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Implementation of Solar Powered Brushless DC Motor Driven Water Pumping System using Quasi-Z Source Inverter

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Abstract: This work deals with designing a brushless DC (BLDC) motor driven water pumping system powered by a Solar Photovoltaic (SPV) array with Quasi-Z Source Inverter (q-ZSI). The Induction motor (IM) driven water pumps can be replaced by the BLDC motor driven water pumps due to its several advantages over IM. Also, the Quasi- Z source Inverter has various advantages over Current Source Inverter (CSI), Voltage Source Inverter (VSI) and Z-Source Inverter (ZSI) as it provides better shoot through states which in turn provides a single stage power conversion. The propriety of the proposed system is cleared through its performance analysis using MATLAB/Simulink based simulated results.

Keywords: SPV array, BLDC motor, Water pump, VSI, q-ZSI

I. INTRODUCTION

The foreknown worldwide energy crisis in near future due to the fast depletion of fossil fuels and a constant decrease in costs of SPV modules, power electronic components and microprocessors motivate the researchers and industrialists towards an effective use of Solar energy. A standalone PV powered water pumping system seems to be the most promising source in Off-Grid rural areas and an alternative to On-Grid pumping system areas which comes under improper billing schemes as discussed below.

Agricultural consumers, consume 26% of the electricity distributed by MSEDCL in India, but account for only 3% of the revenues. Currently, most farmers are charged on a “per hp” basis, as opposed to on a “per unit” basis like most of us. And the rate is Rs.3, 000 per hp, in return for getting 24*7 electricity supply. So if a farmer has a 3 hp pump in his farm, he will be charged Rs.9, 000 per year, irrespective of how much electricity he consumes. However, farmers do not get 24*7 electricity, they typically get it for eight hours, and many times they get it from midnight to 8 a.m. MSEB needs to provide electricity to farmers when they need it. And farmers need to pay for what they use. Granted that MSEB is not giving them 24*7 electricity as promised, but if they are giving them electricity for eight hours, the farmers’ needs to pay at least 1/3rd of the amount that they owe to MSEB, which is not the case. Thus, a standalone PV powered water pumping system seems to be the most promising and attractive for pumping system infarming.[6]
The BLDC motor is attracting growing attention for automotive and pumping applications. The BLDC motor has a number of advantages suchas high efficiency, better speed torque characteristics, higher speed ranges and low maintenance cost. Among them, the efficiency is the main reason for electric water pumps. BLDC motor drive is a promising solution to the problem of the bad environmental impacts of water pumps which are based on induction motor. Due to the low efficiency of the current residential water pumps a high energy cost is paid by every household. For reducing energy consumption, improved efficiency and reduced volume and weight, induction motor driven water pumps are replaced by the BLDC drive water pumps.[1]

The VSI fed BLDC motor are widely used because of its better performance at low speed but the traditional CSI and VSI cannot provide the wide range of obtainable voltage. The ZSI employs a unique impedance network to couple the circuit to the power source. There are several disadvantages of the ZSI such as input current is discontinuous and capacitor has high voltage stress that overcomes by theq- ZSI. The q-ZSI is also suitable for applications which require large range of gain such as in motor controllers or renewable energy sources and it has several advantages such as: reduce source stress, lower component ratings and simplified control strategies.[1]

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II. CONVENTIONAL TOPOLOGY

The conventional topologies of SPV fed BLDC motor driven water pumping system adopt two stage solar energy conversion systems, which necessarily require an intermediate DC-DC converter to optimize the operating power point of a PV array. This power conversion stage causes an increased cost, size, complexity and reduced efficiency. Figs. 1 represents the schematics of the conventional brushless DC motor drive for PV-water pumping. The maximum power point tracking (MPPT) is performed by a DC-DC converter. Two phase currents are required to be sensed for motor control. A DC-DC converter is used to maximize the operating power of a PV array, speed control of a BLDC motor-pump, and soft starting. A bulky capacitor is required at the DC link due to adopting a topology which implements fundamental frequency operation of VSI.[2]

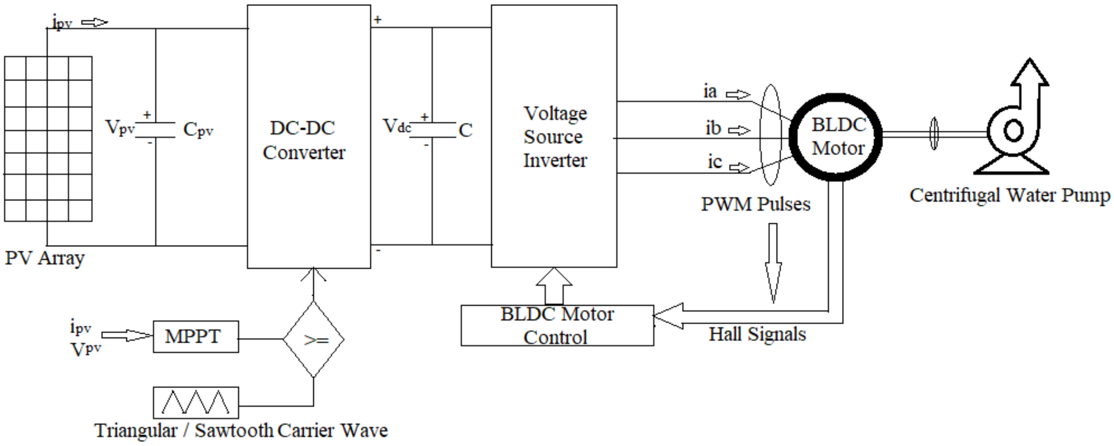

Figure1. Conventional BLDC motor driven water pumping system based on a two stage solar PV energy conversion system.

III. PROPOSED SPV FED QZSI FED BLDC MOTOR DRIVE FOR WATERPUMP

The quasi -Z source topology consists of an inverter drawing a constant current from the PV array and is capable of handling a wide input voltage range .It also features lower components ratings and reduced source stress compared to the traditional ZSI. By using this quasi-Z source topology, the inverter draws a constant current from the PV array and is capable of handling a wide input voltage and current range. Figure 2 represents the qZSI fed BLDC motor driven pumping system using PVarray.[7]

The qZSI has two types of operational states at the dc side: the non-shoot-throughstates (i.e. the six active states and two conventional zero states of the traditional VSI)and the shoot-through state (i.e. both switches in at least one phase conductsimultaneously).

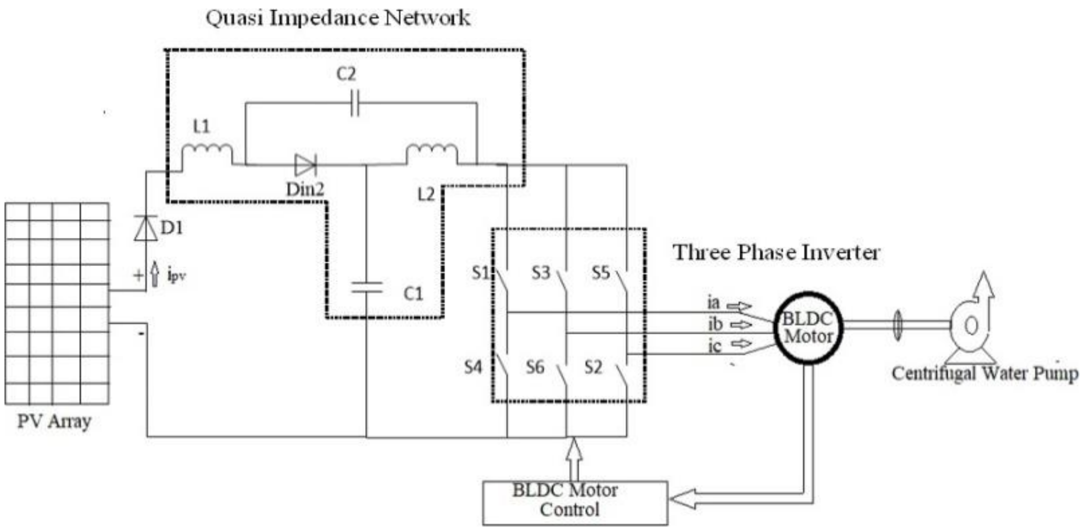

Figure 2 qZSI fed BLDC motor driven pumping system using PV array

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This shoot-through state is forbidden in the traditional VSI, becauseit will cause a short circuit of the voltage source and damage the devices. The qZSIprovides a unique LC and diode network connected to the inverter bridge whichmodifies the operation of the circuit, allowing the shoot-through state. This networkwill effectively protect the circuit from damage when the shoot-through occurs and byusing the shoot-though state, the (quasi-) Z-source network boosts the dc-link voltage.The major advantage of qZSI over ZSI is: it draws a continuous constant dc currentfrom the source while the ZSI draws a discontinuous current and the voltage oncapacitor C2 is greatly reduced. Thus, the continuous and constant dc current drawnfrom the source with this qZSI make this system especially well-suited for PV power conditioning systems.[10]

IV. CONFIGURATION AND PRINCIPLE OF OPERATION

Figure 2 represents the proposed BLDC motor-water pumping system basedon single stage Solar PV energy conversion system using quasi impedance network.The solar PV array is connected to quasi impedance network to boost the voltage and achieve protection against damage due to short circuit of the PV array which may occur during shoot through state. This PV array connected impedance network is further connected to three phase inverter which transfers power to the BLDC motor to achieve pumping through centrifugal pump. qZSI uses two inductors and two capacitors in order to boost the DC input voltage when it is needed.

V. DESIGN OF PROPOSED WORK

A. Design of Solar PVArray

For designing the Solar PV Array, MATLAB block available from NREL System Advisor Model (Jan. 2014) is used. Module used in the project work is ALFASOLAR M6L60-250. Array is formed by adding 8 solar modules in series in one string. The parameters of module are given in table 1.

Table 1 Solar Module Parameters

Maximum Power (Wmp)	250.2672 W
Cells per module (Ncell)	60
Open circuit Voltage (Voc)	37.75 V
Short Circuit Current (Isc)	8.71 A
Voltage at maximum power point (Vmp)	30.67 V
Current at maximum power point (Imp)	8.16 A
Temperature coefficient of Voc	-0.33729 %/deg C
Temperature coefficient of Isc	0.034397 %/deg C

B. Design of Quasi Z-Source Inverter

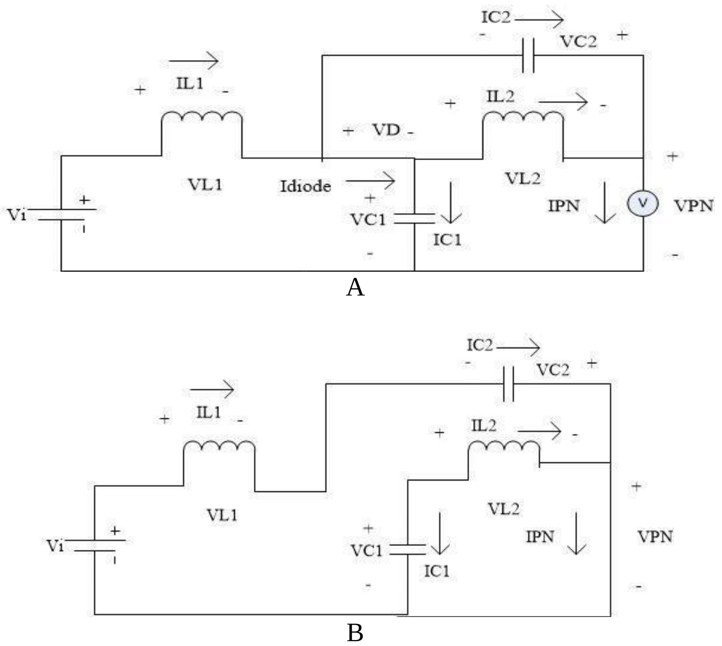

Figure 3. Circuit Arrangement during A. Non shoot through states B. Shoot through states

Voltage and Current polarities are as shown in figure 3A and 3B. Assuming that during one switching cycle, T, the interval of the shoot through state is T0; the interval of non-shoot-through states is T1; thus one has T = T0 + T1 and the shoot- through duty ratio, D= T0 /T. During the interval of the non-shoot-through states, T1, one canget,

$$V_{L1}=V_i-V_{C1} \qquad V_{L2} = -V_{C2}$$

$$V_{PN}=V_{C1}-V_{L2}=V_{C1}+V_{C2} \qquad V_D=0 \tag{1}$$

The interval of the shoot-through states, T_0, one can get,

$$V_{L1}=V_i+V_{C2} \qquad V_{L2}=-V_{C1}$$

$$V_{PN}=0 \qquad V_D= V_{C1}+V_{C2} \tag{2}$$

At steady state, the average voltage of the inductors over one switching cycle is zero. Thus,

$$V_{C1}=\frac{T_1}{T_1-T_0}\times V_i \qquad V_{C2}=\frac{T_0}{T_1-T_0}\times V_i \tag{3}$$

The peak dc-link voltage across the inverter bridge is

$$V_{PN}= V_{C1}+V_{C2}=B\times V_i \tag{4}$$

Where B is the boost factor of the qZSI. This is also the peak voltage across the diode. The average current of the inductors L_1, L_2 can be calculated by the system power rating P

$$I_{L1}=I_{L2}=I_i={}^{P}/_{V_i} \tag{5}$$

According to Kirchhoff's Current law,

$$I_{C1}=I_{C2}=I_{PN}-I_{L1} \qquad I_{diode}=2\times I_{L1}-I_{PN} \tag{6}$$

The inductors in the qZSI network will limit the current ripple through the devices during boost conversion mode. During shoot-though, the inductor current increases linearly. With the maximum constant boost control mode, the shoot through interval, T0, is evenly split into two intervals of half the duration. Choosing an acceptable peak to peak current ripple, rc%, can be calculated by,

$$L_1 = L_2 = \frac{V_L \Delta T}{\Delta I} \approx 365\mu H \tag{7}$$

The two capacitors are in series in the qZSI network when in the non-shoot-through states. These two capacitors absorb the current ripple and limit the voltage ripple on the inverter bridge so as to keep the output voltage sinusoidal. Assuming that the capacitance should be the same for each capacitor, the capacitance needed to limit the PN voltage ripple by r_v%, can be calculated by,

$$C_1 = C_2 = 2 \times \frac{I_C \Delta T}{\Delta(V_{C1} - V_{C2})} \approx 370\mu F \tag{8}$$

C. Design of BLDCmotor

The BLDC motor block used in the work is Permanent Magnet Synchronous Machine block. The three-phase machine can have sinusoidal or trapezoidal back EMF waveform. The rotor can be round or salient-pole for the sinusoidal machine, it is round when the machine is trapezoidal. Preset models are available for the Sinusoidal back EMF machine. The parameters used in the work are shown in table2.

Table 2. BLDC motor parameters

Number of phases	3
Back EMF waveform	Trapezoidal
Mechanical input	Torque Tm
Stator phase resistance (Rs)	18.7 ohm
Stator phase inductance (Ls)	8.5 mH
Machine Constant Flux linkage	0.1717 V/s

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The overall simulation model is shown in figure 4.

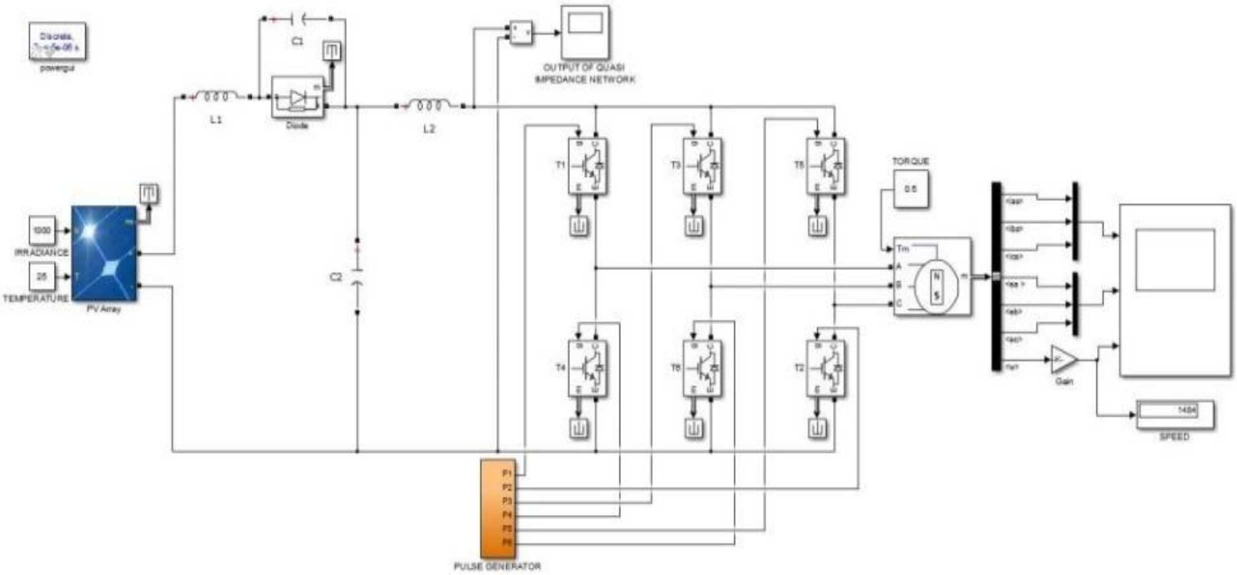

Figure 4 Simulation model of proposed work

VI. SIMULATED PERFORMANCES

A. Performance of PVArray

The I-V characteristic of solar PV array is shown in figure 5. The I-V curve is also used to compare the performance of PV / Solar Modules. The curve is, therefore generated based on the performance under Standard Test Conditions (STC) of sunlight and device temperature of 25 Â°C. It assumes there is no shading on the device. Standard sunlight conditions on a clear day are assumed to be 1,000 Watts of solar energy per square meter (1000 W/m2 or 1kW/m2).

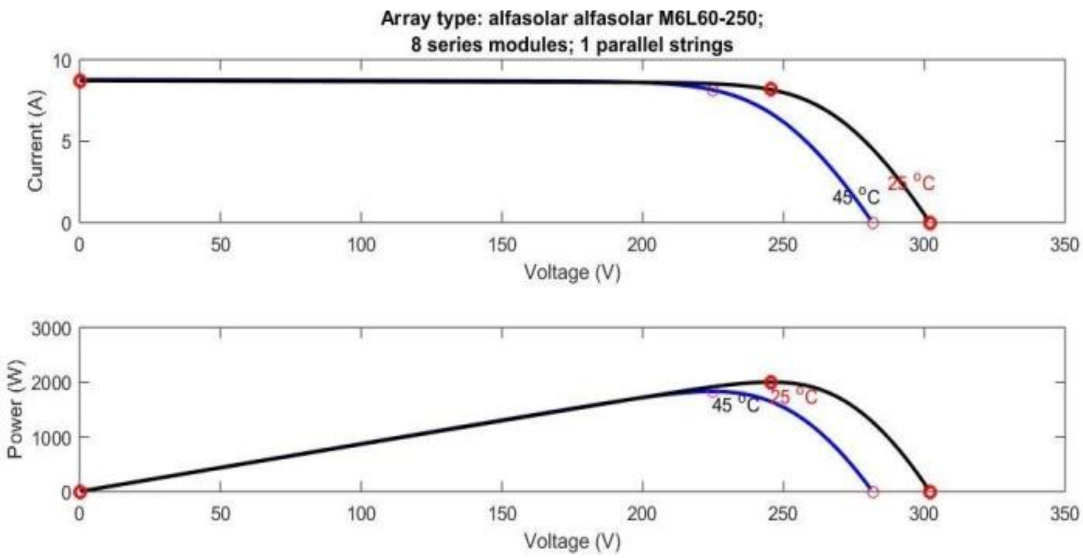

Figure 5. I-V Characteristics of PV array

B. Performance of Quasi Z-source inverter

The fundamental advantage of quasi impedance network is that it boosts the voltage obtained by Solar PV array (which is 246 Volt). This boost in supply voltage was achieved from 246 V to 289 V as shown in figure 6.

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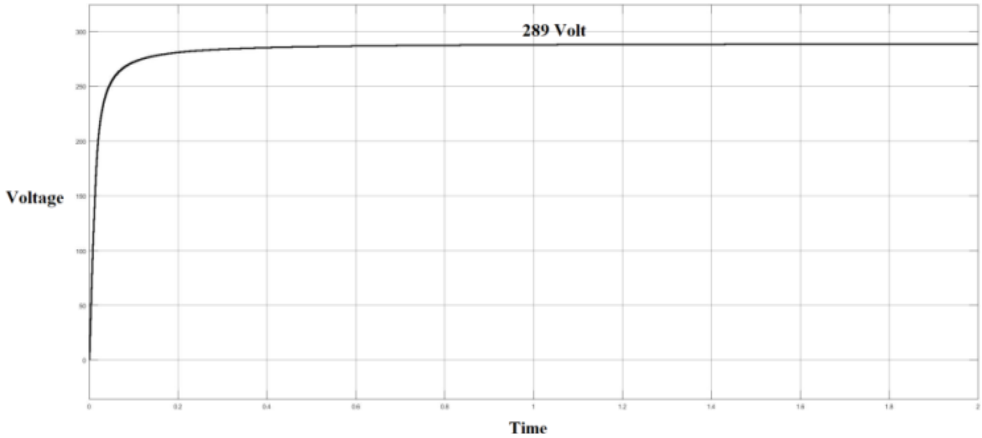
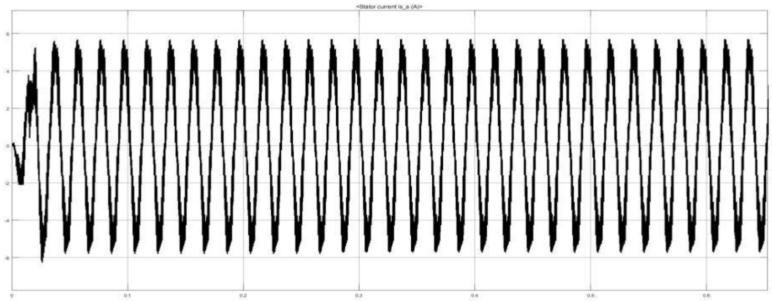


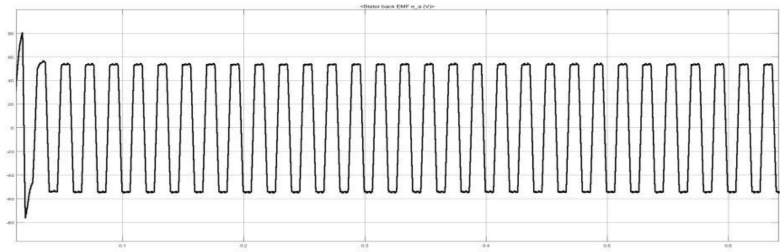
Figure 6 Simulated result obtained by Quasi Impedance Network

C. Performance of BLDC motor pump

The basic requirement of a centrifugal water pump is that it must be rotated at a speed of 1100 rpm. Here, the motor-pump attains speed of 1487 rpm to 1500 rpm which serves the purpose and is slightly higher than the rotor speed of 4 poles IM. Figure 7 represents the phase 'a' stator current, Stator back EMF of phase 'a' and speed of BLDC motor pump.



A



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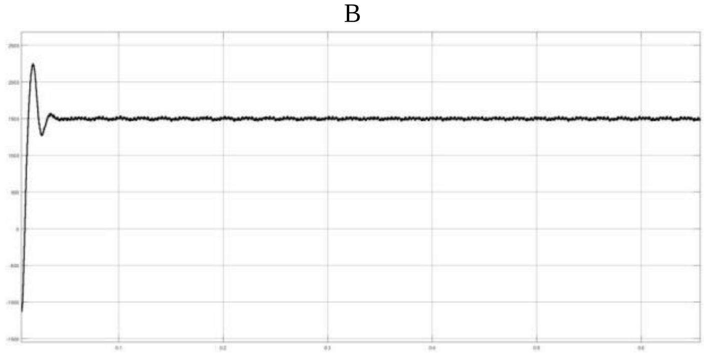

C

Figure 7 Simulation results of BLDC motor pump A. Stator Current of phase 'a' BLDC motor pump B. Stator Back EMF of phase 'a' of BLDC motor pump C. Speed of BLDC motor pump

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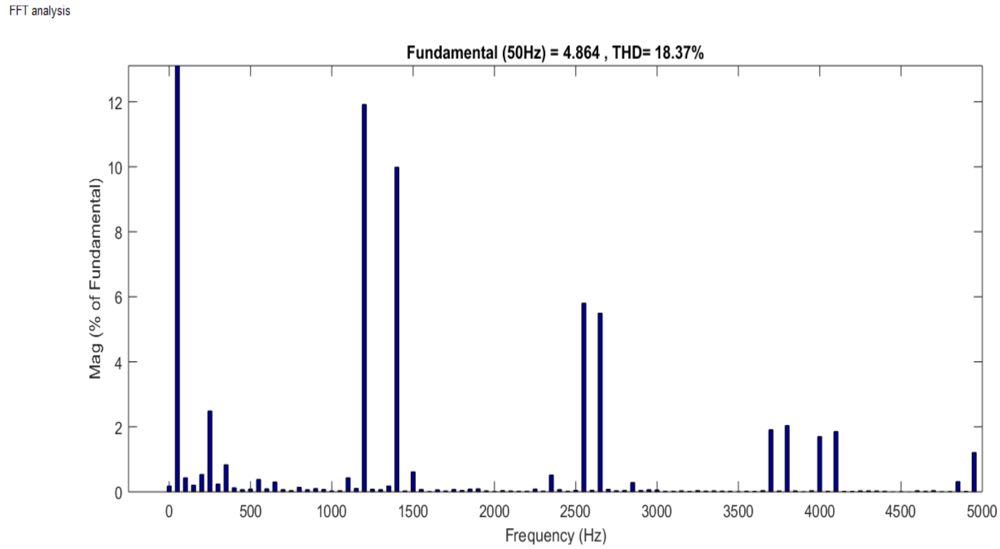
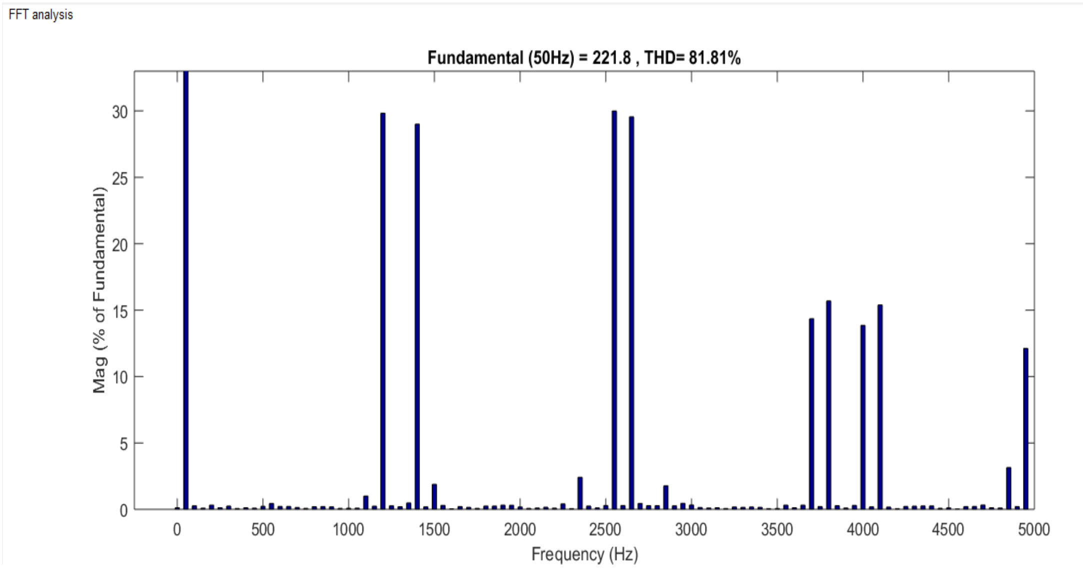
Figure 8 represents the harmonic analysis of the proposed work which shows the total harmonic distortion (THD) of Stator current and Phase Voltage is 18.37 and 81.81 percent respectively.



A



B

Figure 8 Harmonic analysis of BLDC stator Current (A) and Phase voltage (B)

CONCLUSION

The proposed BLDC motor driven water pumping system based on a solar fed three phase inverter employing quasi impedance network has been validated through a demonstration at steady state conditions. The system has been simulated using the MATLAB Simulink software. It inherits all the advantages of the ZSI and features its unique merits. The topology of the proposed system has provided a single stage DC-DC power conversion along with boost in voltage for PV fed brushless DC motor driven water pumping. Also, the current sensing elements for motor have been eliminated, resulting in a simple and cost-effective setup. By using SPWM technique particular switching pulses can be obtained specially during starting conditions so that the starting current is limited within permissible values which in turn provide soft starting of the motor- pump without using any additional circuits. The proposed topology has ultimately manifested its superiority over ZSI on behalf of current and voltage THD, continuous input current, reduced source stress, and lower component ratings which has been seen to be relatively less in qZSI.

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