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ZETA CONVERTER BASED SIMULATION MODEL FOR BLDC MOTOR FED WATER PUMPING SYSTEM

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ABSTRACT

The main objective of this research work is to develop a simple simulation model, cost effective and efficient brushless DC (BLDC) motor drive for solar photovoltaic (SPV) array combined with wind energy fed water pumping system. The maximum sun irradiance and Wind energy is utilized according to the availability. The speed of the BLDC motor is controlled through a variable DC link voltage of VSI. An appropriate control of zeta converter through maximum power point tracking (P&O MPPT) algorithm offers soft starting of the BLDC motor. In this Maximum power point tracking is achieved by using Perturbation and Observation (P&O) method, also known as hill climbing method, is popular and most commonly used in practice because of its simplicity in algorithm and ease of implementation. The voltage stress can be reduced by employing zeta converter. Power factor can be improved and fourth order harmonics can be reduced. The proposed water pumping system is designed and modeled 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, P&O-MPPT

I. INTRODUCTION

Renewable energy sources in recent years brought a drastic change in few decades in which solar energy and wind energy proved to be a viable source which is used for various applications such as emergency lighting, water heaters, smart grid, and industrial application and so on. The sources of renewable such as wind and solar are cost effective and the availability is abundance. The water pumping, a standalone application of the SPV array generated electricity is receiving wide attention now days for irrigation in the fields, household applications and industrial use. Lot of research work has been carried out in the field of Computer Applications to Electrical Engineering [1-26]. This paper brings a new dimension of utilizing both solar and wind energy. Although there are several researches carried out in solar and wind using DC-DC converter for DC motors this paper exhibits combined renewable energy sources employing zeta converter topology fed water pumping in association with a permanent magnet brushless DC (BLDC) motor. This combined energy source 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 combined with wind energy fed BLDC motor driven water pump with zeta converter has been reported and its

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significance has been presented with experimental validation. This paper mainly concentrates on solar array than wind energy but the utilization of renewable sources can still move on with better efficiency. The merit of BLDC motor contribute soft switching which is challenging task .The 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 [27-40]. The zeta converter exhibits following advantages over other converter topologies which include buck, boost, buck-boost converters and Cuk converter when employed in SPV based applications.The zeta converter has been proved for reduced voltage stress and also improves the power factor with Total harmonic reduction. Zeta converter may be operated to increase the output voltage or decrease the output voltage. The property of increasing or decreasing the output voltage offers a boundless region for maximum power point tracking.

These merits of the zeta converter such as power factor improvement, reduced voltage stress are favorable for proposed SPV array fed water pumping system. An Perturbation and Observation (P&O) MPPT algorithm is used to operate the zeta converter such that SPV array always operates at its maximum power point even though the irradiance changes. The existing method explore SPV array based DC motor driven water pump is based on a configuration shown in Fig. 1. A DC-DC converter is used for tracking the maximum irradiance level of the SPV array. The two phase currents are sensed along with Hall signals feedback and this is used to control the BLDC motor, which results in increased cost. The control scheme used to control the speed of BLDC motor includes complexity and increased cost which is not appreciable.

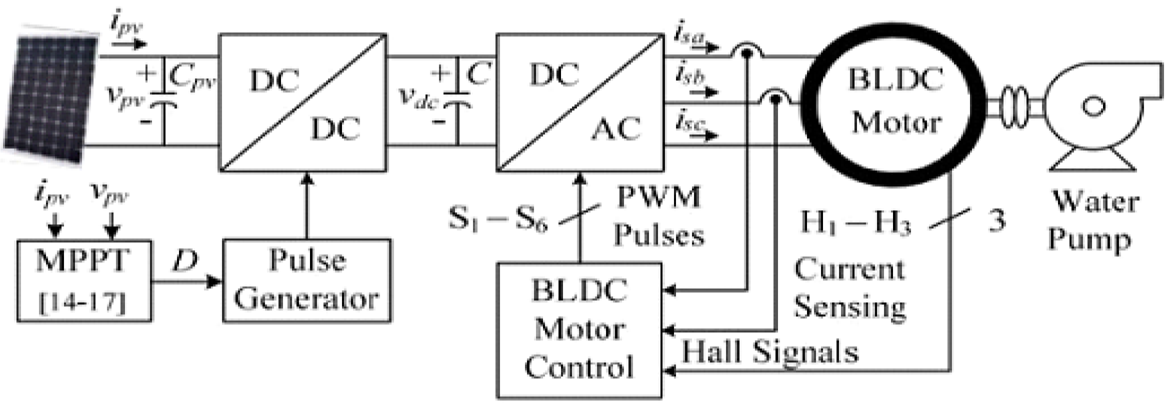

Fig. 1 Conventional SPV fed BLDC motor driven water pumping system.

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. Employing a Z-source inverter (ZSI) which replaces DC-DC converter, results in 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 caused by voltage stress in existing methodology and drawbacks of the control scheme employed to control the speed of BLDC motor, a simple, cost-effective and efficient water pumping system based on SPV array combined with wind energy fed BLDC motor is proposed, by modifying the existing topology to as shown in Fig. 2. A zeta converter is utilized in order to extract the maximum power available from a PV array, soft starting and speed control of BLDC motor coupled to a water pump. The Zeta converter with a single switch, has very good efficiency and offers boundless region for MPPT. This Zeta converter is operated in continuous

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conduction and in Discontinuous conduction mode usually. Here the converter is operated in Continuous conduction mode resulting in a reduced voltage stress on its power devices and components. However, 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. Soft starting of BLDC motor is achieved by proper initialization of MPPT algorithm of SPV array. The steps taken for cost effective of the proposed system bring challenges by adding additional losses associated with VSI, BLDC such as electrical and mechanical losses includes .Moreover these losses are compensated by implementing mppt algorithm for peak power utility.

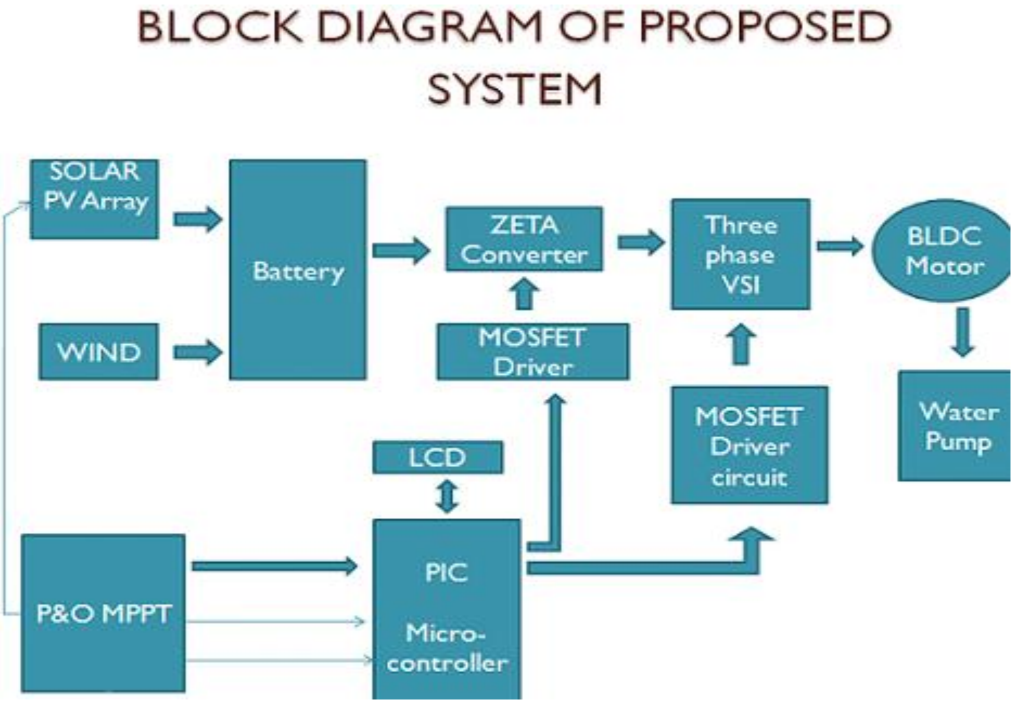

Fig. 2 ZETA Converter based BLDC motor driven water pumping system.

II. ZETA CONVERTER BASED BLDC MOTOR DRIVEN WATER PUMPING 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. 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 P&O-MPPT algorithm, switching pulses for IGBT (Insulated Gate Bipolar Transistor) switch of the zeta converter. The P&O-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.

A. Design of SPV Array

As per above discussion, the practical converters are associated with various power losses. In addition, the 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 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. SolarWorld make Sunmodule® *Plus SW 280 mono* 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,				
$I_{mpp} = P_{mpp}/V_{mpp} = 3400/187.2 = 18.16$ A ………. (1)				
	TABLE I			
SPECIFICATIONS OF SUNMODULE® PLUS SW 280 MONO 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,

$N_s = V_{mpp}/V_m = 187.2/31.2 = 6$ (2)

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

$N_p = I_{mpp}/I_m = 18.16/9.07 = 2$ (3)

Connecting 6 modules in series, having 2 strings in parallel, a SPV array of required size is designed for the proposed system.

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 which is estimated as,

$$D = \frac{V_{dc}}{V_{dc}+V_{mpp}} = 200/(200+187.2) = 0.52 \quad (4)$$

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.

An average current flowing through the DC link of the VSI, I_{dc} is estimated as,

$$I_{dc} = P_{mpp}/V_{dc} = 3400/200 = 17 \text{ A} \quad (5)$$

Then L_1, L_2 and C_1 are estimated as,

$$L_1 = \frac{DV_{mpp}}{f_{sw}I_{L1}} = \frac{0.52*187.2}{20000*18.16*0.06} = 4.5*10^{-3} \approx 5\text{mH} \quad (6)$$

$$L_2 = \frac{(1-D)V_{dc}}{f_{sw}\ I_{L2}} = \frac{(1-0.52)*200}{20000*17*0.06} = 4.7*10^{-3} \approx 5\text{mH} \quad (7)$$

$$C_1 = \frac{DI_{dc}}{F_{sw}V_{C1}} = \frac{0.52*17}{20000*200*0.1} = 22\mu F \quad (8)$$

where f_{sw} is the switching frequency of IGBT switch of the zeta converter; ΔI_{L1} is the amount of permitted ripple in the current flowing through L_1, same as $I_{L1} = I_{mpp}$; ΔI_{L2} is the amount of permitted ripple in the current flowing through L_2, same as $I_{L2} = I_{dc}$; ΔV_{C1} is permitted ripple in the voltage across C_1, same as $V_{C1} = V_{dc}$.

C. Estimation of DC Link Capacitor of VSI

A new design approach for estimation of DC link capacitor of the VSI is presented here. This approach is based on a fact that 6th harmonic component of the supply (AC) voltage is reflected on the DC side as a dominant harmonic in the three phase supply system [41-63]. Here, the fundamental frequencies of output voltage of the VSI are estimated corresponding to the rated speed and the minimum speed of BLDC motor essentially required to pump the water. These two frequencies are further used to estimate the values of their corresponding capacitors. Out of these two estimated capacitors, larger one is selected to assure a satisfactory operation of proposed system even under the minimum solar irradiance level. The fundamental output frequency of VSI corresponding to the rated speed of BLDC motor, ω_{rated} is estimated as,

$$\omega_{rated} = 2\pi f_{rated} = 2\pi \frac{N_{rated}\ P}{120} = 2\pi * \frac{3000*6}{120} = 942 \text{ rad/sec.} \quad (9$$

The fundamental output frequency of the VSI corresponding to the minimum speed of the BLDC motor essentially required to pump the water (N = 1100 rpm), ω_{min} is estimated as,

$$\omega_{min} = 2\pi f_{min} = 2\pi \frac{NP}{} = 2\pi * {}^{1100*6} = 345.57 \text{ rad/sec.} \quad (10)$$

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where f_{rated} and f_{min} are fundamental frequencies of output voltage of VSI corresponding to a rated speed and a minimum speed of BLDC motor essentially required to pump the water respectively, in Hz; N_{rated} is rated speed of the BLDC motor; P is a number of poles in the BLDC motor.

The value of DC link capacitor of VSI at ω_{rated} is as,

$$C_{2,rated} = \frac{I_{dc}}{6*\omega_{rated} * V_{dc}} = \frac{17}{6*942*200*0.1} = 150.4\ \mu F \quad (11)$$

Similarly, a value of DC link capacitor of VSI at ω_{min} is as,

$$C_{2,mi} = \frac{I_{dc}}{6*\omega_{min} * V_{dc}} = \frac{17}{6*345.57*200*0.1} = 410\ \mu F \quad (12)$$

where ΔV_{dc} is an amount of permitted ripple in voltage across DC link capacitor, C_2.
Finally, C_2 = 410 µF is selected to design the DC link capacitor.

D. Design of Water Pump

To estimate the proportionality constant, K for the selected

water pump, its power-speed characteristics is used as,

$$K = \frac{P}{\omega_r} = \frac{2.89*10^3}{(2\pi*3000/60)} = 9.32*10^{-5}$$

where P = 2.89 kW is rated power developed by the BLDC motor and ω_r is rated mechanical speed of the rotor (3000 rpm) in rad/sec.
A water pump with this data is selected for proposed system.

III. CONTROL OF BLDC MOTOR BASED WATER PUMPING SYSTEM

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

3.1 Perturb and Observe Algorithm

In this algorithm a slight perturbation is introduced by the MPPT system. Due to this perturbation, changes the power of the module. If the power increases due to the perturbation then the perturbation is continued in that

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direction. After the peak power is reached the power at the next instant decreases and hence after that the Perturbation reverses. When the steady state is reached the algorithm oscillates around the peak point. In order to keep the power variation small the perturbation size is kept very small. The algorithm is developed in such a manner that it sets a reference voltage of the module corresponding to the peak voltage of the module. A PI controller then acts moving the operating point of the module to that particular voltage level. It is observed that there some power loss due to this perturbation also it fails to track the power under fast varying atmospheric conditions. But still this algorithm is very popular and simple. This algorithm is selected and certain changes are made in the present work. The flow chart of the algorithm is shown in the Fig 3. 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 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 (ΔD = 0.001) is selected, which contributes to soft starting and also minimizes oscillations around the MPPT.

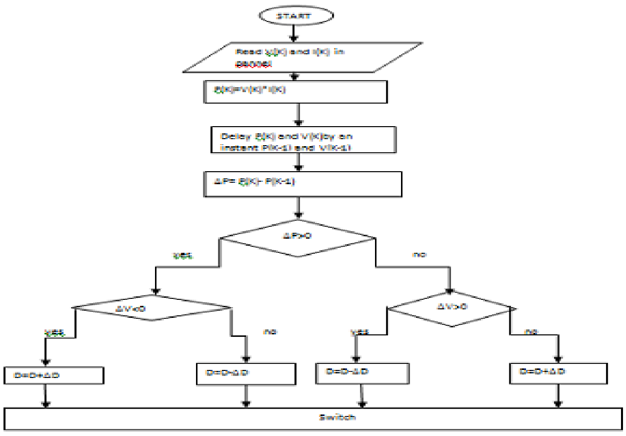

Fig 3 . Simulated Performance of Proposed System

3.2 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 centre 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 120º 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. TETRA 115TR9.2, a motor power company make BLDC motor with inbuilt encoder is selected for proposed system

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TABLE. II, SWITCHING STATES FOR ELECTRONIC COMMUTATION OF BLDC MOTOR

Rotor position θ(°)	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

IV RESULTS

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, modeled 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 estimated.

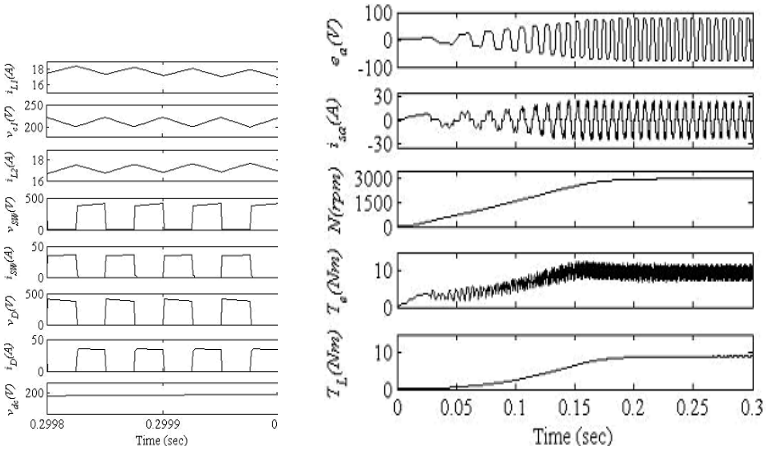

Fig.4 Starting and steady state performances of the proposed SPV array based Zeta converter fed BLDC motor drive for water pump (a) SPV array variables, (b) Zeta converter variables, and (c) BLDC motor-pump variables.

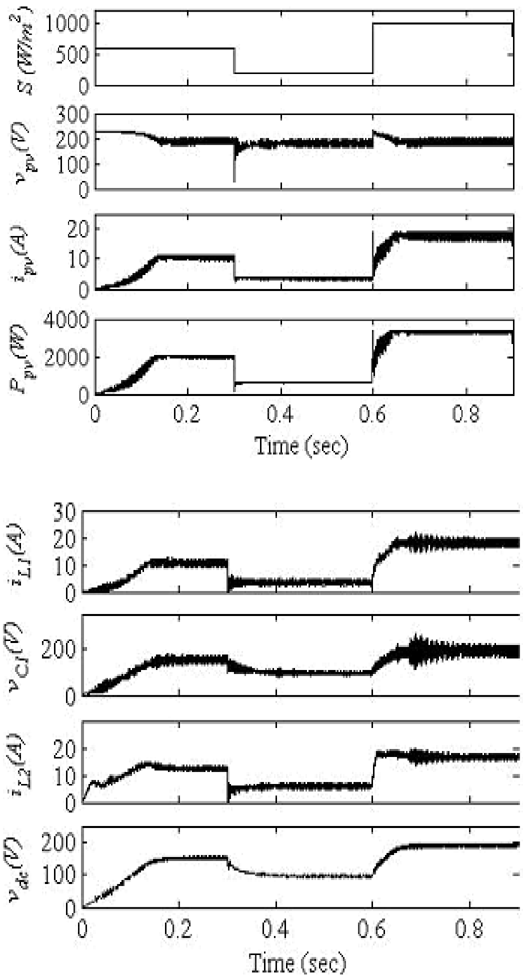

Fig. 5 Dynamic performances of the proposed SPV array based Zeta converter fed BLDC motor drive for water pump (a) SPV array variables, (b) Zeta converter variables

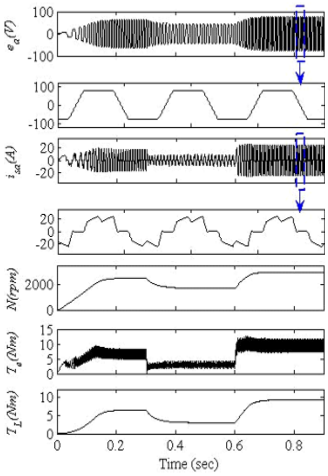

Fig. 5 Dynamic performances of the proposed SPV array based Zeta converter fed BLDC motor drive for water pump (c) BLDC motor-pump variables.

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 as shown in Fig. 5(c). The BLDC motor always attains a higher speed than 1100 rpm, a minimum speed required to pump the

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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. The performance of developed system is tested for solar irradiance level varying from 400 W/m2 to 1000 W/m2.

The recorded ppv-vpv and ipv-vpv characteristics shown in Figs. 6(a) and (b), respectively at 1000 W/m2 and 400 W/m2 verify excellent performance of MPPT. A tracking efficiency for both irradiance levels is observed more than 99% is shown below

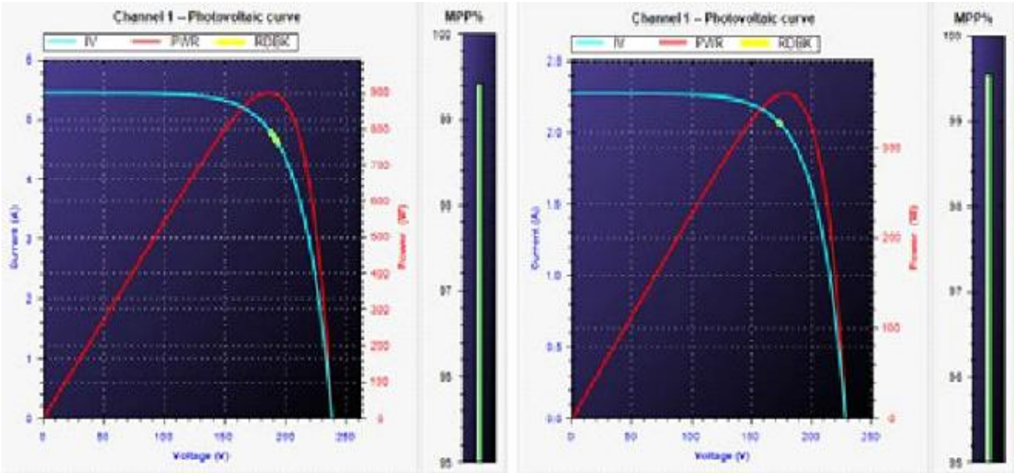

Fig. 6 (a) (b) MPPT performance at (a) 1000 W/m^2, (b) 400 W/m^2

V. CONCLUSIONS

The SPV array-zeta converter fed VSI-BLDC motor-pump has been proposed and its suitability has been demonstrated through validation. The proposed system has been designed and modeled appropriately to accomplish the desired objectives and validated to examine various performances under starting, dynamic and steady state conditions. The zeta converter quickly changes its mode of operation following the 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.

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