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Page Numbers:- 109 - 117

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Zeta Converter Fed BLDC Motor-Drive for Solar PV Array-based Water Pumping System using Fuzzy logic controller

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Abstract: The best alternative to the conventional energy sources is ever lasting solar energy it is one among the cheapest and widely used. This paper deals with the design and analysis of zeta converters, it has been used as intermediate between voltage source inverter (VSI) and solar PV array. MPPT technique is been used for gaining maximum efficiency from solar PV array for proper control of permanent magnet brushless DC (BLDC). Compared to other methods of MPPT technique, Fuzzy logic based MPPT technique is best used because it provides better results for randomly varying atmospheric conditions. BLDC motor has higher efficiency and noise less operation compared to induction motor. Maximum power loss of PV generator is well matched with the load characteristic of BLDC motor. Matlab based simulation is carried out for the different topology of the DC-DC converters and the results are analyzed and compared.

Keywords: Brushless dc (BLDC) motor, incremental conductance maximum power point tracking (INC-MPPT), solar photovoltaic (SPV) array, voltage-source inverter (VSI), water pump, zeta converter.

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 photo voltaic (SPV) generated electrical energy for various applications as far as possible. Water pumping, a standalone application of the SPV array generated electricity is receiving wide attention now days for irrigation in the fields, house hold 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 in. None the less, 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, and high torque/inertia ratio, improved cooling, low radio frequency interference and noise and requires practically no maintenance.

In this paper, various environmental conditions is considered for extracting maximum power from the PV array, we require MPPT technique for this process. Fuzzy based MPPT technique is proved the best by providing better results for varying weather conditions. BLDC motor is driven by inverter interface.

The existing literature exploring SPV array-based BLDC motor-driven water pump is based on a configuration shown in Fig.1. A dc–dc converter is used for MPPT of an SPV array as usual. Two phase currents are sensed along with Hall signals feedback for control of BLDC motor, resulting in an increased cost. 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-

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frequency PWM pulses, resulting in an increased switching loss and hence the reduced efficiency.

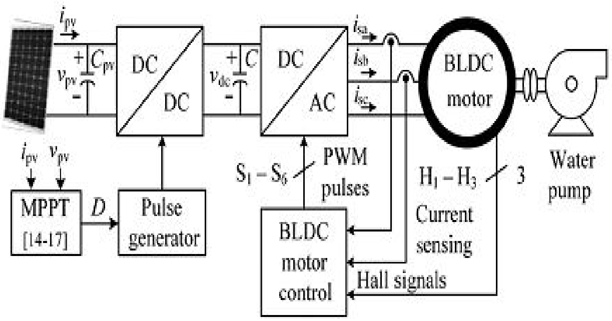

Fig.1. Conventional SPV-fed BLDC motor-driven water pumping system

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.3.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. A step-by-step operation of proposed system is elaborated in Section III 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 [23], slightly less amount of power is transferred to feed the VSI. The pulse generator generates, through INC-MPPT algorithm, switching pulses for insulated gate bipolar transistor (IGBT) switch of the zeta converter. The INC-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 there by eliminated, contributing in an increased efficiency of proposed water pumping system.

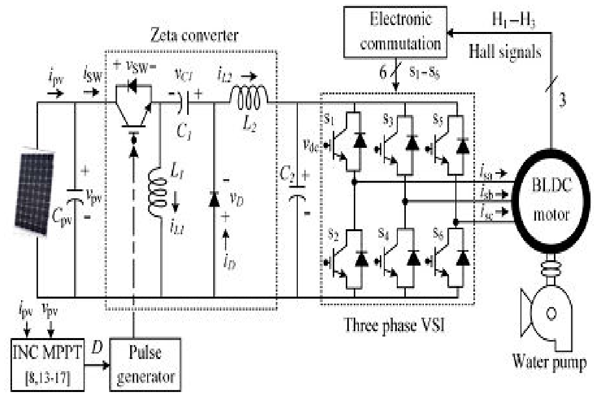

Fig.2. Conventional SPV-zeta converter-fed BLDC motor drive for water pump

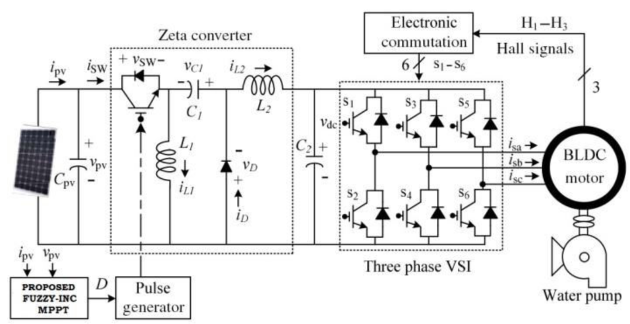

Fig.3. Proposed SPV-zeta converter-fed BLDC motor drive for water pump

IV. DESIGN OF PROPOSED SYSTEM

Various operating stages shown in Fig.3 are properly designed to develop an effective water pumping system, capable of operating under certain conditions. A BLDC motor of 2.89-kW power rating and an SPV array of 3.4-kW peak power capacity under standard test conditions (STC) are selected to design the proposed system. The detailed designs 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 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 regard less of power losses.

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Therefore, the SPV array of peak power capacity of P_{mpp}=3.4 kW under STC (STC: 1000 W/m^2, 25^{o}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 280 mono [24] SPV module is selected to design the SPV array of an appropriate size and number of modules required to connect in series/parallel are estimated by selecting the voltage of SPV array at MPP under STC as V_{mpp}= 187.2V.

The mathematical modeling of PV device is necessary to analyze the electronic converters that are used in building a entire PV generation module. As the manufactures provide set of data at different operating conditions that can be used to develop a mathematical model for the PV device. The process of mathematical modeling of PV device provides the initial step in obtaining the final model of PV generation system.

Single diode model

The PV cell modeled based on single diode will have current source in parallel with a reverse biased diode and with series/parallel internal resistances, as shown in Figure.3. The output current (I) can be written as

$$I = I_{PV} - I_o\left[exp\left(\frac{V + IR_s}{aV_T}\right) - 1\right] - \left(\frac{V + IR_s}{R_p}\right)$$

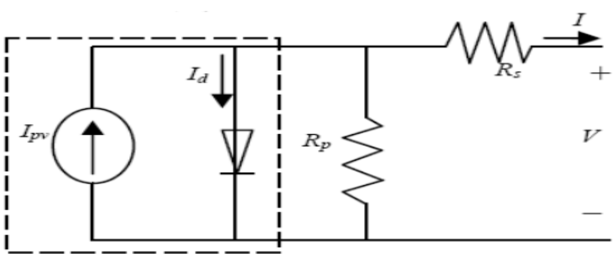

Fig.3. Single Diode Model

where I_{PV} is the current generated by the incidence of light, Io is the reverse saturation current, V_T is the thermal voltage of the PV module having N_s cells connected in series, q is the electron charge, k is the Boltzmann constant, T is the temperature of PN junction in Kelvin and a is the diode ideality factor. This equation Originates electrical characteristics of single diode PV cell in the form of V-I curves with the computation of five parameters namely I_{pv}, I_o, R_p, R_s and a, as shown in Figure.4. This model was extensively used in the literature as this model provides a good compromise between its simplicity and accuracy. But the single diode models were proposed on the assumption that recombination loss in the depletion region is absent. In practice this loss accounts for a substantial amount, which can not be neglected under extreme working conditions.

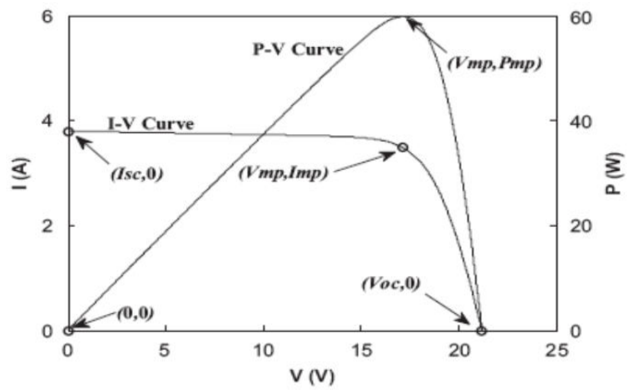

Fig.4. Output characteristics of PV cells

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

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

The numbers of modules required to connect in series are as follows:

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

The numbers of modules required to connect in parallel are as follows:

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

Connecting six modules in series, having two strings in parallel, an 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 inductorL_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 [6]

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

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

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

Then L_1, L_2, and C_1 are estimated as

$$L_1 = \frac{DV_{mpp}}{f_{sw}\Delta I_{L1}} = \frac{0.52 \times 187.2}{20\,000 \times 18.16 \times 0.06} = 4.5 \times 10^{-3} \approx 5 \text{ mH} \quad (6)$$

$$L_2 = \frac{(1-D)V_{dc}}{f_{sw}\Delta I_{L2}} = \frac{(1-0.52) \times 200}{20\,000 \times 17 \times 0.06} = 4.7 \times 10^{-3} \approx 5 \text{ mH} \quad (7)$$

$$C_1 = \frac{DI_{dc}}{f_{sw}\Delta V_{C1}} = \frac{0.52 \times 17}{20\,000 \times 200 \times 0.1} = 22\ \mu\text{F} \quad (8)$$

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 $I_{L2}=I_{dc}$; $\Delta VC1$ 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 sixth harmonic component of the supply (ac) voltage is reflected on the dc side as a dominant harmonic in the three-phase supply system. 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 pumping 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

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

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

$$\omega_{min} = 2\pi f_{min} = 2\pi \frac{NP}{120} = 2\pi \times \frac{1100 \times 6}{120} = 345.57 \text{ rad/s} \quad (10)$$

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 follows:

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

Similarly, a value of dc link capacitor of VSI at ω_{min} is as follows:

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

Where ΔV_{dc} is an amount of permitted ripple in voltage across dc-link capacitorC_2.Finally, C_2= 410μF 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

$$K = \frac{P}{\omega_r^3} = \frac{2.89 \times 10^3}{(2\pi \times 3000/60)^3} = 9.32 \times 10^{-5} \quad (13)$$

Where P=2.89Kw is rated power developed by the BLDC motor and ω_r is rated mechanical speed of the rotor (3000r/min) in rad/s.

A water pump with these data is selected for proposed system.

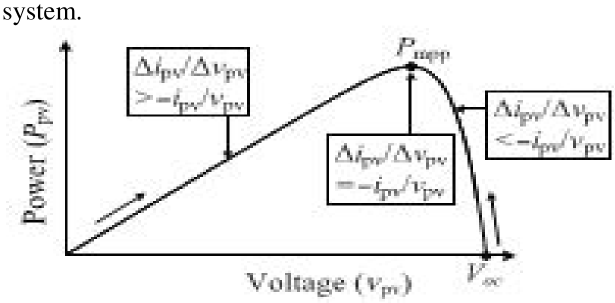

Fig.5. Illustration of INC-MPPT with SPV array $P_{pv}-v_{pv}$ characteristics.

TABLE.I
Switching States for Electronic Commutation of BLDC Motor

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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

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. INC-MPPT Algorithm

An efficient and commonly used INC-MPPT technique [8],[13] 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 proportional-integral(PI) controller to generate a duty cycle [8] for the zeta converter, which increases the complexity. Hence, the direct duty cycle control is adapted in this work. The INC-MPPT algorithm determines the direction of perturbation based on the slope of Ppv−vpv curve, shown in Fig.5. As shown in Fig.5, the slope is zero at MPP, positive on the left, and negative on the right of MPP, i.e.,

$$\left.\begin{aligned} \frac{dP_{pv}}{dv_{pv}} &= 0; \quad \text{at mpp} \\ \frac{dP_{pv}}{dv_{pv}} &> 0; \quad \text{left of mpp} \\ \frac{dP_{pv}}{dv_{pv}} &> 0; \quad \text{right of mpp} \end{aligned}\right\} \tag{14}$$

Since

$$\frac{dP_{pv}}{dv_{pv}} = \frac{d(v_{pv} * i_{pv})}{dv_{pv}} = i_{pv} + v_{pv} * \frac{di_{pv}}{dv_{pv}} \cong i_{pv} + v_{pv} * \frac{\Delta i_{pv}}{\Delta v_{pv}} \tag{15}$$

Therefore, (14) is rewritten as

$$\left.\begin{aligned} \frac{\Delta i_{pv}}{\Delta v_{pv}} &= -\frac{i_{pv}}{v_{pv}}; \quad \text{at mpp} \\ \frac{\Delta i_{pv}}{\Delta v_{pv}} &> -\frac{i_{pv}}{v_{pv}}; \quad \text{left of mpp} \\ \frac{\Delta i_{pv}}{\Delta v_{pv}} &< -\frac{i_{pv}}{v_{pv}}; \quad \text{right of mpp} \end{aligned}\right\} \tag{16}$$

Thus, based on the relation between INC and instantaneous conductance, the controller decides the direction of perturbation as shown in Fig.5, 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. 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($\Delta D=0.001$)is selected, which contributes to soft starting and also minimizes oscillations around the MPP.

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 decoder logic. It symmetrically places the dc input current at the center of each phase voltage for 120^o. 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^o [5], [6]. The generation of six switching states with the estimation of rotor position is tabularized in Table I. It is perceptible that only two switches conduct at a time, resulting in 120^oconduction 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 makes BLDC motor [28] with inbuilt encoder is selected for proposed system and its detailed specifications are given in the Appendixes.

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VI. FUZZY LOGIC CONTROL

L. A. Zadeh presented the first paper on fuzzy set theory in 1965. Since then, a new language was developed to describe the fuzzy properties of reality, which are very difficult and sometime even impossible to be described using conventional methods. Fuzzy set theory has been widely used in the control area with some application to power system [5]. A simple fuzzy logic control is built up by a group of rules based on the human knowledge of system behavior. Matlab/Simulink simulation model is built to study the dynamic behavior of converter. Furthermore, design of fuzzy logic controller can provide desirable both small signal and large signal dynamic performance at same time, which is not possible with linear control technique. Thus, fuzzy logic controller has been potential ability to improve the robustness of compensator.

The basic scheme of a fuzzy logic controller is shown in Fig 6 and consists of four principal components such as: a fuzzification interface, which converts input data into suitable linguistic values; a knowledge base, which consists of a data base with the necessary linguistic definitions and the control rule set; a decision-making logic which, simulating a human decision process, infer the fuzzy control action from the knowledge of the control rules and linguistic variable definitions; a de-fuzzification interface which yields non fuzzy control action from an inferred fuzzy control action [10].

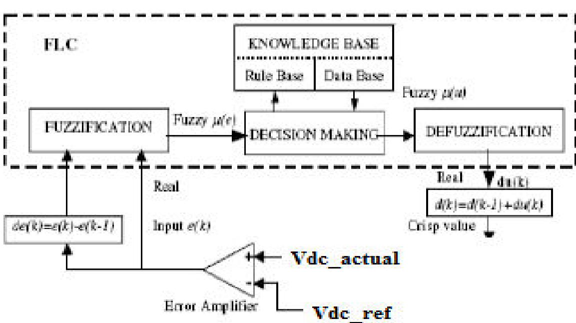

Fig.6.Block diagram of the Fuzzy Logic Controller (FLC) for proposed converter.

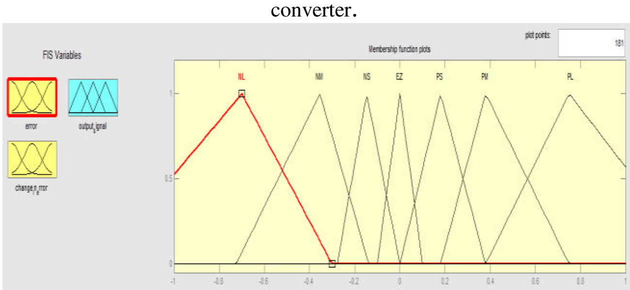

Fig.7. Membership functions for error.

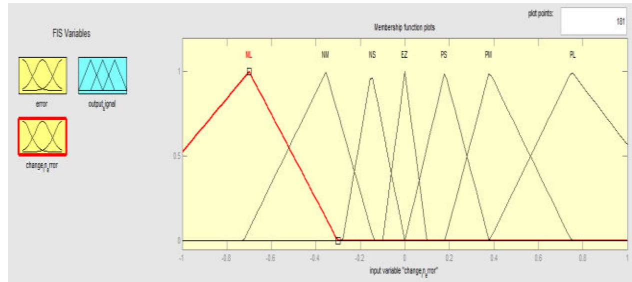

Fig.8. Membership functions for change in error.

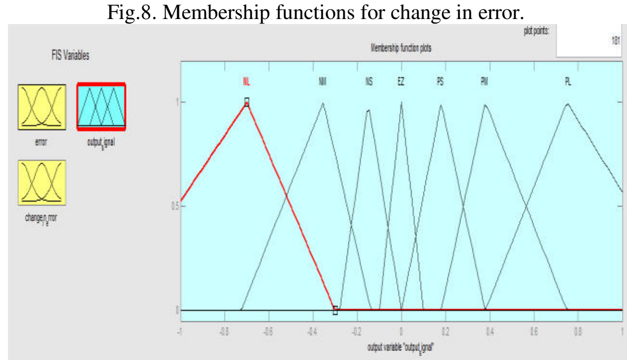

Fig.9. Membership functions for Output.

Table II Table rules for error and change of error.

Change error \ Error	NL	NM	NS	EZ	PS	PM	PL
NL	NL	NL	NL	NL	NM	NS	NL
NM	NL	NL	NL	NM	NS	EZ	NM
NS	NL	NL	NM	NS	EZ	PS	NS
EZ	NL	NM	NS	EZ	PS	PM	EZ
PS	NM	NS	EZ	PS	PM	PL	PS
PM	NS	EZ	PS	PM	PL	PL	PM
PL	EZ	PS	PM	PL	PL	PL	PL

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VII. MATLAB/SIMULATION RESULTS

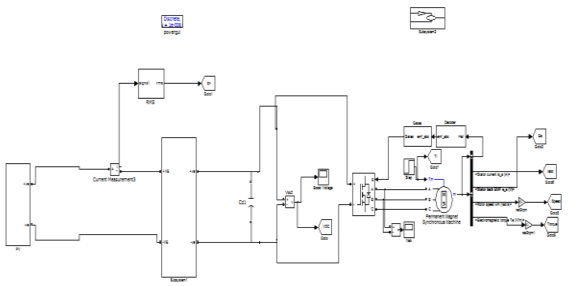
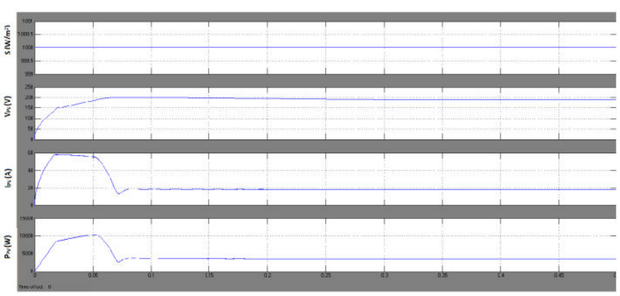
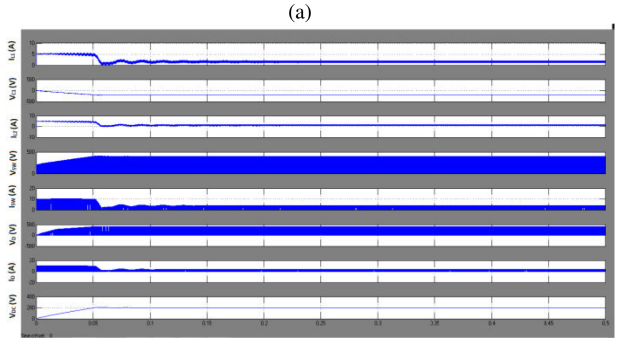


Fig.10 Matlab/Simulink circuit of Starting and steady-state performances of the proposed SPV array based zeta converter-fed BLDC motor drive for water pump



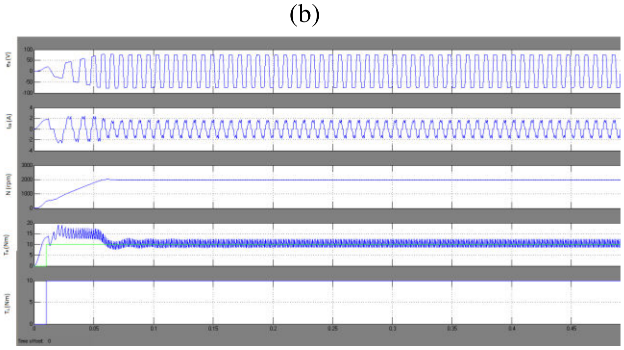
Time (s)

(a)



Time (s)

(b)



Time (S)

(c)

Fig.11 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. (c) BLDC motor-pump variables.

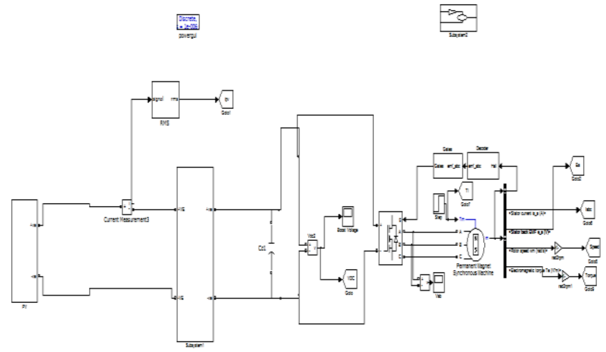
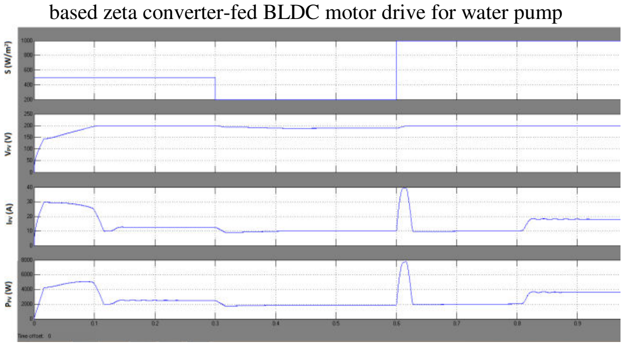
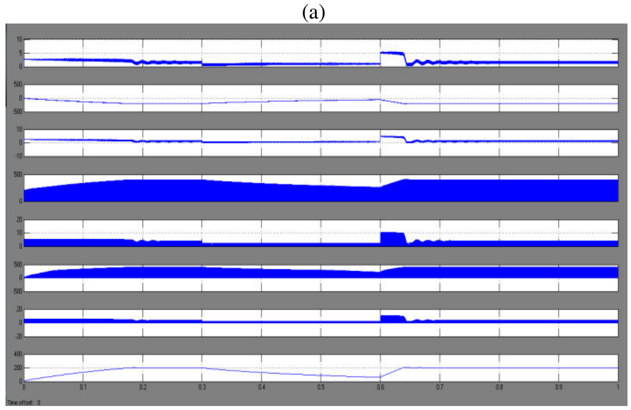


Fig.12 Matlab/Simulink circuit for Dynamic performance of SPV array-based zeta converter-fed BLDC motor drive for water pump

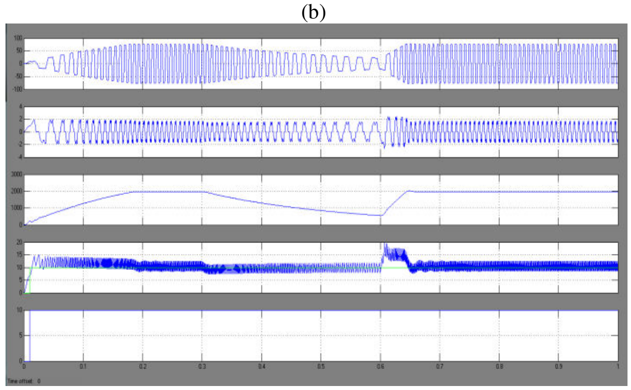


Time (S)

(a)



(b)



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(c)

Fig.13 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. (c) BLDC motor-pump variables.

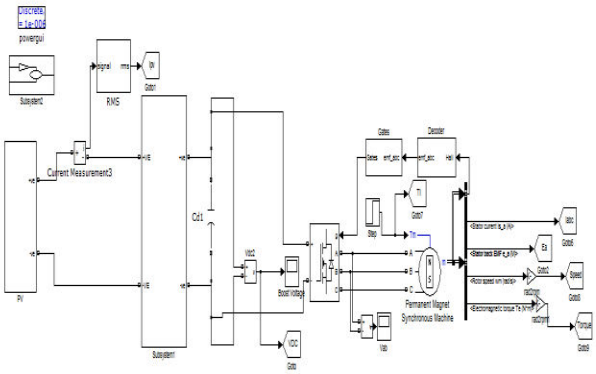
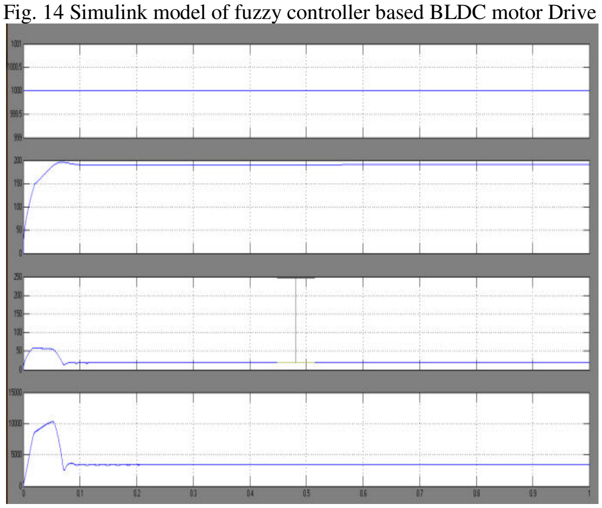
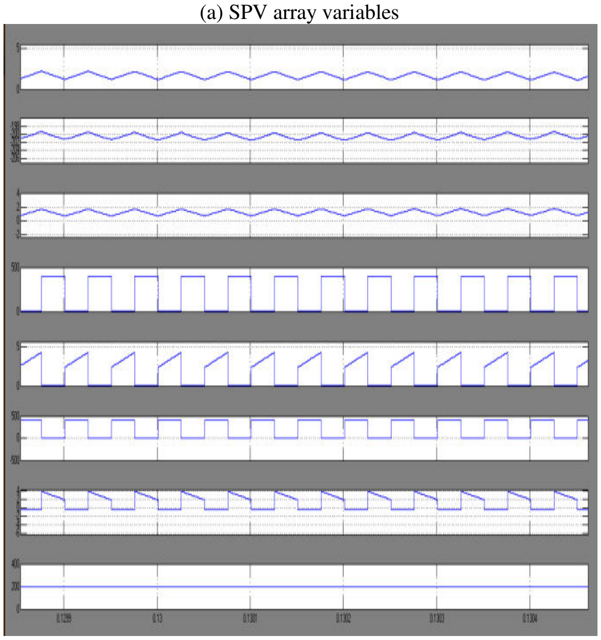


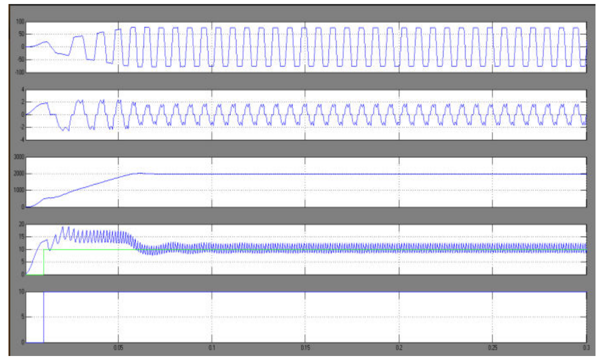
Fig. 14 Simulink model of fuzzy controller based BLDC motor Drive



(a) SPV array variables



(b) Zeta converter variables



(c) BLDC motor-pump variables.

Fig.15 BLDC motor (a) SPV array (b) Zeta converter (c) water pump variables

VIII CONCLUSION

A solar photovoltaic array fed Zeta converter based BLDC motor has been proposed to drive water-pumping system. The proposed system has been designed, modeled and simulated using MATLAB. In order to extract the maximum possible power from the PV module, a Fuzzy based MPPT technique along with zeta converters was modeled and evaluated. The BLDC motor was driven by a Voltage source Inverter with switching signals generated by the Hall Effect sensors. The overall system was found to behave similar to any normal operation of the motor. The current simulated system will be able to act as a constant speed motor. The only mode of powering remote areas for applications such as pumping, grinding, etc. can be achieved by solar power, so it is better to use a buck-boost converter fed BLDC motor owing to their losses.

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