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PERFORMANCE ANALYSIS OF SPV FED BLDC MOTOR BASED WATER PUMPING SYSTEM WITH ZETA CONVERTER USING FUZZY LOGIC CONTROLLER

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ABSTRACT:

The best alternative to the conventional energy sources is everlasting solar energy it is one among the cheapest and widely used. This paper deals with the design and analysis of zeta converters, it is been used as intermediate between voltage source inverter (VSI) and solar PV array. MPPT technique is been used for gaining maximum efficiency form 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 noiseless operation compared to induction motor. Maximum power locus 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.

Key words: 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

Solar Photovoltaic have gained prominence over the years since it is pollution free, world wide availability etc. But the fact is that it is required to meet the needs of the current power requirements. The modelling of PV modules have been done in various literatures [1]. For extracting the power from a PV module, we make use of Maximum Power Point Tracking algorithms. The heart of any MPPT technique is a DC – DC converter which regulates the source impedance which varies with atmospheric conditions and the converter duty ratio is changed to match the load impedance so that maximum power transfer occurs [2]. Of the various available Buck boost configurations, a Zeta Converter has found to possess several advantages over other configurations such as Cuk, Flyback etc. The main and notable advantage being that of a non-inverted output. The advancement of the power electronics and evolution of control techniques enabled the use of Induction motors for most of the Industrial applications. But now, Induction motors are being replaced by BLDC motors which have a higher efficiency as compared to Induction motors, high Speed – Torque characteristics and reduced size of machine etc. A BLDC motor can infact be considered as a DC motor which runs on AC power. In order to drive BLDC motors, we have to use an inverter whose gate pulse are generally created from the hall voltage of the motor extracted with Hall Effect sensors. In this work, a PV system with varying

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environmental conditions is considered and for such conditions we require MPPT techniques. A Fuzzy based MPPT system has proven to extract much more power with low settling time and little dynamic response. In fact a Zeta converter can a little more power as compared to other converter. A BLDC motor is driven through an inverter interface. The hall sensor provides the required control strategy for driving the inverter. The speed is fed back to the inverter to make it a constant speed variable load motor. The first part of the paper deals with the modelling and simulation of PV module. The modelling of the system based on Matlab\Simulink has been proposed in many papers. The next is the modelling of the Fuzzy based MPPT and is followed by the Zeta converter fed BLDC motor simulation and analysis of the motor parameters is done.

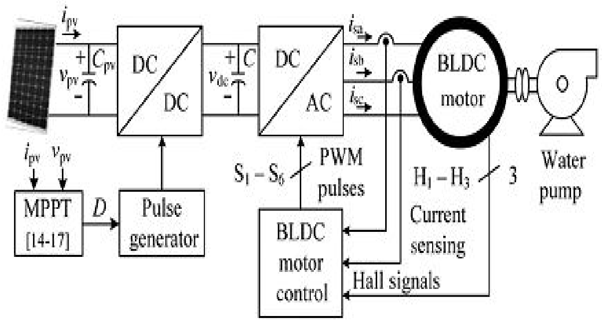

Fig.1. Conventional SPV-fed BLDC motor-driven water pumping system

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

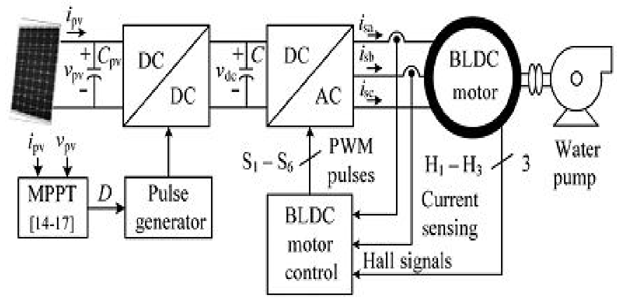

Fig.1. Conventional SPV-fed BLDC motor-driven water pumping system

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.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. A step-by-step operation of proposed system is elaborated in Section III in detail.

III. OPERATION OF PROPOSEDSYSTEM

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 INCMPPT 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 thereby eliminated, contributing in an increased efficiency of proposed water pumping system.

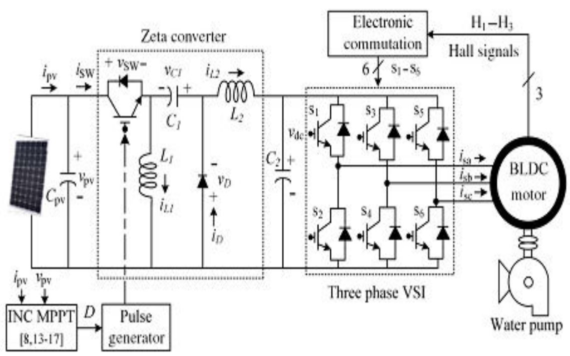

Fig.2. Proposed SPV-zeta converter-fed BLDC motor drive for water pump

IV. DESIGN OF PROPOSEDSYSTEM

Various operating stages shown in Fig.2 are properly designed to develop an effective water pumping system, capable of operating under uncertain conditions. A BLDC motor of2.89-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 regardless of power losses. 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. Electrical specifications of this module are listed in Table.1 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}= 187.2V.

TABLE1
Specifications of Sun module plus SW 280monoSPV Module

Peak power, P_m (W)	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 current of SPV array at MPPI_{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:

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

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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 VSII_{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

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

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

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

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 throughL_1, sameasI_{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 voltageacrossC_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 [25]. 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:

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

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

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

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 [26], [27] 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 = 2.89 kW 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.

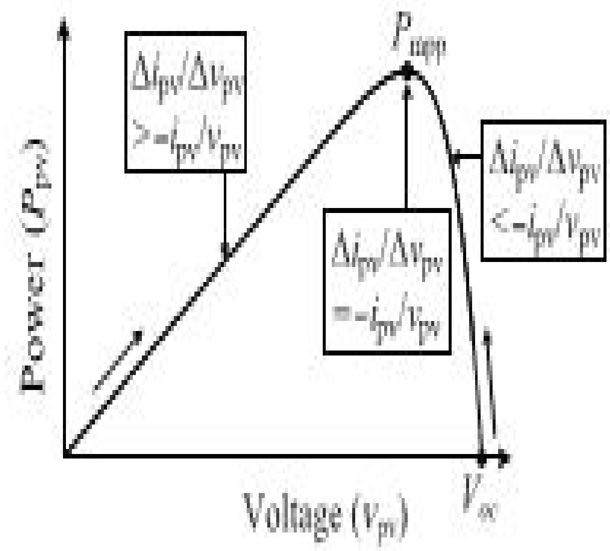

Fig.3. Illustration of INC-MPPT with SPV array P_{pv}–v_{pv} characteristics.

TABLE.2
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

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 $P_{pv} - v_{pv}$ 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, i.e.,

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

Since

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

Therefore, (14) is rewritten as

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

Thus, based on the relation between INC 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. 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 II. 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.

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

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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 fuzzyfication 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].

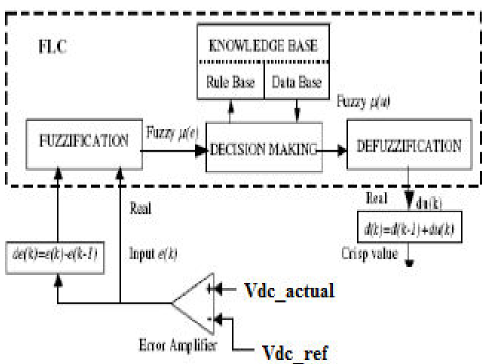

Fig.4.Block diagram of the Fuzzy Logic Controller (FLC) for proposed converter.

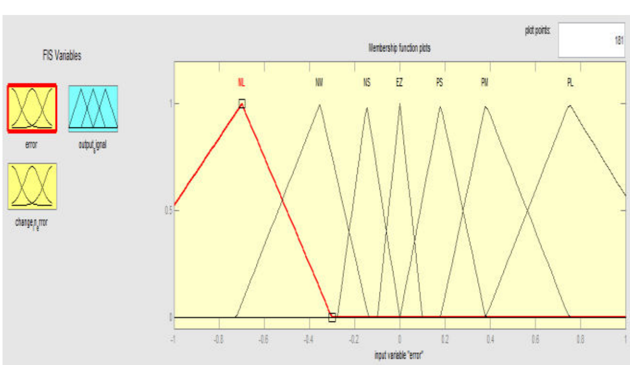

Fig.5. Membership functions for error.

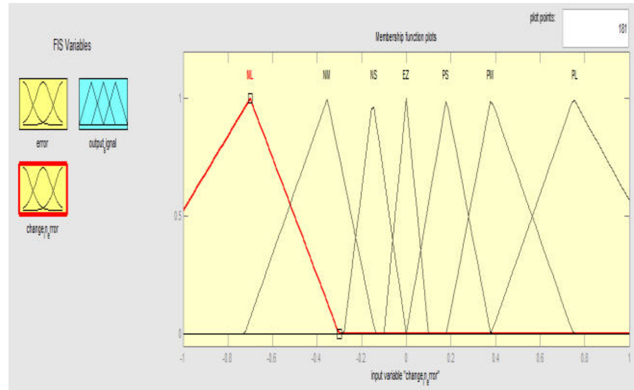

Fig.6. Membership functions for change in error.

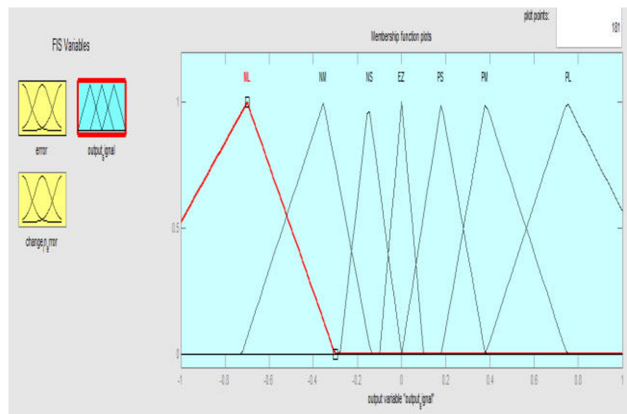

Fig.7. Membership functions for Output.

Error / Change 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

Table 3 Table rules for error and change of error.

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VII. MATLAB/SIMULATION RESULTS

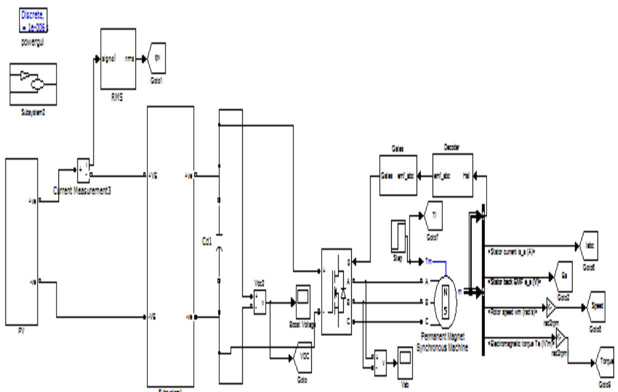
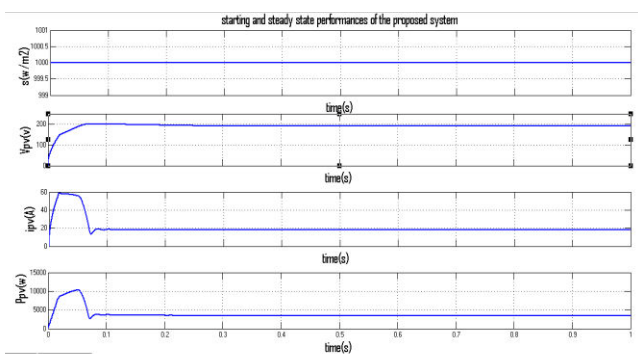
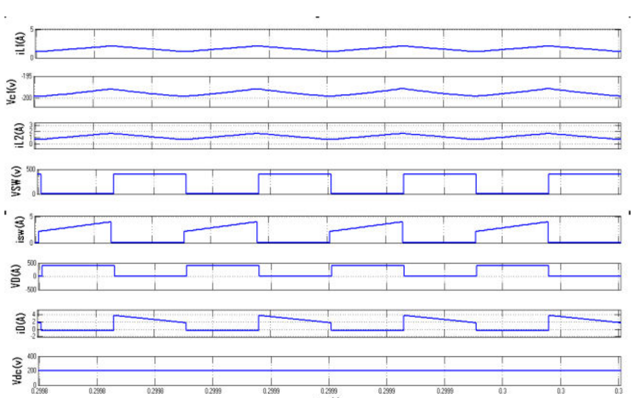


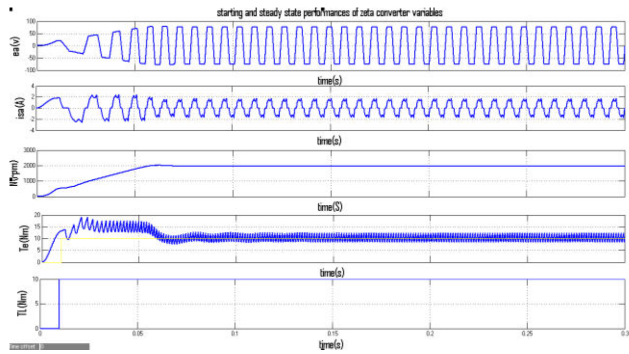
Fig. 8 Matlab/Simulink circuit of Starting and steady-state performances of the proposed SPV array based zeta converter-fed BLDC motor drive for water pump



(a)



(b)



(c)

Fig.9 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.

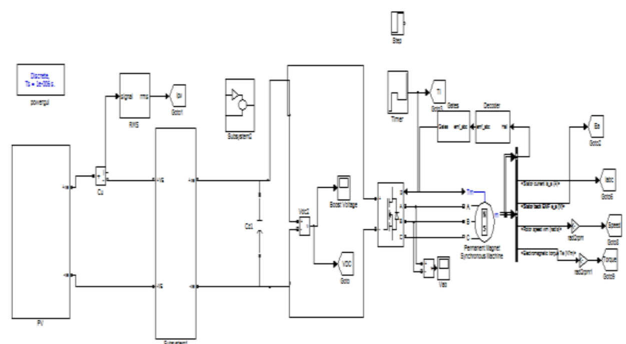
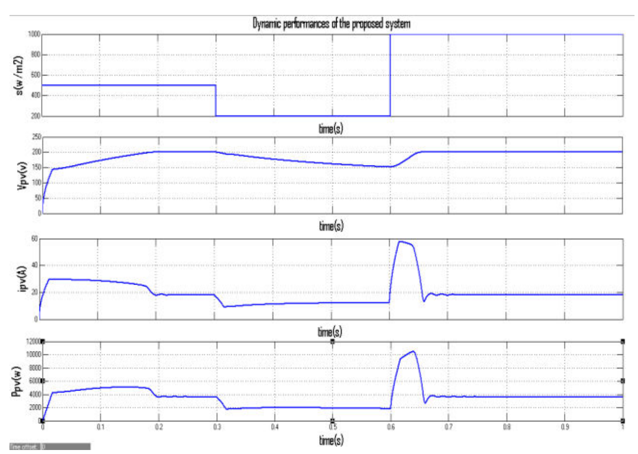


Fig.10 Matlab/Simulink circuit for Dynamic performance of SPV array-based zeta converter-fed BLDC motor drive for water pump



(a)

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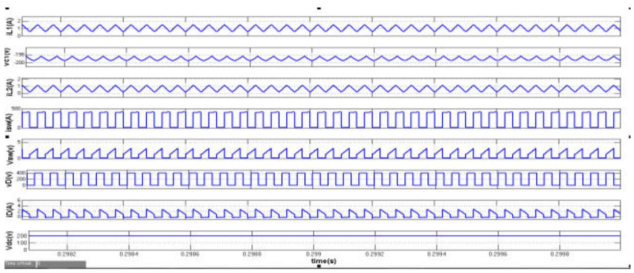
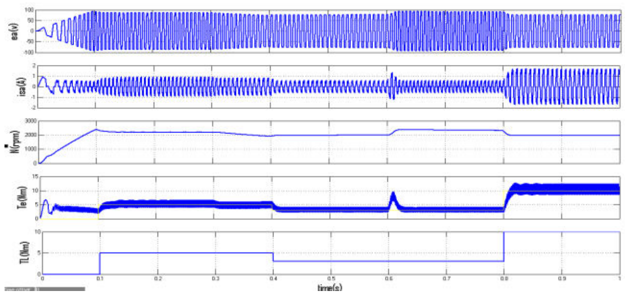


(b)



(c)

Fig.11 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.

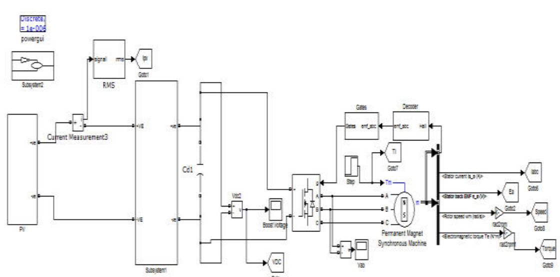
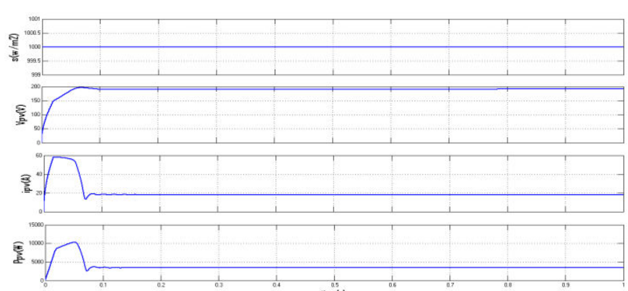
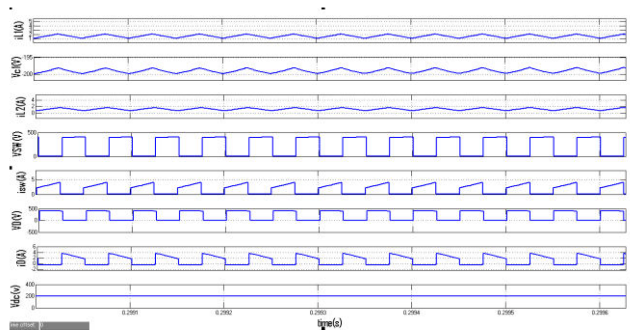


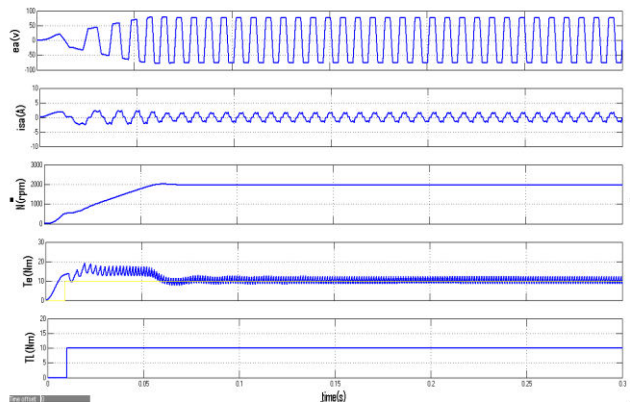
Fig. 12 Simulink model of fuzzy controller based BLDC motor Drive



(a) SPV array variables



(b) Zeta converter variables



(c) BLDC motor-pump variables.

Fig.13 BLDC motor (a) SPV array (b) Zeta converter (c) water pump variables

VIII CONCLUSION

The simulation of a PV based Brushless DC Motor was done. In order to extract the maximum possible power from the PV module, a Fuzzy based MPPT technique along with a Zeta converter was modelled 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 simulation was done for a constant torque, the motor operated at constant speed, but the torque generated seemed to fluctuate more than usual. This may be due to the inability of the PV module to deliver the required power at every instant. So by using a PV system that can drive a BLDC motor with an excess of about 20% of the connected load. Still 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 can be achieved by solar power, so it is better to use a BLDC motor instead of using Induction motor owing to their losses.

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