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Solar Powered Water Pumping System Using BLDC Motor and Zeta Converter

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ABSTRACT: This paper proposes a simple, cost effective and efficient brushless DC (BLDC) motor drive for solar photovoltaic (SPV) array fed water pumping system. A zeta converter is utilized in order to extract the maximum available power from the SPV array. The proposed control algorithm eliminates phase current sensors and adapts a fundamental frequency switching of the voltage source inverter (VSI), thus avoiding the power losses due to high frequency switching. No additional control or circuitry is used for speed control of the BLDC motor. The speed is controlled through a variable DC link voltage of VSI. An appropriate control of zeta converter through the proportionate integral maximum power point tracking (PI-MPPT) algorithm offers soft starting of the BLDC motor. The proposed water pumping system is designed and modelled such that the performance is not affected under dynamic conditions. The suitability of proposed system at practical operating conditions is demonstrated through simulation results using MATLAB/ Simulink followed by an experimental validation.

KEYWORDS: BLDC motor, SPV array, Water pump, Zeta converter, VSI, PI-MPPT.

I. INTRODUCTION

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 is receiving wide attention nowadays 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. Moreover, a topology of SPV array fed BLDC motor driven water pump with zeta 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 zeta 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 zeta converter exhibits following advantages over the conventional buck, boost, buck-boost converters and Cuk converter when employed in SPV based applications.

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- Belonging to a family of buck-boost converters, the zeta 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 zeta converter has a continuous output current. The output inductor makes the current continuous and ripple free.
- Although consisting of same number of components as a Cuk converter the zeta 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 zeta converter are favourable for proposed SPV array fed water pumping system. An PROPORTIONATE INTEGRAL (PI) MPPT algorithm is used to operate the zeta converter such that SPV array always operates at its MPP.

The existing literature exploring SPV array based SRM motor driven water pump is based on a configuration shown in Fig. 1. A DC-DC converter is used for MPPT of a SPV array as usual. 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. However, a ZETA converter (ZSI) used as DC-DC converter, capable 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.

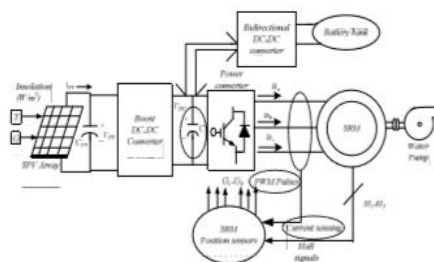


Fig.1. Conventional SPV+ battery fed SRM driven water pumping system [23].

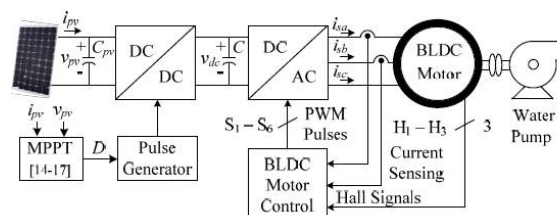


Fig. 2 Conventional SPV fed BLDC motor driven water pumping system .

water pumping system based on SPV array fed BLDC motor is proposed, by modifying the existing topology (Fig. 1) to as shown in Fig. 2. A zeta converter is utilized in order to extract the maximum power available from a SPV array, soft

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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 sacrificing its performance. The speed of BLDC motor is controlled, without any additional control, through a variable DC link voltage of VSI. Moreover, a soft starting of BLDC motor is achieved by proper initialization of MPPT algorithm of SPV array. 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 behavior 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) a 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. A step by step operation of proposed system is elaborated in the following section in detail.

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, through PI-MPPT algorithm, switching pulses for IGBT (Insulated Gate Bipolar Transistor) switch of the zeta converter. The PI-MPPT algorithm uses voltage and current as feedback from SPV array and generates an optimum value of duty cycle. 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. DESIGN OF PROPOSED SYSTEM

Various operating stages shown in Fig. 2, are properly designed in order to develop an effective water pumping system, capable of operating under uncertain conditions. A BLDC motor of 2.89 kW power rating and a SPV array of 3.4 kW peak power capacity under standard test conditions (STC) are selected to design the proposed system. The detailed design of various stages such as SPV array, zeta converter and water pump are described as follows.

A. Design of SPV Array

As per above discussion, the practical converters are associated with various power losses. In addition, the

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performance of BLDC motor-pump is influenced by associated mechanical and electrical losses. To compensate these losses, the size of SPV array is selected with slightly more peak power capacity to ensure the satisfactory operation regardless of power losses. Therefore, the SPV array of peak power capacity of $P_{mpp} = 3.4$ kW under STC (STC: 1000W/m², 25°C, AM 1.5), slightly more than demanded by the motor-pump is selected and its parameters are designed accordingly. Solar World make Sun module® Plus SW 280mono [24] SPV module is selected to design the SPV array of an appropriate size. Electrical specifications of this module are listed in Table I and numbers of modules required to connect in series/parallel are estimated by selecting the voltage of SPV array at MPP under STC as, $V_{mpp} = 187.2$ V.

The current of SPV array at MPP, I_{mpp} is estimated as,

$$I_{mpp} = P_{mpp} / V_{mpp} = 3400 / 187.2 = 18.16 \text{ A} \quad (1)$$

TABLE I
SPECIFICATIONS OF SUNMODULE® PLUS SW
280MONO SPV MODULE

Peak power, P_m (Watt)	280
Open circuit voltage, V_o (V)	39.5
Voltage at MPP, V_m (V)	31.2
Short circuit current, I_s (A)	9.71
Current at MPP, I_m (A)	9.07
Number of cells connected in series, N_{ss}	60

The numbers of modules required to connect in series are as,

$$N_s = V_{mpp} / V_m = 187.2 / 31.2 = 6$$

The numbers of modules required to connect in parallel are as,

$$N_p = I_{mpp} / I_m = 18.16 / 9.07 = 2$$

Connecting 6 modules in series, having 2 strings in parallel, a SPV array of required size is designed for the proposed system and its data are given in Appendix A.

B. Design of Zeta Converter

The zeta converter is the next stage to the SPV array. Its design consists of an estimation of various components such as input inductor, L_1 , output inductor, L_2 and intermediate capacitor, C_1 . These components are designed such that the zeta 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 zeta converter.

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

where V_{dc} is an average value of output voltage of the zeta converter (DC link voltage of VSI) equal to the DC voltage rating of the BLDC motor.

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V. CONTROL OF PROPOSED SYSTEM

The proposed system is controlled in two stages. These two control techniques, viz. MPPT and electronic commutation are discussed as follows.

A. PI-MPPT Algorithm

An efficient and commonly used PI-MPPT technique in various SPV array based applications is utilized in order to optimize the power available from a SPV array and to facilitate a soft starting of BLDC motor. This technique allows perturbation in either the SPV array voltage or the duty cycle. The former calls for a PI (Proportional-Integral) controller to generate a duty cycle for the zeta converter, which increases the complexity. Hence, the direct duty cycle control is adapted in this work. The PI-MPPT algorithm determines the direction of perturbation based on the slope of Ppv-vpv curve, shown in Fig. 3. As shown in Fig. 3, the slope is zero at MPP, positive on the left and negative on the right of MPP

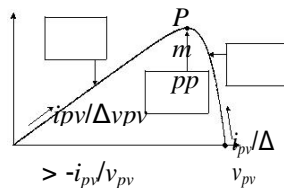


Fig.3

Thus, based on the relation between proportional integral and instantaneous conductance, the controller decides the direction of perturbation as shown in Fig.3, and increases/decreases the duty cycle accordingly. For instance, on the right of MPP, the duty cycle is increased with a fixed perturbation size until the direction reverses. Ideally, the perturbation stops once the operating point reaches the MPP.

Rotor position $\theta(^{\circ})$	Hall Signals			Switching States					
	H_3	H_2	H_1	S_1	S_2	S_3	S_4	S_5	S_6
NA	0	0	0	0	0	0	0	0	0
0-60	1	0	1	1	0	0	1	0	0
60-120	0	0	1	1	0	0	0	0	1
120-180	0	1	1	0	0	1	0	0	1
180-240	0	1	0	0	1	1	0	0	0
240-300	1	1	0	0	1	0	0	1	0
300-360	1	0	0	0	0	0	1	1	0
NA	1	1	1	0	0	0	0	0	0

However, in practice, operating point oscillates around the MPP. As the perturbation size reduces, the controller takes more time to track the MPP of SPV array. An intellectual agreement between the tracking time and the perturbation size is held to fulfill the objectives of MPPT and soft starting of BLDC motor. In order to achieve soft starting, the initial value of duty cycle is set as zero. In addition, an optimum value of perturbation size ($\Delta = 0.001$) is selected, which contributes to soft starting and also minimizes oscillations around the MPP

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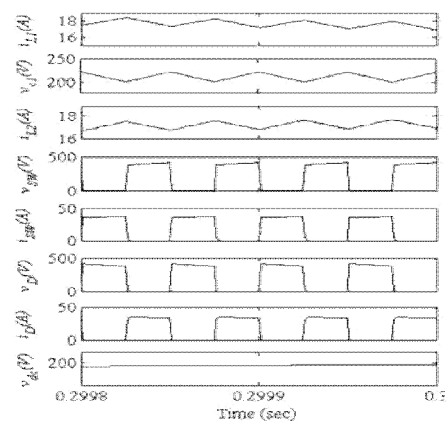
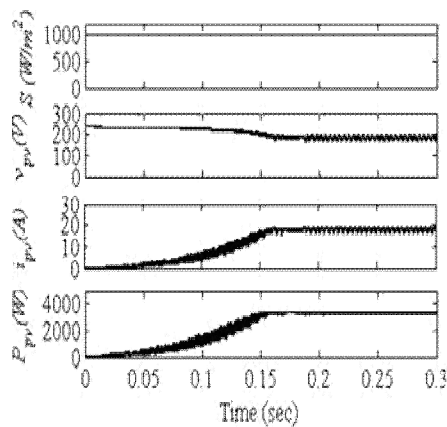
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VI. SIMULATED PERFORMANCE OF PROPOSED SYSTEM

Performance evaluation of proposed SPV array fed BLDC motor driven water pump employing a zeta converter is carried out using simulated results. The proposed system is designed, modelled and simulated considering the random and instant variations in solar irradiance level and its suitability is demonstrated by testing the starting, steady state and dynamic behavior as illustrated in Figs. 4-5. To demonstrate the suitability of the system under dynamic condition, solar irradiance level is instantly reduced from 600 W/m² to 200 W/m² and then increased to 1000 W/m².

A. PERFORMANCE OF SPV ARRAY

The MPP is properly tracked. The tracking time is intentionally increased at the starting by adapting a low value of perturbation size ($\Delta D = 0.001$) in order to achieve the soft starting of BLDC motor. The low value of D causes the reduced rate of rise of DC link voltage of VSI resulting in a smooth and soft starting of the motor. However, a negligible tracking time is required under the dynamic variation in irradiance level.

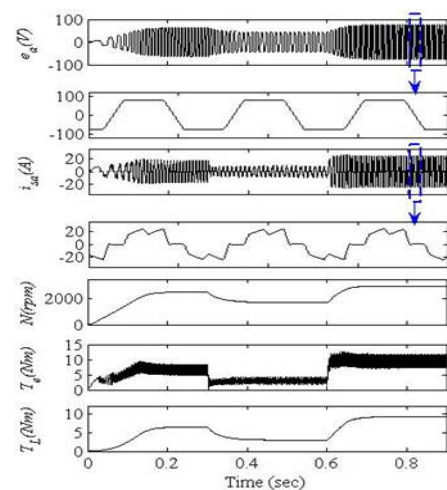
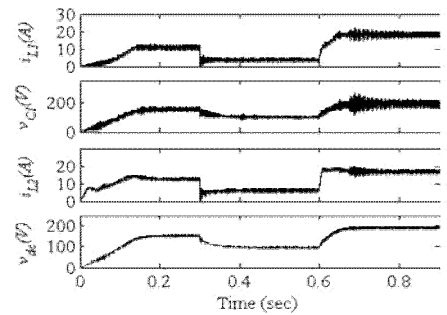
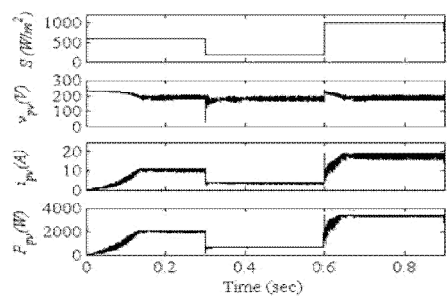
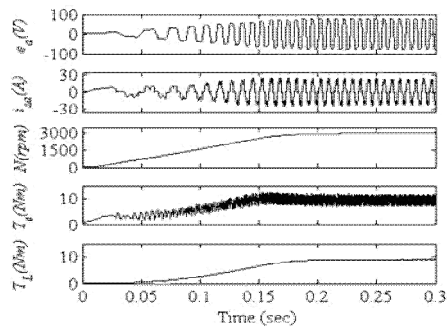


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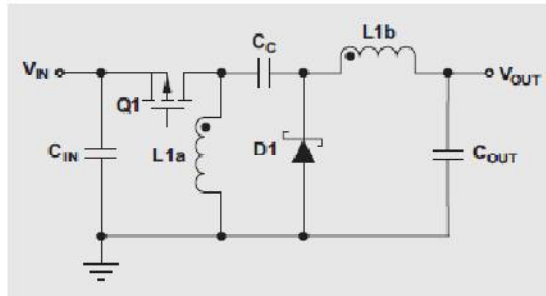
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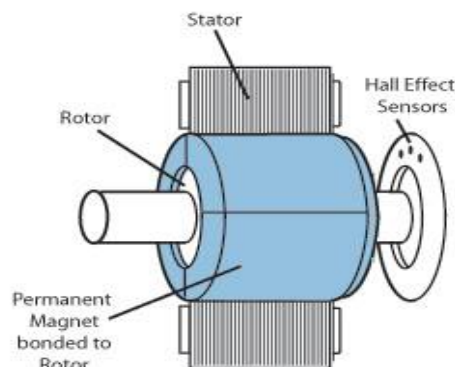
B. Performance of Zeta Converter



The steady state performance of zeta converter at 1000 W/m². 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 in order 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 in order to optimize the size of the components.

C. Performance of BLDC Motor-Pump

The starting and steady state behaviors of the BLDC motor-pump at 1000 W/m². All the motor 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 reach their corresponding rated values under steady state condition. The soft starting along with the stable operation of motor-pump is observed and hence the successful operation of proposed system is verified. However, a small pulsation in T_e results in due to the electronic commutation of the BLDC motor. As the solar irradiance level alters, all the BLDC motor – pump indices vary in proportion to the solar irradiance level. The BLDC motor always attains a higher speed than 1100 rpm, a minimum speed required to pump the water at a minimum solar irradiance level of 200 W/m². Performance of BLDC motor-pump is not deteriorated by weather conditions and it pumps the water successfully.



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VII. CONCLUSION

The SPV array- zeta converter fed VSI-BLDC motor-pump has been proposed and its suitability has been demonstrated through simulated results and experimental validation. The proposed system has been designed and modelled appropriately to accomplish the desired objectives and validated to examine various performances under starting, dynamic and steady state conditions. The performance evaluation has justified the combination of zeta converter and BLDC motor for SPV array based water pumping. The system under study has shown various desired functions such as MPP extraction of the SPV array, soft starting of BLDC motor, fundamental frequency switching of VSI resulting in a reduced switching losses, speed control of BLDC motor without any additional control and an elimination of phase current and DC link voltage sensing, resulting in the reduced cost and complexity. The proposed system has operated successfully even under minimum solar irradiance.

APPLICATIONS

BLDC motors are used in water pumping system, electric and hybrid vehicles, refrigeration system, air conditioning systems and industrial applications.

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