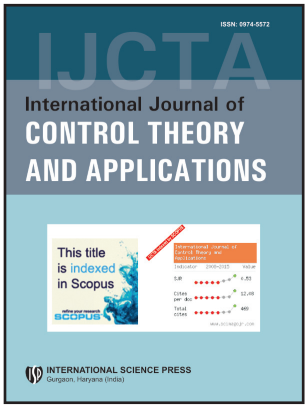

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Solar PV Array Fed BLDC Motor using DC-DC Converter

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Abstract: This paper deals with the simple and efficient Permanent Magnet Brushless DC Motor (BLDC) which is supplied by solar photovoltaic (SPV) array. A DC-DC Landsman converter meets the desired performance of this proposed work. The primary function of the Landsman converter is to optimize the power output of the solar array. An appropriate control of Landsman converter through Incremental Conductance Maximum Power Point Tracking (MPPT) algorithm offers smooth and soft starting on BLDC motor. The proposed control algorithm eliminates phase current sensors and adapts a fundamental frequency switching of the voltage source inverter. Thus avoiding the power losses due to high frequency switching. The additional features of the PV fed system is that; the motor current is limited to an upper limit of PV array current. So that motor winding and power semi conducting switches can be protected against excessive current flow. The starting, dynamic and steady-state behaviours of the SPV array fed BLDC motor driven water pump are presented to demonstrate the novelty of the proposed system. The simulations are carried out using MATLAB.

Keywords: Solar PV array, Landsman Converter, Incremental Conductance Maximum Power Point Tracking (INC MPPT), Brushless DC (BLDC) Motor.

1. INTRODUCTION

The photovoltaic (PV) energy is a clean energy, with a long lifespan and a high reliability. So, it can be considered as one of the most sustainable renewable energy. Photovoltaic (PV) modules based renewable energy generation systems is more suitable and prominent solution for both domestic as well as industrial applications. An efficient motor substantially reduces the size of Solar Photovoltaic (SPV) array and hence it's cost. The Permanent Magnet Brushless DC (BLDC) motor incorporating the merits of higher efficiency, high reliability, high ruggedness, easy-to-drive, capability to operate successfully at low voltage and excellent performance over a wide range of speed. To optimise the operating point of the SPV array in order to get maximum possible power output by means of the superior maximum power point tracking (MPPT) technique. A converter acts as an interface between the SPV array and Voltage Source Inverter (VSI) feeding the BLDC motor. The starting inrush current of BLDC motor is restricted within the permissible range by appropriate control of Landsman converter through MPPT algorithm.

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 [1]. To get over from the aforementioned problems associated with DC motors, the induction motor is employed in this work [1], due to its robustness, low cost, high efficiency, availability in local markets and low-maintenance cost. Nevertheless, this motor is not adapted in this work owing to some of the limitations it possess such as requirement of complicated control and prone to overheating if the voltage is too low [2, 3]. 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 [4, 5]. The BLDC motor has already superseded partially the DC and AC motors employed to drive the water pump using SPV array as the source of electricity [6–13] and continuously attracting the industrialist and customers. It is mandatory to optimise the operating point of the SPV array in order to get maximum possible power output by means of the superior maximum power point tracking (MPPT) technique [14– 20]. An incremental conductance (INC) algorithm is frequently reported in the literature as a less confused MPPT technique under fast varying irradiance [17] and hence adapted in this work. The MPPT of SPV array is accomplished by introducing a DC–DC converter as an interface between the SPV array and voltage source inverter (VSI) feeding the BLDC motor. A DC–DC boost converter [6], buck–boost converter [7], Luo converter [8],canonical switching cell (CSC) converter [9], zeta converter [10] and Z-source inverter (ZSI) [11] are already utilised with SPV array fed BLDC motor driven water pump. Investigating the various non-isolated DC–DC converters viz. buck, boost, buck– boost, Cuk and single-ended primary inductor converter for photovoltaic applications, although not based on water pumping, it is concluded in [21] that the best selection of DC–DC converter in the PV system is buck–boost converter, allowing an unbounded region for MPPT. On the contrary to it, a buck–boost converter always calls for a ripple filter at its both input and output for coveted operation of the overall system, resulting in an associated circuitry. Likewise, the converters used in [8–10] also necessitate filtering elements at either input or output or both. The ZSI used in [11] needs complex control and additional sensing elements, and operated with a high-frequency pulse-width modulation (PWM) switching pulses, resulting in an increased switching loss. On the other hand, any converter besides the buck–boost topology, for example buck and boost converter, is not recommended because of their inability to track MPP independent of the loading and atmospheric conditions [21]. A Landsman converter, one of the topology of a DC–DC buck– boost converter, capable to overcome the aforementioned limitations of various previously used converters in SPV array fed water pumping, is adapted in this work. This converter is apparently derived by a CSC [22] or topological transformations on a DC–DC boost converter [23]. A small input inductor of the Landsman converter, as shown in Figure 1, acts as an input-ripple filter, eliminating the external ripple filtering. This inductor also damps the oscillation occurred, due to the snubber elements of insulated gate bipolar transistor (IGBT) module, in the current through the module. A Landsman converter, one of the topology of a DC–DC buck–boost converter, capable to overcome the aforementioned limitations of various previously used converters in SPV array fed water pumping, is adapted in this work. This converter is apparently derived by a CSC [22] or topological transformations on a DC–DC boost converter [23]. A small input inductor of the Landsman converter, as shown in Figure 1, acts as an input-ripple filter, eliminating the external ripple filtering. This inductor also damps the oscillation occurred, due to the snubber elements of insulated gate bipolar transistor (IGBT) module, in the current through the module.

The proposed system using a DC–DC Landsman converter is designed such that the operation is not deteriorated by variation in irradiance level and losses associated with the converters and motor pump. Moreover, the Landsman converter is designed to operate always in continuous conduction mode (CCM) irrespective of the variation in irradiance level, resulting in a reduced stress on its power devices and components. The VSI is operated with the pulses of fundamental frequency by means of electronic commutation, resulting in a reduced

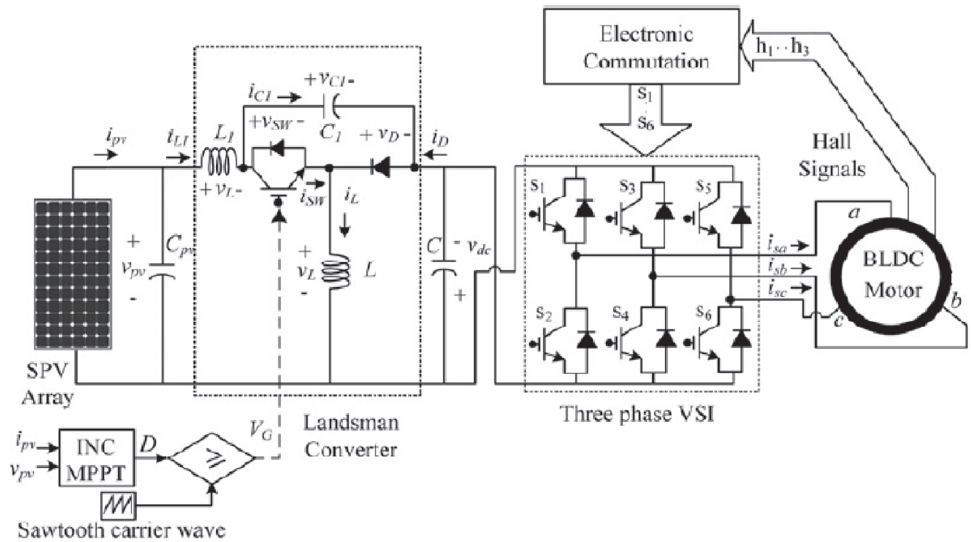


Figure 1: Configuration of SPV array – Landsman converter fed BLDC motor driven water pumping system

switching loss. The speed of BLDC motor is controlled by variation in the DC-link voltage. No additional phase current sensors, additional control or associated circuitry are imposed unlike in [6, 11–13], for the speed control. In addition, the DC-link voltage sensing is not required for control at any stage. Therefore, the resultant motor drive offers simplicity, compactness, cost effectiveness and easy-to-drive features without scarifying the performance. The starting inrush current of BLDC motor is restricted within the permissible range by appropriate control of Landsman converter through MPPT algorithm. The motor always attains the required speed to pump the water irrespective of the atmospheric variation.

2. CONFIGURATION AND OPERATION OF PROPOSED SYSTEM

Figure 1 illustrates the detailed configuration and operation of the proposed SPV array-based BLDC motor driven water pumping system using the Landsman converter. The proposed system

Consists of an SPV array, Landsman converter, VSI and the BLDC motor with a water pump coupled to its shaft. The Landsman converter, acting as an interface between the SPV array and the VSI, is operated by the execution of INC-MPPT algorithm in order to extract the maximum power available from the SPV array. The VSI, operated through the electronic commutation, feeds the BLDC motor pump. The motor has three inbuilt low-cost Hall-effect position sensors, generating a particular combination of three Hall signals according to the rotor position.

3. OPERATING PRINCIPLE OF LANDSMAN CONVERTER

The Landsman converter is designed to operate in CCM irrespective of the variation in irradiance level. The circuit operation is divided into two modes as shown in Figures 2(a) and (b), and the associated waveforms are shown in Figure 4.

3.1. Mode I: When Switch is ON

When the switch is on, V_{C1}, the voltage across intermediate capacitor C_1 reverse biases the diode. The inductor current i_L flows through the switch. Since V_{C1} is larger than the output voltage V_{dc}, C_1 discharges through the switch, transferring energy to the inductor L and the output. Therefore, vc1 decreases and i_L increases, as shown in Figure 2(c). The input feeds energy to the input inductor L_1.

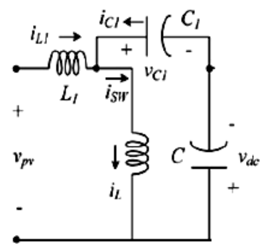


Figure 2: Mode 1 operation

3.2. Mode II: When Switch is OFF

When the switch is off, diode is forward biased. The inductor current i_L flows through the diode. The inductor L transfers its stored energy to output through the diode. On the other hand, C_1 is charged through the diode by energy from both the input and L_1. Therefore, V_{C1} increases and i_L decreases.

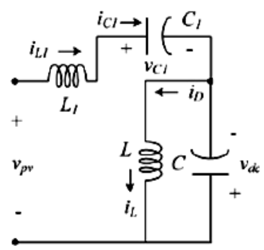


Figure 3: Mode 2 operation

The ripple in input current, that is the current through L_1, I_{L1} For CCM of operation, assuming that all of the ripple component in i_{L1} flows through C_1. The shaded area in the waveform of V_{C1} represents an additional flux $\Delta\Phi$.

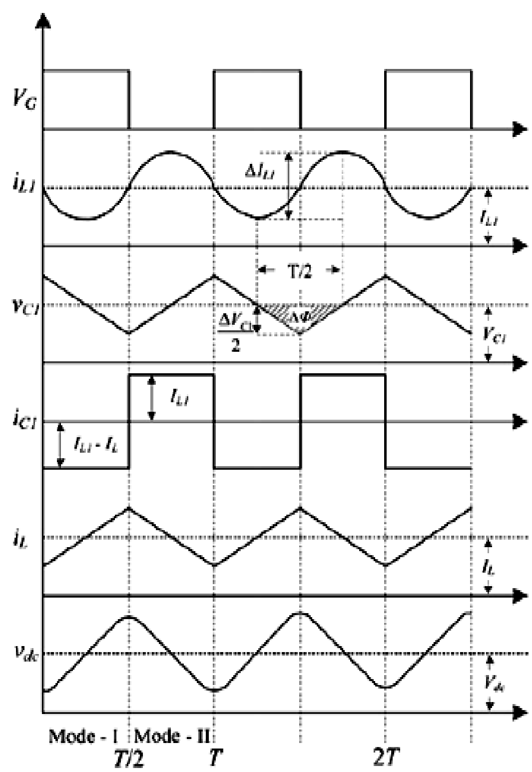


Figure 4: Waveform of Landsman Converter

4. SOLAR PHOTOVOLTAIC ARRAY

The photovoltaic energy is a clean energy, with a long lifespan and a high reliability. So, it can be considered as one of the most sustainable renewable energy. Solar cell is the basic element of PV module. Solar cells consist of a *p–n* junction fabricated in a thin layer of semiconductor . They are like *p–n* diodes The cell converts light energy into electricity using photovoltaic effect. Using the effect the photons contained in sunlight can excite electrons in the PV module into a higher state of energy, producing electric current. Thus the operation of a photovoltaic (PV) cell requires absorption of sunlight, electron-hole pair generation and then charge carriers of opposite types are separated and extracted to an external circuit. A solar panel consists of a series or a parallel combination of the cells in order to enhance the power output of the module .The obtained energy depends on the solar radiation, the temperature of the cell and the voltage produced in the photovoltaic module.

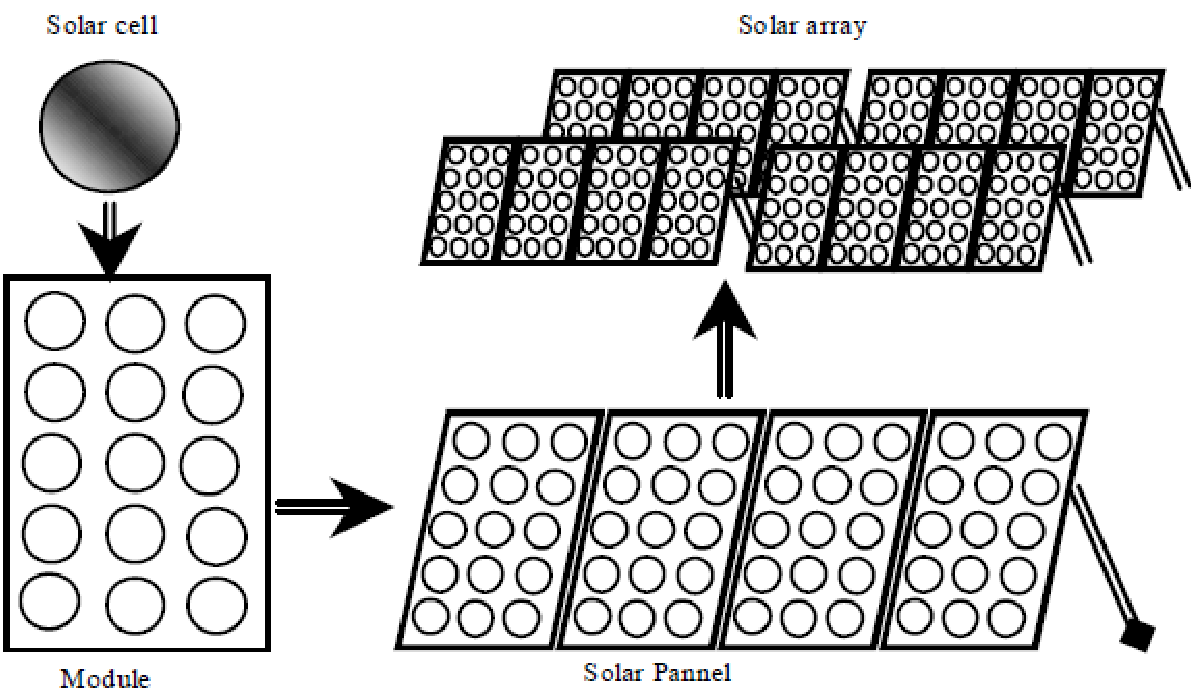


Figure 5: PV Generator Hierarchy

To ensure the successful operation even at the minimum solar irradiance of 200 W/m2 and considering the losses associated with converters and motor pump, an SPV array of 6.8 kW peak power rating is selected and designed for the proposed system. An array of the required size is made by using HBL Power System Ltd. make SPV module, HB-12100 with peak power capacity of 100 W [24]. The maximum voltage of SPV array is selected as 289 V.

5. DESIGN OF BLDC MOTOR

BLDC motor is a kind of permanent magnet synchronous motor, having permanent magnets on the rotor and trapezoidal shape back-EMF. BLDC motors are generally controlled using a three-phase inverter which requires a rotor position sensor for starting and for providing the proper commutation sequence to control the inverter. Hall-effect sensor may be used for this purpose. Brushless DC motor is driven by a three-phase inverter with so called “six-step commutation”. The conducting interval for each phase is 120 electrical degrees. Each conducting stage is called one step. Therefore, only two phases are energized in each step, leaving the third phase floating. In order to produce maximum torque, the inverter should be commutated every 60 degree. The commutation times are governed by the rotor position that can be either detected by Hall sensor. BLDC motor ratings are given in the Table 1.

Table 1: Rating of BLDC motor

S.No.	*Parameters*	*Value*
1	Number of poles	4
2	Phase resistance	14.56 ohm
3	Phase inductance	25.7 mH
4	Rated speed	2000 rpm
5	Moment of inertia	1.3×10^{-4} Nm/s^2

6. CONTROL OF PROPOSED SYSTEM

There are two control methodologies used in the proposed system at two different stage one for MPPT of SPV array and another for BLDC motor operation.

A. INC-MPP tracking

An INC-MPPT technique is applied to track the optimum operating point of SPV array. This technique states that the power slope of the PV array is null, positive and negative, respectively, at MPP ($dp/dv = 0$), left of MPP and right of MPP]. Due to this fact, the MPP can be found in terms of INC as:

$$p_{pv} = p_{pv} \times i_{pv}(1)$$

$$\frac{\partial p_{pv}}{\partial v_{pv}} = i_{pv} + v_{pv} \times \frac{\partial i_{pv}}{\partial v_{pv}} = 0 \tag{2}$$

$$\frac{\partial i_{pv}}{\partial v_{pv}} = -\frac{i_{pv}}{v_{pv}} \text{ at MPP} \tag{3}$$

$$\frac{\partial i_{pv}}{\partial v_{pv}} > -\frac{i_{pv}}{v_{pv}} \text{ at the left of MPP} \tag{4}$$

$$\frac{\partial i_{pv}}{\partial v_{pv}} < -\frac{i_{pv}}{v_{pv}} \text{ at the right of MPP} \tag{5}$$

To implement the INC-MPPT algorithm, the direct duty ratio control is adapted in view of the simplicity. This method obviating the proportional–integral (PI) controller, directly uses duty ratio as the control parameter. The direct duty ratio perturbation offers very good stability characteristics and high energy utilisation efficiency due to the low impact of noise and the absence of oscillation. Moreover, higher perturbation rates up to the PWM rate can be used without losing the global stability of the system. An excellent tracking performance under dynamic condition with negligible oscillations around optimum operating point is achieved. Optimally selecting the initial value of duty ratio and its perturbation size offer soft starting of BLDC motor by slowly increasing the DC-link voltage of VSI.

B. Electronic commutation of BLDC motor

An electronic commutation of BLDC motor stands for commutating the currents flowing through windings of BLDC motor in a predefined sequence using a decoder circuit [4]. Three inbuilt low-cost Hall sensors generate three Hall signals according to the rotor position at an interval of 60°. These Hall signals are then converted, using a decoder circuit, into the six switching pulses to operate the VSI feeding a BLDC motor. In this manner, fundamental frequency switching of VSI is obtained, resulting in a reduced switching loss. Table 3 shows the switching states of VSI for each particular combination of Hall signal states. It is perceptible that only two switches conduct at a time, resulting in 120° conduction mode of operation of VSI and hence the reduced conduction losses.

7. SIMULATED PERFORMANCE OF PROPOSED SYSTEM

The various starting, dynamic and steady-state performances of the proposed SPV array fed BLDC motor driven water pump using a Landsman converter are evaluated in MATLAB/SIMULINK environment

A. State Performances at 1000 W/m^2

(i) **Performances of INC-MPPT:** Figure 6 depicts the responses of voltage, v_{pv}, current, i_{pv} and power, p_{pv} of SPV array for irradiance level, S of 1000 W/m^2. These indices express that MPP is tracked properly with negligible oscillation around the peak power point by applying the INC-MPPT technique. The initial duty ratio and its perturbation are selected appropriately (0 and 0.001, respectively) in order to achieve the soft starting of the BLDC motor.

(ii) **Operation of Landsman converter:** Figure 7(b) depicts various converter output voltage of VSI, vdc. These responses demonstrate the operation of converter in CCM with reduced stress on power devices. The operation of the converter in boost mode is observed by duty ratio, D which is larger than 0.5.

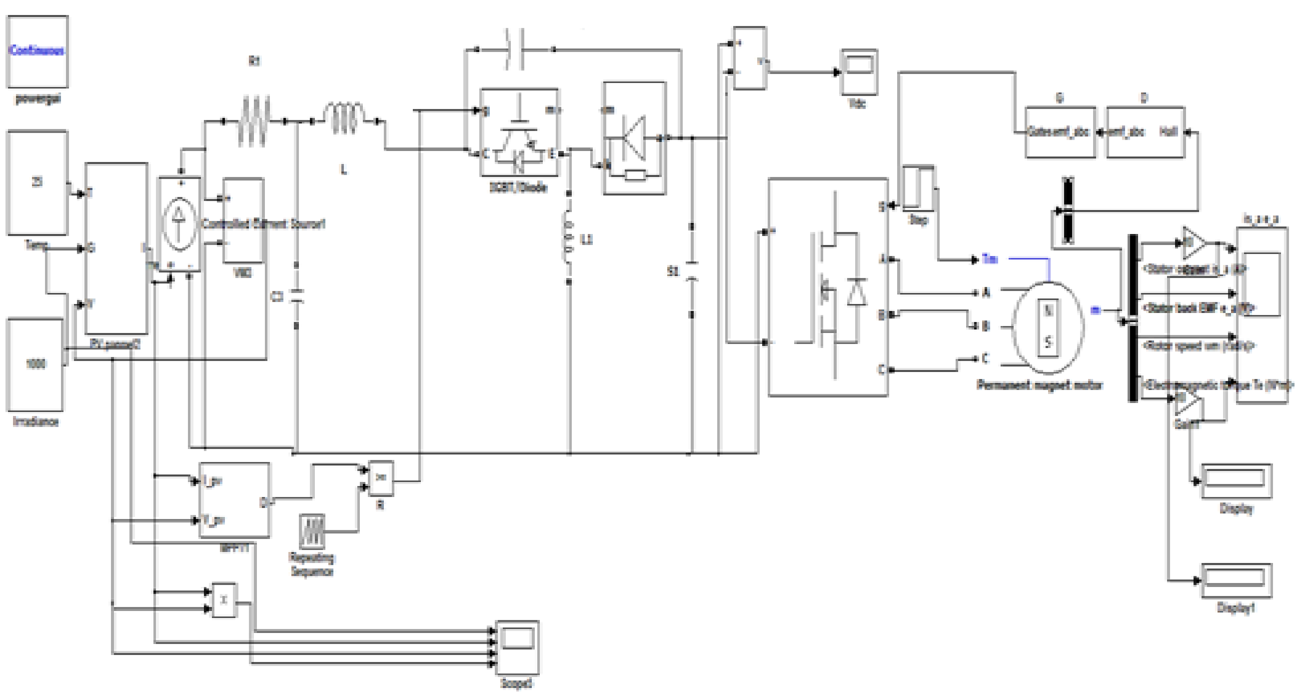
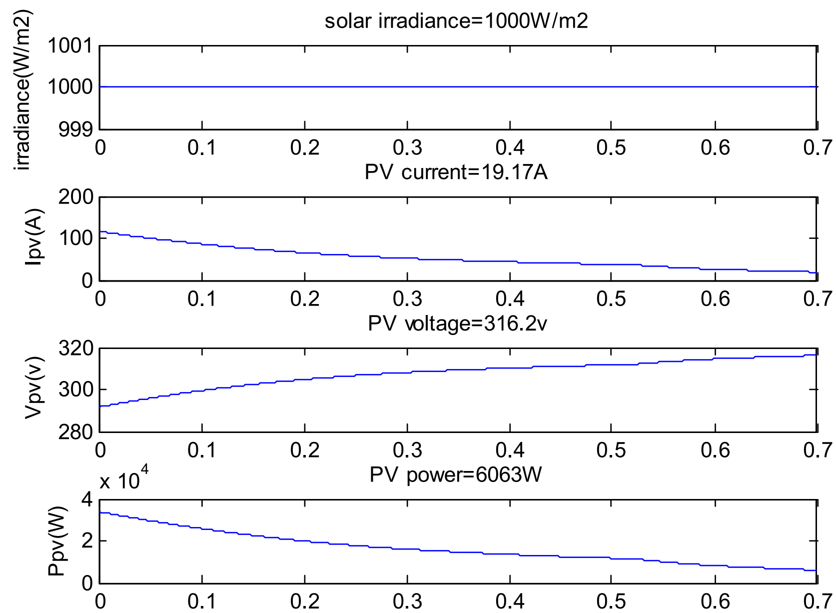


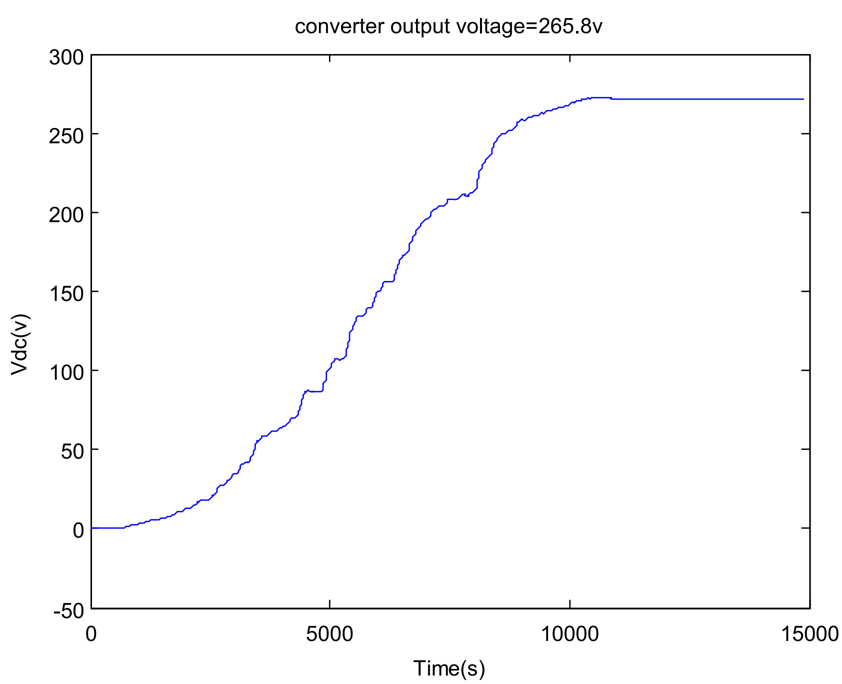
Figure 6: Simulink Model for solar array fed BLDC motor under Steady state condition

(iii) **Performance of BLDC motor pump:** The various motor variables viz. back emf of phase 'a,' ea; stator current of phase 'a,' isa; speed, N; electromagnetic torque, Te The BLDC motor develops its rated torque and attains the rated speed. An electronic commutation of BLDC motor causes a small pulsation in electromagnetic torque. The soft starting of the motor is achieved as shown by the response of isa.

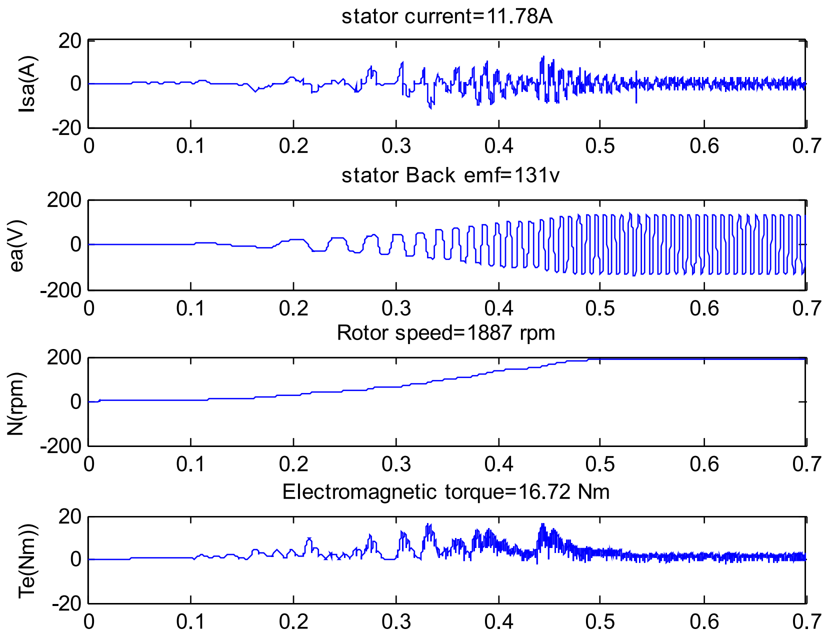
Figure 6 shows the simulation diagram of solar array fed BLDC motor under steady state condition. For steady state behavior of BLDC motor the solar irradiance level is 1000W/m^2.



(A)



(B)



(C)

Figure 7: Performance of SPV array– Landsman converter fed VSI-BLDC motor system at 1000 W/m^2: (A) SPV array indices, (B) Landsman converter indices, (C) BLDC motor indices

B. Dynamic Performance of Proposed System

Performance of the proposed system is affected by the random variation in solar irradiance level as shown in Figure 8. Figures 9(a) to (c) show the dynamic behaviour of INC-MPPT, Landsman converter and BLDC motor respectively. All the indices are abided by the atmospheric conditions.

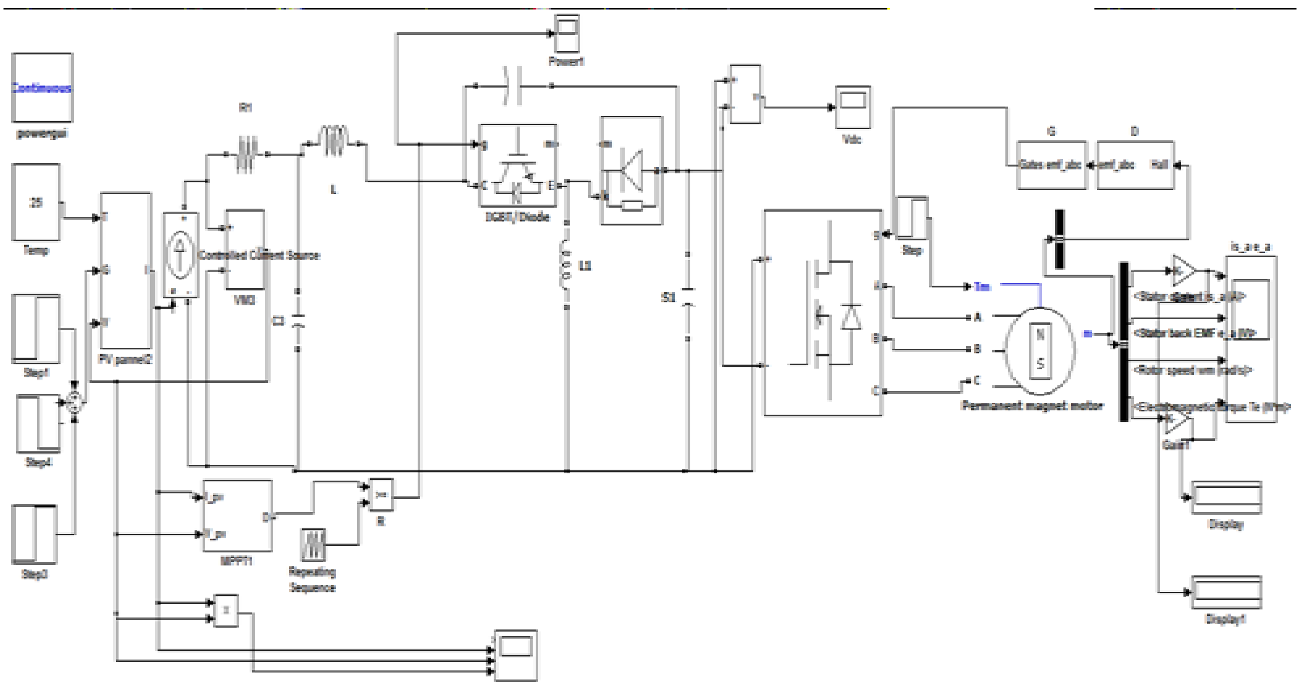
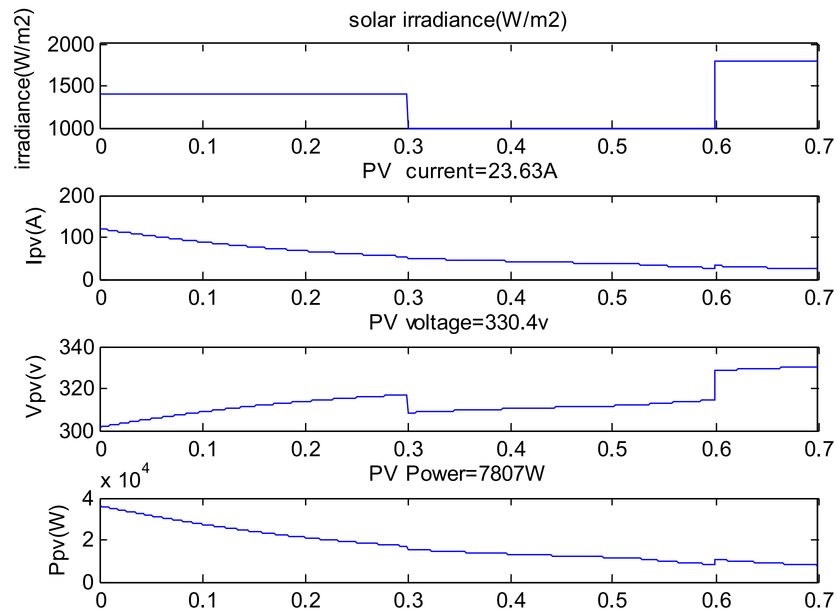


Figure 8: Simulink Model for solar array fed BLDC motor under Dynamic condition

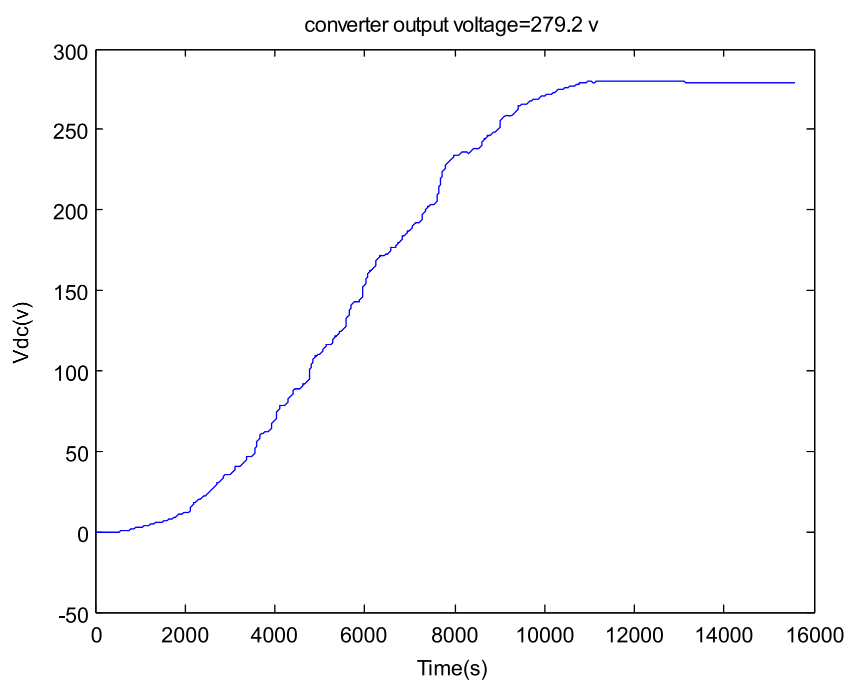
Figure 8 shows the simulation diagram of solar array fed BLDC motor under dynamic condition. For dynamic behavior of BLDC motor the solar irradiance level is suddenly varied from 1400W/m^2 to 1000W/m^2 and changes to 1800 W/m^2.

8. CONCLUSION

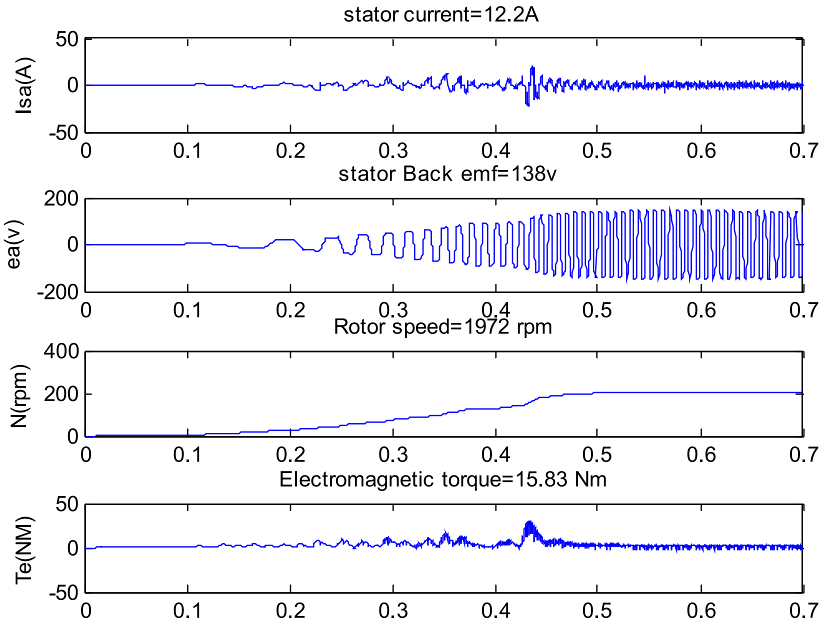
This project focuses on a solar PV array based BLDC motor employing Landsman converter. The steady state and dynamic behaviours have been analysed through simulation. The utilisation of Landsman converter has eliminated



(A)



(B)



(C)

Figure 9: Performance of SPV array – Landsman converter fed VSI-BLDC motor under dynamic condition:(A) SPV array indices, (B) Landsman converter indices, (C) BLDC motor pump indices

external filtering requirement and has also contributed to damp the oscillations occurred in the module current due to snubber elements. The speed control of BLDC motor by variable DC-link voltage. Which eliminates the additional phase current sensing, DC-link voltage sensing, additional control and associated circuitry. The proposed system include simplicity control, compactness, and soft starting of the BLDC motor. The operation of Landsman converter in CCM results reduced stress on devices.

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