Solar Water Pump using BLDC Motor Drive with High Gain DC-DC Converter

Kavya Pramod M
Dept. of Electrical and Electronics Engineering
Government Engineering College
Bartonhill, Thiruvananthapuram, India

Elizabeth Cherian
Dept. of Electrical and Electronics Engineering
Government Engineering College
Bartonhill, Thiruvananthapuram, India

Abstract— **This paper proposes a simple solar photovoltaic (PV) fed water pump using a high gain step-up DC-DC converter. An energy-efficient brushless DC (BLDC) motor is used to drive the water pump. As the low voltage obtained from solar panel is inadequate for driving the motor pump, the system is incorporated with a novel high gain DC-DC converter to step up the voltage. The maximum power from the solar PV array is extracted by adjusting the duty ratio of the step-up DC-DC converter. To control the duty ratio, an incremental conductance (INC) based maximum power point tracking (MPPT) control technique is used. The proposed system eliminates the requirement of complex speed control methods. Constant speed of the motor is achieved by maintaining DC link voltage at a constant value. The MATLAB/Simulink-based simulations are carried out to validate the efficacy of the system.**

Keywords— ***Solar photovoltaic; Step-up DC-DC converter; BLDC; MPPT.***

I. INTRODUCTION

Diminishing conventional energy resources creates a large gap between energy required and supplied. Climatic changes, depleting fossil fuels, increasing carbon footprint and global warming have led to the use of green energy. Among the green energy sources, solar power has become the recent trend on account of its inexhaustible nature, cleanness, cost free and ease of availability [1]. In a country like India, groundwater irrigation has been expanding at a very rapid pace. India uses more than 18 million grid tied pumps and 8 million diesel operated pump sets for agriculture[2]. But high running cost is the major problem addressed. Solar pumps are the attractive alternative where grid electricity is unavailable and other sources are very expensive. Multiple configurations of both AC and DC solar powered pumps are available in the market. Solar powered AC pumps require high capacity PV panel and suffer from poor efficiency[3]. Solar powered DC pumps are considered to be more suitable than AC pumps due to the high efficiency and wide operating ranges. Because of its high efficiency, low maintenance cost, better speed-torque characteristics, low electromagnetic interference issues BLDC motor is found to be more suitable to be operated with solar DC power. Moreover when comparing DC and AC pumps for a given capacity of solar panel, it is found that BLDC motor-pump has higher water output[4].

The size of the solar panel is directly dependent on rating of the motor, the quantity of water that is required and the solar irradiance available. As PV panel makeup most of the system cost, a DC-DC converter with MPPT is usually incorporated to boost the low voltage generated from the solar panel. Although conventional boost converter, Single Ended Primary Inductor Converter(SEPIC), buck-boost converter , cuk converter etc. are used for many applications, low gain and poor efficiency are the major drawbacks of these converters[5][6].

Recently, several high voltage gain DC-DC converters have been proposed which use passive elements in boosting stages. A High Frequency Transformer is utilized in isolated DC-DC converter to boost the input voltage by varying its turns ratio[7]. But isolated DC-DC converters have high input current ripple and high voltage stress on the secondary side. In addition, large size of transformer and multistage power conversion process are also the shortcomings of these converters. Non-isolated high gain DC-DC converters with compact size and high efficiency are utilized as an alternative for PV application. Various high gain converters are proposed in [8][9] for solar PV applications which use voltage lifting techniques such as cascading, interleaving etc. In reference [10], the converter is provided with several number of voltage multiplier cells eventhough, it has low voltage gain. A high gain DC-DC converter with Switched inductors and capacitors is presented in [11]. But this converter has higher component count and hence the conduction and switching losses are higher and efficiency is found to decrease with increase in number of components due to the effect of uncontrolled diodes. In [12] an active network based high gain DC-DC converter is proposed. This converter attains high gain but with a pulsating input current. The converter is controlled with two switches and makes the system more complex and less efficient. Moreover, discontinuous input current is also a drawback of the circuit.

A solar water pump using a high gain step-up DC-DC converter with single switch is proposed in this paper. Proposed converter is designed to provide high gain with lesser number of components. As the converter possesses only one

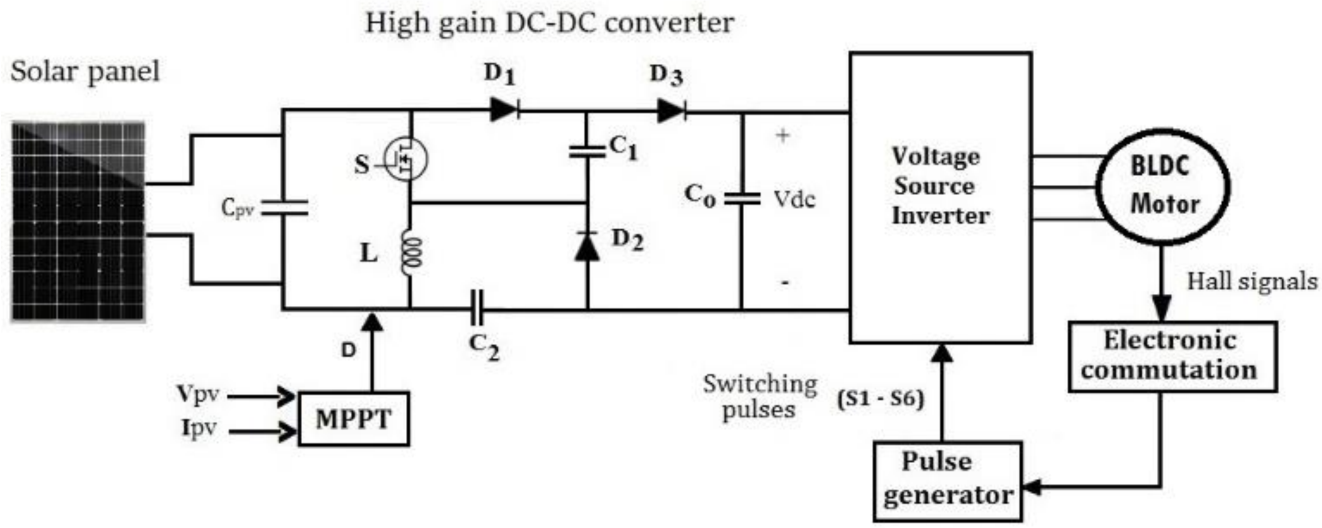

Figure 1: Schematic diagram of solar water pumping system with proposed DC-DC converter

switch, the control circuit is simple and easy. The converter boosts the input solar voltage to the required dc voltage for the effective operation of the BLDC motor. The maximum power from the PV cell is extracted by using MPPT technique[13][14]. The water pumping system with the proposed converter is designed, modeled and analyzed by simulation.

The remaining sections of the paper are organized follows. Section II gives the proposed water pumping system. In section III the operating principle of DC-DC converter is discussed. In section IV the design of the solar PV array and the DC-DC converter are presented. Section V discusses the simulation results and section VI gives the conclusion and future scope.

II. PROPOSED SYSTEM

A. System Configuration

The topology of the proposed solar fed water pump driven by BLDC motor using a high gain step-up DC-DC converter is presented in Fig.1. This system consists of solar PV array, a high gain step-up DC-DC converter, a three phase VSI[15], a BLDC motor and a water pump. The PV array feeds the BLDC motor through the step-up DC-DC converter and VSI. PV array consist of suitable number of series and parallel connected solar PV modules. The step-up DC-DC converter carries out the MPPT of PV array. The VSI performs the electronic commutation of the BLDC motor. The merit of this system is that the high gain of the proposed boost converter is achieved with lesser number of components than the existing high gain boost converters.

B. Operating Principle

The solar PV is the power source to the whole system. The maximum power from the solar PV panel is extracted by using INC MPPT technique which decides the duty ratio of the DC-DC converter. The low voltage from the solar panel is boosted by using high gain DC-DC converter. The output of step-up converter is the required DC link voltage, which serves as the input DC voltage to VSI. The VSI feeds power to the BLDC motor. Inbuilt hall effect sensors which are attached on the shaft of the motor senses the position of rotor and feeds the signal back to the controller which generates the gating signals to the VSI switches. Thus the BLDC motor which is coupled to the water pump rotates.

III. HIGH GAIN STEP-UP DC-DC CONVERTER

A new topology of high gain step-up DC-DC converter as shown in Fig.2 is used in this system.

The converter circuit consists of only one inductor(L), three diodes (D_1, D_2, D_3) and three capacitors(C_1,C_2,C_3) which are

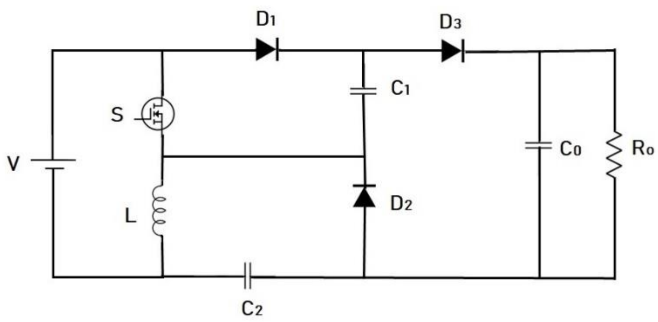

Figure 2: Proposed high gain step-up DC-DC converter

controlled by a single switch(S). It works on Continuous Conduction Mode (CCM). Initially capacitors C_1 and C_2 are assumed to be in charged condition. When switch is ON diodes D_1, D_2 are reverse biased and diode D_3 is forward biased. Inductor (L) charges and capacitor C_1, C_2 discharges to output capacitor C_o. When switch is OFF diode D_1 and D_2 are forward biased and diode D_3 is reverse biased. Inductor discharges, capacitors C_1, C_2 charges and C_o discharges.

The prominent feature of the proposed converter is that, the number of elements in the path of the current at any interval of time is small which results in decreased power loss during conduction and hence increased efficiency. The use of single switch in the converter circuit makes the control simple and manageable. Inductor and capacitors serve as the voltage boosting elements.

IV. SYSTEM DESIGN

A. *Design of solar PV array*

The solar panel is selected in view of the input power of the BLDC motor including the power loss associated with converter and motor (approximately 10%). A commercially available 4 pole, 1.3 kW BLDC motor which has a rated speed of 3000 rpm is selected to run the water pump. Hence, to drive the selected BLDC motor a 1.5 kW peak solar PV array is selected. A PV module having MPP voltage of 28.5V and current of 7.5 A under standard test condition(1000 W/m^2, 25°C) is selected to acquire the desired capacity. The number of series and parallel modules required are calculated by selecting solar PV array voltage at MPP as 100 V.

The solar PV array current at MPP is[16],

$$I_{MPP} = \frac{\text{Power at MPP}}{\text{Voltage at MPP}} \tag{1}$$

Number of modules in series,

$$N_S = \frac{V_{MPP}}{v_m} \tag{2}$$

where V_{MPP} and v_m are the MPP voltage of solar array and module.

Number of modules in parallel,

$$N_P = \frac{I_{MPP}}{i_m} \tag{3}$$

where I_{MPP} and i_m are the MPP current of a solar array and module.

B. *Design of High Gain Step-Up DC-DC Converter*

The step-up DC-DC converter is designed to provide an output of 270 V. During CCM the voltage gain of the converter is expressed as,

$$\frac{V_0}{V_{in}} = \frac{2}{1-D} \tag{4}$$

where V_{in} is the input voltage and V_0 is the output voltage. And the ratio of current is given by,

$$\frac{I_0}{I_{in}} = \frac{1-D}{2} \tag{5}$$

where I_{in} is the input current and I_o is the output current. The duty ratio is estimated as,

$$D = \frac{V_0 - 2V_{in}}{V_0} \tag{6}$$

The inductor L is given by,

$$L_{min} = \frac{D(1-D)^2 R}{4(1+D)f_S} \tag{7}$$

where f_s is the switching frequency.

The value of capacitor is estimated as,

$$C_1 = C_2 = \frac{2V_{in}}{(1-D)Rf_S\Delta V_C} \tag{8}$$

The value of output capacitor is estimated as,

$$C_0 = \frac{I_0(1-D)}{f_S \Delta V_0} \tag{9}$$

From equation (4), the gain of the converter is found to be higher than the gain of existing high gain converters[6][10]. The parameters designed are shown in Table I.

TABLE I. DESIGN PARAMETERS

Parameters	Values
SPV array voltage at MPP	100 V
SPV array current at MPP	15 A
SPV array power at MPP	1.5 kW
Motor capacity	1.3 kW
Number of poles	4
Speed	3000 rpm
Stator resistance	3.58 Ω
Stator inductance	9.13mH
Voltage constant	68 V/krpm
Switching frequency	10kHz
Inductor	2 mH
Capacitor C1, C2	200 μF
Capacitor Co	1000 μF

V. RESULTS AND DISCUSSION

An analysis of the proposed system based on simulation is performed to check the effectiveness and performance.The results showing the performance of the solar PV panel, DC-DC converter and BLDC motor are given in Fig.3 and 4.

A. *Performance of DC-DC Converter*

The performance characteristics of the DC-DC converter under standard testing condition is shown in Fig.3. Fig.3(a) shows the standard solar irradiance of 1000 W/m^2 at the standard temperature of 25°C. Fig.3(b) shows the voltage output (100V) of the solar panel which is the input to the converter. The PV output current is shown in Fig.3(c). The step-up converter boosts the input voltage to 270 V as shown

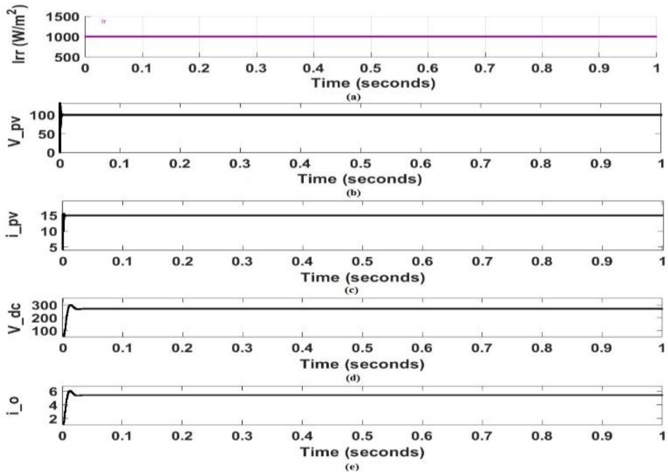

Figure 3: PV and converter characteristics: (a) solar irradiance (b) PV output voltage (c) PV output current (d) converter output voltage (e) converter output current.

in Fig.3(d) and the output current of the converter is shown in Fig.3(e).

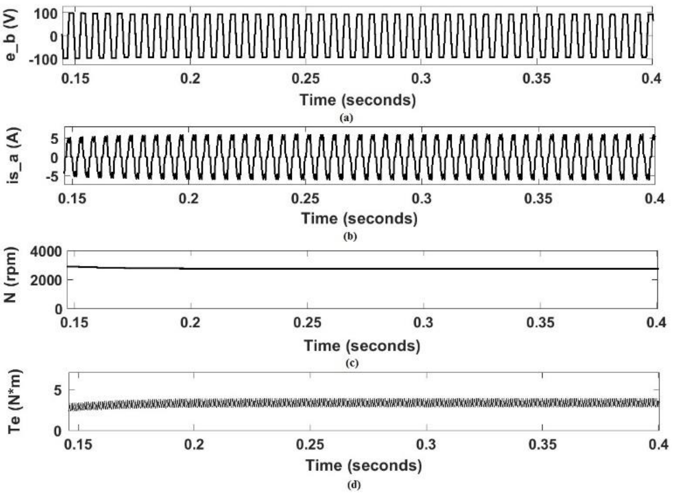

Figure 4: BLDC Motor indices (a) stator back emf (b) stator current (c) speed (d)electromagnetic torque

B. *Performance of BLDC Motor Drive*

Working of BLDC motor when connected with PV array through the proposed high gain step-up converter is analyzed. The system is simulated for standard irradiance of 1000 W/m^2. The performance characteristics of BLDC motor in one phase is shown in Fig.4. BLDC motor generates a trapezoidal back emf of peak value 100 V as shown in Fig.4(a). It runs effectively with a stator current of peak value 6.5 A as shown in Fig.4(b). The rated speed of the motor is 3000 rpm as shown in Fig.4(c). The motor produces electromagnetic torque of 3.9 Nm as shown in Fig.4(d). Although the torque contains a small ripple, it is well within acceptable limit[17] and does not create any problem in the water pumping operation.

VI. CONCLUSION AND FUTURE SCOPE

A solar water pump using BLDC motor drive is implemented and the performance is analyzed by simulation. The inclusion of a high gain DC-DC boost converter with lesser number of components improves the overall efficiency. The system effectively tracks MPP with an acceptable tolerance value at varying solar irradiance. A simple and economical, current sensor-less based technique is incorporated for BLDC motor speed control. The simulation results depict the effectiveness of the pumping system. The proposed system finds its application in irrigation in rural areas, gardening in urban and rural areas, water fountain in municipal areas and community water pumping to overhead tanks in residential areas.

Being a standalone system, the water pump fed by the PV panel, has only solar PV energy as input. Intermittent power generation is the major drawback of PV panel. Hence as a future scope the performance of the system can be enhanced by providing a backup in the form of battery or utility grid so as to meet the continuous demand irrespective of weather conditions.

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