Embedded System Based Control of BLDC Motor Drive for Commercial and Industrial Applications

S. Sathish Kumar[1], Dr. R. Meenakumari.R[2],
[1]Assistant Professor Dept of EEE, Jansons Institute of Technology,Coimbatore, Tamilnadu, India
[2]Professor Dept of EEE Kongu Engineering College, Erode, Tamilnadu, India
E.mail:sat_mea2k5@rediffmail.com,oremkay@gmail.com.

Abstract— **Brushless DC(BLDC) motors are now a days becoming popular in battery operated vehicles, fuel pumps, medical equipments, printers and in many applications because of its light weight, high operating speed and excellent speed-torque characteristics. However, BLDC motor requires complex and expensive high speed drives and converter circuits to perform electronic commutation and suitable control circuits for implementing control technique. Since the conventional drive circuits are expensive, bulky and more complex, this paper proposes a low cost, compact, high performance BLDC drive system employing solar module with DC –DC converters and Pulse Width Modulation (PWM) control strategy. The proposed drive consists of a solar module, charge controllers, batteries, SEPIC converter and BLDC motor, henceforth developed into the Solar Powered BLDC motor drive and solar powered equipments and three phase inverter containing six MOSFET switches. A microcontroller or DSP will be used to control the overall system. This project explains the study of designing a Solar Powered BLDC Motor Drive which is one of the solutions for the oncoming crisis. The approach of selecting the appropriate components for this application is studied and each of them are simulated.**

Index Term-- **BLDC, Solar Module, SEPIC Converter, Inverter**

1. INTRODUCTION

Brushless DC Motor is a rotating electric machine where the stator is a classic three phase stator like that of an induction motor and the rotor has surface mounted permanent magnets. The BLDCM is driven by rectangular strokes coupled with the given rotor position. The generated stator flux interacts with the rotor flux, which is generated by a rotor magnet that defines the torque and the speed of the motor. The voltage strokes must be properly applied the two phases of three phase winding system, so that the angle between the stator flux and rotor flux is kept close to 90 degree. BLDC motors are a type of synchronous motor. This means the magnetic field generated by the stator and the magnetic field generated by the rotor rotate at the same frequency. BLDC motors do not experience the slip that is normally seen in Induction motors. Even though conventional DC motors are highly efficient, it had some drawbacks due to commutator and brushes which need proper maintenance. But in BRUSHLESS DC MOTOR when the functions of commutator and brushes were implemented by solid- state switches, maintenance free motors were realized. Instead of commutating the armature current by using brushes, here electronic commutation is used. This eliminates the problems associated with the brush and the commutator arrangement, thereby, making a BLDC more rugged as compared to a DC motor. BLDC motors are come in single phase, 2-phase and 3-phase configurations. Corresponding to its type, the stator has the same number of windings. Out of these, 3-phase motors are the most popular and widely used. Three-phase motors have a number of slots (and teeth) that are evenly divisible by three. A phase is an individual group of windings with a single terminal accessible from outside the motor. Most of the brushless motors are available in three-phase motor.

In this paper three phase BLDC motor drive is designed for commercial applications which is controlled by using proportional and integral controller. Power converter in the BLDC motor drives system consists of two parts, which is a rectifier and 3-phase full bridge inverter. Control schemes for this motor drives typically a PWM waveform driving the inverter. A suitable switching technique is needed to generate pulses to drive the power device circuit. To produce the desired output, PWM switching technique will be used to generate the pulses for power device via microcontroller. Factors to be considered in designing the converter for the BLDC motor drives in order to meet the requirement includes a suitable switching technique and controlling switching angles for the BLDC motor rotation and controllable magnitude and frequency of the output voltage.

A.BLDC motor equation

When DC supply is switched on to the motor the armature winding draws a current. The current distribution within the stator armature winding depends upon rotor position and the device is turned on. An EMF perpendicular to permanent magnet field is set up. Then the armature conductors experience a force. The reactive force develops a torque in the rotor. If this torque is more than the opposing frictional and load torque, the motor starts. It is a self starting motor. The voltage equation of the BLDC motor is given as

$$V_{dc} = 2[R_s I_a + (L-M)\, dI_a/dt] + e_1 - e_2 = R_a I_a + L_a\, dI_a/dt + e_1 - e_2 \quad (1)$$

The electromagnetic torque is proportional to stator current and is given by

$$T_e = K_b I_a. \quad (2)$$

$$V_{dc} = R_a I_a + L_a\, di_a/dt + K_b \omega \quad (3)$$

The load torque which varies with motor speed is given by

TL=K T ω. (4)

The mechanical equation of the rotor is

Te- TL=J d ω/d t+ B ω. (5)

Substituting equations (3) and (4) into equation (5) we get

Kb I a- K T ω=J d ω /d t + B ω (6)

B. Functional block diagram of BLDC motor drive

The Brushless DC Motor is a combination of a Permanent Magnet AC Motor and an Electronic Commutator. In BLDC motor inverter has to replace the commutator of a conventional DC motor. The commutator acts like a three phase frequency converter. The commutation of a brushless DC motor depends upon the position of the rotor. The angle between the magneto - motive force of stator and magneto – motive force of rotor is fixed to 90 degrees (electrical).

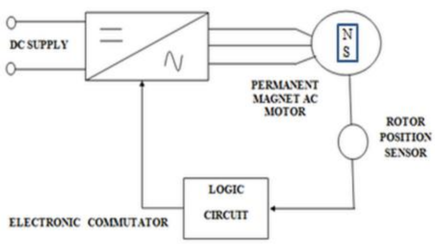

Fig. 1. Functional Block Diagram of BLDC motor

There are several methods to convert DC to AC. They differ mainly in their approximation to a perfect sinusoidal signal. As one would expect the best approximation yields the best transfer of power to a device that expects a sinusoidal signal. The applied DC voltage is supplied to the inverter block an thereby it converts DC to AC. The function of an inverter is to change a DC input voltage to AC output voltage of desired frequency and magnitude. In case of 3-phase inverter, the inverter circuit changes DC input voltage to a symmetrical AC output voltage of desired magnitude and frequency. Output voltage could be fixed or variable at a fixed or variable frequency. Variable output voltages are obtained by varying the input DC voltage with maintaining the gain of the inverter constant.

Rotor Position Sensor is used to sense the position of the rotor of the BLDC motor. Hall Effect sensor is a transducer that varies its output voltage in response to a magnetic field. Hall Effect sensors are used for proximity switching, positioning, speed detection, and current sensing in BLDC motor drive. Hall sensors are commonly used to time the speed of wheels and shafts, such as for internal combustion engine ignition timing, tachometers and anti-lock braking systems. They are used in brushless DC electric motors to detect the position of the permanent magnet. Hall sensors can be used to operate as a switch. It's cost is less than other mechanical switches. It is also used in the brushless DC motor to sense the position of the rotor and to switch the transistor in the right sequence.

C.Circuit diagram of BLDC motor

Figure 2 shows the block diagram for a 3-phase BLDC drives, which consists of a 3-phase inverter and a BLDC motor. The 3-phase inverter uses a signal generated by the microcontroller to trigger the power device to produce necessary current in the motor winding for rotor shaft rotation

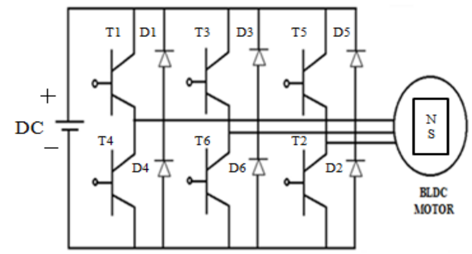

Fig. 2. BLDC Motor Circuit

The inverter is controlled by PWM switching schemes to drive the BLDC motor. The gating signals of MOSFET are shifted by 60º by each gate to obtain a 3-phase balanced fundamental voltage with 120º phase shift. The setting of the conduction period is done by programming the desired on time of the MOSFET onto the microcontroller. The power semiconductor chosen for BLDC motor drive is MOSFET. It requires continuous operation of a gate-source voltage of appropriate magnitude in order to be in the on state. The switching time is very short, that is in range of nanoseconds to picoseconds depending on the device type. However, because of the switching speed is very fast, the switching losses can be very small. So the switching power loss in a semiconductor varies linearly with the switching frequency and the switching times. The three phase inverter which is used to drive the BLDC motor consists of six switches (MOSFET). Depending upon the control power supply capability, the motor with the correct voltage rating of the stator can be chosen.48 V, or less than that voltage rated motors are used in automotive, robotics, small arm movements etc. Motors with 100 V or higher than that rating are used in appliances, automation and in industrial applications. BLDC motors have come to dominate many applications, particularly devices such as computer and hard drives, CD/DVD. Small cooling fans in electronic equipment are powered exclusively by BLDC motors. They can be found in cordless power tools where the increased efficiency of the motor leads to longer periods of use before the battery needs to be charged. Low speed, low power BLDC motors are used in direct-drive turntables for gramophone records. BLDC motors are commonly used as pump, fan and spindle drives in adjustable speed drives.

II. MODELING OF BLDC MOTOR

Computer simulation plays a great role in research to analyze the behavior of new circuits, which leads to improved understanding of the circuit[1]. In industry, they are used to shorten the overall design process, since it is usually easier to study the influence the parameter on the system behavior in simulation, as compared to accomplishing it in the laboratory on the hardware breadboard. The simulation is used to calculate the circuit waveform, the dynamic and steady state performance of the system, voltage and current rating of various components. Simulink is an interactive tool for modeling, simulating and prototyping analog and mixed signal system using the block sets rather than the line of code. It works as an integral part of the MATLAB environment. MATLAB/ Simulink platform is being used in industries also to simulate algorithms and evaluate alternatives early in the design process and convenient tool for monitoring simulation results.

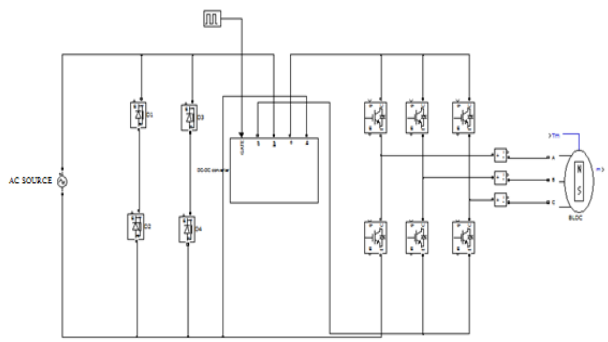

Fig. 3. Simulation Model of BLDC Motor

The BLDC motor has to be equipped with a position sensor which informs the controller what the position of the rotor magnetic pole is, with respect to the particular stator phase winding.[3] The above figure shows the simulation model of BLDC Motor drive and the mathematical equations that are modeled are incorporated in the SIMULINK block diagram and the characteristics of the motor are studied from the output waveforms of simulation. Since BLDC motor drive is a special machine, an inverter is required for its operation. A typical BLDC drive consists of a Voltage source inverter, BLDC motor and rotor position sensors for finding the rotor position after every switching sequence of the inverter. The induced voltages and currents in a BLDC motor drive are trapezoidal in nature. The BLDC motor fed from a DC source through a standard three phase inverter bridge. Two switches should be conducting for every pattern, one from lower leg and another from upper leg resulting in alternate excitation of two phases at a time out of three phases which facilitates continuous rotation of the rotor.PI is a feedback controller which drives the plant to be controlled with a weighted sum of the error and the integral of that value. PI controllers are widely used in industrial application, due to their simplicity, low cost and robustness. These controllers can also be implemented easily through analog components. The general operation of PI can be represented by the following equation.

$$M(t)=K_p\, e(t) + K_i \int e(t)\, dt \qquad (7)$$

Where,

e (t) is the speed error
M (t) is the output of the controller
Kp is the proportional constant and
Ki is the integral constant

Here the controller provides an appropriate feedback to the system based on the error signal. This feedback takes account of the magnitude as well as its rate of change and integral effect. Filter is widely used in power electronics to reduce harmonic components at the output waveform. It is also used for smoothing the voltage wave of a load fed from a rectifier in reducing the harmonic content of an inverter output, preventing unwanted harmonic component being reflected into AC system. Output of the inverter is a "chopped DC voltage with zero DC components"[2]. In some applications such as AC motor drives, filtering is not required. Besides, with PWM switching schemes algorithm, elimination of certain harmonic can be done without using external filter circuit on the converter system

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III. BLDC MOTOR POWERED BY SOLAR MODULE

The below figure shows the SEPIC converter based drive for *BLDC* motor. Front-end single-ended primary inductance converter (SEPIC) and a switch in series with each phase is proposed for driving a permanent magnet brushless dc (BLDC) motor with unipolar currents.

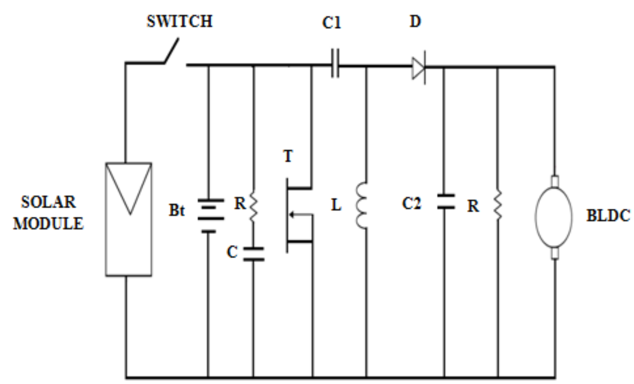

Fig. 4. Circuit Diagram of Sepic Converter along with BLDC motor

A DC to DC converter is an electronic circuit which converts a source of direct current (DC) from one voltage level to another. DC to DC converters are important in portable electronic devices, which are supplied with power from batteries primarily[4]. Such electronic devices often contain several sub circuits, each with its own voltage level requirement different from that supplied by the battery or an external supply (sometimes higher or lower than the supply voltage). Most DC to DC converters also regulate the output voltage. In these DC-to DC converters, energy is periodically stored into and released from a magnetic field in an inductor by adjusting the duty cycle of the charging voltage (that is, the ratio of on/off time), the amount of power transferred can be controlled. Usually, this is applied to control the output voltage, though it could be applied to control the input current, the output current, or maintain a constant power. Chopper systems are characterized by high efficiency, fast response and regeneration operation capability.

A. SEPIC Converter

The DC to DC converter here used is SEPIC converter Single-ended primary-inductor converter (SEPIC) is a type of DC-DC[5] converter allowing the electrical potential (voltage) at its output to be greater than, less than, or equal to that at its input; the output of the SEPIC is controlled by the duty cycle of the control transistor. A SEPIC is similar to a traditional buck-boost converter, but has advantages of having non-inverted output (the output has the same voltage polarity as the input), using a series capacitor to couple energy from the input to the output (and thus can respond more gracefully to a short-circuit output), and being capable of true shutdown: when the switch is turned off, its output drops to 0 V. In SEPIC converter the voltage drop and switching time of diode is critical to a SEPIC's reliability and efficiency. The diode's switching time needs to be extremely fast in order to not generate high voltage spikes across the inductors, which could cause damage to components. Fast conventional diodes or Schottky diodes may be used.

B. Solar Module

Solar modules use light energy (photons) from the sun to generate electricity through the photovoltaic effect. The structural (load carrying) member of a module can either be the top layer or the back layer. Cells must be protected from mechanical damage and moisture. Most solar modules are rigid, but semi-flexible ones are available, based on thin-film cells. These early solar modules were first used in space in 1958.Electrical connections are made in series to achieve a desired output voltage and/or in parallel to provide a desired current capability. The requirements for residential and commercial are different in that the residential needs are simple and can be packaged so that as solar cell technology progresses, the other base line equipment such as the battery, inverter and voltage sensing transfer switch still need to be compacted and unitized for residential use.

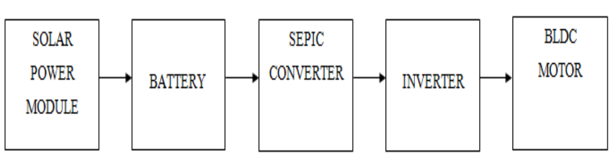

Fig. 5. Schematic Approach of Proposed System

The usage of solar energy is used to power up for commercial appliances. In order to achieve the required voltage, the Photo Voltaic (PV) Module may be connected either in parallel or series, but it’s costlier. Thus to make it cost effective, power converters and batteries are been used. The electrical charge is consolidated from the PV panel and directed to the output terminals to produce low voltage (Direct Current). The charge controllers direct this power acquired from the solar panel to the batteries. According to the state of the battery, the charging is done, so as to avoid overcharging and deep discharge. The voltage is then boosted up using the SEPIC power converter, ultimately running the BLDC motor which is used as the drive motor for our commercial application. In the course work, the characteristic features of the components are required for the commercial applications were studied and also were modeled individually using MATLAB/SIMULINK and the complete hardware integration of the system is tested to meet up the application’s requirement.

IV. SIMULATION OF PROPOSED SYSTEM

The simulation of the proposed BLDC motor drive was done using the software package MATLAB/ SIMULINK.

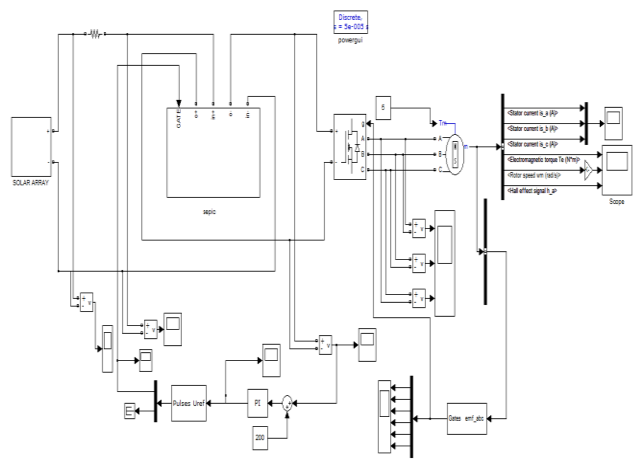

Fig. 6. Simulation Diagram of Proposed System

V. SIMULATION RESULTS AND DISCUSSIONS

After running the simulation, the speed, torque, current, input and output power waveforms were recorded and analyzed using m-file. The below figures show the waveforms of the electrical and mechanical quantities after the stator was supplied with a desired sinusoidal voltage and frequency. From the simulation results we can obtain the stator current, rotor speed, electromagnetic torque and hall effect signal waveforms are plotted in figure 7, 8, 9 and 1[6-11].

A . Stator Current

Stator current of the proposed system is nearly about 5 ampere. The stator current wave form is as shown in the below figure. This waveform can be obtained from MATLAB/ SIMULINK.

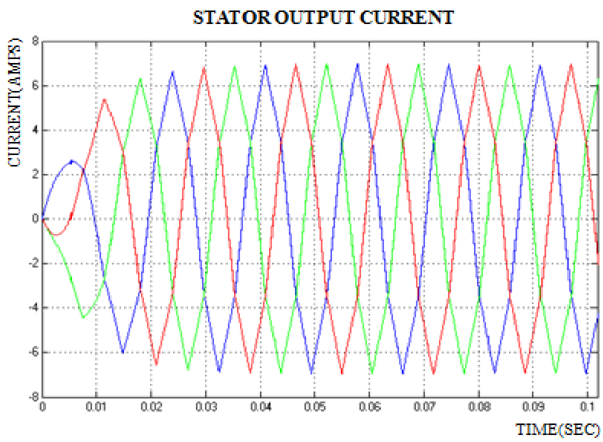

Fig. 7. Stator Current Waveform

B. Rotor Speed

The Figure 8 shows the speed of the Proposed BLDC motor drive.The speed of motor is 1800 rpm.This rotor speed waveform can be done by using MATLAB/ SIMULINK .It can be plotted between speed and time.

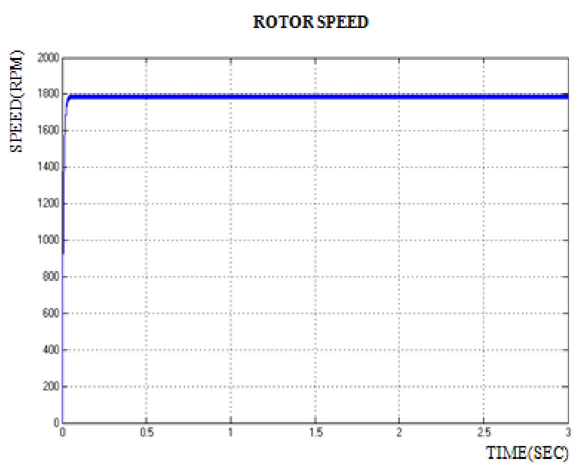

Fig. 8. Rotor Speed Waveform

C. Electro Magnetic Torque

The figure shows the electromagnetic torque waveform of the proposed BLDC motor drive. It is plotted between torque and time.

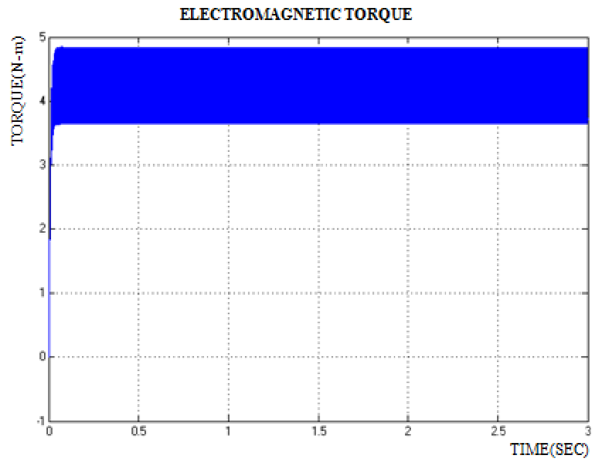

Fig. 9. Torque Waveform

D. Hall Effect Signal Waveform

The Hall Effect signal waveform is shown in the figure 10.It is plotted between voltage and time.

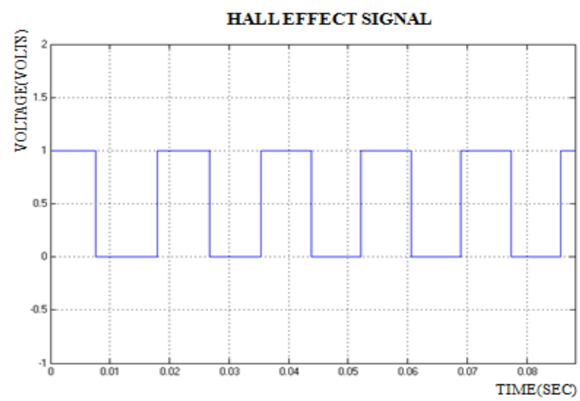

Fig. 10. Hall Effect Signal Waveform

The easiest way to know the correct moment to commutate the winding currents is by means of a position sensor. Many BLDC motor manufacturers supply motors with a three-element Hall Effect position sensor[12]. Each sensor element outputs a digital high level for 180electrical degrees of electrical rotation, and a low level for the other 180 electrical degrees[13-14]]. The three sensors are offset from each other by 60 electrical degrees so that each sensor output is in alignment with one of the electromagnetic circuits

Table I
BLDC Motor Specifications

POWER	25
RATED VOLTAGE	48 volts
RATED CURRENT	0.5 ampere
RATED SPEED	4000 rpm

V1 CONCLUSIONS

This paper discusses the simulation of microcontroller based BLDC motor drive and their results. We designed and simulated the solar powered BLDC motor drive using SEPIC converter has been done in MATLAB/SIMULINK. In this paper the speed control is achieved by using PI controller which is best choice for small scale BLDC motor applications like cooling fans in air conditioner, exhaust fans in kitchen, ceiling exhaust fans etc. The PI controller provides a better performance in terms of low ripples, high efficiency. The BLDC motor along with SEPIC converter provides a better performance in term of overshoot limitation, fast operation and smooth response. The dynamic performance of BLDC is analyzed by simulation in MATLAB/SIMULINK environment. Simulation results will be verified by hardware implementation in future. Hardware Implementation is done using PIC 16F877A. The PIC Microcontroller generates high-resolution PWM outputs in order to get high efficiency and high response. The rotor position is obtained from the Hall Effect Position Sensing Unit. Hence the closed loop control technique is easily achieved by using PI controller.

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