A Four Quadrant control Strategy forBLDC motor Using dSPIC

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Abstract—BLDC Motors are permanent magnet Synchronous motors. The stator is having control windings and the rotor is having the permanent magnets. So the construction is like a DC motor turned inside out. When the back EMF goes higher than the supply voltage, it can be functioned like an alternator as the load will feed the supply side. The motor can be controlled in all the four quadrant of a speed torque plane without any energy lose. Control is done by dSPIC. Four Quadrant operations come when the motor is allowed to rotate in both clockwise and counter-clockwise direction. Whenever there is a change in direction, back EMF goes higher than the supply side voltage, it is called the regeneration mode. The two motoring and two regeneration interval comprises the Four quadrant. This paper intends to save and reuse of regenerated electrical energy. The energy at the regeneration interval is stored in the supply side battery which can be used further instead of wasting as heat at the load

Keywords—BLDC motor, Regenerative braking, Four quadrant operation, backEMF

I. INTRODUCTION

We live now in a world of thinking about energy conservation. Once the electrical energy is used for any purpose it is considered as a wasted energy and it can never be reused. Due to advancement of technology of power electronics, electric machines and control methods, it has been changed a lot. This project has been done with an intention to save electrical energy and reuse it. Brush less DC motors are permanent magnet AC motors having permanent magnets at the rotor side. When the rotor shaft is made to rotate by hand itself we can see the current flowing through the windings. A back EMF is generated in the windings with that current. That is called the regeneration. When motor operated in regenerating interval we can have a reverse current flow to the supply side. Brushless motors are commonly used as pump, fan and spindle drives in adjustable or variable speed applications. When motor speed is changed to a lower level, it may take some time to get that speed due to load inertia. Meanwhile regenerated EMF developed will oppose the forward current; the conflict between the current s may result in heat. If we provide a battery at the supply side the regenerated current can be directed towards supply side and the wasted energy can save in a battery.BLDC motors are so commonly used in all our electrical appliances now days. They can develop high torque with good speed response. In addition, they can be easily automated for remote control. Due to their construction, they have good thermal characteristics and high energy efficiency. To obtain a variable speed response, brushless motors operate in an electromechanical system that includes an electronic motor controller and a rotor position feedback sensor.

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. The control electronics replace the function of the commutator and energize the proper winding. 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 often incorporate either internal or external position sensors to sense the actual rotor position or its position can also be detected without sensors. BLDC motors are used in automotive, aerospace, consumer, medical, industrial automation equipments and instrumentation.

Brushless DC (BLDC) motors have the advantage of higher power density than other motors such as induction motors because of having no copper losses on the rotor side and they do not need mechanical commutation mechanisms as compared with DC motors, which results incompact and robust structures. Owing to these features, BLDC motors have become morepopular in the applications where efficiency is a critical issue, or where spikes caused bymechanical commutation are not allowed. A BLDC motor requires an inverter and a rotorposition sensor to perform commutation process because a permanent magnet synchronousmotor does not have brushes and commutator in DC motors.

However, the position sensorpresents several disadvantages from the standpoints of drive's cost, machine size, reliability, and noise immunity. As a result, many researches have been reported for sensor less drives that can control position, speed, and/or torque without shaft-mounted position sensors.. Brushless motor combines high reliability with high efficiency, and for a lower cost in comparison with brush motors.Brushless DC Motors are driven by DC voltage but current commutation is controlled by solid state switches.

The commutation instants are determined by the rotor position. The rotor shaft position is sensed by a Hall Effect sensor, which provides signals to the respective switches whenever the rotor magnetic poles pass near the Hall sensors, they give a high or low signal, indicating either N or S pole is passing near the sensors. The numbers shown around the peripheral of the motor diagram in Fig. 1.1 represent the sensor position code.

The north pole of the rotor points to the code that is output at that rotor position. The numbers are the sensor logic levels where the Most Significant bit is sensor C and the Least Significant bit is sensor A. Based on the combination of these three Hall sensor signals, the exact sequence of commutation can be determined. These signals are decoded by combinational logic to provide the firing signals for 120degree conduction on each of the three phases. The rotor position decoder has six outputs which control the upper and lower phase leg MOSFETs of Fig. 1.2

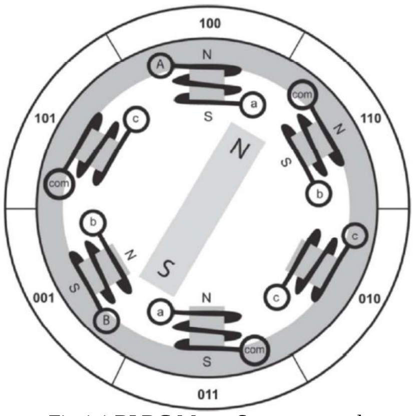

Fig 1.1 BLDC Motor Star connected.

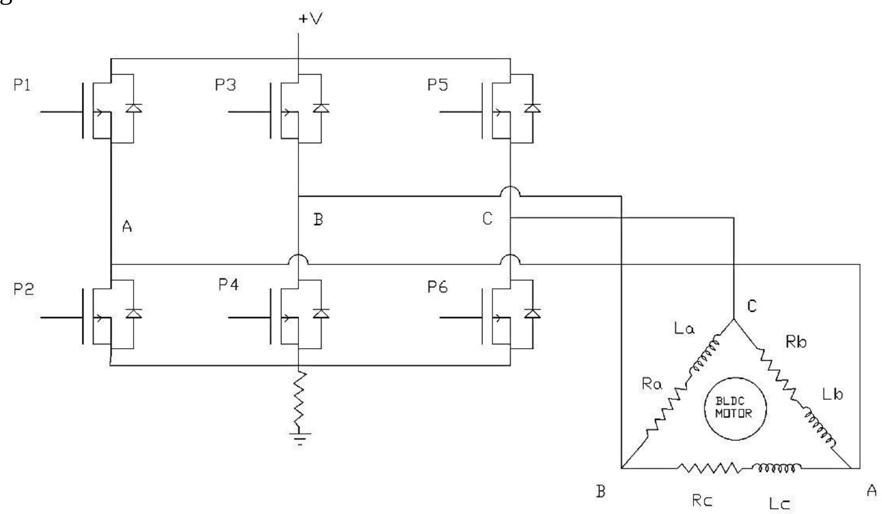

Fig 1.2 Equivalent Circuit of power stage of BLDC motor

II. FOUR QUADRANT OPERATION

There are four possible modes or quadrants of operation using a Brushless DC Motor Which is depicted in Fig. 2.1. When BLDC motor (Fig. 2.2) is operating in the first and third quadrant, the supplied voltage is greater than the back EMF which is forward motoring and reverse motoring modes respectively, but the direction of current flow differs. When the motor operates in the second and fourth quadrant the value of the back EMF generated by the motor should be greater than the supplied voltages which are the forward braking and reverse braking Modes of operation respectively, here again the direction of current flow is reversed. The BLDC motor is initially made to rotate in clockwise direction, but when the speed reversal command is obtained, the control goes into the clockwise regeneration mode, which brings the rotor to the standstill position. 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. Therefore, there is the necessity for determining the instant when the rotor of the machine is ideally positioned for reversal. Hall Effect sensors are used to ascertain the rotor position and from the Hall sensor outputs, it is determined whether the machine has reversed its direction. This is the ideal moment for energizing the stator phase so that the machine can start motoring in the counter clockwise direction.

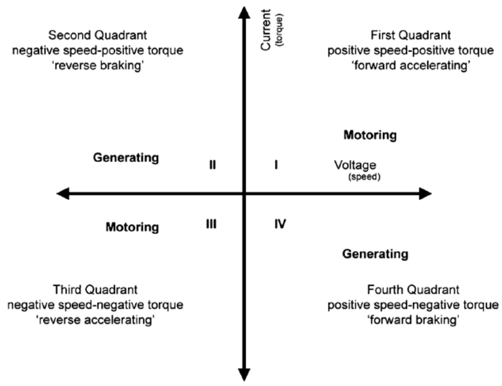

Fig 2.1 Four quadrants of operation

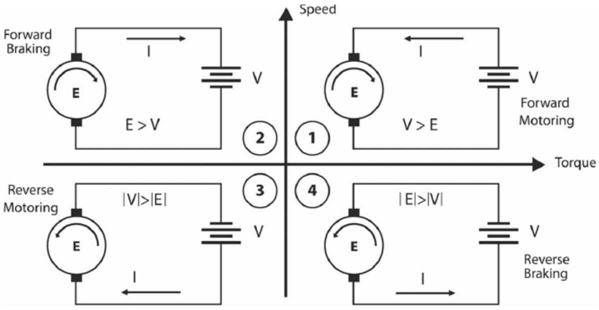

Fig.2.2 Operating modes

A. *Maintaining the Integrity of the Specifications*

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III. BLDC MOTOR FUNDAMENTALS

To simplify the explanation of how to operate a three-phase BLDC motor a fundamental BLDC with only three coils is considered as shown in the figure.3.1[3] To make the motor rotate the coils are energized (or "activated") in a predefined sequence, making the motor turn in one direction, say clockwise. Running the sequence in reverse order makes the motor run in the opposite direction. One should understand that the sequence defines the direction of the current flow in the coils and thereby the magnetic field generated by the individual coils. The direction of the current determines the orientation of the magnetic field generated by the coil. The magnetic field attracts and rejects the permanent magnets of the rotor. By changing the current flow in the coils and thereby the polarity of the magnetic fields at the right moment – and in the right sequence – the motor rotates. Alternation of the current flow through the coils to make the rotor turn is referred to as commutation

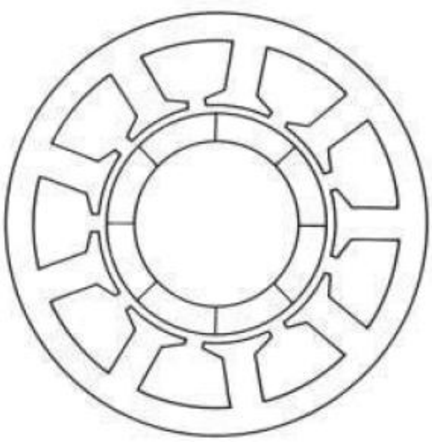

Fig. 3.1 BLDCM having Three sets of coils and eight poles

A three-phase BLDC motor has six states of commutation. When all six states in the commutation sequence have been performed the sequence is repeated to continue the rotation. The sequence represents a full electrical rotation. For motors with multiple poles the electrical rotation does not correspond to a mechanical rotation. A four-pole BLDC motor uses two electrical rotation cycles per mechanical rotation. When specifying the number of Rotations per Minute subsequently, the number of electrical rotations is referred to unless otherwise mentioned.

The most elementary commutation driving method used for BLDC motors is an on-off scheme: A coil is either conducting (in one or the other direction) or not conducting. Connecting the coils to the power and neutral bus induces the current flow (accomplished using a driver stage). This is referred to as square wave commutation or block commutation. An alternative method is to use a sinusoidal type waveform. This application note covers the block commutation method. The strength of the magnetic field determines the torque and speed of the motor. By varying the current flow through the coils the speed and torque of the motor can be varied. The most common way to control the current flow is to control the (average) current flow through the coil. This can be accomplished by switching the supply voltage to the coils on and off so that the relation between on and off time defines the average voltage over the coil and thereby the average current. For BLDC motors the commutation control is handled by electronics. The simplest way to control the commutation is to commutate according the outputs from a set of position sensors inside the motor. Usually Hall sensors are used. The Hall sensors change their outputs when the commutation should be shown in the figure 3.2

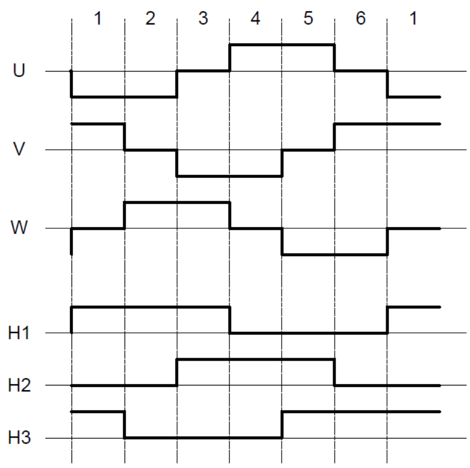

Fig. 3.2 Current flow through the coils and Hall sensor outputs

A. *Commutation*

Commutation provides the creation of a rotation field. As previously explained, it is necessary to keep the angle between stator and rotor flux close to 90° for a BLDC motor to operate properly. Six-step control creates a total of six possible stator flux vectors. The stator flux vector must be changed at a certain rotor position. The rotor position is usually sensed by Hall sensors. The Hall sensors generate three signals that also comprise six states. Each of Hall sensors' states corresponds to a certain stator flux vector. The informations are detailed in Table 2.1 and Table 2.2. The following two figures depict the commutation process.

Hall sensor A	Hall sensor B	Hall sensor C	Phase A	Phase B	Phase C
1	0	0	$-V_{DCB}$	$+V_{DCB}$	NC
1	0	1	NC	$+V_{DCB}$	$-V_{DCB}$
0	0	1	$+V_{DCB}$	NC	$-V_{DCB}$
0	1	1	$+V_{DCB}$	$-V_{DCB}$	NC
0	1	0	NC	$-V_{DCB}$	$+V_{DCB}$
1	1	0	$-V_{DCB}$	NC	$+V_{DCB}$

Table 3.1. Commutation Sequence for Clockwise Rotation

Hall sensor A	Hall sensor B	Hall sensor C	Phase A	Phase B	Phase C
1	0	0	$+V_{DCB}$	$-V_{DCB}$	NC
1	0	1	NC	$-V_{DCB}$	$+V_{DCB}$
0	0	1	$-V_{DCB}$	NC	$+V_{DCB}$
0	1	1	$-V_{DCB}$	$+V_{DCB}$	NC
0	1	0	NC	$+V_{DCB}$	$-V_{DCB}$
1	1	0	$+V_{DCB}$	NC	$-V_{DCB}$

Table 2.2. Commutation Sequence for Counter Clockwise Rotation

B. Regenerated braking

Based on the operating principle of brushless PM motor, the direction of motor output torque is reversed by changing the direction of the stator current under the same poles. While maintaining the same rotation direction, motor output torque is reversed by changing the direction of the stator current to achieve the effect of braking. To reverse the direction of the stator current, the conduction sequences of the power devices of three-phase inverter are only changed. In this period , defined as the charging state, the power device is switched off, the magnetic field energy previously stored in the inductors is released and superposes the back EMF, resulting in charging to storage battery and the decrease of the armature current.

IV. FOUR QUADRANT CONTROL STRATEGY

The proposed system in this project enables the four quadrant operation of BLDC motor, most importantly part of energy conservation. The common regenerative braking methods include adding an extra converter, or adding an extra ultra-capacitor, or switching sequence change of power switches. But the method of adding a converter not only increases cost but also reduces conversion efficiency. The method of adding an ultra-capacitor doesn't require extra DC-DC converter, but it needs a sensor to detect the ultra-capacitor voltage. This makes the circuit very complex and hard to implement. Moreover ultra-capacitor is very expensive.

A. Conventional systems

The conventional methods of BLDC motor operation are in single quadrant or two quadrant system. When speed reversal occurred the motor has to be run in more than one quadrant. The kinetic energy developed in the rotor has to be wasted as heat when mechanical braking is employed or if only operated in two quadrants. This can be changed and the energy can preserved if motor employs a four quadrant strategy. The produced energy is stored in the battery and which can be reused further.

B. Four quadrant system

The method proposed in this paper is simple and reliable. It conserves energy in a rechargeable battery during the regenerative braking mode. The schematic diagram of the drive arrangement of the three phaseBLDC motor is shown in Fig. 4.1. Suppose the motor is started to rotate CW direction. The position signals obtained from the Hall sensors of the motor are read by the I/O lines of the dSPIC controller. Controller determines the position code from the I/O lines and generate PWM pulses according to the signal obtained from CCW rotation enable pin. If the CCW enable pin is low, then motor continues to rotate in CW direction. When the CCW enable pin is high, motor lower its speed and because of load inertia it continues in the CW direction. This is the forward regenerating mode, in this mode back EMF goes high than the supply voltage hence stator voltage also goes higher than supply voltage. As the current goes from higher potential area to the lower potential area, stator current is reversed. The reversed current will charge the battery in the supply side. So when ever the motor goes to the regenerative mode the battery will be charging and it will be discharging in the motoring mode. The same process repeats when motor direction changed from CCW to CW. This interval is called the reverse braking interval. So, altogether forward motoring, forward braking, reverse motoring and reverse braking comprises the four quadrant operations.

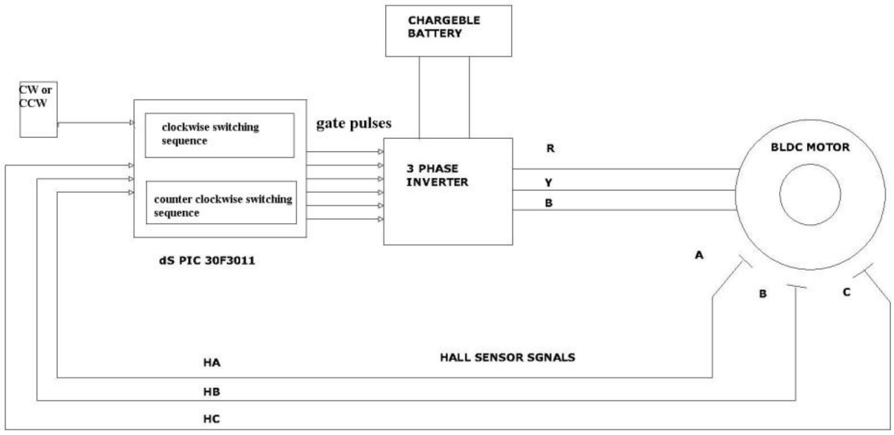

Fig 4.1 block diagram of the four quadrant system

The frequent reversal of direction of rotation will result in the continuous charging of the battery. The energy thus stored can be used to run the same motor when there is an interruption of power supply. This method is applicable in electric motor vehicles where battery is used to run the machine. Frequent reversal of rotation comes in spindle mills there heavy supply is coming from AC source there some mechanism has to be implemented like UPS or some thing like that. Otherwise the regenerated energy cant be stored in the same supply source it needs to be stored in some other systems like an external battery.

Now days BLDC motor are used in home appliances like AC or washing machine where there is frequent change in speed or change in rotation comes, which is most important in this project. A four quadrant operation can save some sort of energy which is wasted as heat in the control windings at the time of any change in speed.

An open loop control system is used in this project; if we need to operate motor in specific range of speed we should implement closed loop mechanism which includes a PI or PID controller. PI controller minimizes the error between the required speed and actual speed. An additional programming is required in the dSPIC for PI controller, which is followed by a PWM duty cycle selector to select the appropriate PWM duty, which in turn minimizes the error between set speed and actual speed. dSPIC is so versatile in doing such programming where as it is designed to do power electronics and drive application.

V. MATLAB SIMULATION OF SYSTEM

The MATLAB simulation of four quadrant control of BLDC motor has been done as a part of this project work. The snap shots of MATLAB work will be explained in the below sections. The simulation of proposed system includes BLDC motor with increased inertia of 0.05552 kgm^2. It gives the HALL sensor signal which is decoded to EMFs and followed by the PWM pulse generator which gives pulses for the gates of 6 pulse inverter. Inverter feeds the BLDC motor. The invertor is power from a DC source. Scopes are connected to view back EMF Stator currents, theta of rotation, HALL sensor signals. Apart from that two scopes are connected to demonstrate the four quadrant operation which is the comparison of speed and torque also the supply source mean value of current.

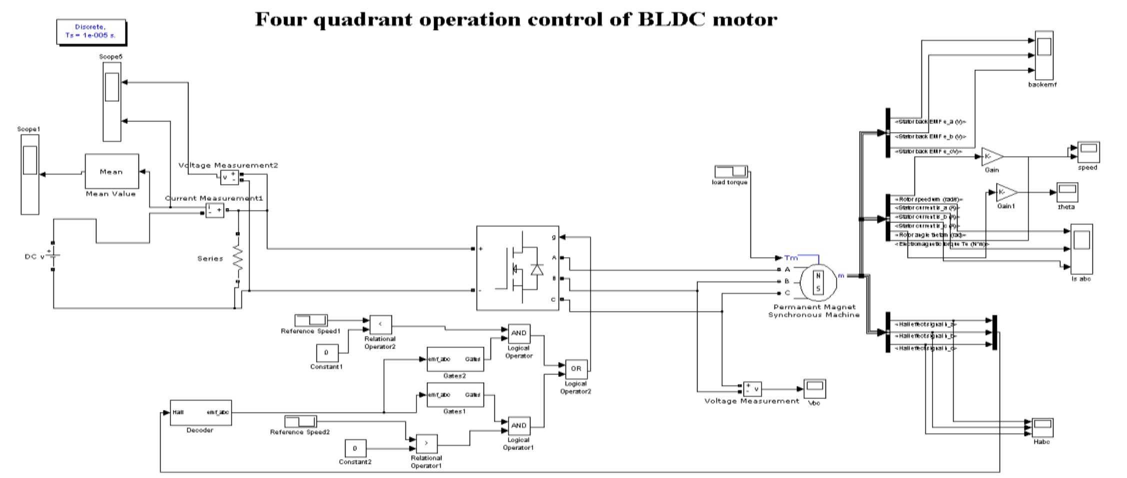

Fig 5.1 Simulation of proposed system

A. Results

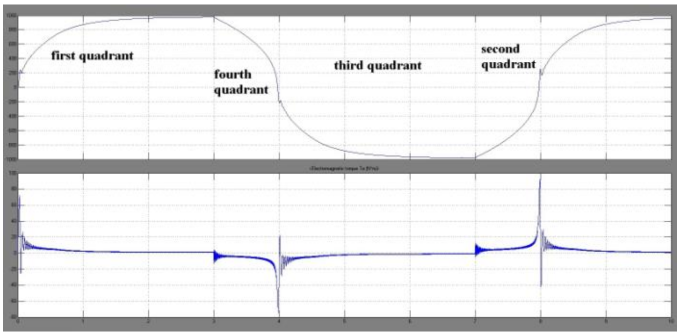

Fig 5.2 Comparison of speed and torque

If we look in to the each quadrant separately, it is show in the below figures

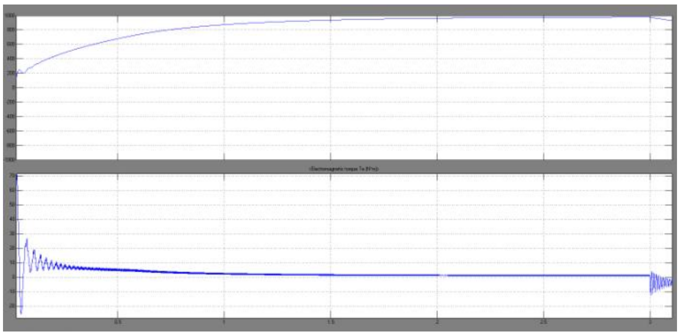
Figure 5.3.first quadrant speed torque comparison

In the first quadrant speed and torque is positive. In the figure 5.3 we can see for the simulation time 0 seconds to 3 seconds motor runs in clockwise motoring mode and speed reaches a settling value of 1000 rpm and the electromagnetic torque varies from 70 Nm to 1Nm as unchanged from positive value.

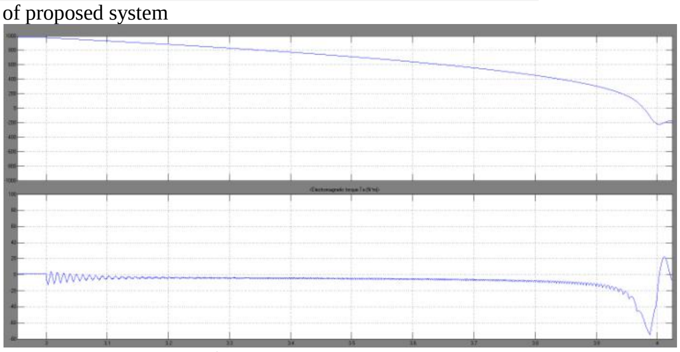
Figure 5.4 fourth quadrant speed torque comparison

In the figure 5.4, we can see the simulation running time from 3 seconds to 4 seconds motor operates in regeneration mode.in this interval of time speed and torque are in opposite sign. Speed is positive and torque is negative. Speed value decrease from 1000 rpm to 0 rpm and torque is varying from -10Nm to -1Nm and at the starting time of counter clockwise rotation at 4 seconds torque goes higher value of -60Nm due to starting inertia.

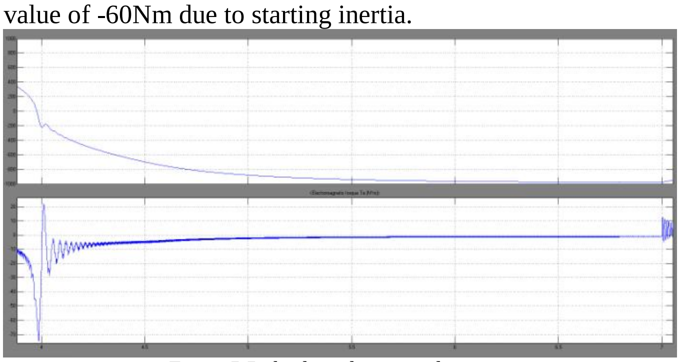
Figure 5.5 third quadrant speed torque comparison

In the third quadrant speed and torque are negative. It is shown in the figure 5.5. Motor starts rotating in the counter clockwise direction and speed increases to a higher value, due to a reference of counter clockwise direction it's a higher negative value. Speed increases from 0 to -1000 rpm, and torque initially goes to a high negative value and settles to a value of -1 Nm.

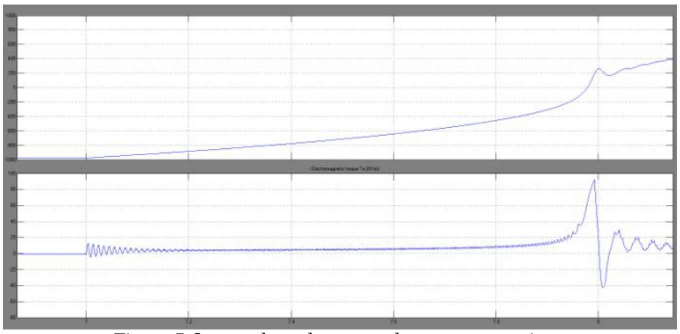

Figure 5.6 second quadrant speed torque comparison

Lastly but not least one more operating mode, it is the reverse braking mode. Due to negative speed and positive torque it lays in second quadrant. As shown in the figure 5.6. Speed decrease to 0 from -1000 rpm and torque is changed to a positive value of 1Nm from -1 Nm.

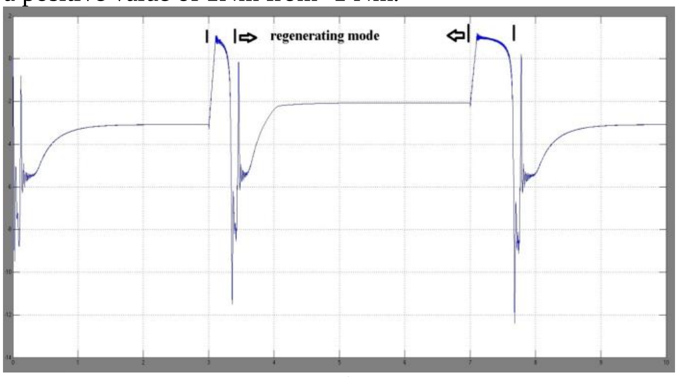

Fig 5.7 Mean value of supply side current

The above figure5.7 shows what the project is for rather than a speed torque comparison this figure gets the importance. There are two regions marked they are the regenerating interval. Normal time of motoring interval the value of current is negative. We can see in those two intervals at 3 seconds and 7 second; At 3s motor gets a signal to change it direction from clockwise to counterclockwise and motor starts reducing its speed. Regeneration starts at this time and backEMF gets back to supply side and current value goes to positive, as the motor reducing its speed, the value of current goes to zero at zero speed then when it starts to rotate in counter clock wise direction again the value goes to negative. The same procedure happens at 7s, that reverse braking occurs. The current is again reversed to supply side. This reverse current is stored in the supply side battery instead of resisting in the control windings, which only helps to increase the heat at the windings.

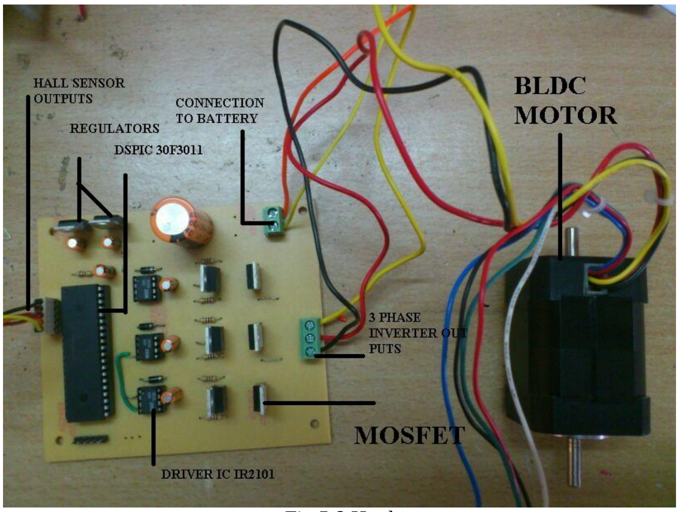

Fig 5.8 Hardware set up

Fig 5.8 shows the hardware setup.The motor is 42BL61 of 24 v, 60W, so the electronic capacitor is chosen as 40 v at the input side. DSPIC used is dSPIC 30F3011. Driver IC included in the circuit is IR2101. Driver IC is used in the circuit to avoid the ground sharing by different voltage levels (supply voltage and MOSFET gate voltage). A boost trapping method is followed here. The gate pulses given to MOSFET gate through a 100 ohm resistor. The diode used is IN4007

VI. CONCLUSION

In this paper it has been tried to demonstrate the four quadrant operation of a BLDC motor. Motor is supplied from a battery of 24V. The energy developed during the regenerative period is saved in the same supply battery. So the energy can be re used instead of wasting as heat. A BLDC Control drive is developed and implemented in between the battery and BLDC motor. DSPIC 30F3011 is used to develop the drive. A 6 pulse inverter is designed and developed for the 3 phase BLDC motor. The regenerative mode is developed by adding a flywheel at the rotor shaft instead of adding external weights. Due to the flywheel motor tends to rotate in the same direction even though the direction of rotation is changed. The back EMF developed at this interval of time is directed towards the battery at the supply side. The energy is stored in the battery can be re used. So this project gets an importance because of the energy conservation concept.

The world is behind anything that conserves energy. So this topic has some sort of importance in the upcoming researches. This technique can be implemented in the system where there is frequent change of direction or reduction of speed of the motor involves. For example spindle mills, or electric vehicles.

I sincerely wish to convey thanks to all my friends and teachers to give me all the supports in doing this paper. Special thanks to my guide Mr. Nizam N. assistant professor, MEA Engineering college.

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