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BLDC MOTOR-DRIVEN GRID INTERFACED SOLAR PV BASED WATER PUMPING USING ZETA CONVERTER

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Abstract: In this project zeta converter-fed brushless direct current (BLDC) motor drive as a cost-effective solution for low-power applications is presented. 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. By adjusting the dc link voltage of the voltage source inverter (VSI) feeding a BLDC motor, the speed of the BLDC motor is controlled. This paper deals with the implementation of pulse width modulated Zeta converter, lower total harmonic distortion factor and better efficiency. The proposed zeta converter based BLDC Motor drive is implemented to improve the efficiency of water pumping system and to obtain a wide range of speed control.

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

I INTRODUCTION

The drastic reduction in the cost of power electronic devices and annihilation of fossil fuels in near future invite to use the solar photovoltaic (SPV) generated electrical energy for various applications as far as possible. The water pumping, a standalone application of the SPV array-generated electricity, is receiving wide attention nowadays for irrigation in the fields, household applications, and industrial use. Although several researches have been carried out in an area of SPV array-fed water pumping, combining various dc–dc converters and motor drives, the zeta converter in association with a permanent-magnet brushless dc (BLDC) motor is not explored precisely so far to develop such kind of system. However, the zeta converter has been used in some other SPV-based applications [1]–[3]. 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 [4].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. On the other hand, a zeta converter exhibits the following advantages over the conventional buck, boost, buck–boost converters, and Cuk converter when employed in SPV-based applications.

1) 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.

2) This property also facilitates the soft starting of BLDC motor unlike a boost converter which habitually steps up the voltage level at its output, not ensuring soft starting.

3) Unlike a classical buck–boost converter [10], the zeta converter has a continuous output current. The output inductor makes the current continuous and ripples free.

4) Although consisting of same number of components as a 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 requirement of associated circuits for negative voltage sensing, and hence reduces the complexity and probability of slow down the system response [12].These merits of the zeta converter are favorable for proposed SPV array-fed water pumping system. An incremental conductance maximum power point tracking (INC-MPPT) algorithm [8], is used to operate the zeta converter such that SPV array always operates at its MPP.The existing literature exploring SPV array-based BLDC motor-driven water pump [19]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.

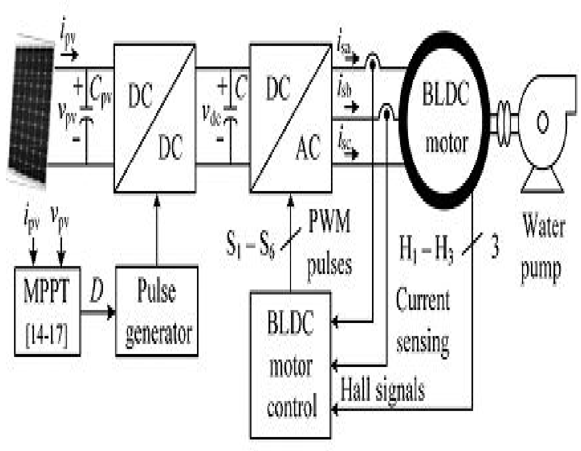

Fig.1. Conventional SPV-fed BLDC motor-driven water pumping system

Although a Z-source inverter (ZSI) replaces dc–dc converter in [22], other schematic of Fig.1 remains unchanged, 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 and drawbacks, a simple, cost effective, and efficient water pumping system based on SPV array-fed BLDC motor is proposed, by modifying the existing topology (Fig. 1) as shown in Fig.2. 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 and experimental performances are examined to demonstrate the starting, dynamics, and steady-state behavior of proposed water pumping system subjected to practical operating conditions. The SPV array and BLDC motor are designed such that proposed system always exhibits good performance regardless of solar irradiance level.

2 System Configuration

The schematic of proposed grid interfaced PV fed brushless DC motor driven water pumping system is shown in Fig2. A PV array of 6.4 kWp, possessing a sufficient power to run the water pump at its full capacity under the standard climatic conditions, feeds a BLDC motor via a boost converter and a VSI. The DC-DC boost converter and the VSI respectively carry out the MPPT of PV array and an electronic commutation of the motor. Three Hall Effect sensors are used to generate the commutation signals. A 6 pole, 5.18 kW BLDC motor which has a rated speed of 3000 rpm at 310 V (DC), is used to run the water pump. A single phase utility grid support is provided, via a bridge rectifier and a PFC boost converter, at the common DC bus of VSI. The power transfer is controlled by operating the PFC converter through a unidirectional power flow control. The developed control enables a power transfer from utility grid to the DC bus if a PV generated power is insufficient to meet the power demand, otherwise no power is transferred from the utility.

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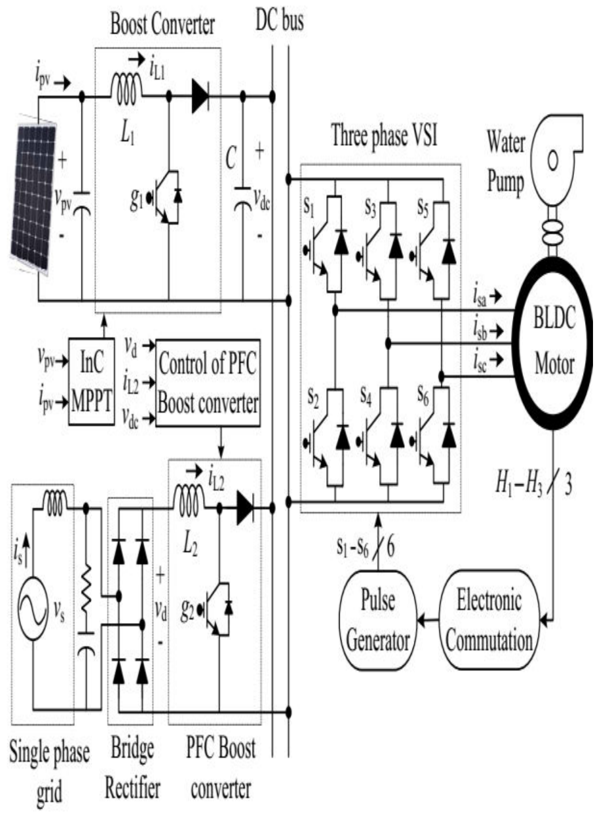

Fig.2 Schematic of proposed water pumping system

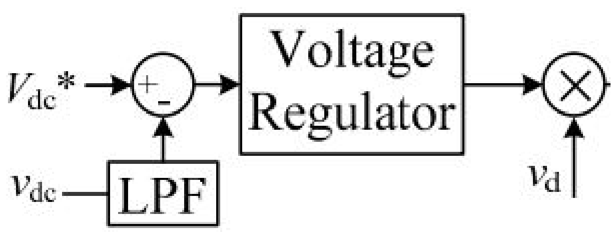

Fig. 3 Structure of the proposed unidirectional power flow control

3 Proposed Unidirectional Power Flow Control

The unidirectional power flow control, as its name implies, enables a power flow only in one direction i.e. from utility grid to the common DC bus. The control meets the power quality standards required by the grid in terms of total harmonic distortion (THD) and power factor (PF) [12]. The structure of the proposed control is illustrated in Fig.2. After passing through a low pass filter (LPF), the sensed DC bus voltage, vdc is compared with a reference value, Vdc* which is nothing but a rated DC voltage of the BLDC motor. The generated error is passed through a PI (proportional-integral) controller acting as a voltage regulator. The intention is to maintain the DC bus voltage at the rated voltage of BLDC motor irrespective of the operating conditions. Subsequently, the output of voltage regulator is multiplied with the rectified input voltage, vd to get a reference inductor current, i_{L2}*. This is made to configure a current flowing through the inductor, iL2 as the wave shape of vd, and place it in phase with the input supply voltage, vs. Consequently, the input supply current, is appears in phase with vs ensuring a unity power factor (UPF) operation. The sensed actual current, iL2 is compared with i_{L2}* and an error is passed through a hysteresis current controller to generate a gating signal for PFC boost converter. The PFC boost converter is designed and controlled to be operated in a continuous conduction mode (CCM). While regulating the DC bus voltage, the control decides whether the power from the utility is required to be transferred or not. Under the healthy climatic condition, the PFC converter is made indolent as the control obviates the power transfer. On the contrary, when the water pumping is required at night, the controller allows to draw a full amount of power required to run the pump at its full capacity. In between the two aforesaid circumstances, if a fraction of sunlight is available, a portion of power demand is met by the PV array, a transfer of remaining power is thereby permitted by the controller.

4 BLDC Motor Soft Starting And Speed Control

At standstill, due to the absence of back EMF (Electromotive Force) a high inrush current is drawn by the stator windings of the motor which may harm the windings and power devices of the converters. To prevent this current surges at starting, the pulse width of switching devices is modulated for a predefined interval. This practice slow down the rate of rise of winding current and hence confirms a safe starting. At certain speed, once a sufficient back-EMF is generated, the pulse width of switching devices is no longer modulated and a fundamental frequency mode of operation takes place.The speed of BLDC motor is maintained at its rated value, throughout the operation, regardless of the availability of sunlight such that the pump delivers a full volume of water. This is achieved by the DC bus voltage regulation. A concept of current sensor-less based speed control [6] is applied which eliminates the phase current sensors and governs the operating speed as per the DC bus voltage. So long as the power grid backup is available, the bus voltage is regulated, no matter what is the instant operating condition. However, in case the grid is not available, the DC bus voltage is not regulated at the rated DC voltage of BLDC motor under bad climatic conditions, and the speed is governed by a variable DC bus voltage.

5 CONFIGURATION OF PROPOSEDSYSTEM

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 detail.

6 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.4. 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

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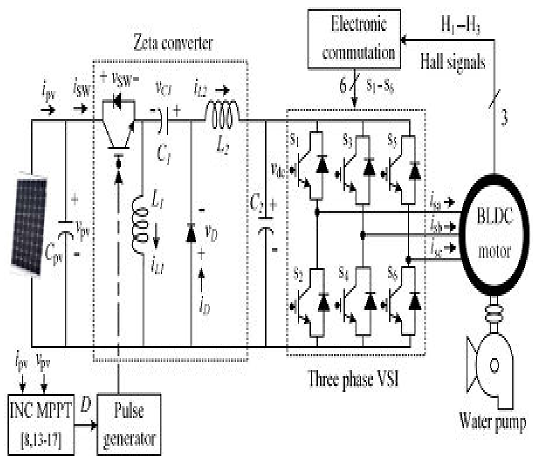
commutation of BLDC motor assisted by its built-in encoder. The high frequency switching losses are thereby eliminated, contributing in an increased efficiency of proposed water pumping system.



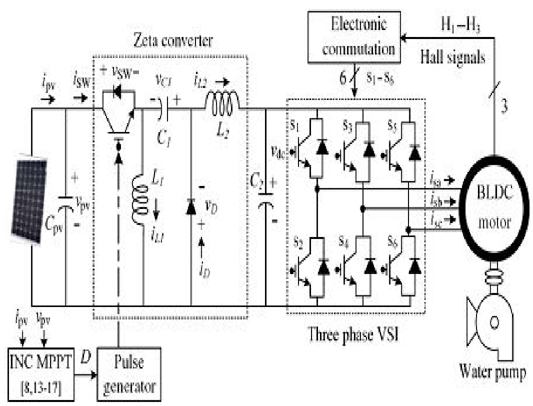


Fig.4. Proposed SPV-zeta converter-fed BLDC motor drive for water pump

7.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 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.

i) 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.

TABLE 1
Specifications of Sun module plus SW 280 mono SPV 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 MPP I_{mpp} is estimated as

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

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

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

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

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

Connecting six modules in series, having two strings in parallel, an SPV array of required size is designed for the proposed system.

(ii) 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 Dinitiates the design of zeta converter which is estimated as [6]

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

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

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

Then, L_1, L_2, and C_1 are estimated as

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

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

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

Where f_{sw} is the switching frequency of IGBT switch of the zeta converter; $\Delta I_{L1}$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 IL2=Idc; ΔVC1 is permitted ripple in the voltage across C_1, same as $V_{C1}=V_{dc}$.

VII .MATLAB/SIMULATION RESULTS

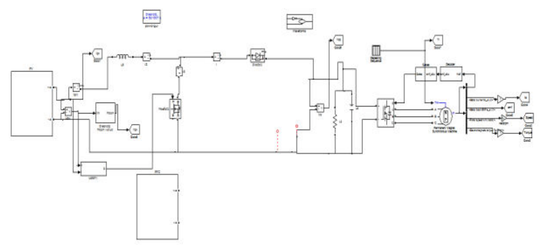

Fig 5 simulation circuit Conventional SPV-fed BLDC with motor-driven water pumping system

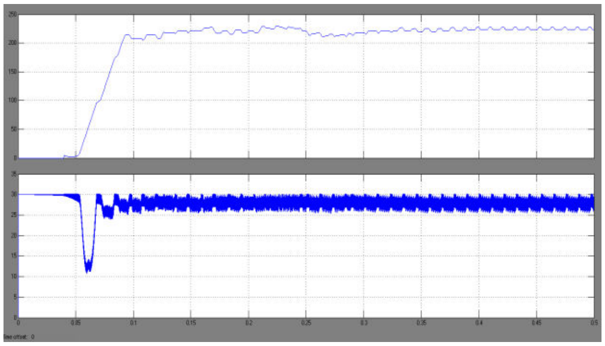

Fig6 Pv cell voltage and current waveforms Steady state behavior

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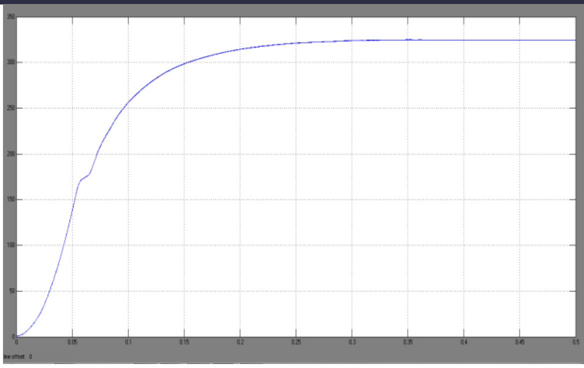
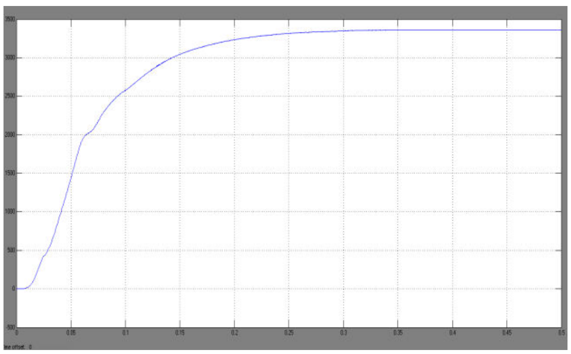
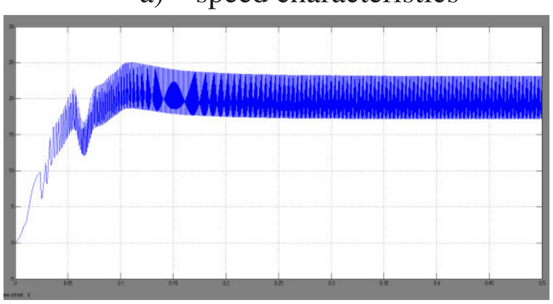


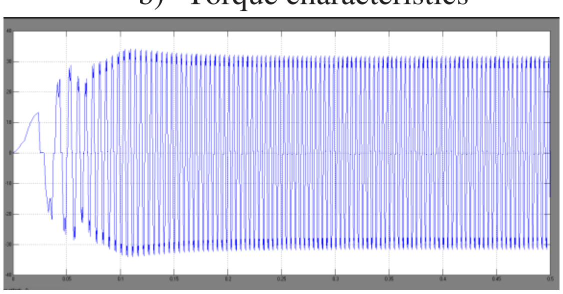
Fig7 Dc voltage of proposed concept Steady state behavior



a) speed characteristics

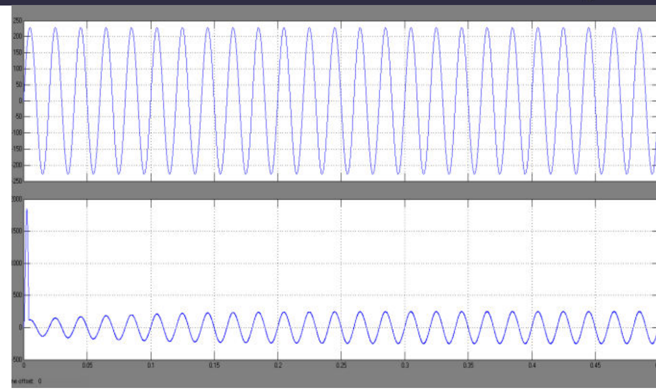


b) Torque characteristics

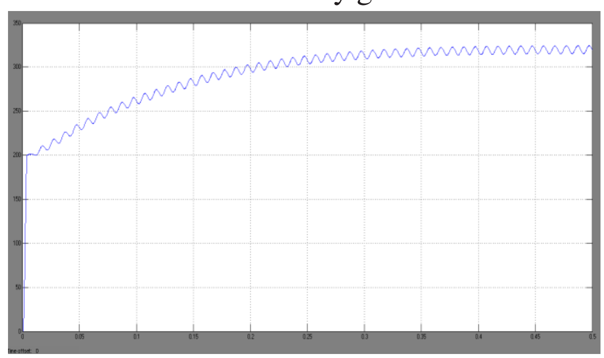


c) Current waveform

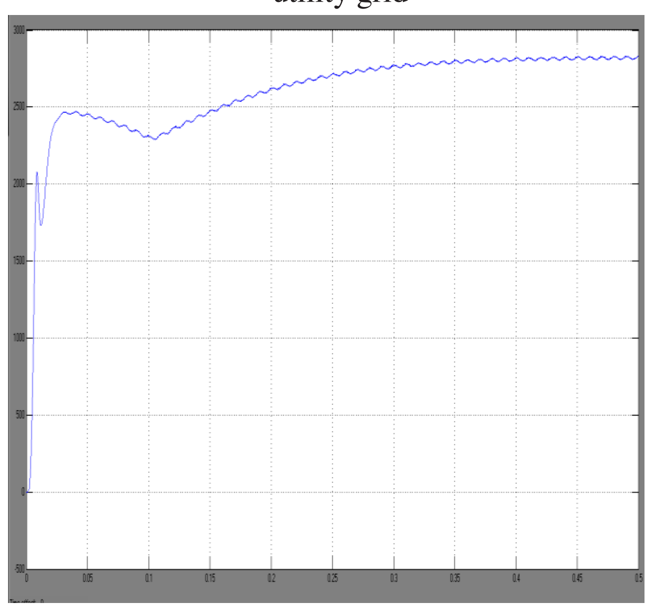
Fig 8 starting performance of BLDC motor-pump, when only PV array feeds Steady state behavior of BLDC motor-pump



(a) Vs and Is of Steady state behavior of utility grid



(b) Vdc of Steady state behavior of utility grid



© Speed characteristics BLDC MOTOR

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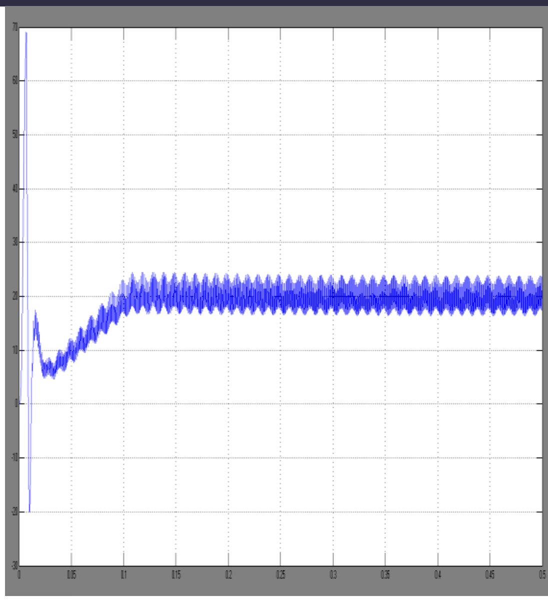
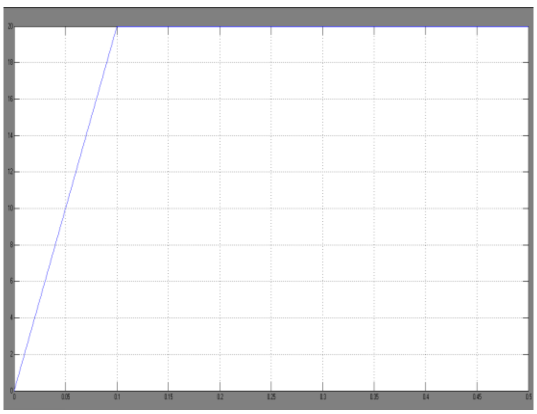
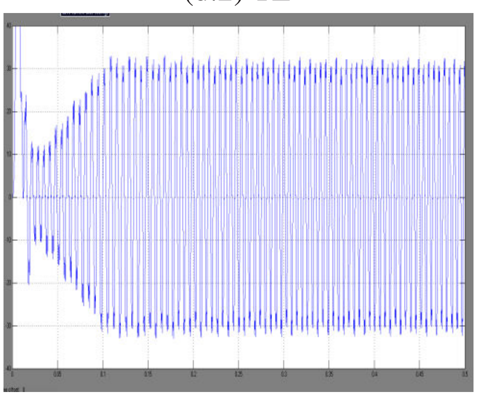


(d.1) Te



(d.2) TL



(e)current

Fig. 9 Steady state behavior of BLDC motor- pump, and THD and harmonic spectrum of supply current, when only utility grid feeds BLDC motor-pump

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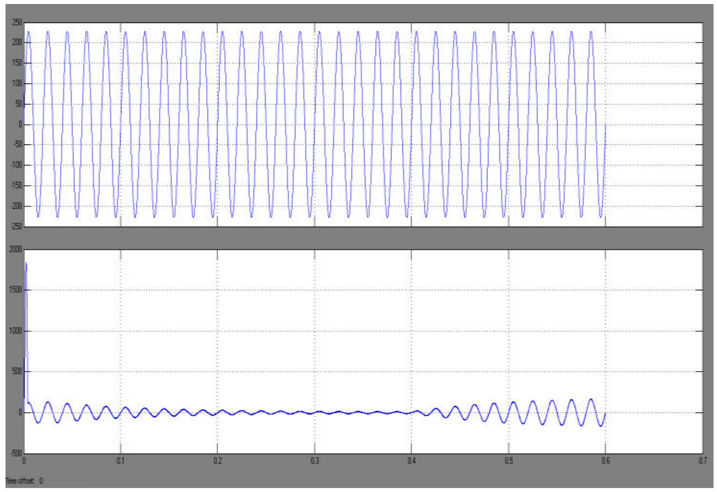
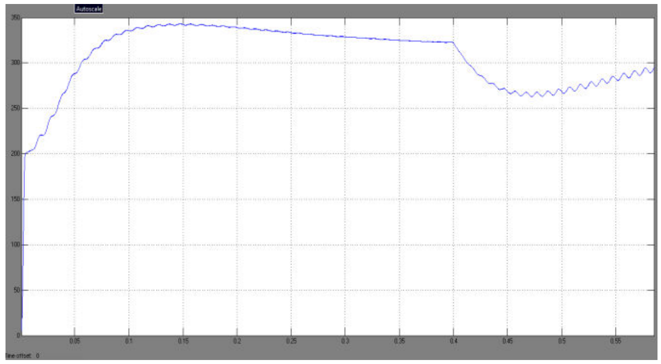
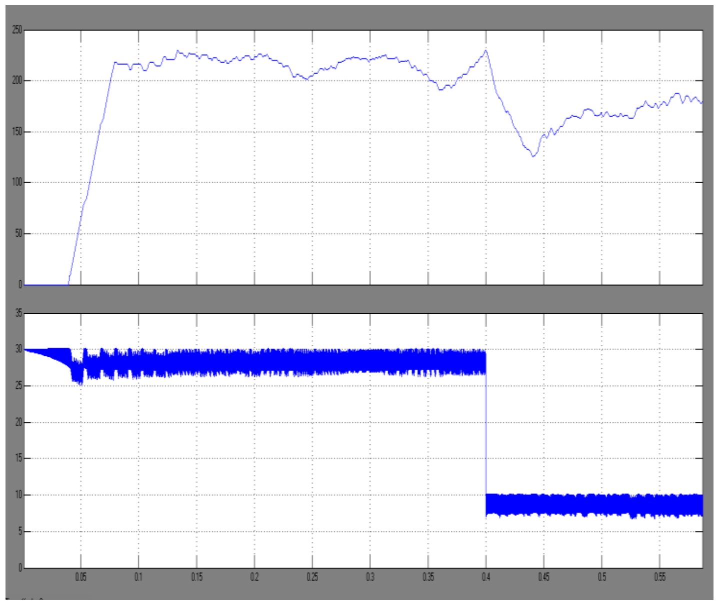


(a) Vs and Is



(b) Dc voltage



(c) Vpv and Ipv

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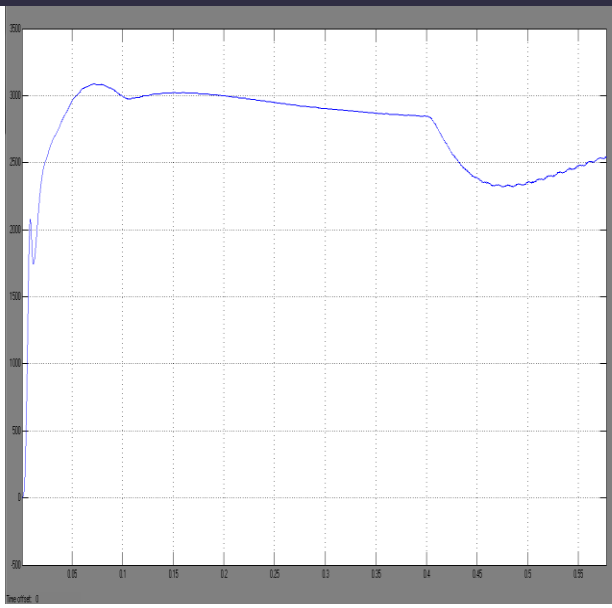
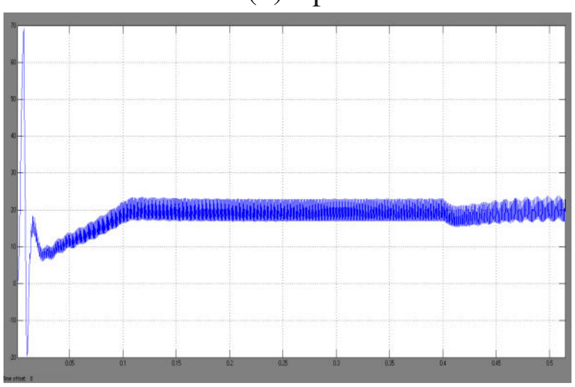


(d) Speed



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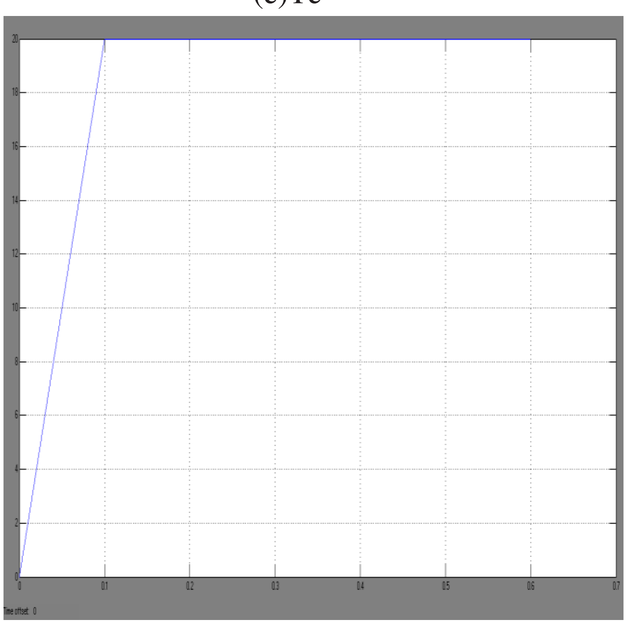
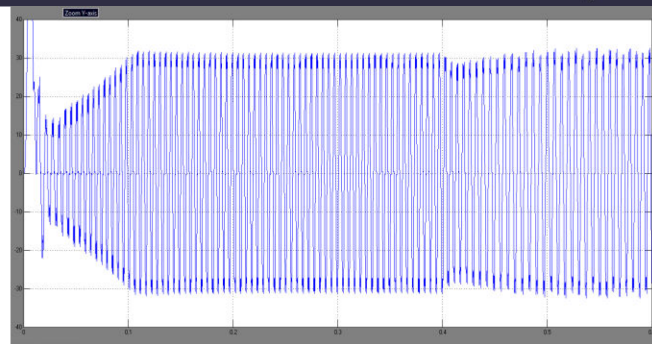
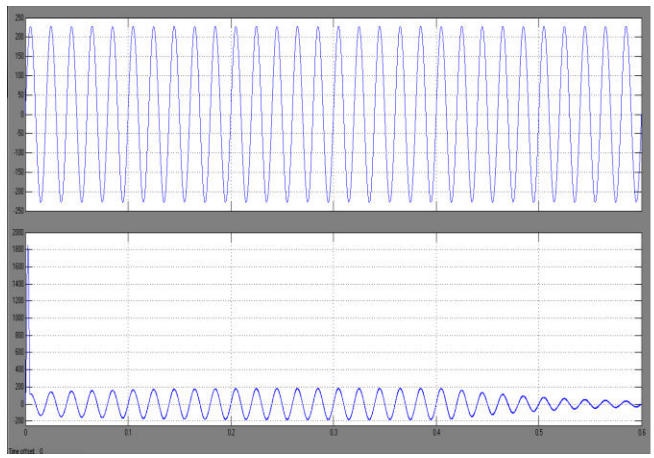


(f)TL

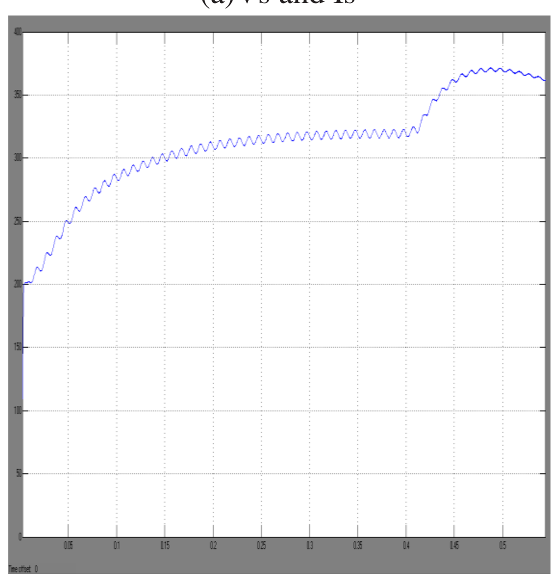


(g) current

Fig. 10 Dynamic behavior of PV array, utility grid and BLDC motor-pump, under a transition
From PV array feeding pump to both PV array and grid feeding pump



(a)Vs and Is



(b)dcvoltage

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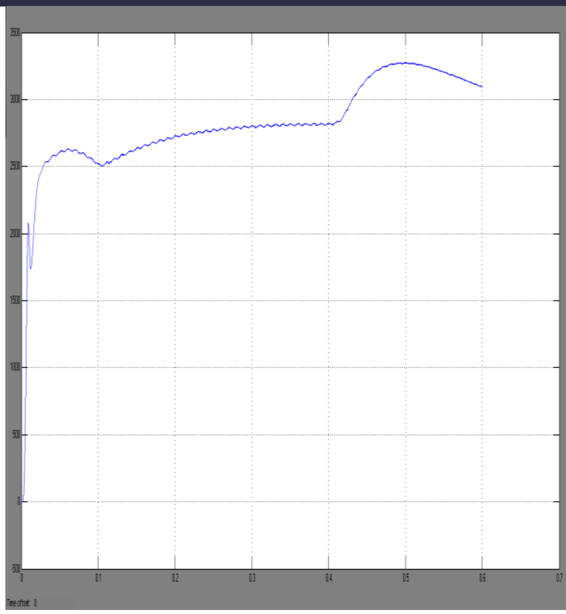

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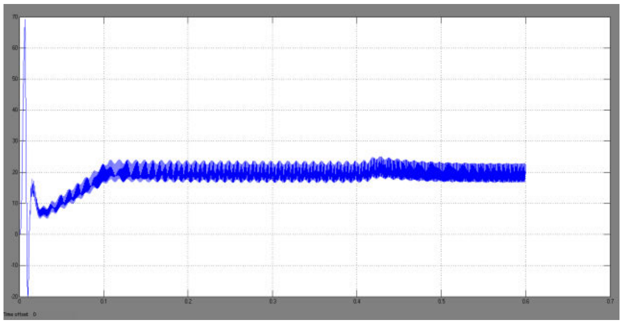
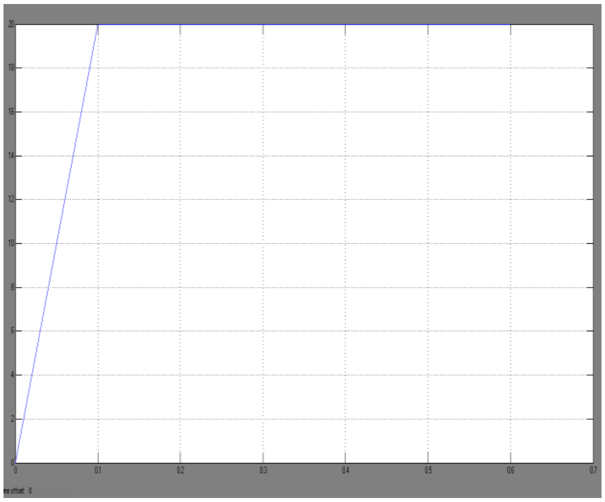
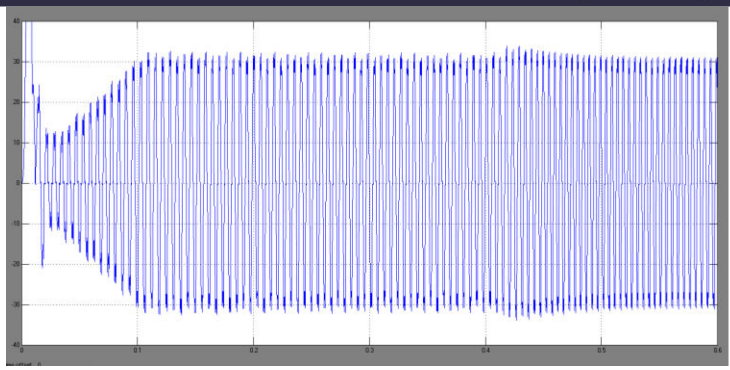


(d)Te



(e)TL



(f)current

Fig. 11 Dynamic behavior of PV array, utility grid and motor-pump, under a transition from grid feeding pump to PV array feeding pump.

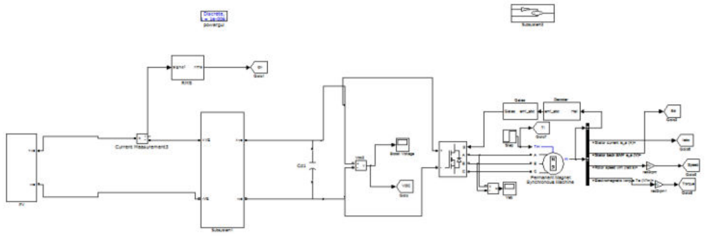
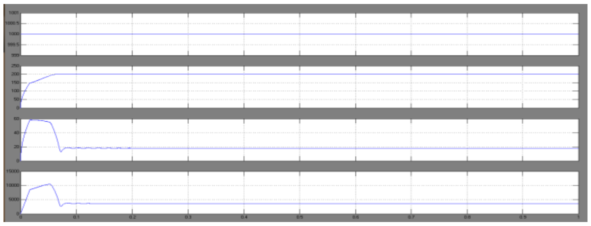
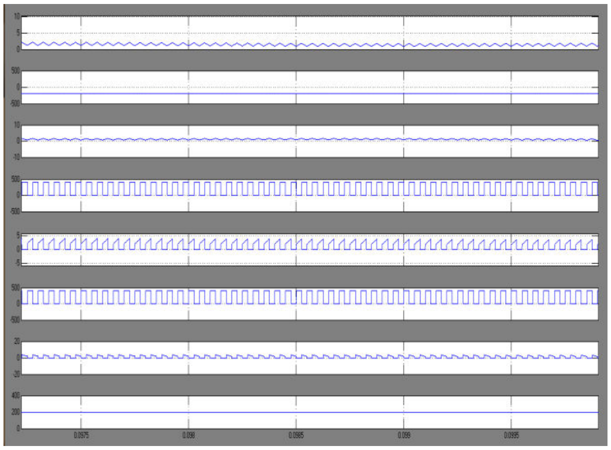


Fig 12 simulation circuit Conventional SPV-fed BLDC motor-driven water pumping system



(a)



(b)

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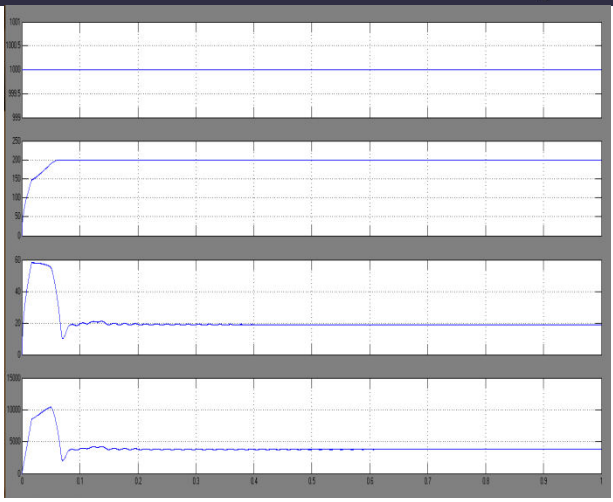
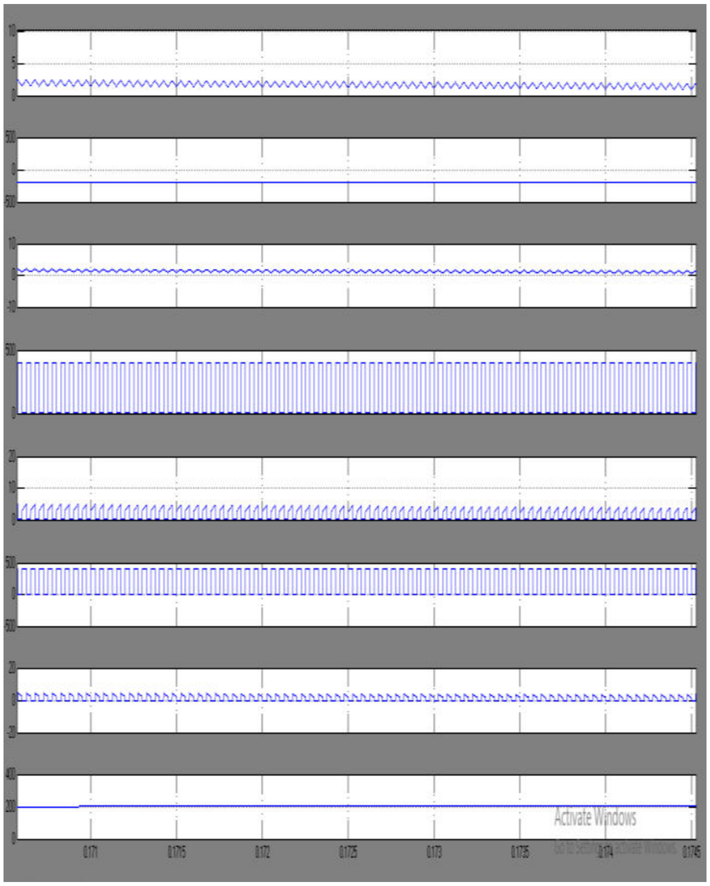
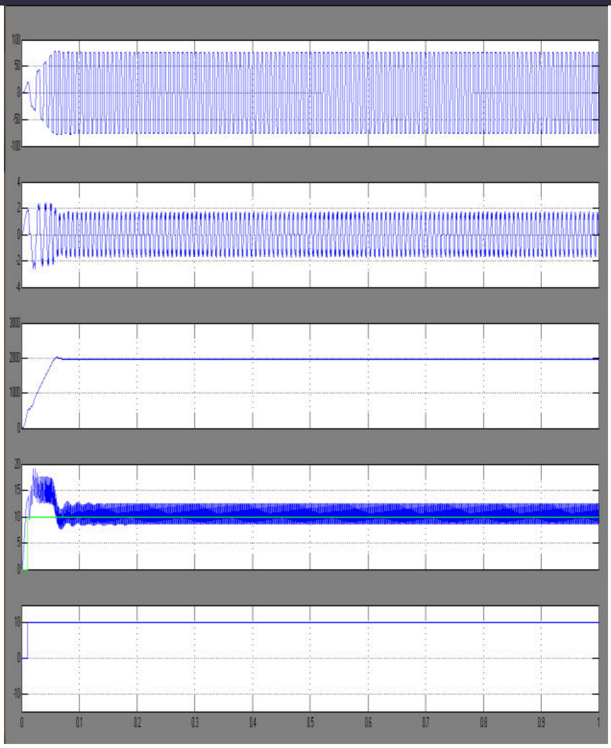


(a)



(b)



(c)

Fig 13 Starting and steady-state performances of the proposed SPV arraybased zeta converter-fed BLDC motor drive for water pump. (a) SPV array variables. (b) Zeta converter variables. (c) BLDC motor-pump variables

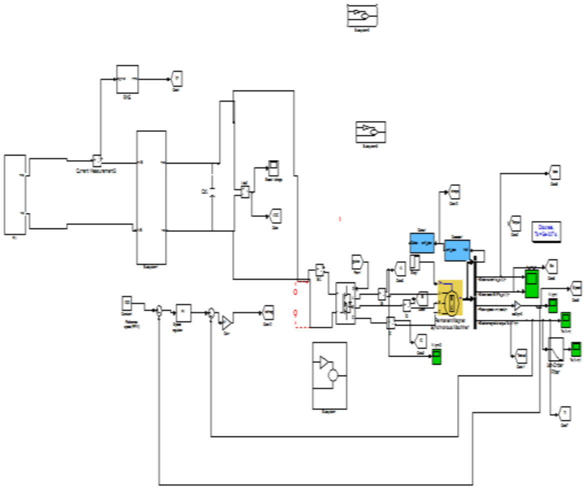
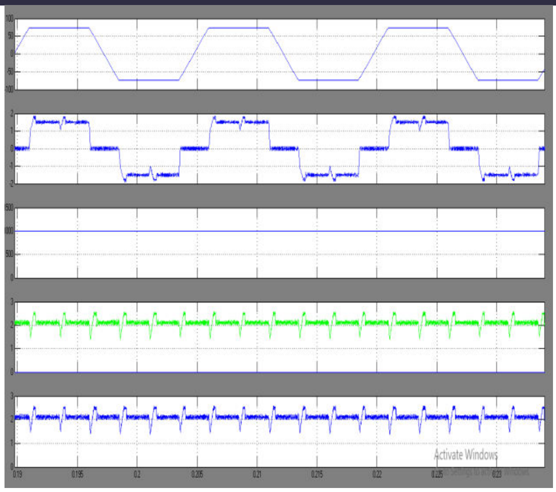


Fig 14 simulation circuit Conventional SPV-fed BLDC motor-driven water pumping system with speed controller



(c)

Fig 15 Starting and steady-state performances of the proposed SPV arraybased zeta converter-fed BLDC motor drive for water pump. (a) SPV array variables. (b) Zeta converter variables. (c) BLDC motor-pump variables with hysteresis voltage controller

CONCLUSION

The SPV array-zeta converter-fed VSI–BLDC motor-pump has been proposed and its suitability has been demonstrated through simulated results and experimental validation. The proposed system has been designed and 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 has operated with hysteresis voltage controller successfully even under minimum solar irradiance.

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