Implementation of Solar Powered PMBLDC Motor Drive

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Abstract— Renewable energy sources are being increasingly implemented in many applications due to the growing concern of environmental pollution. The PV (Photovoltaic) system appears to be most promising one because it is environmentally clean in nature and it directly converts solar energy into electrical energy. This paper presents the FPGA (Field programmable gate array) based speed control of PMBLDC (Permanent magnet Brushless DC) motor & this BLDC motor is driven by the solar energy. The solar panel is used to obtain the energy needed to run BLDC motor. The voltage obtained from solar panel is stored in battery due to the non-constant nature of solar energy. The voltage from battery is not sufficient to run BLDC motor & hence boost converter is used to boost the voltage required to run BLDC motor. Commutation is implemented on FPGA. FPGA based speed control scheme reduces the complexity of motor control hardware & in turn boost the demand for mobile applications.

Key words: PMBLDC motor (Permanent magnet Brushless DC motor), Photovoltaic (PV), Boost converter, PWM (Pulse width modulation), FPGA (Field programmable gate array), VSI (Voltage source inverter).

I. INTRODUCTION

The non-renewable energy sources like coal, oil, diesel & petrol, etc. are naturally decreasing which is leading to energy crisis. It's a pro-active approach is to shift from non-renewable energy sources to renewable energy sources like solar energy. Solar energy is a large, inexhaustible source of energy & it is capable to supply all the present & future energy needs of the world on a continuing basis. This makes it as one of the most promising of the unconventional energy sources. Solar energy mainly has two advantages; firstly it is an environmentally clean in nature. Secondly, it is free & available in adequate quantities in almost all parts of the world.

In general the supply to BLDC motor is taken from ac main supply through DBR (Diode Bridge Rectifier) & VSI circuit. The various converters like buck DC-DC converter [1], half bridge converter [2], SEPIC (Single Ended Primary-Inductor Converter) [3] & cuk converter [4] are used as PFC (Power factor correction) converter that are connected between DBR & VSI circuit to reduce the problems like THD (Total harmonic distortion), poor quality & poor power factor at ac mains. Even though these converters are used still there will be little problems due to THD, poor power factor, ripple torque & poor quality, etc at ac mains. So to overcome all these problems 'Solar powered PMBLDC motor drive' is proposed where there is no conversion of ac to dc, instead we directly obtain dc electrical energy from solar panel & it is independent from mains. The proposed drive needs 7 PWM pulses, 6 for VSI of BLDC & 1 for boost converter & hence FPGA is used as controller. The commutation of three phase VSI is implemented by FPGA.

The photovoltaic pumping system with maximum power point tracker in which operation of BLDC motor driving a centrifugal pump has been proposed [5] & [6]. These papers consist of PV generator converter with switching unit. The speed control of BLDC motor using FPGA is discussed in [7], [8] & [9]. APEX20K Altera FPGA kit is used in [7], FPGA SPARTAN-3A kit from Xilinx with the help of VHDL/VHSIC (Very High Speed Integrated Circuits) Hardware Description language & Verilog programming algorithm is used in [8]. In [9] Xilinx SPARTAN 3E FPGA board & the digital controller algorithm were written using verilog HDL. The FPGA SPARTAN 3E from Xilinx i.e., XC3S250E & the VHDL programming language is used in this paper.

Photovoltaic is a technology in which the radiant energy from the sun is converted to direct current (DC). The use of solar energy to run the BLDC motor has been developed in this paper. Solar panels are the devices which are used to convert the solar radiation/light into electricity. In order to achieve the required voltage to run the BLDC motor, the PV module may be connected either in series or parallel, but it's costlier. Thus to make it cost effective; power converters & batteries are used. Batteries are used to store the DC voltage obtained from solar panel & this voltage is not sufficient to run the BLDC motor, hence boost converter is used which provides the required voltage needed to run the BLDC motor.

BLDC motors are synchronous motors with permanent magnets on rotor & armature windings on stator [10]. BLDC motors require lower maintenance due to the elimination of the mechanical commutator & they are more efficient due to the permanent magnets on rotor which results in lower rotor losses. The commutation in these motors is accomplished by solid state switches of three phase inverter. For proper commutation & motor rotation, the rotor position information is very important & with the help of this information only the electronic switches in the inverter bridge will be switched ON & OFF to ensure proper direction of current flow in respective coils [11]. Hall effect sensors are placed inside the motor as position sensors.

The speed control of PMBLDC motor is obtained by FPGA controller. Commutation is implemented on FPGA as it provides greater flexibility & higher resources for implementing control algorithms. A model of BLDC motor is simulated & its controller is implemented on FPGA system.

II. PROPOSED SPEED CONTROL SCHEME

A. Solar panel:

Solar panels are the devices that convert light into electricity. The mounting of solar cells in series & parallel combination is known as solar panel. By connecting solar cells in a suitable series & parallel combination, the required voltage & current ratings can be obtained [12].

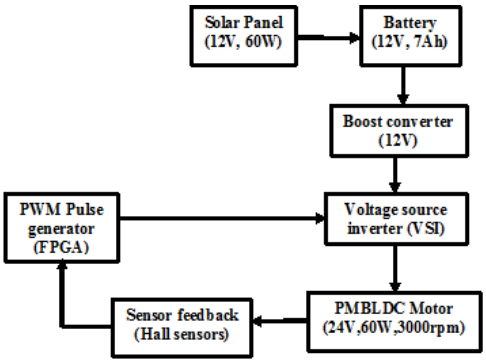

Fig 1: Block Diagram of Proposed Speed Control Scheme

The solar cell is like an ordinary diode. It essentially consists of a silicon PN junction diode in which 'P' nickel plated ring around the 'P' layer acts as positive output terminal (Anode) & the metal contact at the bottom acts as cathode, provided with a glass window on the top surface layer of 'P' material & it is extremely thin so that incident light photon's may easily reach the PN junction. When these photons absorb the sunlight, they excite some of the electrons. When these electrons jump across the band gap from the valence band to conduction band, free holes are generated in valence band. Thus electron-hole pairs are created & hence current starts to flow through the circuit. This current is directly proportional to illumination & also on the size of the surface area being illuminated.

In this paper 12V, 1.67A & 20W solar panel is used & has 36 solar cells which are connected in series to get 12V output voltage. The specifications of solar panel are given in table 1.

Output voltage rating (V)	12V
Output current (I)	1.67A
Output wattage (W)	20W
Max. peak power current (I_{mp})	1.17A
Max. power voltage (V_{mp})	17.1V
Open circuit voltage (V_{oc})	21V
Short circuit current (I_{sc})	1.31A
No. of cells connected in series	36

Table 1: Specifications of solar panel

B. Battery:

The DC voltage produced by solar panel is stored in battery (12V, 7Ah). In this paper two lead acid batteries are used, one battery to run the BLDC motor & another battery is used to operate opto-coupler & driver circuit. The 12V,7Ah battery can supply the specified 12V for 7hours, which means it will take 7 hours for the battery to discharge & on the other hand, the same battery can deliver 7A for an hour & get deeply discharged.

The name of lead acid battery arises from the chemical nature of electrodes (lead) & electrolyte (acid) in which the electrodes are immersed in the charged battery. The active material of positive electrode is lead dioxide (PbO_2) whereas that of negative electrode is metallic lead (Pb). The electrolyte is an aqueous solution of sulphuric acid.

When cell is discharged, the active material of both electrodes is converted into lead sulphate ($PbSO_4$). The process is reversed when the cell is charged; lead dioxide is regenerated at positive electrode & lead at negative electrode [13]. The overall chemical reaction is given by equation (1),

$$PbO_2 + Pb + 2H_2SO_4 \underset{\text{Charge}}{\overset{\text{Discharge}}{\rightleftharpoons}} PbSO_4 + PbSO_4 + 2H_2O \quad (1)$$

When the cell is charged, the sulphuric acid concentration increases & becomes highest when it is fully charged. Meanwhile, when the cell is discharged, the acid concentration decreases & becomes most dilute when the cell is fully discharged [13].

C. Boost converter:

The voltage obtained from battery is not sufficient to drive BLDC motor since it requires 24V for its operation. Thus the voltage obtained from battery is boosted to 24V using boost converter. The boost converter always provides 24V voltage to the motor irrespective of the battery input voltage. Boost converter is the popular non-isolated power stage topology. Boost converter is also called as step up converter because the output voltage is always greater than input voltage.

DC converters can be used as switching mode regulators to convert a DC voltage, normally unregulated to a regulated DC voltage. The regulation is normally achieved by PWM at a fixed frequency & MOSFET is used as switching device.

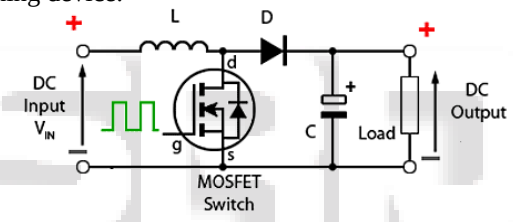

Fig 2: Boost converter circuit

The boost converter circuit is shown in fig 2. In boost converter when switch is ON, the current flows through switch & thus the output stage is isolated from input stage [14]. During this stage the input supplies energy to the inductor & thus inductor gets energized. Hence the energy is stored in inductor during on-period. When the switch is OFF, the current flows through the path consisting of L, D & C. The energy stored in the inductor during on period provides the output & thus the output stage is provided by both input & the inductor. Fig 3 shows the duty cycle applied to the boost converter & fig 4 shows the output of the boost converter (24V).

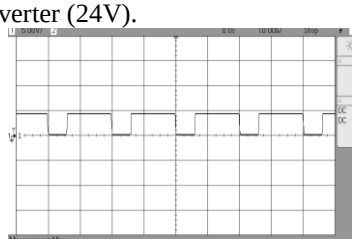

Fig 3: Duty cycle of boost converter

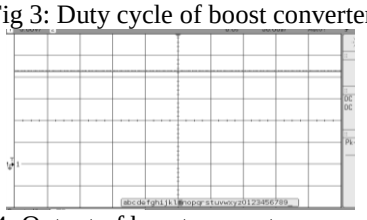

Fig 4: Output of boost converter

D. BLDC motor:

BLDC motor is a rotating electric motor consisting of stator armature windings & rotor permanent magnets, whereas in conventional brushed DC motor the stator is made up of permanent magnets & rotor consists of armature windings [10]. The conventional DC motor commutates itself with the use of a mechanical commutator whereas BLDC motor needs electronic commutation for the direction control of current through the windings. BLDC motors are a type of synchronous motor where the magnetic field generated by stator & rotor both rotates at same frequency. BLDC motors do not experience "slip" as in the case of IM (Induction motor). The BLDC motor uses feedback directly of the rotor angular position so that the input armature current can be switched among the motor phases in exact synchronization with rotor motion.

A permanent magnet BLDC motor has a wide speed range, high efficiency, rugged construction, ease of control & low maintenance requirements. In BLDC motors the phase windings are distributed in trapezoidal fashion in order to generate the trapezoidal back emf waveform. The commutation technique generally used is trapezoidal or called block commutation where only two phases will be conducting at any given point of time.

Each commutation sequence has one of the windings energized to positive power (current enters into the winding), the second winding is negative (current exits from the winding) and the third is in a non-energized condition. Torque is produced because of the interaction between the magnetic field generated by the stator coils and the permanent magnets [15]. Ideally, the peak torque occurs when these two fields are at 90° to each other and falls off as the fields move together. In order to keep the motor running, the magnetic field produced by the windings should shift position, as the rotor moves to catch up with the stator field. A "Six-Step Commutation" defines the sequence of energizing the windings.

The PMBLDC motor is operated at a constant torque with speed control to improve energy efficiency. In fact, back emf of BLDC motor is proportional to the motor speed & developed torque is proportional to its phase current; therefore a constant torque is maintained by a constant current in the stator winding of PMBLDC, whereas the speed can be controlled by varying the terminal voltage of motor. The specifications of BLDC motor used in this paper are given in table 2. Fig 5 shows the back emf of R & Y phase & fig 6 shows the stator current of phase R.

Rated voltage	24V
Rated current	2A
Output power	60W
Rated speed	3000rpm
No. of poles	4

Table 2: Specification BLDC motor

Fig 5: Back emf of phase R & Y

Fig 6: Stator current of phase R

E. Speed Control of Brushless DC Motor:

The speed of the BLDC motor is directly proportional to the applied voltage. The commutation logic specifies the coils that need to be energized for every 60^0 of electrical revolution based on Hall inputs. The Pulse Width Modulation logic specifies the time intervals during which the switches should be ON and OFF to average the DC Bus voltage applied thereby controlling the speed. If the switches are ON for the complete duration of the commutation period, then the DC bus rated voltage is directly fed to the phase windings of the motor. Hence the motor will run at the rated speed. To operate at any speed below this level, the commutation pattern applied at either the High-side or Low-side switch should be pulse-width modulated with the PWM Pulses at a specified frequency [15].

F. Voltage source inverter (VSI):

The VSI fed BLDC motor is shown in fig 7. In order to get constant output power & consequently constant output torque, current is driven through a motor winding during the flat portion of back emf waveform. At a time, only two switches are turned ON, one in a high side & the other in a low side. Thus for a star connected motor winding, two phases are connected in series across the DC bus, while the third winding is open. The switches are operated such that each phase carries current only during 120^0 period when the back emf is constant. Thus there is a commutation event between phases for every 60^0 electrical. Effectively it means that there is a current transisition every 60^0. Appropriate commutation therefore requires knowledge of BLDC motor of rotor position, which can be directly, detected using the hall sensors in this paper.

Speed control in BLDC involves changing of applied voltage across the motor phases, which is obtained by PWM (Pulse width modulation) method in this paper. The pulses of switches of 1 & 2, 3& 4 are shown in fig 8 & 9 respectively & similarly the pulses of 5 & 6 can be shown.

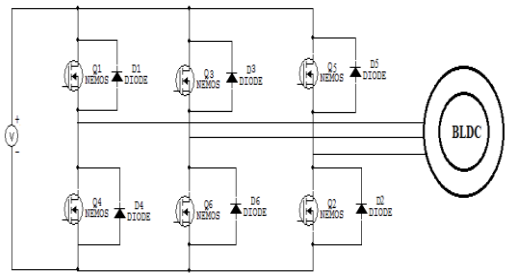

Fig 7: VSI fed BLDC motor

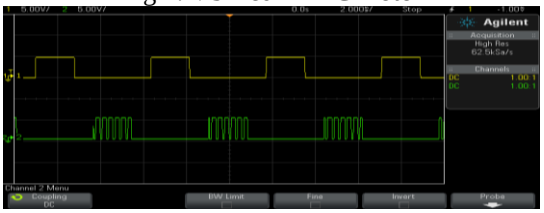

Fig 8: Pulses of 1 & 2

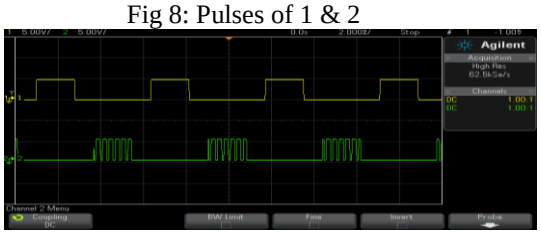

Fig 9: Pulses of switches 3 & 4

G. Sensor feedback (Hall-effect sensors):

The sensor feedback is carried out by hall-effect sensors. Energizing the appropriate phase coils based on Hall Effect sensors inputs is known as commutation logic. Whenever a new hall signal change is detected, the new drive switching pattern is applied. In hall sensor technique, 3 hall sensors are placed inside the motor, spaced 120^0 apart. Whenever hall sensor faces North Pole of rotor it produces '1' & produces '0' whenever it faces south pole of rotor. The rotor position signals are used to generate the switching sequence for VSI [11]. Fig 10 shows the hall sensors of A & B.

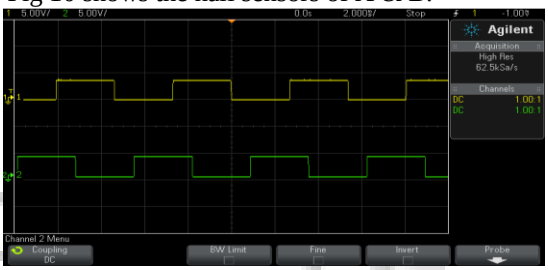

Fig 10: Hall sensors of A & B

H. FPGA (Field programmable gate array):

In this paper the speed control of BLDC motor is obtained by FPGA controller. FPGA is a reconfigurable digital logic platform. It supports parallel execution of considerable amount of bit level operations. The FPGA's have an advantage of embedded multipliers which allows faster multiply-accumulate operations. FPGA also contains CPU soft core, floating point unit, associated memory subsystems & SPI communication interface [9].

FPGA platform used for controlling the BLDC machine is Spartan 3E family from Xilinx i.e., XC3S250E where 'X' denotes Xilinx, 'C' denotes commercial IC, '3S' denotes Spartan 3 & '250E' denotes it includes 2.5 lakh transistor. Reference speed value is set digitally & then the speed loop compares the actual speed & reference speed. Based on the calculated error, the duty cycle for next period is calculated.

Input signals for FPGA device are 3 Hall Effect sensors from BLDC motor. The FPGA generates the gate pulses for switching ON & OFF MOSFET's [16]. In accordance with the required reference speed, a ramp voltage is generated which is applied to controller. As the motor rotates, hall sensor signals are produced in accordance with rotor position. Three phase voltages are produced from gates of MOSFET switches after they receive the decoded signals. These voltages are fed as input to motor & the motor rotates.

III. HARDWARE SETUP

The entire hardware setup is shown in fig 11 & the batteries are charged from solar panel & placed in the entire hardware setup.

Fig 11: Entire hardware setup

The speed control of BLDC motor is obtained in two ways i.e. open loop & close loop speed control which are explained as follow:

A. Open loop speed control:

In open loop speed control, the duty cycle is directly calculated from the set reference speed & there is no actual speed feedback for control purpose. By varying duty cycle, the speed of BLDC motor varies. The variation of speed with respect to duty cycle is shown in table 3.

Duty cycle (%)	Speed in rpm
80	2860
68	2773
54	2534
33	1549

Table 3: Variation Speed W.R.T Duty Cycle

B. Close loop speed control:

In the close loop speed control, the set speed & the actual speed are compared & the error is fed to FPGA controller, which finally outputs the required duty cycle in order to achieve the required speed operation of motor. The variation of set speed & actual speed is shown in table 4.

Set speed(rpm)	Actual speed(rpm)
1212	1208
2038	2035
2216	2160
3000	2893

Table 4: Variation of Set & Actual Speed

IV. CONCLUSION

The importance of making shift in the source of energy which is made cost effective has been put forth, and utilization of solar power in driving & speed control of BLDC motor is implemented. In this paper the implementation of BLDC motor driven by solar energy through FPGA controller has been proposed. It is independent of supply as the BLDC motor is driven by solar energy & hence can be used in solar powered electric vehicle, compressor of Air-conditioner, PV water pumping system & airplanes. In this paper implementation of digital control algorithm for BLDC motor through FPGA is discussed. Using FPGAs gives us flexibility of implementing different algorithms quickly and without complications. Moreover FPGAs are more powerful than

microcontrollers and can implement complex algorithms with relative ease.

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