SOLAR WATER PUMPING SYSTEM WITH BRUSHLESS DC MOTOR

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Abstract- Solar powered water pumping systems (WPS) are gaining popularity in the industrial and agricultural sector since they do not require the use of fossil fuels and are environmental friendly. Moreover, the water pumps that operate on electricity are inefficient and diesel pumps have higher fuel costs. Thus the solar powered water pumping system replaces the use of diesel pumps and electrically driven pumps and it acts as a best alternative choice. A boost converter with optimum efficiency is suggested in this research work to maximize the low PV potential. P&O MPPT method is adopted to track the supreme power point from the solar panel . Generally, DC motors are widely utilized in less power WPS. However, it comprises of commutator and sliding brushes which need routine maintenance. Thus the Brushless DC motor (BLDC) with good dynamic response is selected. The speed regulation of BLDC motor is acheived by employing a PI controller which analogize the actual speed with reference speed. The suitable gating pulse generated by the PWM generator is fed into the 3ϕ VSI and hence it monitors the speed of the motor. The developed solar WPS system is engineered and modelled in such a way that its efficiency is unaffected even when operating in complex conditions. MATLAB simulation result show the feasibility of the developed WPS system under actual operating conditions.
Keywords: WPS, Boost converter, P&O MPPT, 3ϕ VSI, BLDC motor.

1 INTRODUCTION

Water pumping system is considered as the most crucial application for irrigation purpose, but it has some drawbacks due to a lack of electricity since the rural electrification is extremely difficult and most of the time it is impossible [1]. Generally, there are many water pumps around the world that operate on non-renewable energy source or electricity. In terms of cost and emissions, purchasing solar PV WPS is more efficient than purchasing diesel water pumping systems [2]. Also, the PV powered WPS appears to be the most attractive and promising application since it is widely applied in numerous fields like fish farms, rural field irrigation as well as urban street watering [3]. Furthermore, there are numerous advantages to using PV array control, including low maintenance requirements, ease of installation and so on. Water pumping for irrigation and domestic purposes, among the numerous sectors where solar energy is being used and it appears to be one of the easiest and commercially sustainable application.

Changes in solar irradiation and temperature cause the PV module’s output voltages to fluctuate. As a consequence, these PV array’s low variable voltage necessitates DC/DC converters with transfer gain[4], [5]. Thus there are variety of DC/DC converters to achieve a high conversion ratio. Recently, several converters have been suggested as PV and renewable energy interfaces [6], [7]. Therefore this paper recommends an efficient DC-DC boost converter to perform the voltage boosting operation as well as to improve the voltage conversion efficiency.

The efficiency of PV module is poor. It is necessary to run at peak power point in order to provide the full amount of power to the load [8]. Maximum Power Point Tracking (MPPT) methods are commonly employed to optimise the output PV potential. Global MPPT techniques, Traditional MPPT techniques and power electronics-based methods are the three forms of tracking techniques [9]. The traditional perturb and observe (P&O) method is the most prominent technique which perturbs the PV potential and monitor the changes in MPP; the background of this technique can be traced through its various improved versions. Because of its simple implementation and low cost computation, the P&O technique is commonly used. The P&O MPPT operation concept is dependent on the boost converter's duty ratio (D) being perturbed in a way that the output potential of PV is optimized[10], [11].

As the human population increases, the demand for electrical energy has grown exponentially and electric motors have become more widely used. A best quality motor limits the quantity of PV panels used and it also reduces the manufacturing cost. DC motors are widely utilized in minimal power solar WPS. However, the DC motor with commutator and sliding brushes need routine maintenance. In contrast to DC motors, an induction motor-based WPS is more efficient, maintanence free, rugged, with higher performance and more power flexibility. However, in comparison to other commercial motors, the Brushless DC motor (BLDC) performs well in PV pumping (PVP) systems. BLDC motors have been described as a safer alternative to DC and induction motors for PV-fed water pumping. In comparison to an AC motor, this motor is lightweight, rugged, and powerful [12]-[15]. The control signal that is to be fed in to the 3ϕ VSI is controlled using the PI controller [16]. The most popular regulator in a speed regulation system is a PI controller [17], which is commonly used in huge plants because of its ability to control linear plants. The BLDC motor is signaled by a 3ϕ VSI which is a switching device consists of IGBT switches for switching operation [18]. The suitable gating pulse required for the inverter is generated by adopting a PWM [19], [20] generator which is also used to adjust the BLDC motor speed.

2 RELATED WORKS

Vikram et al [21] proposed a BLDC motor drive for a PVP system that is cost effective, quick and reliable. The suggested control algorithm removes phase current sensors and utilizes the VSI's fundamental frequency switching to prevent switching losses. The BLDC motor's speed is regulated without the use of any external controls or circuitry. A variable potential of VSI aids in monitoring the motor pace. Smooth starting of BLDC motor is possible by zeta converter regulation by means of INC-MPPT algorithm. The developed WPS is engineered and designed in such a way that its efficiency is unaffected even when operating in complex conditions.

Chandra et al [22] used in the amalgamation of AI control for effective potential extrication in Solar energy systems. As a result, this paper suggest a topology for a PVP system that employs a RBFNN to monitor the MPP. The duty ratio of a SEPIC converter to meet the MPP is predicted by the RBFNN - MPPT. With varying temperature, partial shading conditions and irradiance, the efficiency of the understudied device is compared to that of simple MPPT techniques.

S. Sashidhar et al [23] suggested that solar fed electric WPS are increasingly common due to the lack of power grids in remote rural areas,. A PV system, on the other hand, has a high initial cost. BLDC motors with permanent magnets are more powerful than induction motors, lowering the cost of a PV module. However, the rising cost of rare-earth magnets such as SmCo and NdFeB used in PM motors in PV systems unprofitable. As a result, ferrite magnets in PM motors are gaining popularity. An innovative "semi-modular dual-stack" ST BLDC motor is suggested for a solar WPS.

S. Sashidhar et al [24] suggested that solar fed BLDC WPS are more common in rural areas due to their high reliability and efficiency than induction motor pumps,. In these rural communities, the ground water is typically higher than 15 metres. As a result, potable water is extracted from the water table using shallow bore-well submersible engines. Owing to the bad environment, the controller and motor are immersed in the ground water table and have a higher temperature increase. To remove the use of hall sensors, a location sensorless control scheme is introduced, increasing the overall system's reliability.

Sreedhar Madichetty et al [25] used the concept of RES as a power source for researching and implementing a standalone air-cooling device is proposed in this article. This form of system is applicable in rural areas that receive a lot of solar energy but don't suitable for power grid access. A photovoltaic (PV) series, boost converter, and buck converter are all part of the proposed system. A DC-DC buck motor is connected to a centrifugal pump. Maintaining the steady velocity of the blower under changing irradiance conditions is a difficult task in an air cooling system.

Agrawal et al [26] suggested that DC motors have a wide range of applications where machine control is a primary goal. A BLDC is one that has the features of a dc motor but it lacks brushes or commutator. Because of their high performance, dependability, low electrical noise as well as high starting torque these motors are common in many commercial processes. There are variety of controllers are used to adjust the motor speed. The operation of motor is studied with and without traditional controllers using PID and PI in this study.

3 PROPOSED WORK

The solar powered WPS developed in this research work includes a boost converter with P&O MPPT algorithm, 3ϕ inverter and a BLDC motor whose speed is controlled by utilizing a PI controller. Figure 1 represents the block diagram of developed system.

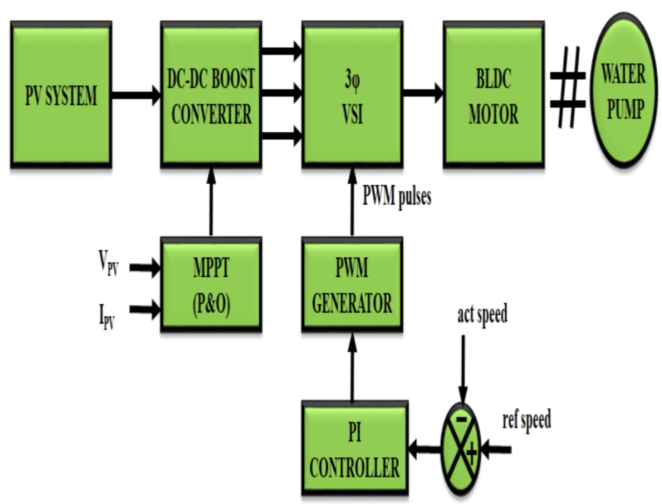


Figure 1 Developed block representation of PVP system

The energy brought out by the PV array is fed into the boost converter which enhances the low DC voltage received from the PV panel. However, due to partial shading and varying environmental condition, the PV system fails to deliver constant energy to the converter. Thus the P&O algorithm based MPPT method is adopted to detect the maximum power point (MPP) in the PV panel which helps extricating optimum power. The output potential generated by the boost converter is fed into the $3\phi\ VSI$. The BLDC motor with high efficiency and excellent dynamic response is connected to the inverter. A PI controller has been assigned to adjust the pace of the BLDC motor. The suitable gating pulse generated by the PWM generator is fed into the VSI.

3.1 PV Cell Model

To simulate the efficiency of solar cells, a variety of models have been created. The circuit model of a photodiode is used in a numerical system to design the load voltage, electrical behavior and load current of a solar cell [27]. Figure 2 depicts the one diode model of PV cell.

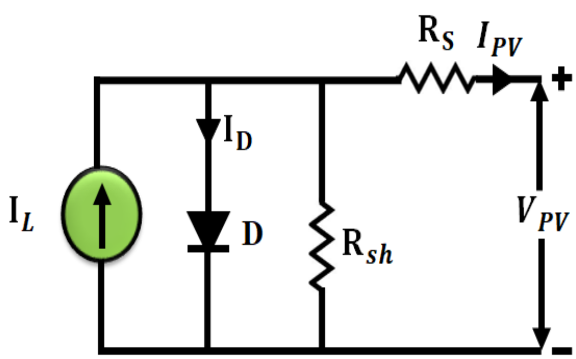


Figure 2 PV cell – One diode model

By applying Kirchoff's law to the circuit, we get

$$I_L = I_D + I_{R_{sh}} + I_{PV} \quad (1)$$

Thus the PV output current can be expressed as,

$$I_{PV} = I_L + I_{R_{sh}} + I_D \quad (2)$$

$$I_{PV} = I_L - I_0\left[exp\left(\frac{V_{PV}+I_{PV}R_s}{V_T}\right) - 1\right] - \left[\frac{V_{PV}+I_{PV}R_s}{R_{sh}}\right] \quad (3)$$

Where,

I_L	-	Light current
R_s	-	Series resistance
R_{sh}	-	Shunt resistance
V_{PV}	-	PV output voltage
I_{PV}	-	PV output current
I_0	-	Reverse saturation current
V_T	-	Thermal voltage

$\therefore V_T = \frac{KT}{q}$

Where, K represents the Boltzmann constant, T denotes temperature and q is the electron charge.

3.2 Design of Boost Converter

DC-DC boost converter acts as a switching regulator which converts an uncontrolled DC voltage source into a controlled DC output voltage. The model of boost converter includes DC voltage source V_{PV}, Switch S, a diode D, a capacitor C and inductor L. The electrical layout of boost converter is highlighted in Figure 3.

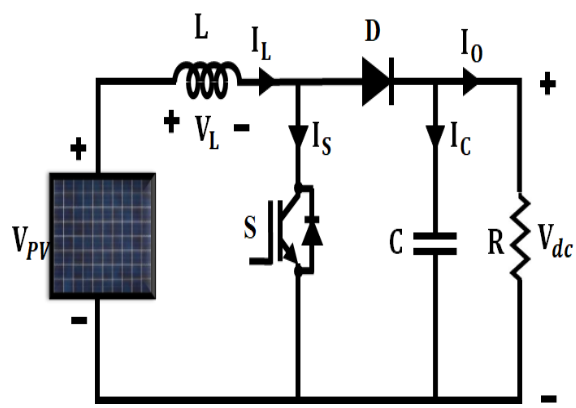


Figure 3 Equivalent circuit model of boost converter

The boost converter has two working modes and are given as follows,

Mode 1: Switch OFF Mode

During switch OFF state, the inductor transfers its energy to the output by means of the diode. Thus the load voltage obtained is the total value of source voltage and the inductor voltage. Figure 4 portrays the OFF state of boost converter.

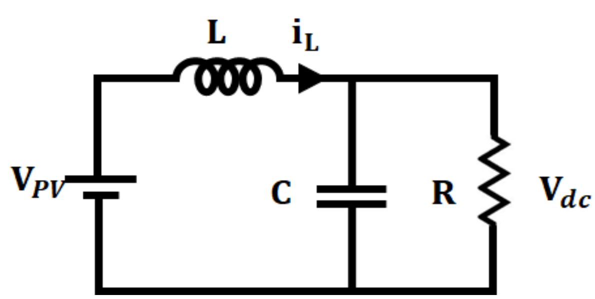


Figure 4 Boost converter - OFF state model

Mode 2: Switch ON Mode

During switch ON state, the inductor current linearly increases and the diode is turned OFF parallely. The input voltage V_{PV} supplies energy to the inductor whereas the capacitor discharges around the load. The ON state illustration of boost converter is highlighted in Figure 5.

Thus the boost converter's duty cycle can be expressed as,

$$D = \frac{T_{on}}{T} \quad (4)$$

$$\therefore T = \frac{1}{f}$$

The voltage balance equation of inductor is given as,

$$V_{PV}(DT_s) + (V_s - V_{dc})(1-D)T_s = 0 \quad (5)$$

$$V_{PV}(DT_s) - V_{PV}(DT_s) - V_{PV}T_s + V_{dc}DT_s - V_{dc}T_s = 0$$

$$V_{dc} = \frac{V_{PV}}{1-D}$$

Thus the convertion ratio is given as,

$$M = \frac{V_{dc}}{V_{PV}} = \frac{1}{1-D} \quad (6)$$

The change in inductor current is given as,

$$\Delta I_L = I_{max} - I_{min} \quad (7)$$

$$\Delta I_L = \frac{V_{PV}}{L} * DT_s \quad (8)$$

$$\Delta I_L = \frac{V_{PV}D}{f_s L}$$

$$L = \frac{V_{PV}D}{f_s \Delta I_L} \quad (9)$$

In CCM mode, where $L > L_b \therefore L_b = \frac{(1-D)2DR}{2f}$ (10)

The ouput of the boost converter receives discontinuous current. In order to limit the voltage ripple at the output, a filter capacitor is utilized. This filter capacitor offers the dc output current to the load only when the diode is turned OFF. Terefore, the value of capacitor minimum is given as,

$$\therefore C_{min} = \frac{DV_{dc}}{V_0 Rf} \quad (11)$$

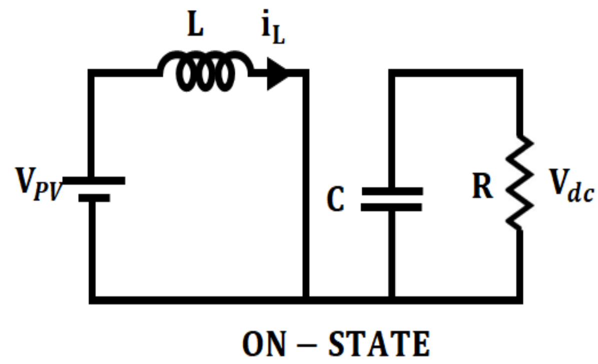


Figure 5 Boost converter - ON state

3.3 P&O MPPT

The P&O algorithm is said to be an iterative method in which the calculated voltage V_{PV} is perturbed with ΔV until the PV power P_{PV} reaches its MPP.

Therefore, there are three operating conditions of P-V characteristics and are given as,

The operating point is said to be on the MPP's left side, if $\frac{\partial P_{PV}}{\partial V_{PV}} > 0$

The operating point is said to be on the MPP's right side, if $\frac{\partial P_{PV}}{\partial V_{PV}} < 0$

The MPP is the operating point, if $\frac{\partial P_{PV}}{\partial V_{PV}} = 0$

Even after hitting the MPP, which gives rise to infinite oscillation around this stage, the extraction process continues to operate. The process flow diagram of P&O MPPT is depicted in Figure 6.

3.4 3ϕ VSI model

The BLDC motor is fed by a 3ϕ VSI. Its architecture involves calculating VA ratings, current and voltage. Since the DC bus voltage is $270\,V$, an IGBT switch's necessary voltage rating is estimated as

$$V_{VSI} = V_{dc} \times voltage\ safety\ factor \quad (12)$$

To account for switching transients, value of voltage protection factor is applied. Likewise, an IGBT switch's necessary current rating is estimated as

$$I_{VSI} = I_{dc} \times current\ safety\ factor \quad (13)$$

$$\therefore I_{dc} = \frac{P_{PV}}{V_{PV}}$$

Eventually, the VSI's VA rating is calculated as,

$$VA_{VSI} = V_{VSI} \times I_{VSI} \quad (14)$$

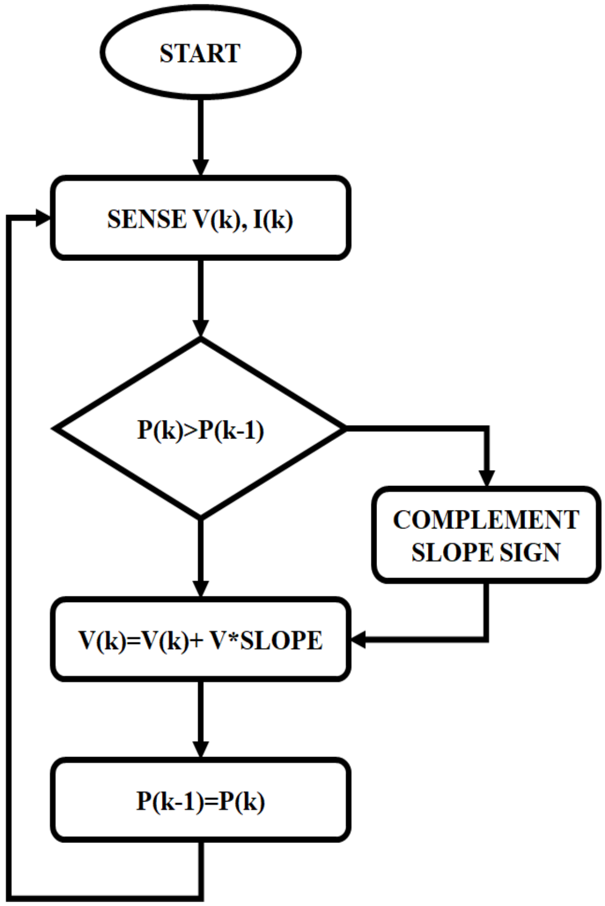


Figure 6 P&O MPPT – Process flow diagram

3.5 BLDC Motor

BLDC motor is specially desined to meet the demand of commercial and industrial sector. Compared to DC motor and induction motor, BLDC motor has various advantages since it has long life, excellent torque to mass ratio, low noise and better reliability. In BLDC motor, there is no mechanical commutator because of the absence of brushes which increases the life of the motor and it also has good dynamic response. Also it comprises low mainatenance cost and high efficiency thus it is used in various industrial sectors. Here, the BLDC motor acts as a load. The inverter that supplies AC current is used to drive one and all phase of BLDC motor. Hence, the actual location of the rotor is measured using a Hall sensor as it is the most important parameter in controlling the motor speed. The simple diagrammatic representation of BLDC motor is illustrated in Figure 7.

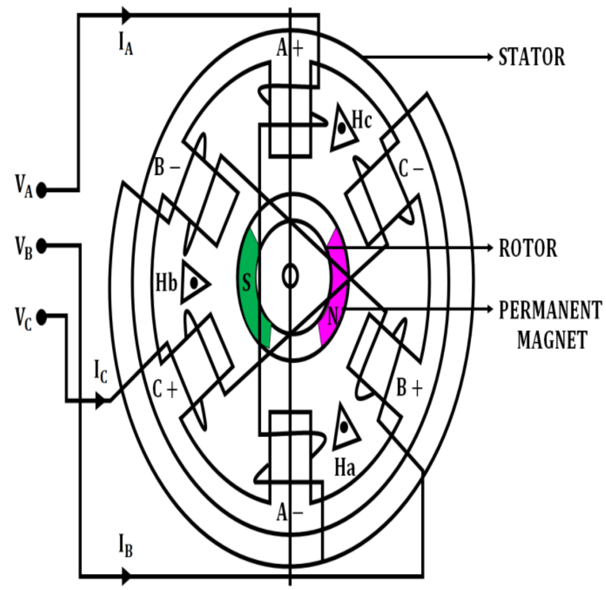


Figure 7 Design of BLDC motor

3.6 PI Speed Controller

The speed location encoder is adopted to determine the actual pace of the BLDC motor. The steady state error is calculated as,

$$\Omega_e = \Omega_r - \Omega_r^* \tag{15}$$

The obtained error signal is given to the PI controller and hence its transfer function is calculated as,

$$G_s(S) = K_p\left(1 + \frac{1}{T_i S}\right) \tag{16}$$

$$\therefore T_i = \frac{K_p}{K_i} \tag{17}$$

Where, K_p refers to the proportional constant, K_i denotes the integral constant. The basic control block of PI controller is illustrated in Figure 8.

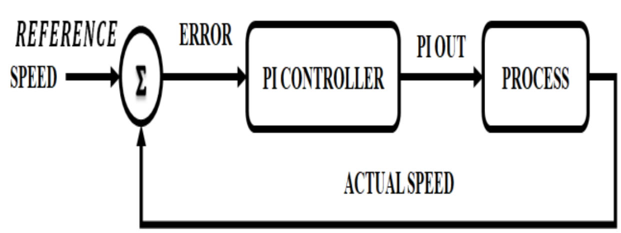


Figure 8 Control block of PI controller

4 RESULTS & DISCUSSION

This paper verifies the overall performance of PV powered BLDC motor for WPS using the MATLAB simulation. It comprises of high gain boost converter which enhances the PV potential and P&O MPPT for trailing the MPP. The BLDC motor with excellent dynamic response is assigned to improvise the system performance. The pace control of BLDC motor is achieved by employing a PI controller which compares the actual and reference pace of the motor. The PV panel parameters and the converter ratings are listed out in Table 1.

Table 1 PV panel parameters and Boost converter ratings

Components	Specifications
No. of series cells	36
Total No. of modules	10
Area of a single cell	$(125 \times 31.26) mm$
Operating Voltage	$16.8\ V$
Maximum Voltage	$1000\ V\ DC$
Operating Current	$5.8\ A$
Rating of Temperature	$-40\ to + 85$℃
Boost converter Ratings	
Input voltage, V_{PV}	$0\ to\ 12\ V\ DC$
Input current, I_i	$25\ A\ (Max)$
Load resistance	$24\ ohms$
Capacitor, C	$150\ \mu F$
Inductance, L_1	$10\ mH$
Output current, I_o	$5\ A$
Operating frequency, f	$10\ KHz$
Duty cycle	0.916

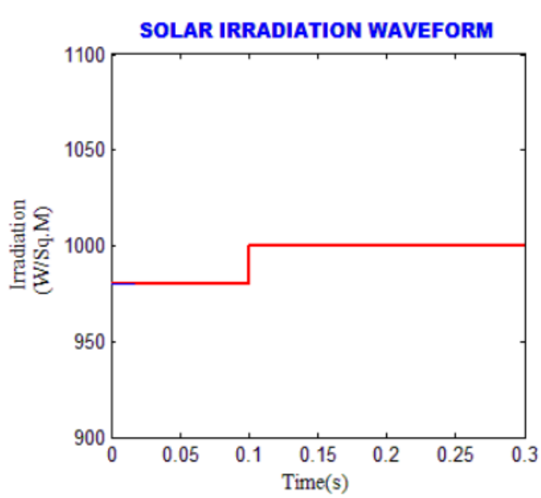


Figure 9 Solar insolation waveform

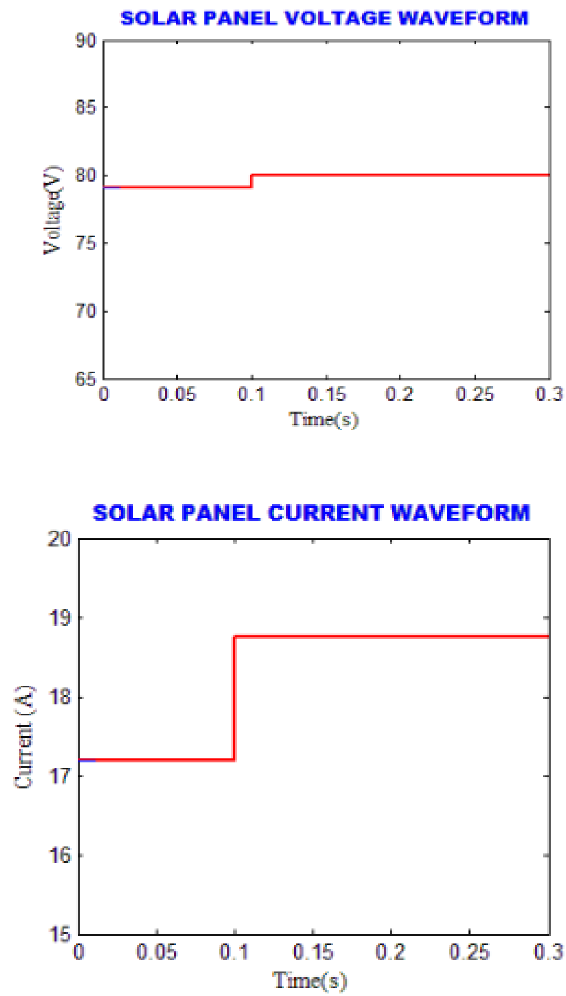


Figure 10 Volatge and current of PV module

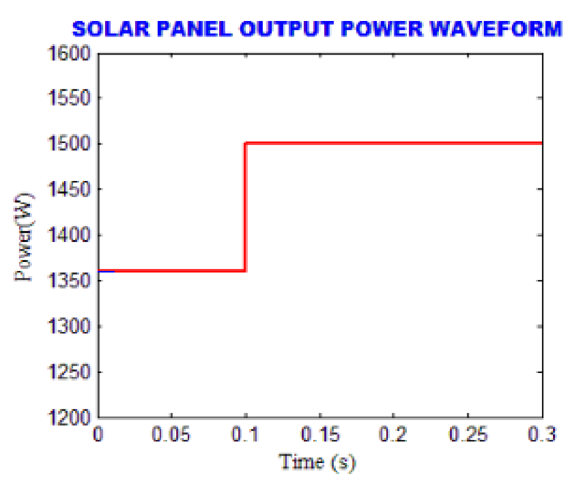


Figure 11 PV output power waveform

Figure 9 highlights the solar insolation waveform which shows that the solar insolation varies from 980 W/m^2 to 1000 W/m^2 at a time period of 0.1 s

The voltage and current of PV panel is illustrated in Figure 10. Due to solar irradiation, the PV panel generates a low DC potential. At the time interval of 0.1 s, the PV module's derived current ranges from $17.2\ A\ to\ 18.8\ A$ whereas at the same time, the PV output voltage ranges from $78\ V\ to\ 80\ V$.

Figure 11 depicts the output power waveform of PV module. From this waveform, it is observed that the panel ouput power varies from $1380\ Watts\ to\ 1500\ Watts$ at the time period of 0.1 s

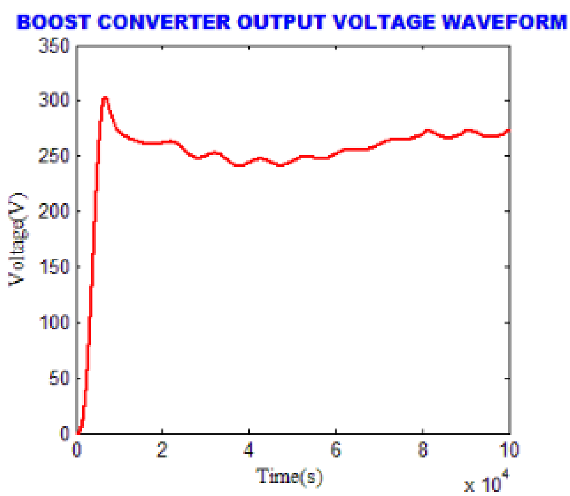


Figure 12 Output volatage waveform of Boost converter

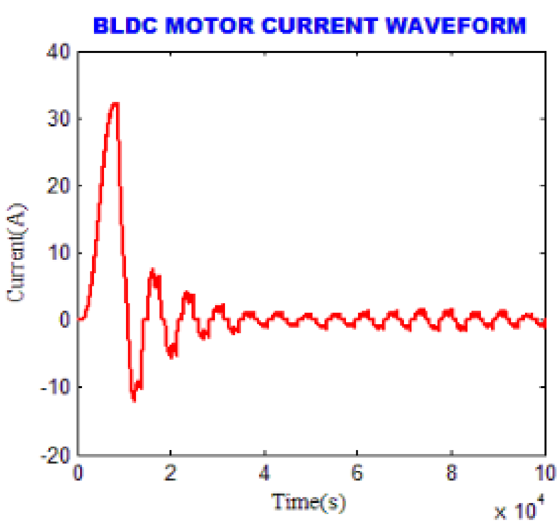
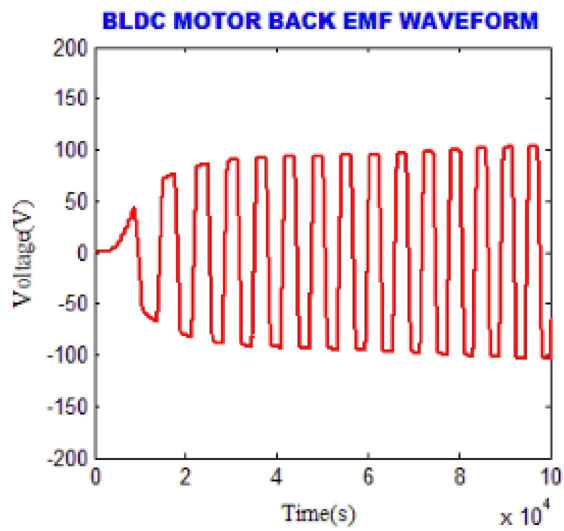


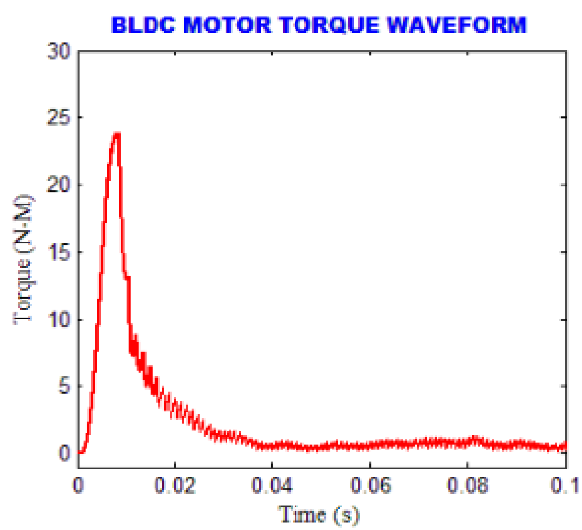
Figure 13 Current waveform of BLDC motor

The low output potential of solar module is given to the high gain boost converter which boost up the low level dc voltage. The P&O algorithm based MPPT is aldo assigned to trail the MPP. Thus the boost converter's output potential is portrayed in Figure 12.

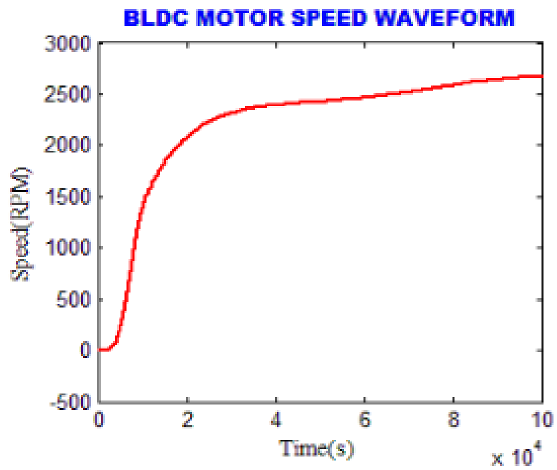
The current waveform of motor is depicted in Figure 13. From the waveform it is clearly observed that the motor current initially rises to $32\ A$ and after sometime it drops down to zero.



(a)



(b)



(c)

Figure 14 BLDC motor (a) EMF waveform (b) Torque waveform (c) Speed waveform

From Figure 14 it is clearly understood that the generated EMF of the BLDC motor ranges from $-100\,V\ to\ 100\,V$. The motor torque initially rises upto $24\,Nm$ and after sometimes it falls down to zero. The pace control of BLDC motor is achieved a PI controller and hence the speed waveform of the motor is portrayed in Figure 14 (c).

5 CONCLUSION

The detailed assessment of the working performance of BLDC driven solar WPS has been discussed in this paper and it is verified through MATLAB simulation. The modes of operation of boost converter along with P&O algorithm based MPPT which aids in tracking the MPP from the PV module have been analyzed. The boost converter eliminates output current ripple and it greatly reduces the switching stress. To optimize the efficiency of solar WPS, BLDC motor with high dynamic response have been chosen. The pace of BLDC motor is adjusted by employing a PI controller. The speed and location of the motor used to produce the switching signal for the inverter are indicated by a feedback signal from the motor.

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