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Design of Solar PV Operated Formal DC-DC Converter Fed PMBLDC Motor Drive for Real-Time Applications

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***Abstract* - The paper presents an efficient speed control of brushless DC (BLDC) motor drive for solar photo-voltaic (PV) system fed system. An interleaved boost converter is employed in the system to boost the solar PV system low output voltage to a level required for the drive system. Interleaved boost converter is operated in closed-loop mode to attain accurate and steady output. The converter (VSI) for BLDC is switched at fundamental frequency and reduces high frequency switching losses. Internal current control method is developed and employed for the speed control of PV fed BLDC motor by sensing the actual speed feedback. The appropriateness of the internal current controller for the speed control of PV fed BLDC motor is verified for incremental speed with fixed torque and decremental speed with fixed torque operating conditions. Also the system with speed control is verified for variable torque condition. The system is developed and results are developed using powersim software. The suitability of proposed system at practical operating conditions is demonstrated through simulation results using powersim followed by an experimental validation.**

Keywords: Solar PV, DC-DC Converter, PMBLDC, Motor, Drives, Real-Time Applications.

I. INTRODUCTION

Drastic reduction in the cost of power electronic devices and annihilation of the fossil fuels in near future invite to use the solar photovoltaic (SPV) generated electrical energy for various applications as far as possible. Water pumping, a standalone application of the SPV array generated electricity is receiving wide attention now a days for irrigation in the fields, household applications and industrial usage. Although the several researches have been carried out in the area of SPV array fed water pumping, combining various DC-DC converters and motor drives, the DC-DC converter in association with the permanent magnet brushless DC (BLDC) motor is still unexplored to develop such kind of system. However, the DC-DC converter has been used in some other SPV based applications.

Moreover, a topology of SPV array fed BLDC motor driven water pump with DC-DC converter has been reported and its significance has been presented more or less. Nonetheless, an experimental validation is missing and the absence of extensive literature review and comparison with the existing topologies, have concealed the technical contribution and originality of the reported work. The merits of both BLDC motor and DC-DC converter can contribute to develop a SPV array fed water pumping system possessing a potential of operating satisfactorily under dynamically changing atmospheric conditions. The BLDC motor has high reliability, high efficiency, and high torque/inertia ratio, improved cooling, low radio frequency interference and noise and requires practically no maintenance. On the other hand, a DC-DC converter exhibits following advantages over the conventional buck, boost, buck-boost converters and Cuk converter when employed in SPV based applications.

Solar power system finds extensive application in remote areas where access to the grid supply is impractical. From livestock watering to remote home or village water supply needs are met from the solar based water pumps. Most of the PV water pumping systems are connected directly to the solar arrays and use DC motor driven pumps. This system is easy to operate but is inefficient and requires frequent maintenance. Solar pump operated with AC drive uses an inverter with ac motor. Induction motor offer better choice in terms of size, ruggedness, efficiency and maintainability.

The DC power from solar array is boosted and fed to an inverter which gives ac. Output of the inverter drives the motor coupled to a water pump. Photovoltaic power system usually requires maximum power point tracking (MPPT) controller, which is an electronic system that operates the Photovoltaic (PV) modules in a manner that allows the modules to produce all the power they are capable of. The drastic reduction in the cost of power electronic devices and annihilation of fossil fuels in near future invite to use the solar photovoltaic (SPV) generated electrical energy for various applications as far as possible. The water pumping, a standalone application of the SPV array generated electricity

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is receiving wide attention now a day for irrigation in the fields, household applications and industrial use.

The merits of both BLDC motor and DC-DC converter can contribute to develop a SPV array fed water pumping system possessing a potential of operating satisfactorily under dynamically changing atmospheric conditions. The BLDC motor has high reliability, high efficiency, high torque/inertia ratio, improved cooling, low radio frequency interference and noise and requires practically no maintenance. On the other hand, a DC-DC converter exhibits following advantages over the conventional buck, boost, buck-boost converters and Cuk converter when employed in SPV based applications. Belonging to a family of buck-boost converters, the DC-DC converter may be operated either to increase or to decrease the output voltage. This property offers a boundless region for maximum power point tracking (MPPT) of a SPV array.

The MPPT can be performed with simple buck and boost converter if MPP occurs within prescribed limits. This property also facilitates the soft starting of BLDC motor unlike a boost converter which habitually steps up the voltage level at its output, not ensuring soft starting. Unlike a classical buck-boost converter, the DC-DC converter has a continuous output current. The output inductor makes the current continuous and ripples free. Although consisting of same number of components as a Cuk converter, the DC-DC converter operates as non-inverting buck-boost converter unlike an inverting buck-boost and Cuk converter. This property obviates a requirement of associated circuits for negative voltage sensing hence reduces the complexity and probability of slow down the system response .These merits of the DC-DC converter are favorable for proposed SPV array fed water pumping system. An fractional order extreme seeking approach (FOESA).

MPPT algorithm is used to operate the DC-DC converter such that SPV array always operates at its MPP. Two phase currents are sensed along with Hall signals feedback for control of BLDC motor, resulting in an increased cost. The additional control scheme causes increased cost and complexity, which is required to control the speed of BLDC motor. Moreover, usually a voltage source inverter (VSI) is operated with high frequency PWM pulses, resulting in an increased switching loss and hence the reduced efficiency.

An electric motor plays a significant role to develop an energy efficient and economical water pumping system based on the SPV array. An efficient motor substantially reduces the size of SPV array and hence its cost. The DC motors have low efficiency and high-maintenance cost due to their commutator and brushes. A permanent magnet brushless DC (BLDC) motor, incorporating the merits of higher efficiency than an induction motor, high reliability, high ruggedness, low Electromagnetic Interference (EMI) problems, simple control, compactness, easy-to-drive, capability to operate successfully at low voltage and excellent performance over a wide range of speed.

II. EXISTING SYSTEM

The PV inverters dedicated to the small PV plants must be characterized by a large range for the input voltage in order to accept different configurations of the PV field. This capability is assured by adopting inverters based on a double stage architecture where the first stage, which usually is a dc/dc converter, can be used to adapt the PV array voltage in order to meet the requirements of the dc/ac second stage, which is used to supply an ac load or to inject the produced power into the grid. This configuration is effective also in terms of controllability because the first stage can be devoted to track the maximum power from the PV array, while the second stage is used to produce ac current with low Total Harmonic Distortion (THD).

Drawbacks

- There is no dynamic response.
- High Total harmonic Distortion (THD).

III. PROPOSED SYSTEM

Proposed SPV array fed water pumping system with an incremental conductance (INC) MPPT algorithm is used to operate the DC-DC converter such that the SPV array always operates at its MPP and the BLDC motor experience a reduced current at the starting.

A three phase voltage source inverter (VSI) is operated by fundamental frequency switching for the electronic commutation of BLDC motor. Simulation results using MATLAB/Simulink software is examined to demonstrate the starting, dynamics and steady state behavior of the proposed water pumping system subjected to the random variation in the solar irradiance. The SPV array is designed such that the proposed system always exhibits satisfactory performance regardless of the solar irradiance level or its variation.

Advantages

- DC-DC converter can be operated either to increase or to decrease the output voltage.
- Facilitates the soft starting of the BLDC motor unlike a boost converter which habitually step-up the voltage level at its output, not ensuring the soft starting.
- Unlike a simple buck-boost converter, the DC-DC converter has a continuous output current. The output inductor makes the current continuous and ripples free.

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- Input to output DC insulation.
- DC-DC converter offers a boundless region for MPPT.
- Efficiency is good compared with other converters due to single switch.
- The switching loss of VSI is reduced by adopting fundamental frequency switching resulting in an additional power saving and hence an enhanced efficiency.
- Reduces the complexity and probability of slow down the system response.

3.1 Functional Block Diagram

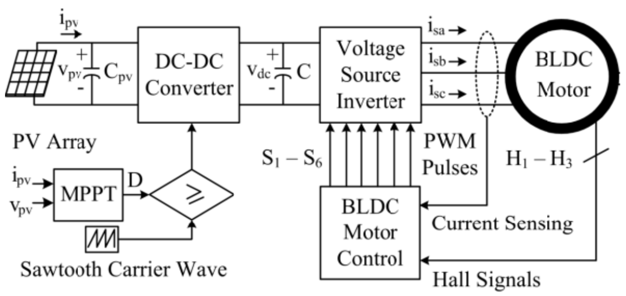

Figure 1: Block Diagram of Proposed System

3.2 Circuit Diagram

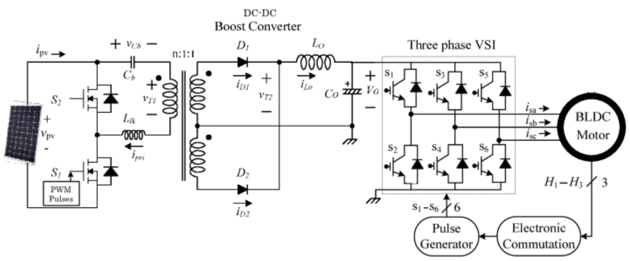

Figure 2: Circuit Diagram of Proposed System

3.3 Description

The proposed system consists of (left to right) a SPV array, a DC-DC converter, a VSI, a PMBLDC motor. The SPV panel converts solar radiation into electrical power that is fed to the converter. The SPV array appears as a power source for the DC-DC converter. The voltage is boosted and power is transferred from the output of DC-DC converter which is the input source for the VSI. A maximum power point tracker (MPPT) is used for extracting the maximum power from the solar PV module and transferring that power to the load. The MPPT algorithm uses voltage and current as feedback from SPV array and generates an optimum value of duty cycle. The pulse generator generates, through INC-MPPT algorithm, switching pulses for IGBT (Insulated Gate Bipolar Transistor) switch of the DC-DC converter.

The gate pulses used to operate the DC-DC converter is supplied by a microcontroller. Further, it generates actual switching pulse by comparing the duty cycle with a high frequency carrier wave. The VSI is operated in fundamental frequency switching by sensing the speed of the BLDC motor with an inbuilt encoder. The high frequency switching losses are thereby eliminated, contributing in an increased efficiency of proposed water pumping system. The VSI, converting DC output from a DC-DC converter into AC, feeds the BLDC motor to drive a water pump coupled to its shaft.

A DC-DC converter is utilized in order to extract the maximum power available from a SPV array, soft starting and speed control of BLDC motor coupled to a water pump. Due to a single switch, this converter has very good efficiency and offers boundless region for MPPT. This converter is operated in continuous conduction mode (CCM) resulting in a reduced stress on its power devices and components. Furthermore, the switching loss of VSI is reduced by adopting fundamental frequency switching resulting in an additional power saving and hence an enhanced efficiency. The phase currents as well as the DC link voltage sensors are completely eliminated, offering simple and economical system without scarifying its performance. The speed of BLDC motor is controlled, without any additional control, through a variable DC link voltage of VSI.

3.4 Control Methodology

The basic schematic diagram of dual-phase interleaved DC-DC converter is depicted in Figure 3. The operating principle of proposed Interleaved DC-DC converter is comprised of two modes, for DG application by using photo-voltaic (PV) system.

Mode I: At position t=0; the switch S1of first phase is conducted (ON-state) by gate pulse provided by gate pulse generator. The current at the inductor L1 linearly rising, the switch S2 is at second phase as non-conducted (OFF-state) and the energy stored in inductor L2 is moved to load via phase L1 goes to rise linearly and charging, other side the inductor L2 goes to discharge the energy to load via followed diode D2. The mode of operation during switch S1of first phase is conducting (ON-state) and switch S2 of second phase is not conducted (OFF-state) is shown in Figure 4 (a).

Mode II: At time t=t1; the switch S1 of first phase is non-conducting position & second phase of switch S2 is conducted by proper gate pulse generation as shown in Figure 4 (b). The current at inductor L2 is linearly raising, the inductor is to be charged with respect to duty ratio of the switch. At same situation, the switch S1 of first phase is un-conducted and the inductor current discharged linearly to load. Transform the stored energy in inductor t1, the switch S1 is non-conducted or

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switched OFF. The inductor of other phase L2 goes to rise linearly and charging, other side the inductor L1 under discharging to load via followed diode D1.

IV. HARDWARE DETAILS

4.1 DC-DC Converter

A DC-DC converter is a fourth order non linear system. With regard to energy input, it can be seen as buck-boost-buck converter. With regard to the output, it can be seen as boost-buck-boost converter. DC-DC converter is fourth order converter that can step down or step up the input voltage.

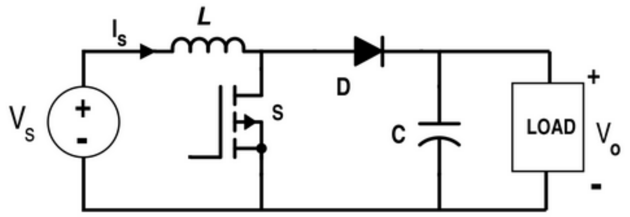

Figure 3: DC-DC Boost converter circuit diagram

4.2 Modes of Operation

Mode-1

The first mode is obtained when the switch is ON (closed) and instantaneously, the diode D is OFF. During this period, the current through the inductor L1 and L2 are drawn from the voltage source Vs. This mode is the charging mode.

When the switch is on, VC1, the voltage across intermediate capacitor C1 reverse biases the diode. The inductor current iL flows through the switch. Since VC1 is larger than the output voltage Vdc, C1 discharges through the switch, transferring energy to the inductor L and the output. Therefore, vc1 decreases and iL increases, as shown in Figure 2(c). The input feeds energy to the input inductor L1.

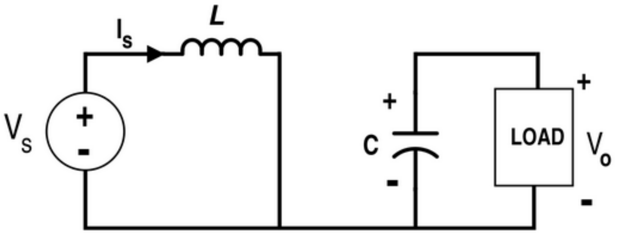

Figure 4: Boost converter circuit when switch S is on (Mode-I)

Mode-2

The second mode of operation starts when the switch is OFF and the diode D is ON position. This stage or mode of operation is known as the discharging mode since all the energy stored in L2 is now transferred to the load R.

When the switch is off, diode is forward biased. The inductor current iL flows through the diode. The inductor L transfers its stored energy to output through the diode. On the other hand, C1 is charged through the diode by energy from both the input and L1. Therefore, VC1 increases and iL decreases.

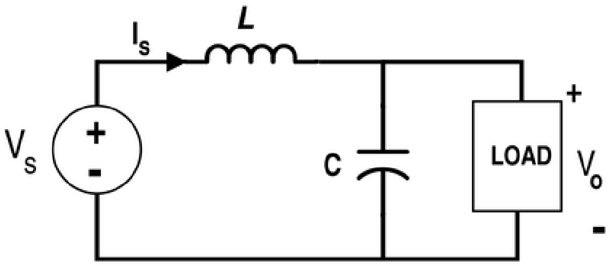

Figure 5: Boost converter circuit when switch S is off (Mode-II)

The DC-DC converter is the next stage to the SPV array. Its design consists of an estimation of various components such as input inductor, L1, output inductor, L2 and intermediate capacitor, C1. These components are designed such that the DC-DC converter always operates in CCM resulting in reduced stress on its components and devices. An estimation of the duty cycle, D initiates the design of DC-DC converter.

$$D = \frac{V_{dc}}{V + V} = \frac{200}{200+187.2} = 0.52$$

Where Vdc is an average value of output voltage of the DC-DC converter (DC link voltage of VSI) equal to the DC voltage rating of the BLDC motor.

Similar analysis can also be done for the other types of converters. Basic circuit diagram of all the fundamental converters are shown in Figure 1. They consist of the same basic elements. The building blocks of these converters are DC supply Vs, load, diode D, power electronics switch S, inductor L, and capacitor C.

It is worth noticing that any converters work in two distinct modes with respect to the inductor current: the continuous conduction mode (CCM) and discontinuous conduction mode (DCM). When the inductor current is always greater than zero, it is in CCM. When the average inductor current is too low due to the high-load resistance or low-switching frequency, then the converter is in DCM.

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The CCM is preferable for high efficiency and efficient use of semiconductor switches and passive components. The DCM requires a special control since the dynamic order of the converter is reduced. Thus, it is required to find out the minimum value of the inductor to maintain the CCM.

Assume that the inductor and capacitor are pure (i.e. no resistive component). However, there is still what we call a small-ripple approximation. In an efficient converter, the output voltage ripple is small. It is assumed that the load is resistive and the DC component of the output voltage has no ripples, or simply the DC output has a fixed value as shown in Fig.2 for making the analysis easier.

4.3 Performance of DC-DC Converter

The steady state performance of DC-DC converter at 1000 W/m2. The input inductor current iL1, intermediate capacitor voltage, vc1, output inductor current, iL2, voltage stress on IGBT switch, vSW, current stress on IGBT switch, iSW, blocking voltage of the diode, vD, current through diode, iD, and DC link voltage, vdc are presented. The DC-DC converter is operated in CCM. The operation of converter in this mode reduces the stress on power devices and components.

These converter indices follow the variation in the weather condition and vary in proportion to the solar irradiance level, such as iL1, vc1,iL2 and vdc. The DC-DC converter automatically changes its mode of operation from buck mode to boost mode and vice versa according to the irradiance level in order to optimize the output power of SPV array. A small amount of ripples in the DC-DC converter variables are observed caused by permitting the ripples up to an extent in order to optimize the size of the components.

4.4 BLDC Motor

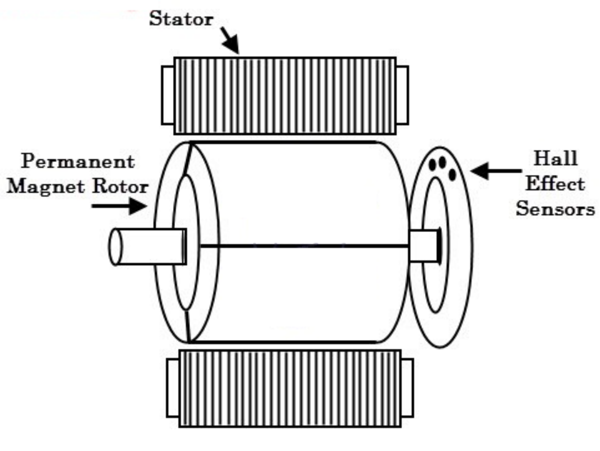

Figure 6: Basic Construction of a BLDC Motor

The use of permanent magnets (PMs) in electrical machines in place of electromagnetic excitation results in many advantages such as no excitation losses, simplified construction, improved efficiency, fast dynamic performance, and high torque or power per unit volume . The advancements in geometries and design innovations have made possible the use of PMBL motors in many of domestic, commercial and industrial applications. PMBL machines are best suited for position control and medium sized industrial drives due to their excellent dynamic capability, reduced losses and high torque/weight ratio. PMBL motors find applications in diverse fields such as domestic appliances, automobiles, transportation, aerospace equipment, power tools, toys, vision and sound equipment and healthcare equipment ranging from microwatt to megawatts.

Advanced control algorithms and ultra fast processors have made PMBLDC motors suitable for position control in machine tools, robotics and high precision servos, speed control and torque control in various industrial drives and process control applications. With the advancement in power electronics it is possible to design PMBL generators for power generation onboard ships, aircraft, hybrid electric cars and buses while providing reduced generator weight, size and a high payload capacity for the complete vehicle.

4.5 Classification of PMBLDC Motor

BLDC motors are classified into two sub categories. The first category uses continuous rotor-position feedback for supplying sinusoidal voltages and currents to the motor. The ideal motional EMF is sinusoidal, so that the interaction with sinusoidal currents produces constant torque with very low torque ripple. This called a Permanent Magnet Synchronous Motor (PMSM) drives, and is also called a PM AC drive, brushless AC drive, PM sinusoidal fed drive, sinusoidal brushless DC drive, etc.

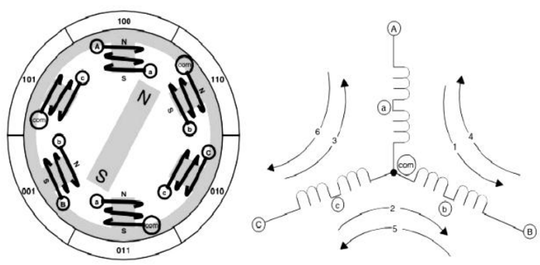

Figure 7: Dynamic Model of BLDC Motor

The second category of PMBL motor drives is known as the brushless DC (BLDC) motor drive and it is also called a trapezoidal brushless DC drive, or rectangular fed drive. It is supplied by three phase rectangular current blocks of 120° duration, in which the ideal motional EMF is trapezoidal, with

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the constant part of the waveform timed to coincide with the intervals of constant phase current. These machines need rotor-position information only at the commutation points, e.g., every 60°electrical in three-phase motors. The PMBLDC motor has its losses mainly in the stator due to its construction; hence the heat can easily be dissipated into the atmosphere. As the back EMF is directly proportional to the motor speed and the developed torque is almost directly proportional to the phase current, the torque can be maintained constant by a stable stator current in a PMBLDC motor. The average torque produced is high with fewer ripples in PMBLDC motors as compared to PMSM. Amongst two types of PMBL motors, PMSM is, therefore, preferred for applications where accuracy is desired e.g. robotics, numerical controlled machines, solar tracking etc. However, the PMBLDCM can be used in general and low cost applications. These motors are preferred for numerous applications, due to their features of high efficiency, silent operation, compact in size and low maintenance.

4.6 Electronic Commutation of BLDC Motor

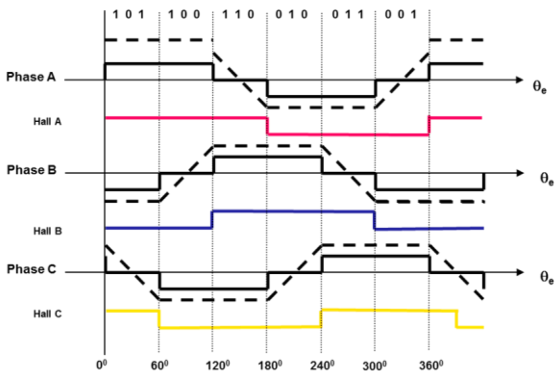

Figure 8: BLDC Electronic Commutation Signals

The BLDC motor is controlled using a VSI operated through an electronic commutation of BLDC motor. An electronic commutation of BLDC motor stands for commutating the currents flowing through its windings in a predefined sequence using decoder logic. It symmetrically places the dc input current at the center of each phase voltage for 120◦. Six switching pulses are generated as per the various possible combinations of three. Hall-effect signals.

V. SIMULATION RESULTS

5.1 Simulation Circuit

An interleaved boost DC-DC converter is employed in the system to boost the PV system low output voltage 200V to a level required for the drive system. Interleaved boost DC-DC converter is operated in closed-loop mode to attain accurate and steady output. The 200 V output from PV system is stepped up to 400 V using interleaved boost converter as shown in the result analysis. Internal current control method is developed and employed for the speed control of PV fed BLDC motor. The appropriateness of the internal current controller for the speed control of PV fed BLDC motor is verified for increamental speed with fixed torque and decreamental speed with fixed torque operating conditions and results for respective cases were depicted. With increamental and decremental speed change command issued to BLDC motor yields respective speed changes with fixed torque with the presence of internal current controller keeping the DC output voltage of DC-DC converter constant at 400V. Speed control method is found to be suitable for variable speed conditions maintaining fixed torque.

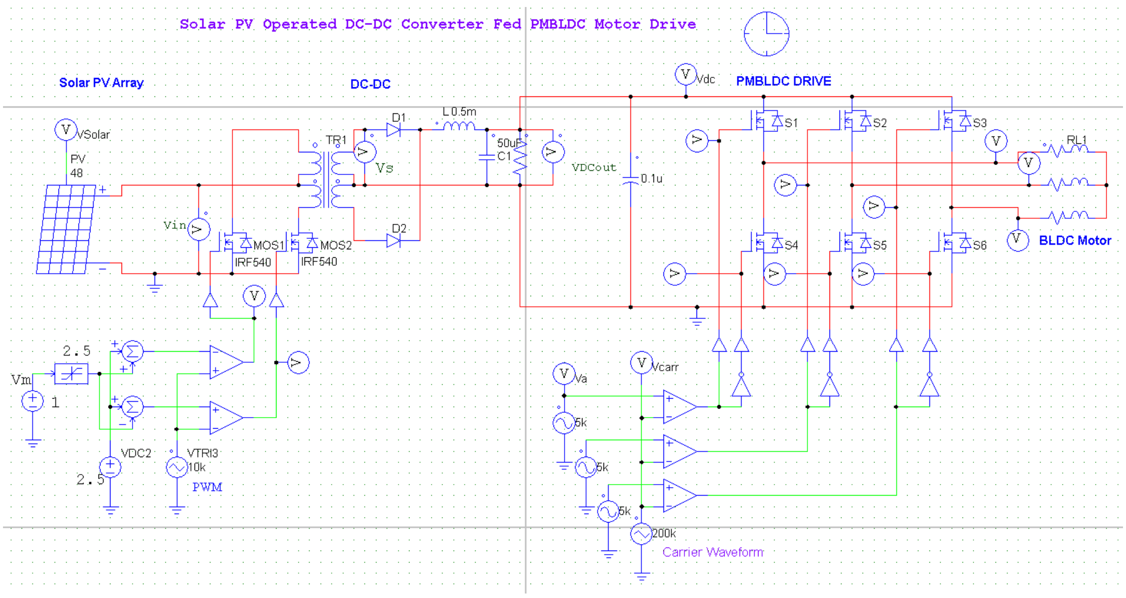

Figure 9: Solar PV Operated Dc-Dc Converter Fed PMBLDC Motor Drive Circuit

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5.2 Outputs Screenshots

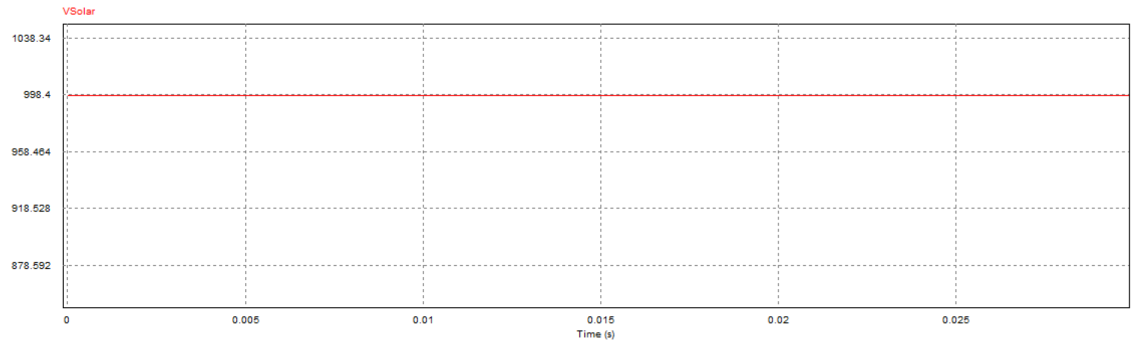

Figure 10: Input Solar PV Panel Voltage

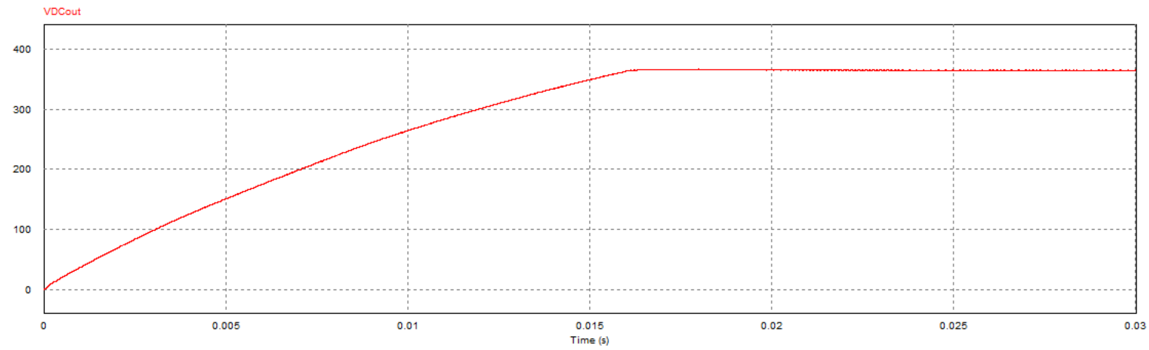

Figure 11: DC-DC Converter Output Voltage

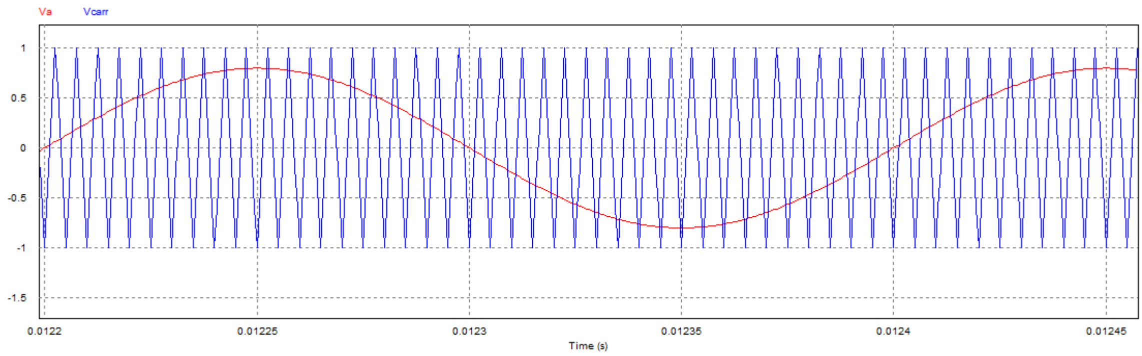

Figure 12: Carrier Generation

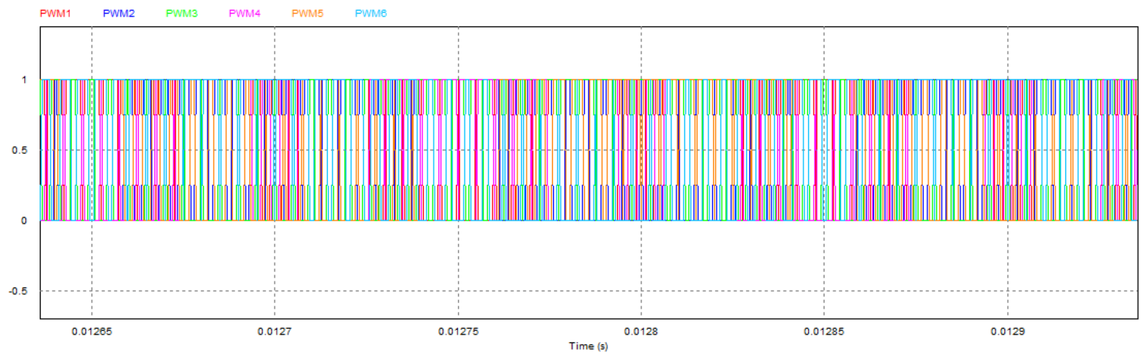

Figure 13: Gate Signals for VSI Drive

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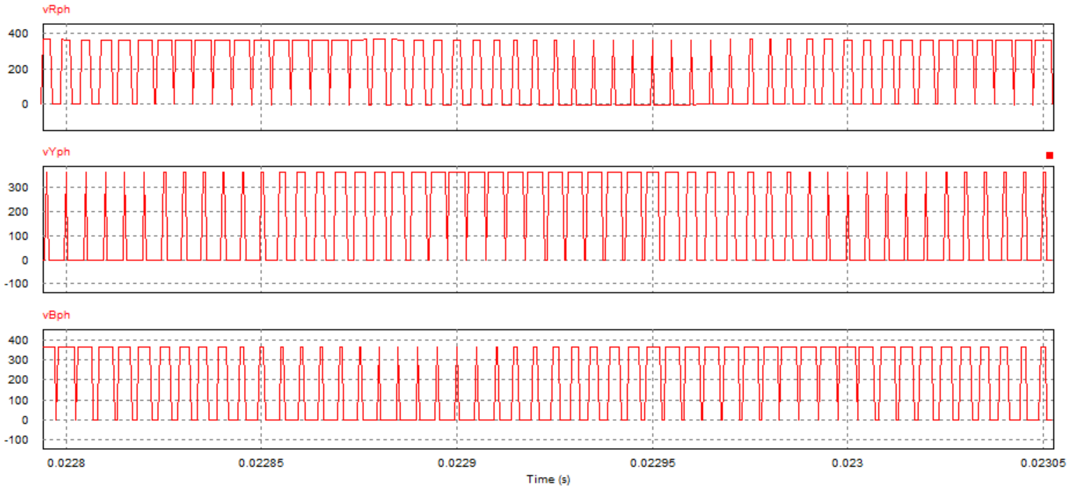

Figure 14: Three Phase Output Voltage of VSI Drive

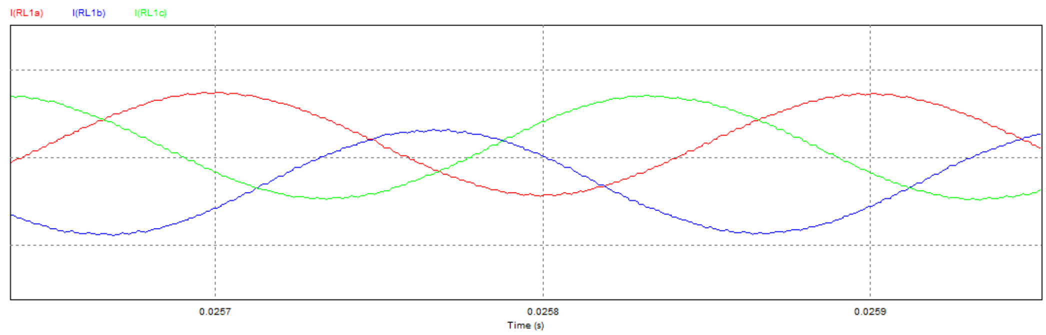

Figure 15: Three Phase Output Current of VSI Drive

VI. CONCLUSION

The paper presents an efficient speed control of brushless DC (BLDC) motor drive for photo-voltaic (PV) system fed system. An interleaved boost DC-DC converter is employed in the system to boost the PV system low output voltage 200V to a level required for the drive system. Interleaved boost DC-DC converter is operated in closed-loop mode to attain accurate and steady output. The 200 V output from PV system is stepped up to 400 V using interleaved boost converter as shown in the result analysis. Internal current control method is developed and employed for the speed control of PV fed BLDC motor. The appropriateness of the internal current controller for the speed control of PV fed BLDC motor is verified for increamental speed with fixed torque and decreamental speed with fixed torque operating conditions and results for respective cases were depicted. With increamental and decremental speed change command issued to BLDC motor yields respective speed changes with fixed torque with the presence of internal current controller keeping the DC output voltage of DC-DC converter constant at 400V. Speed control method is found to be suitable for variable speed conditions maintaining fixed torque. The appropriateness of the internal current controller for the speed control of PV fed BLDC motor is verified for fixed speed with variable torque and when the torque is varied the result shows it is possible to keep speed fixed or constant verifying the operation of speed control technique for varying loads.

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