Solar Water Pumping System Employing ZETA Converter and BLDC Motor

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Abstract: **Solar energy is an important renewable resource which is abundant in nature and free of running cost though its installation cost is higher. Trapped solar energy is used to run motors for different applications. Motors used for applications are DC motors, induction motors or Brushless dc (BLDC) motors of which BLDC motors are more advantageous. This paper deals with the utilization of a ZETA converter in solar PV array based water pumping as an intermediate DC-DC converter between a solar PV array and a voltage source inverter (VSI) in order to achieve the maximum efficiency of the solar PV array and the soft starting of the permanent magnet brushless DC (BLDC) motor by proper control. A Zeta converter is a fourth-order DC-DC converter made up of two inductors and two capacitors and capable of operating in either step-up or step-down mode. A BLDC motor is employed to drive a centrifugal type of water pump because its load characteristic is well matched to the maximum power locus of the PV generator. The transient, dynamic and steady state behaviors of the proposed solar PV array powered zeta converter fed BLDC motor driven water pumping system are evaluated under the rapid and slowly varying atmospheric conditions using the sim-power-system toolboxes of the MATLAB/Simulink environment.**

Keywords: **Brushless dc (BLDC) motor, zeta converter, solar PV array, voltage-source inverter (VSI), centrifugal pump, soft starting.**

I. INTRODUCTION

A continuous reduction in the cost of the solar photovoltaic (SPV) panels and the power electronics devices has encouraged the researchers and the industries to utilize the solar PV array generated power for different applications. The 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 use. Although several researches have been carried out in an area of SPV array fed water pumping, combining various DC-DC converters and motor drives, the zeta converter in association with a permanent magnet brushless DC (BLDC) motor is not explored precisely so far to develop such kind of system. However, the zeta converter has been used in some other SPV based applications. Due to a single switch, the zeta converter possesses very good conversion efficiency. Its utilization is initiated in this paper for soft starting of the BLDC motor coupled to a centrifugal pump for water pumping. A centrifugal pump is selected because of its availability in a wide range of heads and flow rates, simplicity, low maintenance requirements and cost effectiveness. The BLDC motor having the merits of high efficiency, high reliability, high ruggedness, low EMI problems and excellent performance over a wide range of speed is used to drive this centrifugal pump. The ratings of the solar PV array and the BLDC motor are selected such that the proposed system operates successfully under all the variations in the atmospheric conditions. The various performances are analyzed through the simulated results using MATLAB/Simulink environment. Simulated results verify the suitability of the proposed system for solar PV based water pumping. A zeta converter exhibits the following advantages over the conventional buck, boost, buck–boost converters, and Cuk converter when employed in SPV-based applications.

- Belonging to the family of buck-boost converters, the zeta converter can be operated either to increase or to decrease the output voltage.

- The above mentioned property also 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 zeta converter has a continuous output current. The output inductor makes the current continuous and ripples free.
- Reduces the complexity and probability of slow down the system response.

These merits of the zeta converter are favourable for proposed SPV array-fed water pumping system. In 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). 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. Although a Z-source inverter (ZSI) replaces dc–dc converter in, other schematic of Fig. 1 remains unchanged, promising high efficiency and low cost. Contrary to it, ZSI also necessitates phase current and dc link voltage sensing resulting in the complex control and increased cost. To overcome these problems and drawbacks, a simple, cost effective, and efficient water pumping system based on SPV array-fed BLDC motor is proposed, by modifying the existing topology (Fig. 1) as shown in Fig. 2. A zeta converter is utilized to extract the maximum power available from an 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.

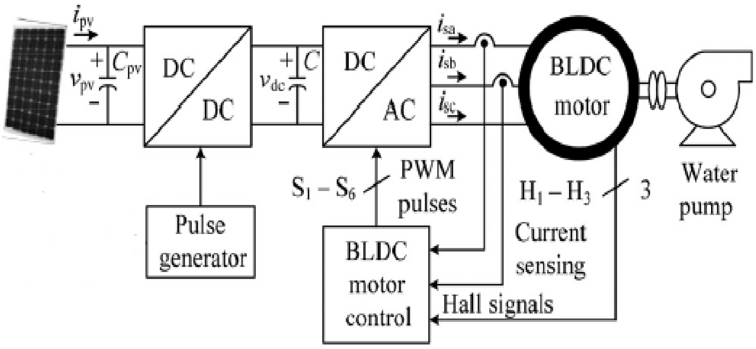


Fig.1. Existing Topology

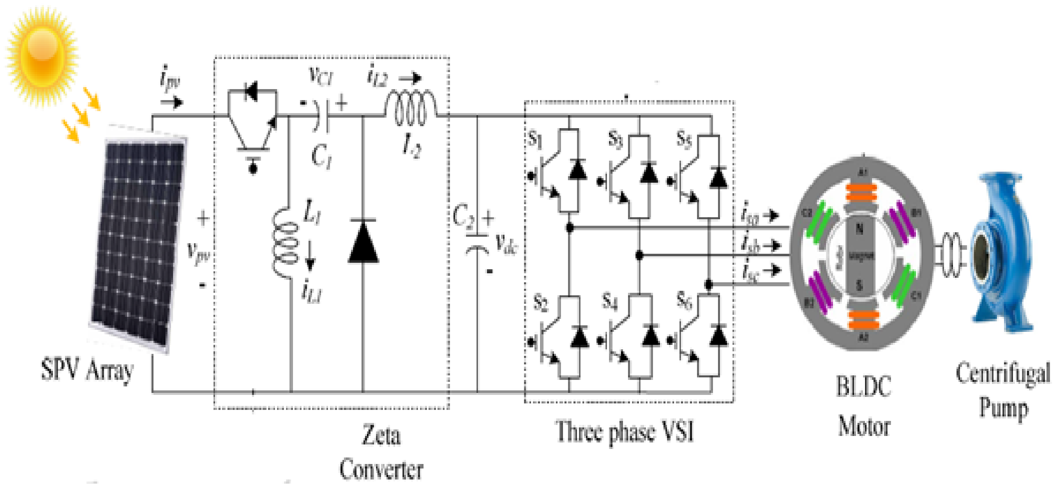


Fig.2. Proposed Topology

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. These features offer an increased simplicity of proposed system. The advantages and desirable features of both zeta converter and BLDC motor drive contribute to develop a simple, efficient, cost-effective, and reliable water pumping system based on solar PV energy. Simulation results using MATLAB/Simulink and experimental performances are examined to demonstrate the starting, dynamics, and steady-state behaviour of proposed water pumping system subjected to practical operating conditions. The SPV array and BLDC motor are designed such that proposed system always exhibits good performance regardless of solar irradiance level.

II. CONFIGURATION OF PROPOSED SYSTEM

The structure of proposed SPV array-fed BLDC motor driven water pumping system employing a zeta converter is shown in Fig. 2. The proposed system consists of (left to right) an SPV array, a zeta converter, a VSI, a BLDC motor, and a water pump. The BLDC motor has an inbuilt encoder. The pulse generator is used to operate the zeta converter.

III. OPERATION OF PROPOSED SYSTEM

The SPV array generates the electrical power demanded by the motor-pump. This electrical power is fed to the motor-pump via a zeta converter and a VSI. The SPV array appears as a power source for the zeta converter as shown in Fig. 2. Ideally, the same amount of power is transferred at the output of zeta converter which appears as an input source for the VSI. In practice, due to the various losses associated with a dc– dc converter, slightly less amount of power is transferred to feed the VSI. The pulse generator generates, switching pulses for insulated gate bipolar transistor (IGBT) switch of the zeta converter. Further, it generates actual switching pulse by comparing the duty cycle with a high-frequency carrier wave. In this way, the maximum power extraction and hence the efficiency optimization of the SPV array is accomplished. The VSI, converting dc output from a zeta converter into ac, feeds the BLDC motor to drive a water pump coupled to its shaft. The VSI is operated in fundamental frequency switching through an electronic commutation of BLDC motor assisted by its built-in encoder. The high frequency switching losses are thereby eliminated, contributing in an increased efficiency of proposed water pumping system.

IV. CONTROL OF PROPOSED SYSTEM

The proposed system is controlled by arduino nano controller and electronic commutation are discussed as follows.

A. Arduino Nano controller

The Arduino Nano is a small, complete and breadboard-friendly board based on the ATmega328 (Arduino Nano 3.x). It has more or less the same functionality of the Arduino Duemilanove, but in a different package. It lacks only a DC power jack, and works with a Mini-B USB cable instead of a standard one. The Arduino Nano can be powered via the Mini-B USB connection, 6-20V unregulated external power supply (pin 30), or 5V regulated external power supply (pin 27). The power source is automatically selected to the highest voltage source. The ATmega328 has 32 KB, (also with 2 KB used for the boot loader. The ATmega328 has 2 KB of SRAM and 1 KB of EEPROM. Each of the 14 digital pins on the Nano can be used as an input or output, using pin Mode(), digital Write(), and digital Read() functions. They operate at 5 volts. Each pin can provide or receive a maximum of 40 mA and has an internal pull-up resistor (disconnected by default) of 20-50 KOhms.

TABLE I: TECHNICAL SPECIFICATIONS OF ARDUINO NANO CONTROLLER

Microcontroller	ATmega328
Architecture	AVR
Operating Voltage	5 V
Flash Memory	32 KB of which 2 KB used by bootloader
SRAM	2 KB
Clock Speed	16 MHz
Analog I/O Pins	8

EEPROM	1 KB
DC Current per I/O Pins	40 mA (I/O Pins)
Input Voltage	7-12 V
Digital I/O Pins	22
PWM Output	6
Power Consumption	19 mA
PCB Size	18 x 45 mm
Weight	7 g
Product Code	A000005

B. Electronic commutation of BLDC motor

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 a 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. These three Hall-effect signals are produced by an inbuilt encoder according to the rotor position. A particular combination of Hall-effect signals is produced for each specific range of rotor position at an interval of 60◦. The generation of six switching states with the estimation of rotor position is tabularized in Table II. 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. Besides this, the electronic commutation provides fundamental frequency switching of the VSI; hence, losses associated with high-frequency PWM switching are eliminated. A motor power company make BLDC motor with inbuilt encoder is selected for proposed system.

TABLE II: HALL SIGNALS AND SWITCHING STATES OF BLDC MOTOR

θ (^{o})	Hall Signals			Switching States					
	H_a	H_b	H_c	S_1	S_2	S_3	S_4	S_5	S_6
NA	0	0	0	0	0	0	0	0	0
0-60	0	0	1	1	0	0	0	0	1
60-120	0	1	0	0	1	1	0	0	0
120-180	0	1	1	0	0	1	0	0	1
180-240	1	0	0	0	0	0	1	1	0
240-300	1	0	1	1	0	0	1	0	0
300-360	1	1	0	0	1	0	0	1	0
NA	1	1	1	0	0	0	0	0	0

V. SIMULATED RESULTS AND PERFORMANCE ANALYSIS

The performance of the proposed solar PV powered zeta converter fed VSI-BLDC motor-pump system is simulated in the MATLAB/Simulink environment using the Sim-power-system toolbox. To elaborate the dynamic performance of the proposed system, the solar insolation level is varied. The performances are evaluated using the simulated results as shown in Figures. 4-6. These results verify the satisfactory performance of the proposed system even under the rapid and slow change in weather condition.

A. Performance of SPV Array

A solar PV array of 1.5 kW peak power capacity, somewhat more than required by the motor, is selected so that the performance of the system is not affected by the losses associated with the converters and the motor. The parameters of the solar PV array are estimated at the standard solar insolation level of 1000 W/m^2. Voltage of the solar PV array at MPP is selected in view of the DC voltage rating of the BLDC motor same as the DC link voltage of the VSI.

B. Performance of Zeta Converter

The steady-state performance of zeta converter at 1000 W/m^2. The input inductor current i_{L1}, intermediate capacitor voltage V_{c1}, output inductor current i_{L2}, voltage stress on IGBT switch V_{SW}, current stress on IGBT switch I_{SW}, blocking voltage of the diode V_D, current through diode i_D and dc-link voltage V_{dc} are presented. The zeta 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 i_{L1}, V_{c1}, i_{L2}, and V_{dc}. The zeta converter automatically changes its mode of operation from buck mode to boost mode and vice-versa according to the irradiance level to optimize the output power of SPV array. A small amount of ripples in the zeta converter variables are observed caused by permitting the ripples up to an extent to optimize the size of the components.

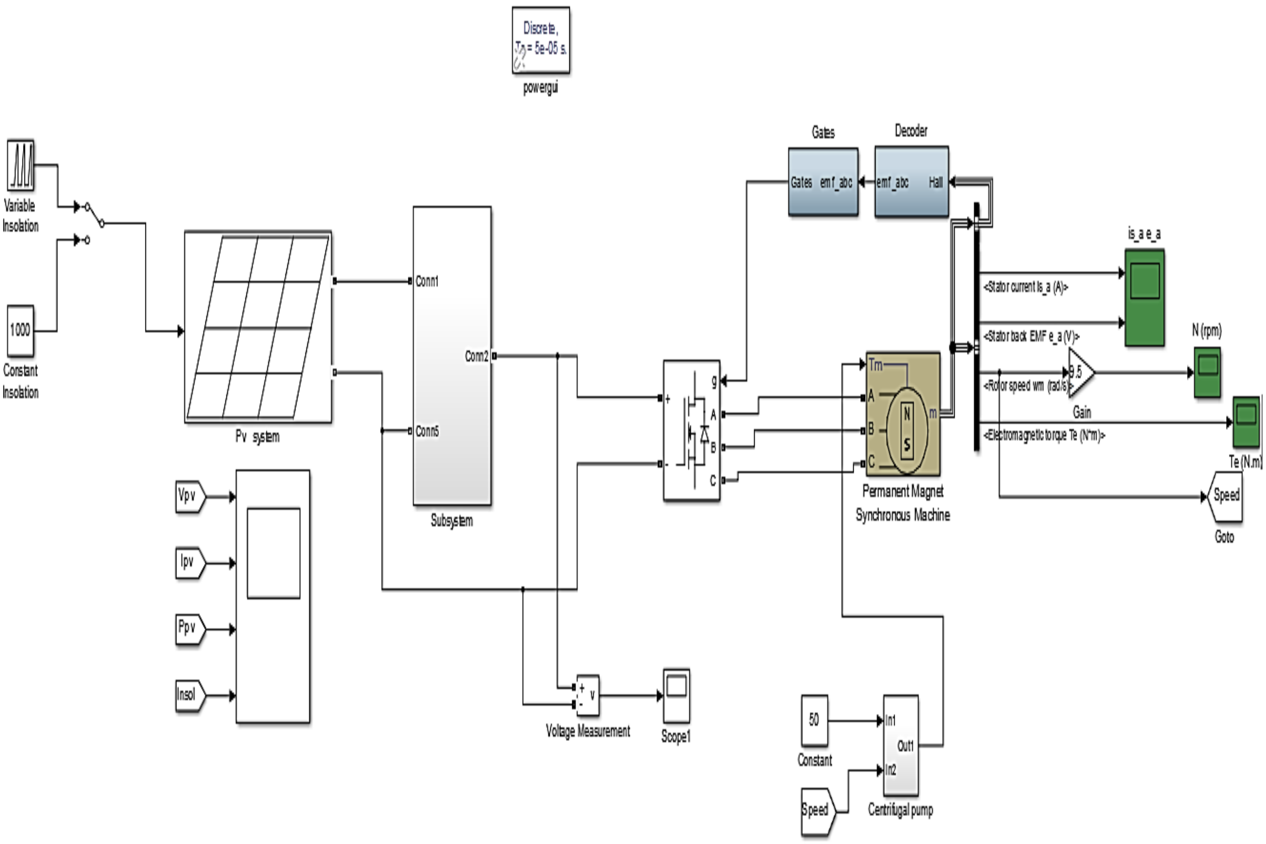


FIGURE 3. SIMULATION DIAGRAM FOR PROPOSED SPV-ZETA CONVERTER-FED BLDC MOTOR DRIVE FOR WATER PUMP

C. Performance of BLDC Motor-Pump

As the solar insolation level alters, the various BLDC motor–pump indices such as the back EMF, e_a, the stator current, i_{sa}, the speed, N, the electro-magnetic torque developed, T_e and the load torque, T_L vary in proportion to the solar insolation level. Two important facts are observed from the simulated results. First, the stator current, i_{sa} at the starting is controlled such that it takes time to reach its steady state value and hence the BLDC motor has a soft starting. Second, the BLDC motor develops the electromagnetic torque, T_e equal to the torque required to drive the pump, T_L under all variations in solar insolation level which manifest the stable operation of the proposed system regardless of the weather condition. However, a small pulsation in T_e results from the electronic commutation of the BLDC motor. Besides these, the BLDC motor attains a speed higher than 1100 rpm, a minimum required speed to pump the water, regardless of the solar insolation level.

D. Performance of BLDC Motor–Pump at 1000 W/m2

The starting and steady state behaviors of the BLDC motor–pump at the standard solar insolation level of 1000 W/m^2 are shown in Fig. 6. All the motor indices increase and reach their rated values under steady state condition. Soft starting along with the stable operation of the motor–pump is observed and hence the successful operation of the proposed system is verified.

E. Performance of BLDC Motor–Pump at 800 W/m2

The satisfactory performance of the BLDC motor–pump is verified at the minimum solar insolation level of 800 W/m^2 also as shown in Fig. 6. The BLDC motor attains a higher speed than 1100 rpm, a minimum speed required to pump the water, under this minimum solar insolation level also. Moreover, the soft starting and stable operation of the BLDC motor–pump contribute to the successful operation of the proposed system.

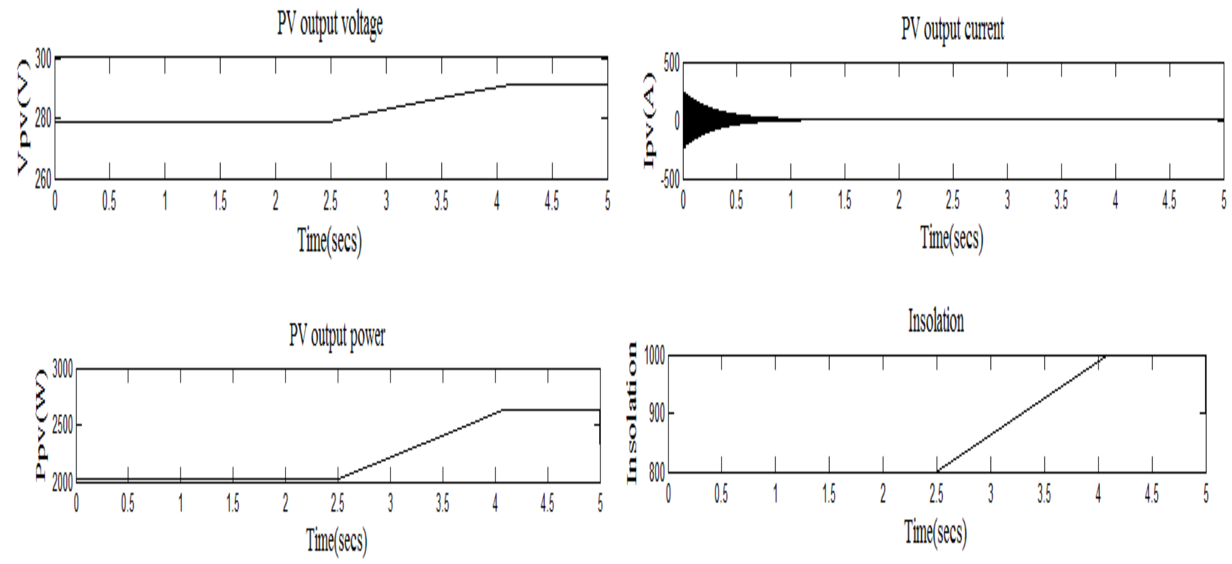


FIGURE 4. PERFORMANCES OF SPV ARRAY

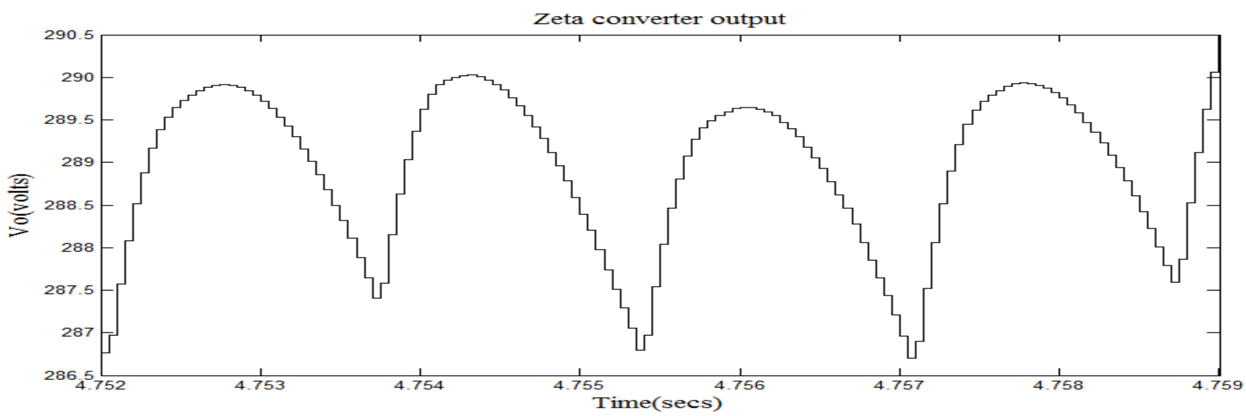
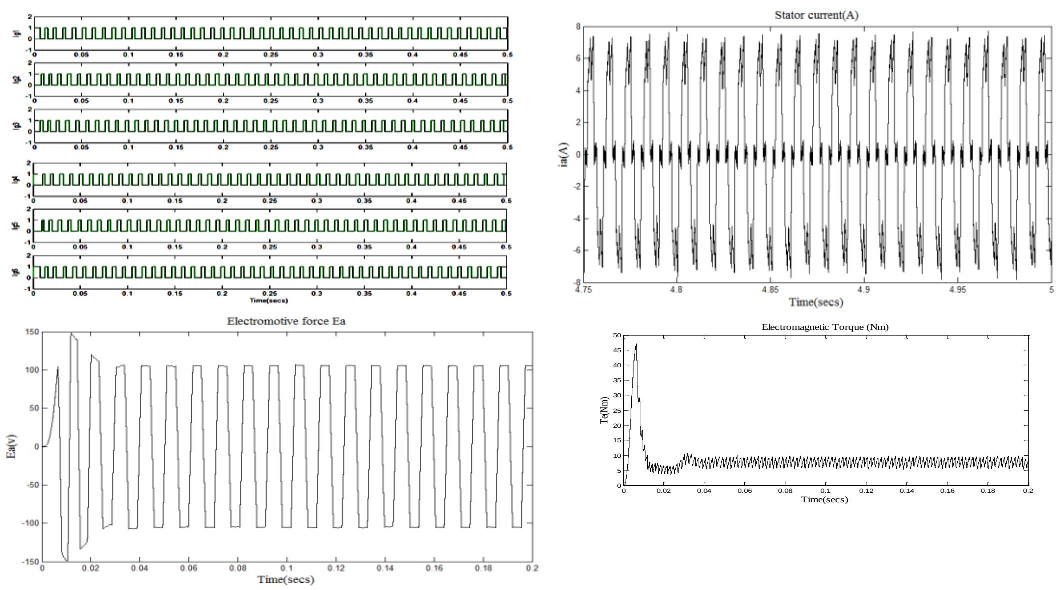


FIGURE 5. PERFORMANCE OF ZETA CONVERTER



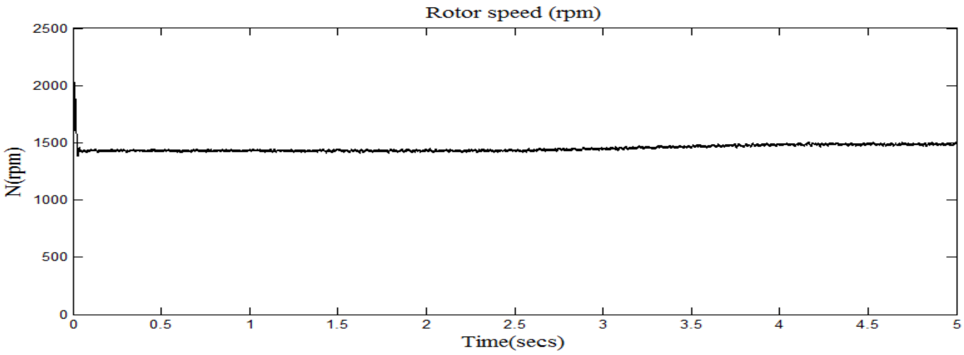


FIGURE 6. PERFORMANCES OF BLDC MOTOR-PUMP

VI. HARDWARE VALIDATION OF PROPOSED SYSTEM

The various performances of SPV array, zeta converter, and BLDC motor-pump are validated on a developed prototype of the proposed system, which is presented in Fig. 7. The system constitutes an SPV array, zeta converter, arduino nano controller (ATmega 328), BLDC motor. To provide the isolation between controller and gate drivers, the optocouplers (6N136) are used.

FIGURE 7. PHOTOGRAPH OF A DEVELOPED PROTOTYPE OF THE PROPOSED SYSTEM.

The performance of developed system is tested for solar irradiance level varying from 800 to 1000 W/m^2. A tracking efficiency for both irradiance levels is observed more than 99%.

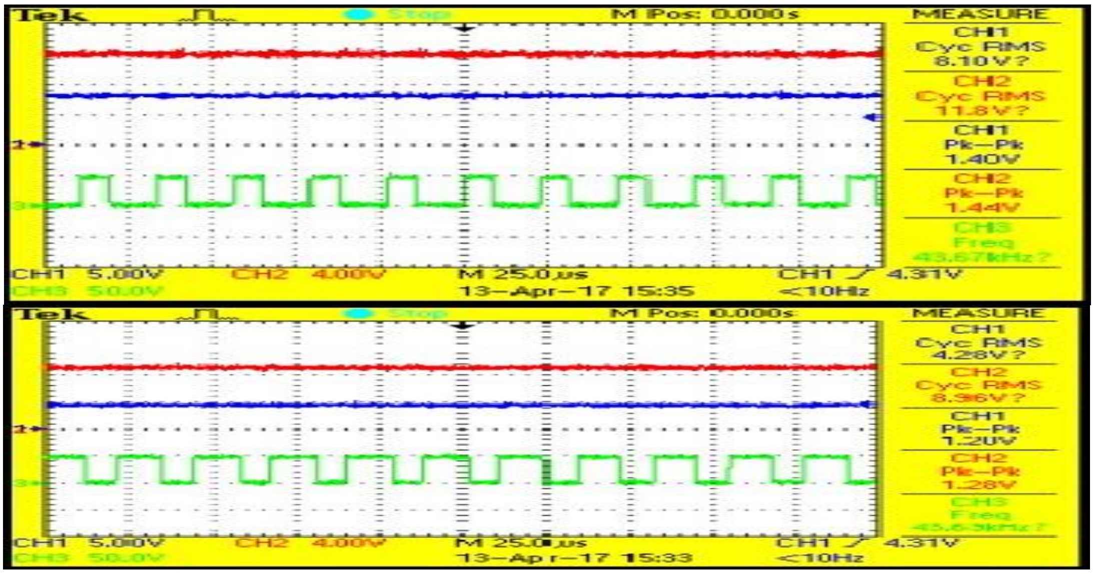


FIGURE 8. WAVEFORMS OF INPUT VOLTAGE, OUTPUT VOLTAGE AND PWM PULSES FOR VARIOUS DUTY RATIO.

The recorded waveforms of various duty ratio D are shown in Fig. 8. The operation of zeta converter in boost mode are observed at D = 0.66 and 0.33. In both the duty ratio the output voltage increased that is the zeta converter operated in boost mode and very good efficiency is obtained to run the BLDC motor.

VII. CONCLUSION

The SPV Array fed zeta converter based BLDC motor driven water pump has been proposed and its suitability has been demonstrated by analyzing its various performance indices using MATLAB based simulation study. A simple, efficient and economical method for speed control of BLDC motor has been suggested, which has offered absolute elimination of current sensing elements. The proper selection of SPV array has made the zeta converter capable of tracking MPP irrespective of weather conditions. An optimum design of the zeta converter has been presented. The safe starting of brushless DC motor has been achieved without any additional control. The desired performance of proposed system even at 20% of standard solar irradiance has justified its suitability for solar PV based water pumping.

REFERENCES

[1] M. Uno and A. Kukita, "Single-switch voltage equalizer using multistacked buck–boost converters for partially-shaded photovoltaic modules," IEEE Trans. Power Electron., vol. 30, no. 6, pp. 3091–3105, Jun. 2015

[2] R. Arulmurugan and N. Suthanthiravanitha, "Model and design of a fuzzy-based Hopfield NN tracking controller for standalone PV applications," Elect. Power Syst. Res., vol. 120, pp. 184–193, Mar. 2015.

[3] S. Satapathy, K. M. Dash, and B. C. Babu, "Variable step size MPPT algorithm for photo voltaic array using zeta converter—A comparative analysis," in Proc. Students Conf. Eng. Syst. (SCES), Apr. 12–14, 2013, pp. 1–6.

[4] R. Kumar and B. Singh, "BLDC motor driven solar PV array fed water pumping system employing zeta converter," in Proc. 6th IEEE India Int. Conf. Power Electron. (IICPE), Dec. 8–10, 2014, pp. 1–6.

[5] Singh, V. Bist, A. Chandra, and K. Al-Haddad, "Power factor correction in bridgeless-Luo converter-fed BLDC motor drive," IEEE Trans. Ind. Appl., vol. 51, no. 2, pp. 1179–1188, Mar./Apr. 2015.

[6] Singh and V. Bist, "Power quality improvements in a zeta converter for brushless dc motor drives," IET Sci. Meas. Technol., vol. 9, no. 3, pp. 351–361, May 2015.

[7] R. F. Coelho, W. M. dos Santos, and D. C. Martins, "Influence of power converters on PV maximum power point tracking efficiency," in Proc. 10th IEEE/IAS Int. Conf. Ind. Appl. (INDUSCON), Nov. 5–7, 2012,pp. 1–8.

[8] M. A. Elgendy, B. Zahawi, and D. J. Atkinson, "Assessment of the incremental conductance maximum power point tracking algorithm," IEEE Trans. Sustain. Energy, vol. 4, no. 1, pp. 108–117, Jan. 2013.

[9] M. Sitbon, S. Schacham, and A. Kuperman, "Disturbance observer based voltage regulation of current-mode-boost converter-interfaced photovoltaic generator," IEEE Trans. Ind. Electron., vol. 62, no. 9, pp. 5776– 5785, Sep. 2015.

[10] R. Kumar and B. Singh, "Solar PV array fed Cuk converter-VSI controlled BLDC motor drive for water pumping," 6th IEEE Power India Int. Conf. (PIICON), 5-7 Dec. 2014, pp. 1-7.

[11] M. A. Elgendy, B. Zahawi and D. J. Atkinson, "Assessment of the Incremental Conductance Maximum Power Point Tracking Algorithm," IEEE Trans. Sustain. Energy, vol.4, no.1, pp.108-117, Jan. 2013.

[12] J.V. Mapurunga Caracas, G. De Carvalho Farias, L.F. Moreira Teixeira and L.A. De Souza Ribeiro, "Implementation of a High-Efficiency, High-Lifetime, and Low-Cost Converter for an Autonomous Photovoltaic Water Pumping System," IEEE Trans. Ind. Appl., vol. 50, no. 1, pp. 631-641, Jan.-Feb. 2014.