SOLAR POWER FED BLDC MOTOR EMPLOYING ZETA CONVERTER FOR WATER PUMPING SYSTEM

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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. To extract the maximum available power from the SPV array a zeta converter is utilized. A fundamental frequency switching of the voltage source inverter is adapted in the control algorithm to eliminates phase current sensors and adapts (VSI), to avoid the power losses due to high frequency switching. No additional control or circuitry is used for speed control of the BLDC motor. A variable dc link voltage of VSI controls the speed. An appropriate control of zeta converter through the incremental conductance maximum power point tracking (INC-MPPT) algorithm offers soft starting of the BLDC motor. The water pumping system is designed and modeled such that the performance is not affected under dynamic conditions. The suitability of system at practical operating conditions is demonstrated through simulation results using MATLAB/Simulink.

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

1. 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. Solar cell is the basic unit of solar energy generation system where electrical energy is extracted directly from light energy without any intermediate process. 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 has concealed the technical contribution and originality of the reported work.

The merits of both BLDC motor and zeta converter can contribute to develop an 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 [5], [6]. On the other hand, a zeta converter exhibits the advantages over the conventional buck, boost, buck–boost converters, and Cuk converter when employed in SPV-based applications.

The merits of the zeta converter are favorable for proposed SPV array-fed water pumping system. 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 an SPV array [7]. The MPPT can be performed with simple buck [8] and boost [9] converter if MPP occurs within prescribed limits.

This property also facilitates the soft starting of BLDCmotor unlike a boost converter which habitually steps upthe voltage level at its output, not ensuring soft starting.Unlike a classical buck–boost converter [10], the zetaconverter has a continuous output current. The outputinductor makes the current continuous and ripple free.Although consisting of same number of components asa Cuk converter [11], the zeta converter operates as non inverting buck–boost converter unlike an inverting buck–boost and Cuk converter. This property obviates a requirementof associated circuits for negative voltage sensing, and hence reduces the complexity and probability of slow down the system response [12].

An incremental conductance maximum power point tracking (INC-MPPT) algorithm [8], [13]–[18] is used to operate the zeta converter such that SPV array always operates at its MPP.

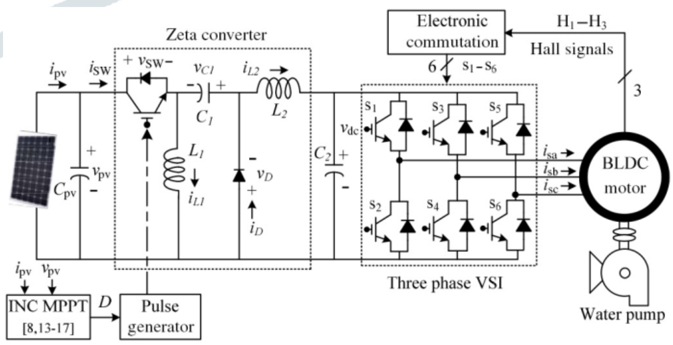


Fig. 1. SPV-zeta converter-fed BLDC motor drive for water pump.

A zeta converter is utilized to extract the maximum power available from an SPV array, soft starting, and speed control of BLDC motor coupled to a water pump. Due to a single switch, this converter has very good efficiency 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 scarifying 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 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) an SPV array, a zeta converter, a VSI, a BLDC motor, and a water a water pump. The BLDC motor has an inbuilt encoder.

The pulse generator is used to operate the zeta converter. Astep-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. 1. 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 thereby eliminated, contributing in an increased efficiency of proposed water pumping system.

IV. DESIGN OF PROPOSED SYSTEM

Various operating stages shown in Fig. 1 are properly designed to develop an effective water pumping system, capable of operating under uncertain 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. Designs of 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/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 280 mono [24] SPV module is selected to design the SPV array of an appropriate size.

Table 1

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

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 = 187.2V.

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 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 [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

$$I_{dc} = \frac{3700}{200} = 17\text{ A}. \quad (5)$$

Then, *L*1, *L*2, and *C*1 are estimated as

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

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

$$C1 = \frac{DIdc}{fsw\Delta Vc1} = \frac{0.52*17}{20000*200*0.1} = 22\ \mu F \quad (8)$$

where *fsw* is the switching frequency of IGBT switch of the zeta converter; Δ*IL*1 is the amount of permitted ripple in the current flowing through *L*1, same as *IL*1 = *I*mpp; Δ*IL*2 is the amount of permitted ripple in the current flowing through *L*2, same as *IL*2 = *I*dc; Δ*VC*1 is permitted ripple in the voltage across *C*1, same as *VC*1 = *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 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

ωrated = 2πfrated = 2πNrated$P$/120= 2π × 3000 × 6/120= 942rad/s.

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

ωmin = 2πfmin = 2πNP/120 = 2π × 1100 × 6/120= 345.57 rad/s.

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; *Nrated* 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:

$$C2,\text{rated} = \frac{Idc}{6*wrated*\Delta Vdc} = \frac{17}{6*942*200*0.1} = 150.4\ \mu F.$$

Similarly, a value of dc link capacitor of VSI at *ω*min is as follows:

$$C2,\text{min} = \frac{Idc}{6*wmin*\Delta Vd\ c} = \frac{17}{6*\omega min*\Delta Vdc} = 410\ \mu F$$

where Δ*V*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

$$K = \frac{P}{wr3} = \frac{2.89*103}{(2\pi \times \frac{3000}{60})3}$$

where *P* = 2.89 kW is rated power developed by the BLDC motor *ωr* is rated mechanical speed of the rotor(3000 r/min) in rad/s.A water pump with these data is selected for proposed system.

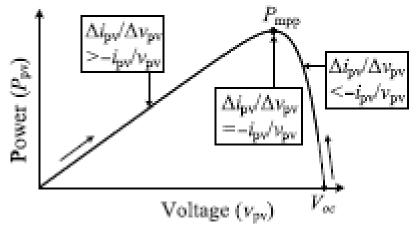


Fig. 2. Illustration of INC-MPPT with SPV array *P*pv−*v*pv characteristics

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. 2. As shown in Fig. 2, the slope is zero at MPP, positive on the left, and negative on the right of MPP, i.e.,

$\frac{dPpv}{dvpv} = 0$; at mpp

$\frac{dPpv}{dvpv} > 0$; right of mpp

$\frac{dPpv}{dvpv} > 0$; left of

$$\text{Since } \frac{dPpv}{dvpv} = \frac{d(vpv*ipv)}{dvpv} = ipv + vpv * \frac{dipv}{dvpv}$$

$$\sim= ipv + vpv * \frac{\Delta ipv}{\Delta vpv}$$

$\frac{\Delta ipv}{\Delta vpv} = \frac{-ipv}{vpv}$ at mpp

$\frac{\Delta ipv}{\Delta vpv} > \frac{-ipv}{vpv}$ left of mpp

$\frac{\Delta ipv}{\Delta vpv} < \frac{-ipv}{vpv}$ right of mpp

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 (Δ*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 is used commutating the currents flowing through its windings in a predefined sequence using a decoder logic. It symmetrically places the dc input current at the center of each phase voltage for 120◦.

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

Six switching pulses are generated as per the various possible combinations of three Hall-effect signals. These three Hall-effect signals are produced by an inbuilt encoder according to the rotor position. A particular combination of Hall-effect signals is produced for each specific range of rotor position at an interval of 60◦.

The generation of six switching states with the estimation of rotor position is tabularized in Table II. It is perceptible that only two switches conduct at a time, resulting in 120◦ conduction mode of operation of VSI and hence the reduced conduction losses. Besides this, the electronic commutation provides fundamental frequency switching of the VSI; hence, losses associated with high-frequency PWM switching are eliminated. A motor power company make BLDC motor with inbuilt encoder is selected for proposed system and its detailed specifications are given in the Appendixes.

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, 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 illustrated in Figs. 3 and 4. To demonstrate the suitability of the system under dynamic condition, solar irradiance level is instantly reduced from 600 to 200W/m2 and then increased to 1000 W/m2 as shown in Fig. 4(a).

A. Performance of SPV Array

Fig. 3(a) exhibits the starting and steady-state performances of SPV array at 1000 W/m2. The MPP is properly tracked. The tracking time is intentionally increased at the starting by adapting a low value of perturbation size (ΔD = 0.001) in order to achieve the soft starting of BLDC motor. The low value of ΔD 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 as shown in Fig. 4(a).

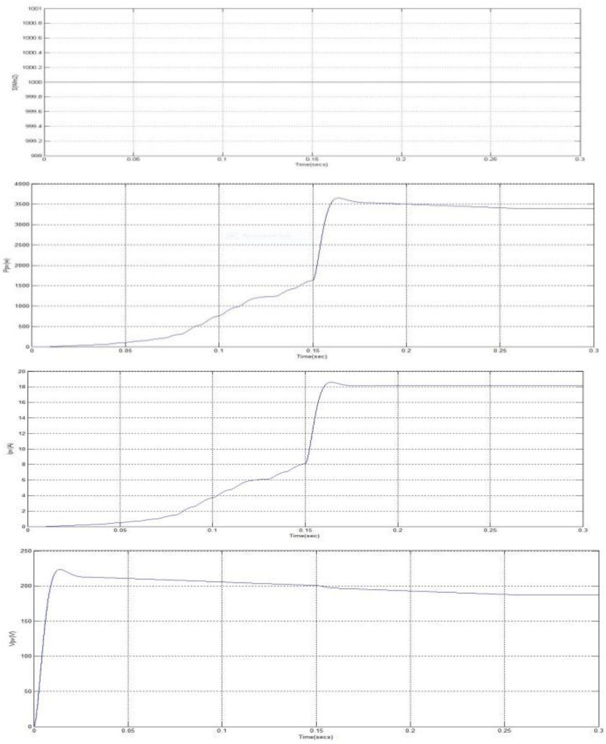
B. Performance of Zeta Converter

Fig. 3(b) presents the steady-state performance of zeta converter at 1000 W/m2. The input inductor current *iL*1, intermediate capacitor voltage *vc*1, 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}, *vc*1, I_{L2}, and V_{dc} shown in Fig. 4(b). The zeta converter automatically changes its mode of operation from buck mode to boost mode and vice versa according to the irradiance level to optimize the output power of SPV array. A small amount of ripples in the zeta converter variables are observed caused by permitting the ripples up to an extent to optimize the size of the components.

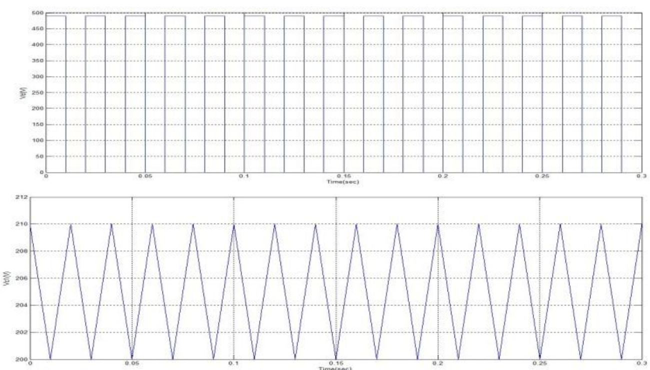
C. Performance of BLDC Motor-Pump

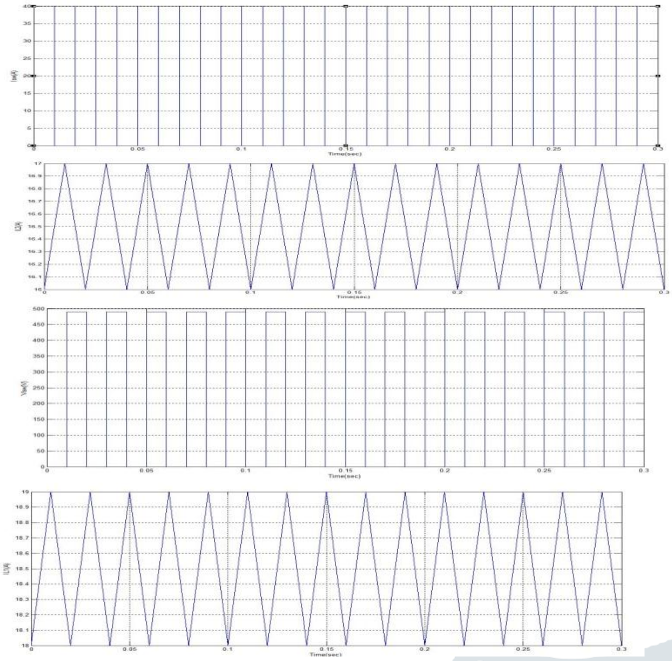
The starting and steady-state behaviors of the BLDC motor pump at 1000 W/m2 is shown in Fig. 4(c). All the motor indices such as the back EMF *ea*, the stator current *i*sa, the speed *N*, the electromagnetic torque developed *Te*, and the load torque *TL* reach their corresponding rated values under 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 *Te* results 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. 4(c). The BLDC motor always attains a higher speed than 1100 r/min, a minimum speed required to pump the water at a minimum solar irradiance level of 200W/m2.

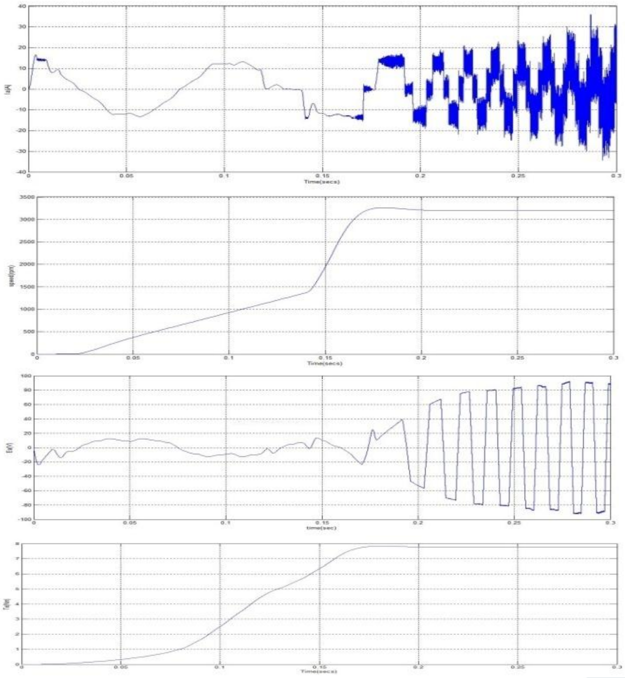


3(a)





3(b)



3(c)

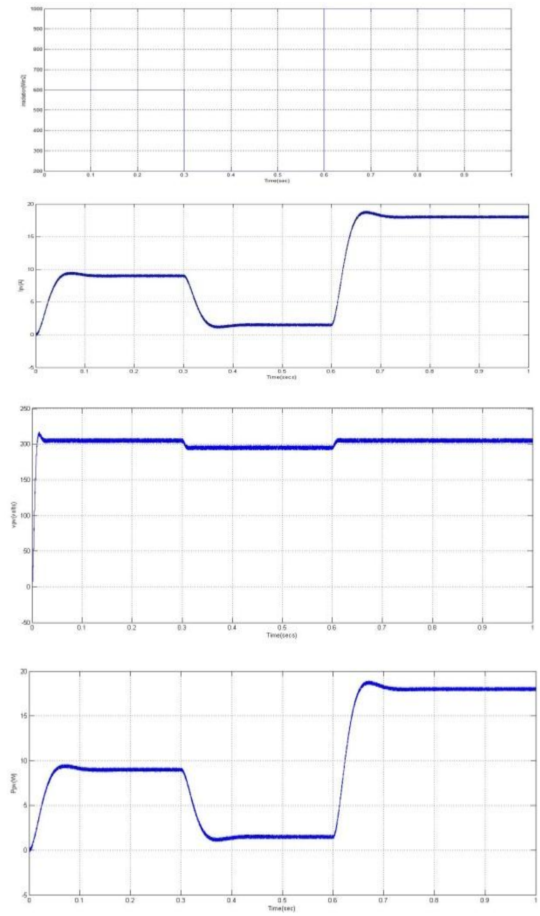
Fig.3. Starting and steady-state performances of the proposed SPV array based zeta converter-fed BLDC motor drive for water pump. (a) SPV array Variables. (b) Zeta converter variables. (c) BLDC motor-pump variables.

Performance of BLDC motor-pump is not deteriorated by weather conditions and it pumps the water successfully.

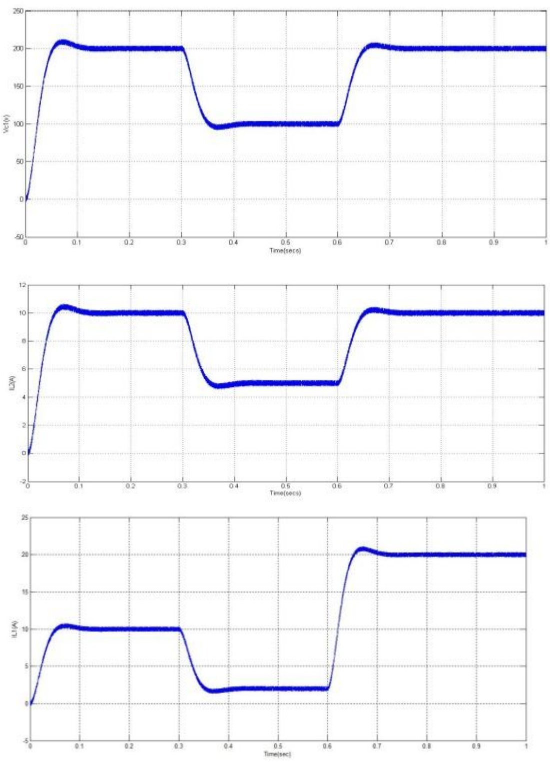
The presented work is a detailed modelling and simulation of the PV cell and module. It is implemented under MATLAB/ Simulink environment; the most used software by researchers and engineers. This model is first drafted in accordance with the fundamentals of semiconductors and the PV cell technology.

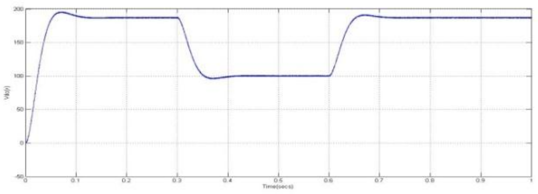
The various performances of SPV array, zeta converter, and BLDC motor-pump are validated on matlab simulink The system constitutes an SPV array simulator zeta converter, VSI ,BLDC motor The steady-state performances of SPV array, zeta converter, and BLDC motor-pump at 1000 W/m2 are validated using the waveforms shown above .The operation of zeta converter in boost mode is observed at $D = 0.52$. A set of the zeta converter indices $iL1$, $iL2$, $vC1$, and $v$dc are shown. These indices justify the operation of converter in CCM and limited stress on its power devices. The peak voltage and peak current of the switch are observed. The IGBT and diode operate in a complementary fashion.

To demonstrate the satisfactory performance of system under dynamically varying atmospheric condition, the solar irradiance is varied from 600 to 200 and 200 to 1000 W/m2 as shown in Fig. 4(a) The waveforms, shown in Fig. 4, are *i*pv, *v*dc,and *N*. It is clearly observed that the MPP is tracked accurately. The zeta converter quickly changes its mode of operation following the variation in atmospheric condition

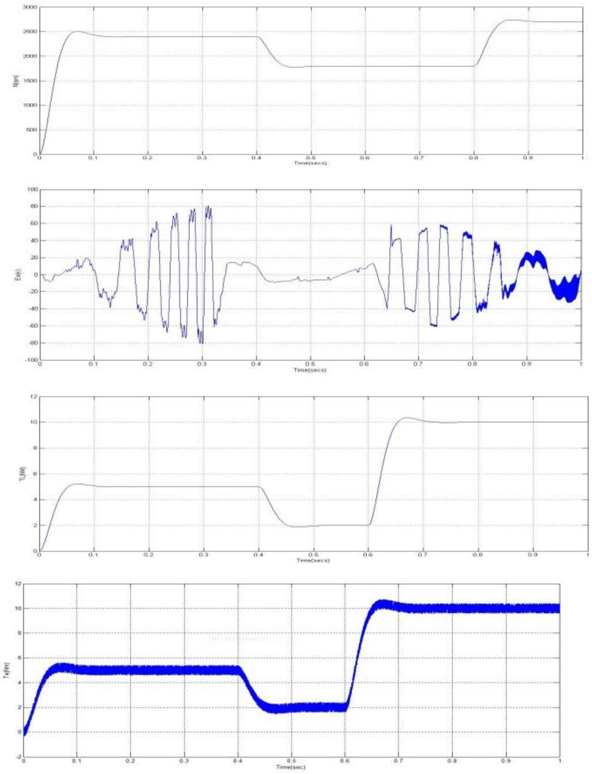


4(a)





4(b)



4(c)

Fig. 4. Dynamic performances of the proposed SPV array-based zetaconverter-fed BLDC motor drive for water pump. (a) SPV array variables. (b) Zeta converter variables. (c) BLDC motor-pump variables.

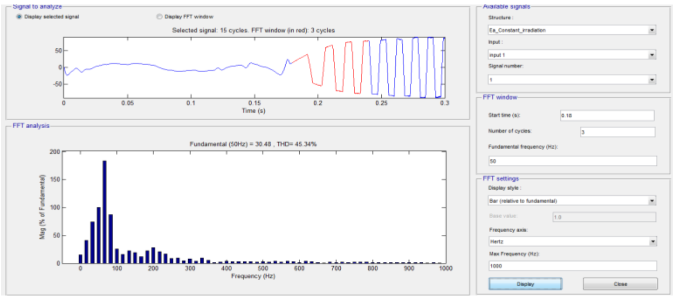
The water pumping, a standalone application of the SPV array generated electricity is receiving wide attention now a days for irrigation in the fields, household applications and industrial use. This project is have two extensions. In mppt controller we are we using incremental conductance with pi controller.(this for zeta converter) and Inverter controller is also have Pi controller. These two pi controllers are are replaced with fuzzy logic controller.

When we use fuzzy logic controller instead of PI controller we will get a reduction of the harmonics of both voltage and current in fuzzy logic controller model than in PI controller model and comparison table is shown below.

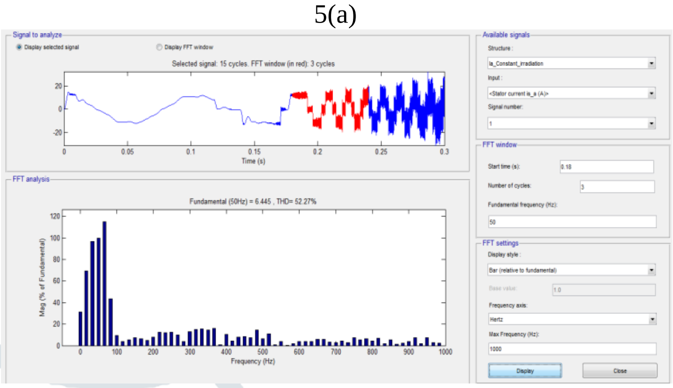
TYPE OF CONTROLLER	THD -E_a	THD- I_a
PI CONTROLLER	45.34%	52.27%
FUZZY LOGIC CONTROL	40.51%	50.55%

From above table we can say that the THD values by using fuzzy logic controller has decreased when PI controller is used. The THD values are obtained by FFT analysis and y comparing the waveforms THD values hence the conclusion is obtained.

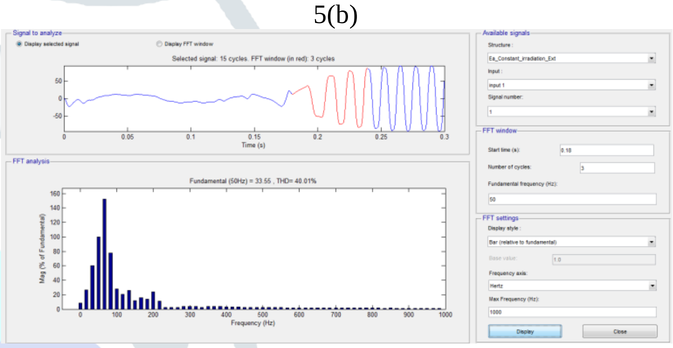
The following figures shows THD values of current waveforms and emf waveforms during constant excitation by using PI controller and fuzzy logic controller through fft analysis.



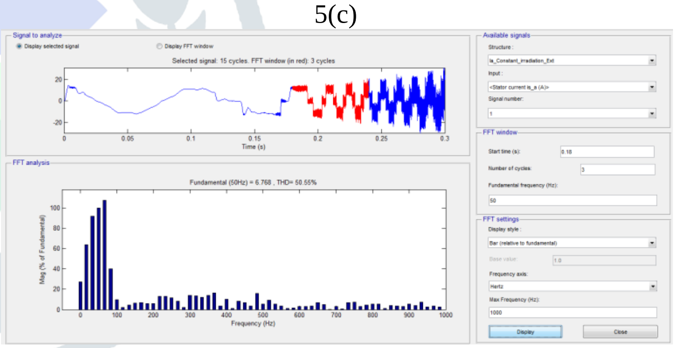
5(a)



5(b)



5(c)



5(d)

THD waveforms during constant irradiation using PI controller for 5(a)voltage 5(b) current THD waveforms during constant irradiation using fuzzy logic controller for 5(c)voltage 5(d) current

VII. CONCLUSION

The SPV array-zeta converter-fed VSI–BLDC motor-pumphas been proposed and its suitability has been demonstrated through simulated results. The 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 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 maximum power 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 using fuzzy logic controller has operated successfully and gives less harmonic distortion than the system eith PI controller which is validated by the simulation results shown.

APPENDIXES

Parameters for BLDC Motor (Simulated Data)

Stator phase/phase resistance, Rs = 0.36 Ω; stator phase/phase inductance, Ls = 1.3 mH; torque constant, Kt = 0.49 Nm/A; voltage constant, Ke = 51 VLL/kr/min; rated speed, Nrated = 3000 r/min; no. of poles, P = 6.

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