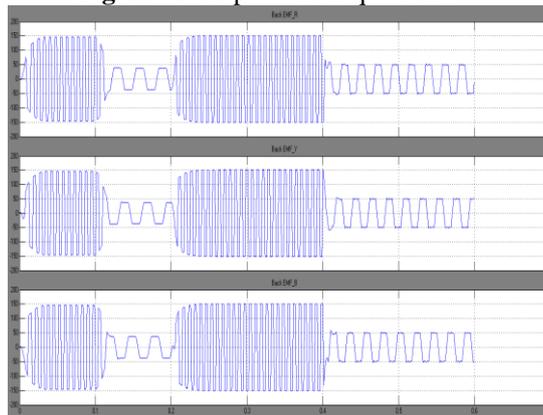
Fig.10 Back Emf of all Quadrants
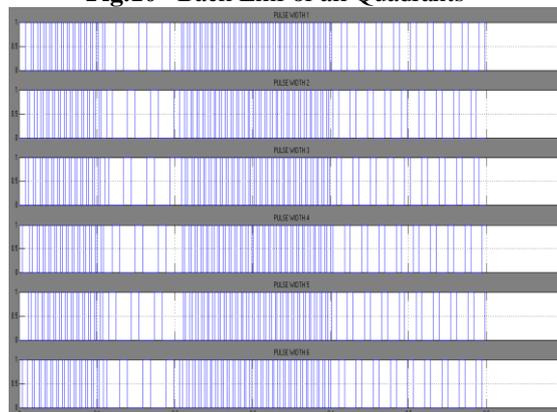
Fig. 11 Gate signal for Six switches

VI.   Simulation Result

The waveform shows the trapezoidal wave, Rotor speed Back emf voltage from the sensor less method. The voltage and current of the battery shown the value of motoring is 0 Vand 0 A But in the braking time the battery volage is increased to300V and current is 0.29 A, while the motoring time the relay contact is open and does not store any energy .The Total Harmonic Distrotion of the battery output is 82.67% based on the 50Hz fundamental frequency. The rotor speed, output of the battery and back emf (sesnsor less method),these are provided the time for motoring braking as per the mat lab function. The oscillations die out gradually as the motor changes its direction of rotation. The Pulse Width Modulation or gate signal (PWM) pulses applied to the inverter circuit at the appropriate time to trigger the appropriate switches are the control signals to the circuit. It depicts that the motor is running in the forward direction, after a time interval brake is applied, the motor stops decelerating at this point the battery starts charging. The battery is energized during the regenerative period.

VII.   Conclusions

This paper shows the simulation of the Digital Controlled four Quadrant Operation Of Sensor less BLDC Motor. The main advantages of this proposal the saving of energy in the regenerative braking time and

also the effectiveness of the sensor less. The time taken to achieve this braking is comparatively less. The generated voltage during the regenerative mode can be returned back to the supply mains which will result in considerable saving of power. This concept may well be utilized in the rotation of spindles, embroidery machines and electric vehicles where there is frequent reversal of direction of rotation of the motor .In the contaminated situation this proposal more effective The significant advantages of the proposed work are: simple hardware circuit, reliability of the control algorithm, excellent speed control, smooth transition between the quadrants and efficient conservation of energy is achieved with and without
load conditions .Simulation result shows DC output and battery energization when the motor is in braking condition.

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