DESIGN AND IMPLEMENTATION OF SOLAR-POWERED, FOUR-QUADRANT OPERATION AND CONTROL OF THREE-PHASE BLDC MOTOR FOR ELECTRIC VEHICLES

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ABSTRACT
Brushless Direct Current Motor (BLDC) overcomes many of the problems associated with brushed D.C. motors and is widely used in a variety of fields. The development of the Brushless Direct Current Motor (BLDCM) control system necessitates a dependable operation, excellent control algorithm performance, low cost, and a short development cycle. In this method proposes solar-powered four-quadrant operation and speed control of a three-phase BLDC motor for an electric vehicle. A digital controller increases the drive system's flexibility. The Smart Power Module is used to feed the BLDC motor in the 3-phase inverter. The proposed system receives Hall sensor signals from the motor and is set to the desired speed. The experimental results confirm the effectiveness of the developed drive operation. This method demonstrates the practical implementation of three-phase BLDC motor control in all four quadrants. This explains how kinetic energy can be converted and stored in a battery. The battery is thus charged by the PV cell and the back Emf generated by the BLDC motor during regenerative braking and can be used to power the same BLDC motor without power interruption.

To achieve precise control, the digital controller ATmega8, which has an advantage over other controllers, is used. The frequent change in rotational direction, and thus the change in quadrants, results

in frequent braking. The kinetic energy is lost as heat energy during the braking process. A theory in which kinetic energy is converted and stored in a battery the charged battery can power the same BLDC motor with no interruption in power supply.

Keywords: Brushless DC motor (BLDCM), Electric Vehicles (E.V.s), Pulse Width Modulation (PWM) Hall sensors, microcontroller.

1. INTRODUCTION

Brushless Direct Current Motors (BLDC) is one of the advanced motors used, rapidly increasing its popularity and applications. BLDC motor has a rotor with permanent magnets and stator with stacked steel laminations with windings inserted in slots. The motor has less inertia, therefore easier to start and stop. BLDC motors are potentially cleaner, faster, more efficient, less noisy and more reliable. In the brushless D.C. motor, polarity reversal is performed by power transistors switching in synchronization with the rotor position. Therefore, 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 Equipment and Instrumentation. Frequency/pulse measurements and as additional sources of external interrupts. The digital pulse width modulation control of the BLDC motor will be efficient and cost-effective. The digital control of the four-quadrant operation of the three-phase BLDC motor is achieved with ATmega8 Controller. This digital controller combines the Digital Signal Processor features and P.I.C. microcontroller features, making it versatile.

2. METHODOLOGY

A. BASIC STRUCTURES

The construction of modern brushless motors is similar to the ac motor, known as the permanent magnet synchronous motor. Figure.1 illustrates the structure of a typical three-phase brushless dc motor. The stator windings are similar to those in a more polyphaser ac motor, and the rotor is composed of one or more permanent magnets. Brushless dc motors are different from ac synchronous motors. The former incorporates some means to detect the rotor position (or magnetic poles) to produce signals to control the electronic switches. The most common position /pole sensor is the Hall element, but some motors use optical sensors.

This limits the use of DC motor in commercial applications. Furthermore,

The proportion of conveyed force to engine size is low, limiting its use to applications where space and weight are critical, such as electric vehicles and aviation applications. As a result, Brushless DC (BLDC) motor have emerged as a superior alternative to traditional. Although the efficient motors are three-phase, two-phase brushless dc motors are also very commonly used for simple construction and drive circuits. Figure 2

shows the cross-section of a two-phase motor having auxiliary salient poles of Electronic commutator.
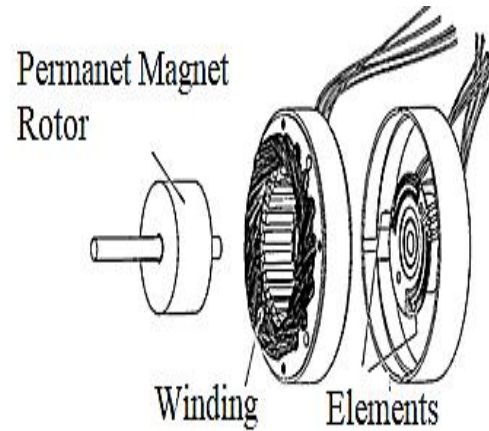

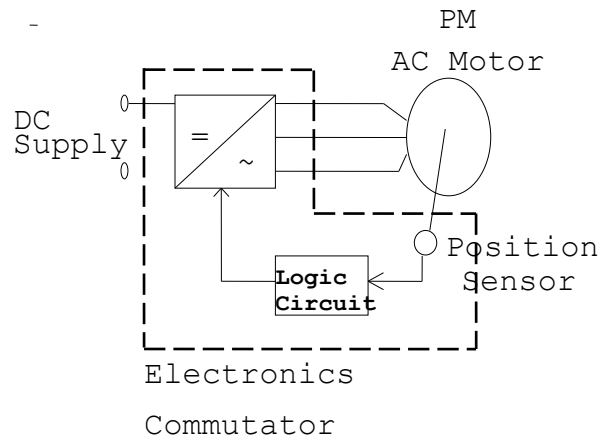**Figure 1: Disassembled view of a brushless D.C. motor**

Figure 2: Brushless DC motor.

When the motor operates in the second and fourth quadrants, the back Emf's value should be greater than the supplied voltage, which is the forward braking and reverses braking modes of operation. Here again, the direction of the current flow is reversed.
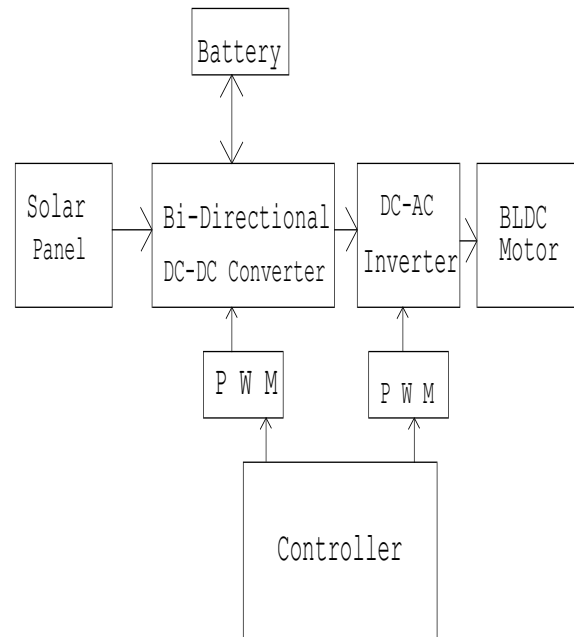
Figure 3: Block Diagram of Proposed System.

B. EXISTING SYSTEM:

The trend of using PM-BLDC motors is growing among domestic and industrial applications due to their characteristics. However, the drawback of having non-linear characteristics makes it difficult to be controlled. Several parameters need to be considered before designing the controller, such as load torque, stator resistance, rotor resistance, and output motor line current.

Complete drive system the schematic diagram of the drive arrangement of the three-phase BLDC motor Figure 4. The position signals obtained from the motor's hall sensors are read by the I/O lines of the ATmega8 controller.

The Pulse Width Modulation (PWM). Module of the applied to the three-phase inverter. When the motor is operating in the motoring mode, the relay contacts are normally open in the clockwise direction. But when braking is applied or when a speed reversal command is received, the relay contacts are closed. All the Digital Signal Processor (DSP) instructions are performed in a single cycle.

The selectable priority levels for each interrupt source, the three external interrupt sources help get the motor's Hall sensor inputs. The reference speed and the required duty cycle can be fed into the controller. The closed-loop control is achieved with the

Proportional Integral (PI) controller. This digital controller combines the Digital Signal Processor features and P.I.C. microcontroller features, making it versatile.

There are four possible modes or quadrants of operation using a Brushless DC Motor, depicted in Figure 5. When the BLDC motor operates in the first and third quadrants, 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.

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 counterclockwise direction.
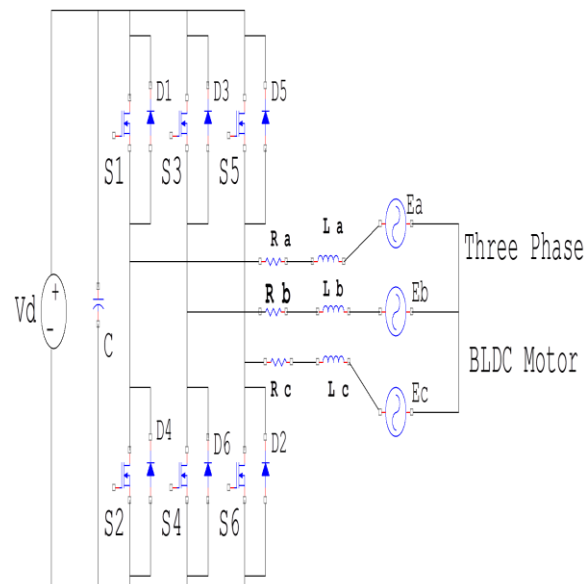

Figure 4: BLDC motor inverter-based drive circuit.

The BLDC motor is initially made to rotate in a clockwise direction. Still, 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 machine's rotor is ideally positioned for reversal
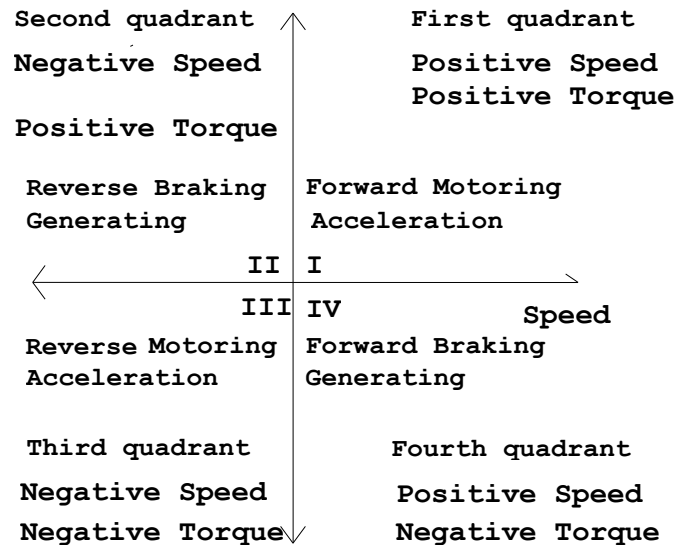
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      Second quadrant    ∧        First quadrant

   Negative Speed        |      Positive Speed
                         |      Positive Torque

   Positive Torque       |

    Reverse Braking   |Forward Motoring
    Generating        | Acceleration
                   II | I
   ←─────────────────────────────────────→
                  III | IV          Speed
    Reverse Motoring  |Forward Braking
    Acceleration      |Generating

     Third quadrant    |       Fourth quadrant

   Negative Speed      |      Positive Speed
   Negative Torque ∨        Negative Torque
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Figure 5: Four quadrant operation

The: structure of the bidirectional converter as illustrated in Figure 6. The bi-directional performance analysis is mentioned. It consists of two switches and two diodes; it behaves as a buck converter when the switch T1 and D2 are operational, these operations are utilized in the drive during motoring mode, and for regenerative braking, T2 and D1 are operational, thus making the converter work in boost operation by boosting the dc-link voltage to charge the battery. Diodes allow the flow of current in one particular direction depending on the operation.
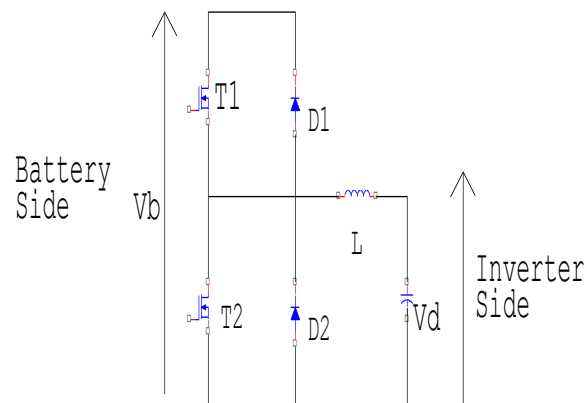
Figure 6: Bi-directional Converter.

During the buck operation on the inverter side, the energy is stored in the inductor (L). Whenever the gate pulse becomes zero (Stage II) is followed, the inductor discharges through the diode D2. During the boost operation, T2 is operated. The inductor stores

the energy from the inverter side; similarly, D1 provides the path to the current (Stage II) back to the supply source when the gate pulse becomes zero.

The operation of the two switches T1, T2 of the bi-directional converter is done with two different methods. During the motoring mode, the switch T1 is triggered with the technique of voltage control. During braking, the switch T2 is triggered with the help of current control as the dc-link voltage should remain constant for the motoring operation to a given speed, and during braking, the reverse dc-link current needs to be controlled.
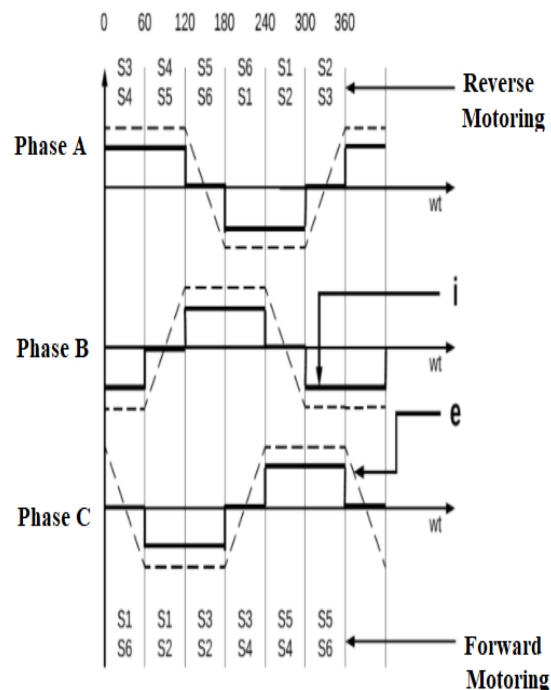

Figure 7: Switching sequence with rotor electrical angle in degrees, back E.M.F, phase current, and switching sequence of switches with rotor electrical angle in degrees.

C. BACKGROUND WORK

Electric motor technology involves machine constructions, materials, electronics, sensors and control technologies. A suitable converter and control techniques need to be developed for different motors to generate high-performance drives. The important aspect of various converter designs is the converter efficiency and its dynamic response. Low power loss in converters is due to high efficiency.

The 3rd harmonic and its corresponding multiples component are eliminated in the output due to this feature three-phase power system is used in D.C. drive systems. Comparing a 1-phase system with that of a 3-phase, the ripple voltage is significantly less. Nowadays, we face many different crises caused by high oil prices and obsolete designs, which have prompted the search for more efficient road vehicles, possibly based on environment-friendly sources located in politically stable areas. This has led to the development of electric vehicles. [1].

Compared with a D.C. motor, the BLDC motor uses an electric rather than a mechanical, so it is more reliable than the D.C. motor. In a BLDC motor, rotor magnets generate the rotor's magnetic flux, so BLDC motors achieve higher efficiency [2]. It has become possible because of their superior performance in terms of high efficiency, fast response and weight, precise and accurate control, high reliability, maintenance-free operation, brushless construction and reduced size, torque to motor size ratio are high, Thermal overload & under load protection are provided. [3, 5, 8]

The microcontroller has more advantages than micro-processors. These I.C.s are cost-effective and can be used for applications ranging from appliances to automobile engines to text or data processing equipment. Because of their higher performance, they perform higher solution control and minimize control loop delays. These efficient controls make it possible to reduce torque ripples and harmonics and improve dynamic behavior in all speed ranges. The motor design has been optimized due to lower vibrations and lower power losses, such as harmonic losses in the rotor. Smooth waveforms allow optimization of power elements and input filters. Overall, these improvements result in a reduction of system cost and better reliability. Switching electric machines from ordinary digital control to microcontrollers significantly improves operating efficiency, saving energy while allowing smaller, less expensive motors.

Since the advancement in battery technology has been relatively sluggish, compared with the power electronics area, the handicap of short-range associated with E.V. remains. With this technology limitation, the E.V. seems to be the viable alternative to the I.C.E. automobile at present. [7] This project aims to design microcontroller-based BLDC motor drives for electric vehicles. Based on several P.W.M. switching schemes, the performance of converter parameters will be tested and observed. Open-loop and closed-loop speed control of the system is done, and the results are tabulated, which verify the effective developed drive operation.

D. METHODOLOGY

The block diagram of the BLDC drive system is shown in Figure 3. It consists of a three-phase inverter, position sensors, signal conditioner and a digital controller. Along with the position sensor arrangement, the inverter is functionally analogous DC motor.

The BLDC motor detects the position of the rotor using Hall sensors. Three sensors are required for position information. With three sensors, six possible commutation sequences could be obtained. In the Hall sensor technique, three Hall sensors are placed inside the motor, spaced 120 degrees apart. Each Hall sensor provides either a High or Low output based on the polarity of the magnetic pole close to it. Rotor position is determined by analyzing the outputs of all three Hall sensors. Based on the output from hall sensors, the voltages to the motor's three phases are switched.

BLDC motor control is to have only one current at a time. Because of which current sensor is not advised to be placed on each phase of the motor; one sensor placed in the line inverter input is sufficient to control the current of each phase. Insulated systems are not required when the sensor is on the ground line. The microcontroller manages the torque and speed of motors. A sufficient amount of processing power is required to solve the algorithms needed to generate Pulse Width Modulated (P.W.M.) outputs for the motor.

Closed-loop control regulates the speed of the motor by directly controlling the duty cycle of the P.W.M. signals that direct the motor-drive circuitry. The duty cycle of the P.W.M. signal controls the ON time of the power switches in the half-bridges of the motor-drive circuit, and this, in turn, controls the average voltage supplied across the motor windings. The major difference between the two control systems is that the open-loop control considers only the speed control input to update the P.W.M. duty cycle. In contrast, the closed-loop control considers both speed-input control and actual motor speed (feedback to the controller) for updating the P.W.M. duty cycle and, in turn, the motor speed.

A PI controller is a closed-loop control implementation widely used and is most commonly used as a feedback controller. In a 3-phase BLDC motor control, one electrical cycle has six Hall states. Depending on the number of poles in the motor, the electrical angle measured between successive Hall state changes can be translated to a respective mechanical angle. The actual motor speed is calculated by tracking the period between successive Hall events, which represents a part of the mechanical cycle of the motor.

3. RESULTS AND DISCUSSION

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.
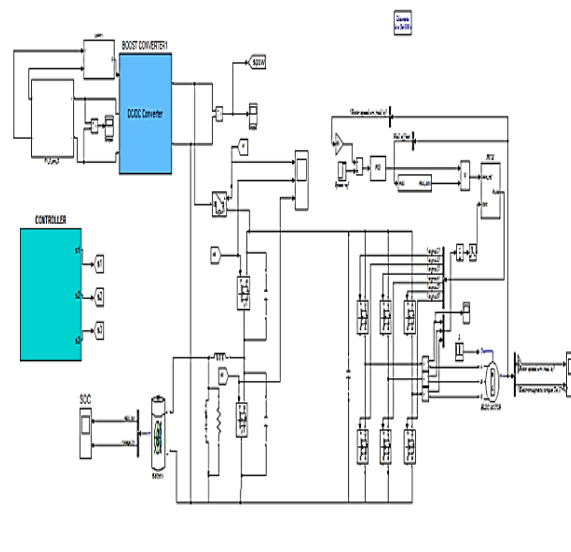
Figure 8: MATLAB Simulation Output

The designed and implemented prototype model may be implemented even for higher-rated motors. When implemented in higher rating motors, arcing might occur during the switching on and off of the relay contacts. But if the proposed method is implemented in low power motors, like motor used in sewing/embroidery machines, arcing will be very less, which is not even visible. This concept can be well utilized in the rotation of spindles, embroidery machines and electric vehicles where there is the frequent reversal of direction of rotation of the motor.The closed-loop controller for a three-phase brushless D.C. motor is modeled using MATLAB/Simulink is shown in Figure 8. Permanent Magnet Synchronous motor with trapezoidal back E.M.F. is modeled as aBrushless DC Motor.
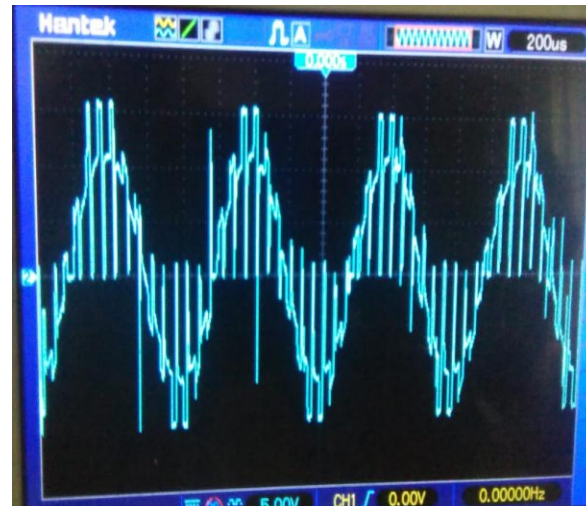
Figure 9: Phase current Ic of drive

The model of the controller receives the Hall Effect sensor signals. The phase current for the brushless D.C. motor is normally trapezoidal or rectangular. Signals as its input convert it into appropriate voltage signals. The gate signals are generated by comparing the actual speed with the reference speed. Thus closed-loop speed control is achieved with the help of P.I. control, present in the controller block and the phase current waveforms are shown in figure 9.

The Hall Effect sensor signals are decoded and given to the P.W.M. module, which gives the required P.W.M. signals to drive the gates of the controlled converter switches. The P.W.M. signals which are applied to the Gates of the inverter are shown in Figure 10. Depending upon these P.W.M. signals, the ON and OFF periods of switches vary, i.e., there will be a variation of the duty cycle. Hence, the output voltage of the electronic is changed, which is applied to the motor.
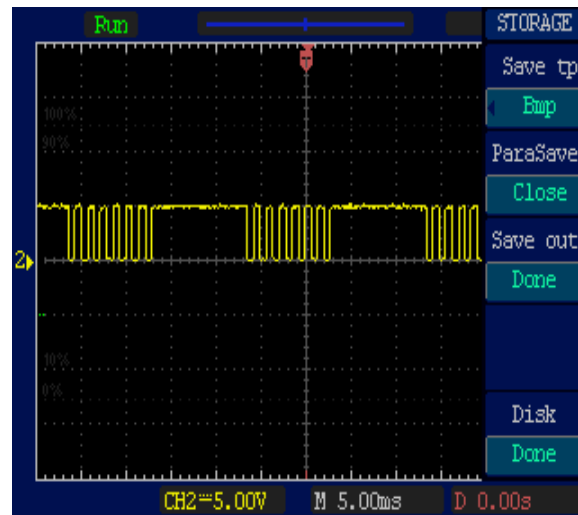
Figure 10: P.W.M. signals applied to gates of the inverter

The sinusoidal stator current, trapezoidal voltages applied to the motor, and the rotor's speed. The stator current of the machine under operation (BLDC Motor) is sinusoidal. It has trapezoidal back E.M.F. waveforms. The motor speed is almost constant after reaching its reference or set speed.

The position signals obtained from the motor's Hall sensors are read by the I/O lines of the Digital controller. Which gives information about the position of the rotor. The Hall sensor inputs give the position of the rotor, which is fed to the controller. The controller compares it with the reference speed and generates an error signal. The required direction of rotation, either clockwise or counterclockwise, can also be fed to the digital controller. The P.W.M. module of the controller generates appropriate P.W.M. signals.
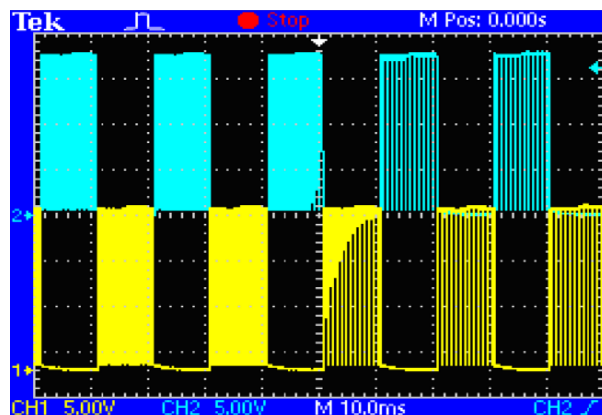

Figure 11: Stator Current of BLDC motor

Figure 11 Shows stator current voltages between the phases R.Y. and Y.B., which are trapezoidal. These trapezoidal waveforms of voltages are given to the BLDC motor for its operation. To operate a brushless D.C. motor, rectangular pulses can also be given in general.

	Motor Data	Value	Unit
1.	Horsepower rating (Hp)	0.31	Hp
2.	Rated speed	1500	rpm
3.	Rated current	6.8	A
4.	Stator equivalent resistance (R)	0.345	n
5.	Stator equivalent inductance (L)	0.314	mH
6.	Moment of inertia (J)	0.0019	y Ncm/s^2
7.	Voltage constant (K_e)	0.0419	V/rad/s
8.	Torque constant (K_t)	4.19	Ncm/A

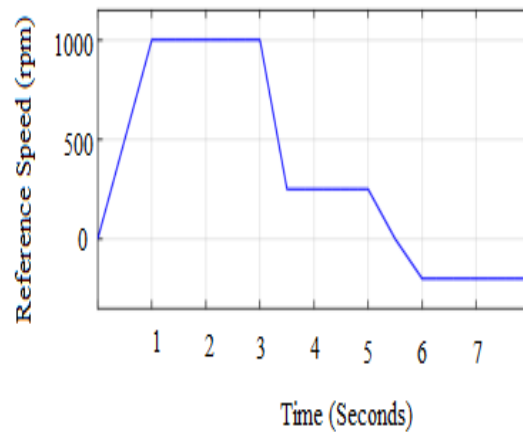**Table 1: Parameters used for BLDC motor modeling**

Figure 12: Reference speed of BLDC Motor

The rotor position sensors determine the replacement moments. The stator stage windings are energized in response to the rotor position signal. There are two types of control strategies: sensor-based control and sensor-less control. The sensor-based BLDC motor control has a number of drawbacks. Mechanical sensors increase the rotor shaft's dormancy. The reference speed and actual speed curve of BLDC motor are shown in Figure 12 and Figure13 respectively.
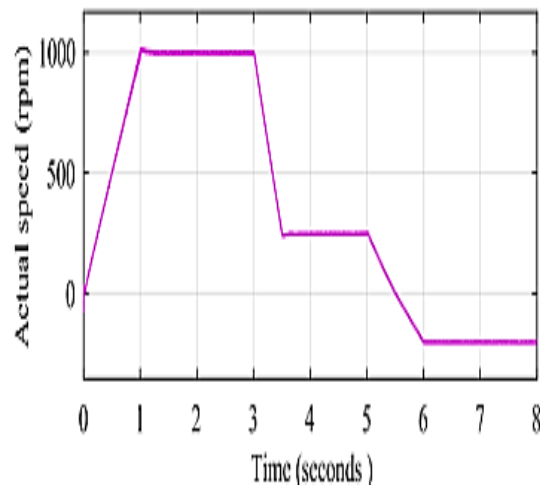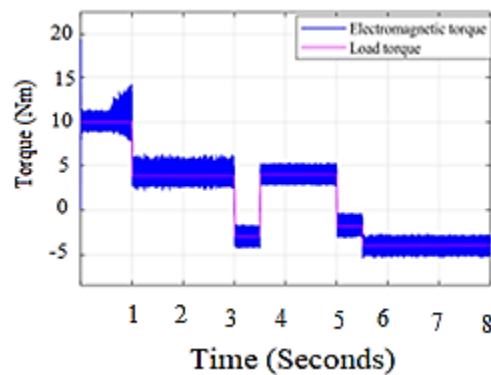

Figure 13: Actual speed of BLDC motor

Figure 14: Electromagnetic torque and motor load torque

Brushless DC Motors, also known as BLDC Motors, have benefited greatly from cutting-edge drive innovation. Their rapid rise in popularity has resulted in an expanding range Regardless of the fact that they have been used for drives and force age for a long time, the sub-kilowatt range, which has been overwhelmed by Brushed DC Motors, has consistently been a hazy situation. Nonetheless, cutting-edge power hardware and microchip innovation have enabled the small Brushless DC Motors to thrive, both in terms of cost and execution
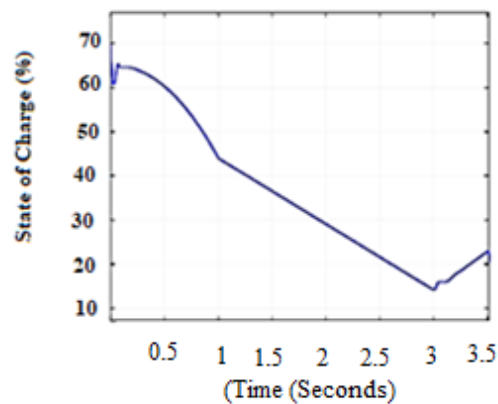

Figure 15: Battery State of charge

The battery will be charged between 3 to 3.5 sec. as shown in Figure 15.

Motor Action	Time Duration (sec)
Acceleration	0-1
Constant speed of 1000 rpm	1-3
Braking	3-3.5
Reverse motoring Beyond	6.0

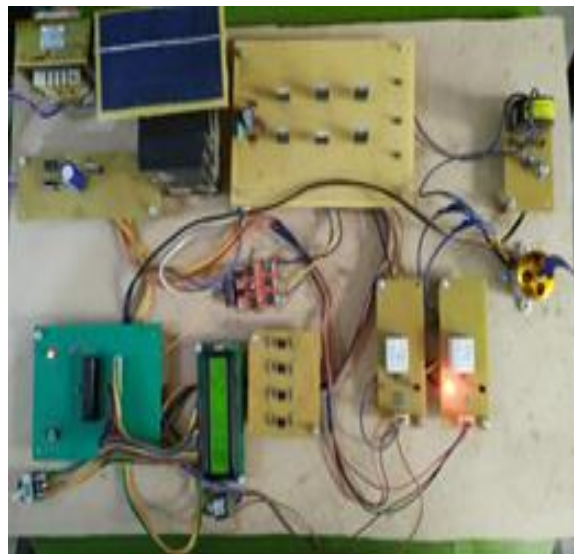**Table 2: Tabulation of BLDC Motor action**

Figure 16: Hardware setup Hardware modules specifications

- Inductor-600mH
- Capacitor-1000uf
- IRF 840 MOSFET
- ATmega8 controller
- 7805 regulator

- MOC3021 gate drive
- BLDC motor
- Solar panel 5w-12v.
- Battery 12/5A VRLA battery
- Software Module.
- A.V.R. studio for embedded C programming.

4. CONCLUSION

A modular design is described for both the inverter and the permanent magnet BLDC motor. A control scheme is proposed for the modular brushless dc motor drive for changing its direction instantaneously. The transition from clockwise to counterclockwise rotation of the motor is too quick. In the regenerative mode of operation, the generated voltage is fed back to the supply so that there will be a saving of power. The modular design of the inverter and the BLDC motor is very advantageous and economical as the power rating of the drive can be changed by removing or adding the inverter and motor modules. The effect of P.W.M. strategies and the results can be achieved by the variation of Proportional and Integral constants of the P.I. controller. For best results, the Tuning process is done by trial and error method, and the Proportional Constant and Integral Constant are 0.1 and 0.03respectively.

The simulation results have shown that the four-quadrant operation of BLDC motor drive employing modular design is well suited for applications such as hybrid electric vehicles, traction systems. The advantages of this proposed project are the reliability of controlling techniques, superior performance in speed control, efficient conservation of energy on load and no-load conditions, quicker and smooth transition from braking to motoring and vice-versa. The disadvantage of this model is arcing might occur when a prototype model is designed for higher rating motors, and if the motor rating is small, this is not a serious issue.

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