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Modeling of Solar Power Based Quasi-Z-Source Inverter to Supply BLDC Motor

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Abstract: In the present world, conventional sources of energy are depleting at a faster rate because of its increased consumption. Renewable sources of energy are the better alternatives for this problem and among this solar energy is the best solution. Among the various PV (photovoltaic) applications, water pumping system using solar energy is growing in interest in isolated areas, where grid availability is difficult. The water pumping system can be driven by DC or AC motor but Brushless DC Motor (BLDCM) which has higher efficiency, lower power range, and simple structure; hence BLDCM is the best option for this application. The conventional PV water pumping system uses two conversion stages; however this problem can be eliminated by quasi-Z-source inverter (qZSI). The qZSI utilizes an LC network and uses shoot-through states, thus reduces the number of power switches, switching losses and cost. An MPPT (Maximum Power Point Tracking) can be controlled to extract the maximum power from PV array. The water pumping system using PV array, MPPT, qZSI and BLDC motor are modeled in Matlab/Simulink.

Keywords: Photovoltaic (PV) array, Maximum Power Point Tracking (MPPT), quasi-Z-source inverter (qZSI), Brushless DC Motor (BLDCM).

I. INTRODUCTION

As the consumption of the conventional sources of energy is increasing at a faster rate, it becomes inevitable to find an alternative source for the sustainability of the environment. Among the various renewable energy sources available, solar energy is the best alternative as it is ultimate free abundant energy source. In future, solar energy will be dominating other energy sources because of its numerous advantages.

Solar energy finds application in industries as well as for residential purposes. In remote areas, stand–alone photovoltaic (PV) water pumping system can be used for agriculture and household purposes. This is because of the difficulty of grid accessibility in isolated remote regions [1]. Most commonly used motors for PV powered pumps are DC and AC motors. System based on DC motor [2] has demerits such as high cost, frequent maintenance, heavy weight etc. Most of the pumping systems are based on AC motor such as induction motor [3] and single phase induction motor is commonly used for residential applications. But they involve complex control circuits. Hence the problems of AC and DC motor can be solved by the use of permanent magnet brushless DC motor (PMBLDC) motor in the water pumping system. The Brushless DC (BLDC) motor has advantages such as less maintenance, higher efficiency and better dynamic performance [8]. A quasi-Z-source inverter (qZSI) is used to extract maximum power from PV array and feeds the BLDC motor [5],[6],[7] and thus overcomes the problems of conventional two stage converters The qZSI has all the features of ZSI [4] and in addition it has an advantage of lower voltage rating components as compared to ZSI. The paper presents the Matlab/Simulink model of the water pumping system. Fig.1 shows the block diagram of the system. It consists of a PV array, a three phase qZSI, a BLDC motor and the control system.

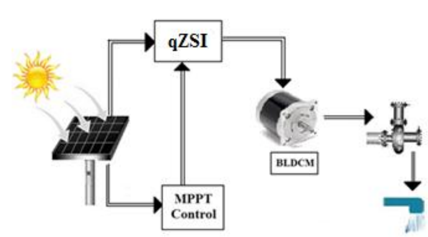

Fig.1 PV Water Pumping System

II. MODELING OF PV ARRAY

The solar cell is the basic unit of PV module and it is an electrical device that converts the energy of light directly into electricity by the photovoltaic effect. A solar panel is a collection of solar cells. Lots of small solar cells spread over a large area can work together to provide

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enough power to be useful. The more light that hits a cell, the more electricity it produces. The output current of the solar cell is directly proportional to the irradiation level of the light falling on the cell. Fig.2 shows the equivalent circuit of the solar cell [9], [10]. The non-linear relationship between V_{pv} -I_{pv} of a solar cell is:

$$V_c = \frac{AkT_C}{e} \ln\left\{\frac{I_{ph} + I_0 - I_C}{I_0}\right\} - R_S I_C \quad (1)$$

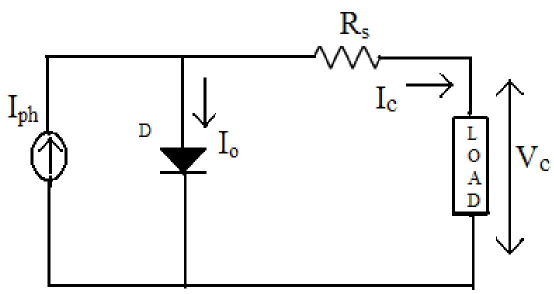

Fig.2 Equivalent Circuit of a Solar Cell

where,

V_c : Cell output voltage
A : curve fitting factor
k : Boltzmann constant (1.38×10^{-23} J/^{o}K).
T_C : Reference cell operating temperature
e : electron charge (1.602 × 10-19 C).
I_{ph} : Photocurrent, function of irradiation level and junction temperature
I_0 : reverse saturation current of diode
I_C : Cell output current
R_S : Series resistance of cell

The power obtained from the solar panel can be increased by increasing the number of series and parallel cells used in the PV array. Based on the irradiation and temperature levels, the voltage and current from the PV array may vary. Fig.3 shows the V_{pv} –I_{pv} and P_{pv}-V_{pv} characteristics of PV array. The parameters used for the modeling of solar panel are given in Table 1.

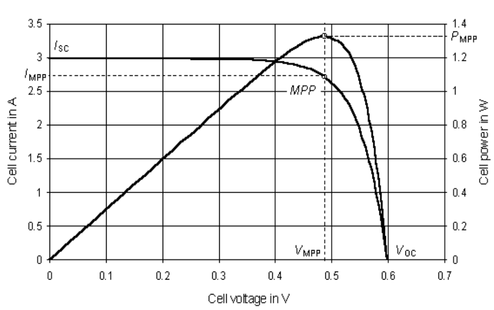

Fig.3 I-V & P-V Characteristics of PV cell

TABLE I
SIMULATION PARAMETERS OF SOLAR CELL

Short circuit current	2.926 A
Open circuit voltage	19.39 V
Series Resistance	0.0277Ω
Reverse saturation current	0.0005A

III. MAXIMUM POWER POINT TRACKING

On every P_{pv}-V_{pv} characteristics, there is only a single operating point where the maximum power can be extracted. This operating point for PV array is called Maximum Power Point (MPP) and the process of operating PV module at this condition is called Maximum Power Point Tracking (MPPT). There are several methods for finding MPPT. In this paper Perturb and Observe (P&O) method [11] is used. Fig.4 shows the flowchart of P&O algorithm.

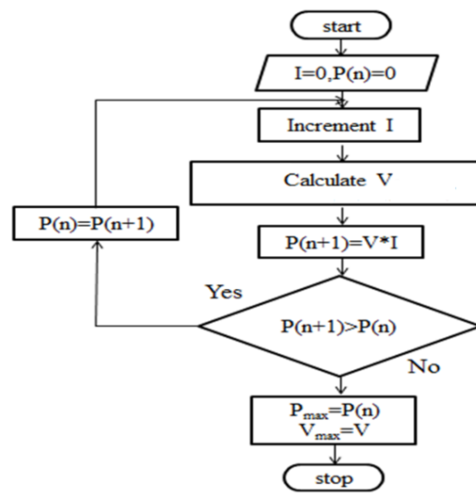

Fig.4 Flowchart of the P&O Algorithm

In the P&O method the output terminal voltage of the PV is periodically incremented or decremented and the power of the current cycle is compared with that of the power of the previous cycle. The control system changes the operating point in that direction if the voltage changes and the power increases else change the operating point in the opposite direction. The current is varied at a constant rate once the direction for change of current is known. This rate is a parameter which should be adjusted to allow the balance between faster responses with less fluctuation in steady state.

The P&O algorithm is simple and can be easily implemented. However it has a drawback of oscillating around the maximum power point because of the perturbing process to find the maximum power point.

IV. MODELLING OF QUASI-Z-SOURCE INVERTER

In conventional Voltage Source Inverter (VSI), there are eight switching states i.e., six active states and two

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zero states and in this case two switches in the same phase-leg cannot be turned on simultaneously which will damage the circuit. This problem can be eliminated by quasi- Z-source inverter (qZSI) [12] that has nine switching states in which eight switching states are the same as that of the VSI and the ninth switching state is the shoot through state. In shoot-through state, both switches within the same phase-leg can be turned on simultaneously so as to boost the input voltage.Fig.5 shows the equivalent circuit of qZSI.

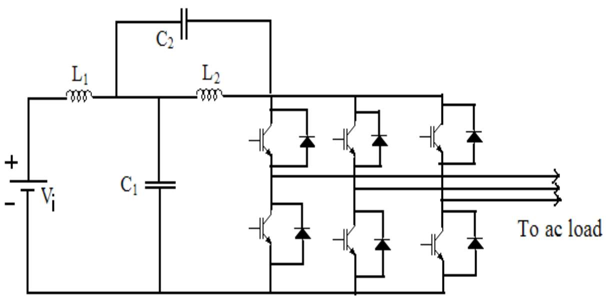

Fig.5 Equivalent Circuit of qZSI

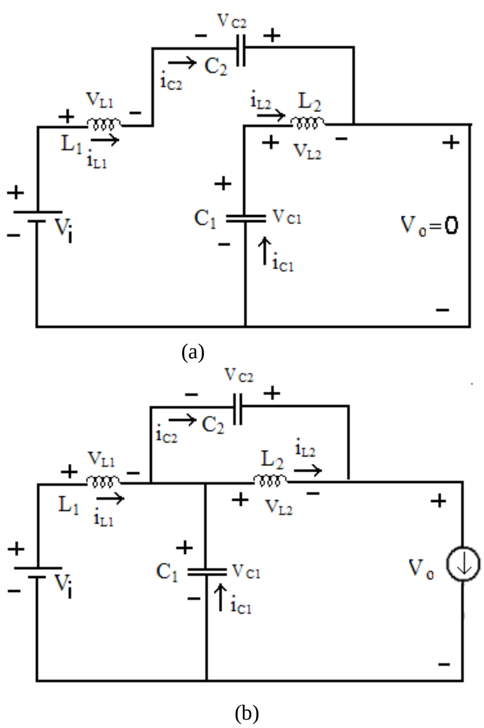

Fig.6 qZSI circuit during (a) Shoot-through mode
(b) Non-shoot through mode

Fig.6 shows the equivalent circuit of qZSI during the shoot through and non-shoot through states.

During the shoot through state for duration of T_0, the following equations can be achieved:

$$V_i + V_{C2} = v_{L1}\ ;\quad V_{C1} = v_{L2}\ ;\quad v_0 = 0 \qquad (2)$$

During the non- shoot through state for duration of T_1, The equation obtained are:

$$v_{L1} = V_i - V_{C1} = V_i - v_0 + V_{C2} \qquad (3)$$

$$v_{L2} = V_{C1} - v_0 = -V_{C2} \qquad (4)$$

Assuming the average voltage across the inductor is zero for a switching period of T, and then the following equations can be defined:

$$V_{L2} = \frac{T_0.V_{C1} + T_1.(-V_{C2})}{T} \qquad (5)$$
$$= \frac{T_0.V_{C1} + T_1.(V_{C1} - v_0)}{T} = 0$$

$$T_0.V_{C1} = T_1.V_{C2} \qquad V_{C1} = \frac{T_1}{T}.v_0 \qquad (6)$$

Based on equations in (4), (5) and (6), next the following is defined.

$$V_{C2} = \frac{T_0}{T}.v_0 \qquad v_0 = V_{C1} + V_{C2} \qquad (7)$$

Same for the average voltage across the L_1, V_{L1} over one switching period can be defined as follow.

$$V_{L1} = \frac{T_0.(V_{C2} + V_i) + T_1.(V_i - V_{C1})}{T} \qquad (8)$$

$$= \frac{T_0.(V_{C2} + V_i) + T_1.(V_i - v_0 + V_{C2})}{T} = 0$$

Based on equations (6), (7) and (8), next the following is defined.

$$v_0 = \frac{T}{(T_1 - T_0)}.V_i \qquad V_i = V_{C1} - V_{C2} \qquad (9)$$

Then the average dc-link voltage across the inverter bridges can be found as follow.

$$V_0 = \frac{T_0.0 + T_1.(V_{C1} - v_{L1})}{T} = \frac{T_1.(V_{C1} + V_{C2})}{T} = V_{C1} \qquad (10)$$

Lastly, from (6), (9) and (10), the average voltage across the bridges can be defined as follow.

$$V_0 = V_{C1} = \frac{T_1}{(T_1 - T_0)}.V_i \qquad (11)$$

Defining shoot-through duty ratio $D = T_0/T$ and $T_0 + T_1 = T$, the following is obtained.

$$V_0 = V_{C1} = \frac{1-D}{1-2D}.V_i \qquad (12)$$

It can be shown that by varying the shoot through time over one switching cycle, the input voltage can be boosted accordingly. As for the case the input voltage comes from the output of PV arrays ($V_{in} = V_{pv}$), from equation (12), if the capacitor voltage V_{c1} can be controlled to be constant, the input voltage V_{pv} increases when the shoot-through time

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is decreased, and decreases when the shoot-through time is increased as in equation (13).

$$V_{pv} = \frac{1-2D}{1-D} . V_{C1} \qquad (13)$$

Considering this fact for the case of MPPT implementation, the maximum power point voltage ($V_{mpp} = V_{pv}$) can be tracked by adjusting the shoot-through duty ratio D.

V. BLDC MOTOR

With rapid developments in the power semiconductor and power electronic technologies, brushless DC (BLDC) motor have been widely used in various industrial and domestic applications. Because of its numerous merits such as small size, long operating life, less maintenance, high output torque, noiseless operation, it is becoming popular among the pump manufacturers to use PMBLDC motor in place of other motors. The equivalent circuit of the BLDC motor is shown in Fig.7.

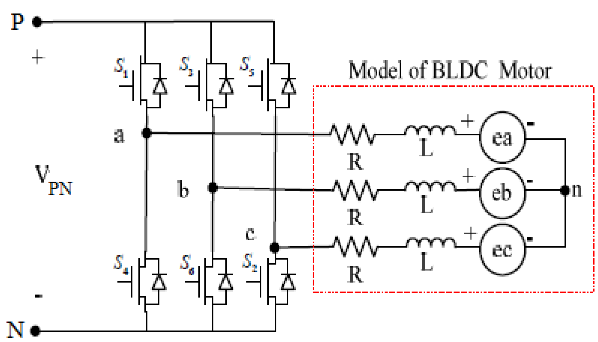

Fig.7 Equivalent Circuit of BLDC Motor

BLDC motor is one type of permanent magnet synchronous motor with coils being the stator and permanent magnet being the rotor. Each commutation sequence has one of the windings energized to positive power (current enters into the winding), the second winding is negative (current exits the winding) and the third is in a non-energized condition. Torque is produced because of the interaction between the magnetic field generated by the stator coils and the permanent magnets. Ideally, the peak torque occurs when these two fields are at 90° to each other and falls off as the fields move together. In order to keep the motor running, the magnetic field produced by the windings should shift position, as the rotor moves to catch up with the stator field. What is known as "Six-Step Commutation" defines the sequence of energizing the windings.

The BLDC motor can be analyzed by the following equations:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L-M & 0 & 0 \\ 0 & L-M & 0 \\ 0 & 0 & L-M \end{bmatrix} p \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \qquad (14)$$

where L is the self inductance of each phase, M is the mutual inductance between any two phases, V_a, V_b, V_c are the phase voltages, i_a, i_b, i_c are the phase currents e_a, e_b, e_c are the back emf signals of BLDC motor and p is the differential operator.

The electromagnetic torque equation is:

$$T_e = (e_a i_a + e_b i_b + e_c i_c)\frac{1}{\omega} \qquad (15)$$

The mechanical equation for torque is:

$$T_e = J\frac{d\omega}{dt} + B\omega + T_l \qquad (16)$$

where J is moment of inertia of drive, ω = mechanical speed of rotor, B= damping constant, T_l= load torque.
For water pumping application, the relation between load torque and speed is given by,

$$T_l = K\omega^2 \qquad (17)$$

VI. CONTROL SYSTEM

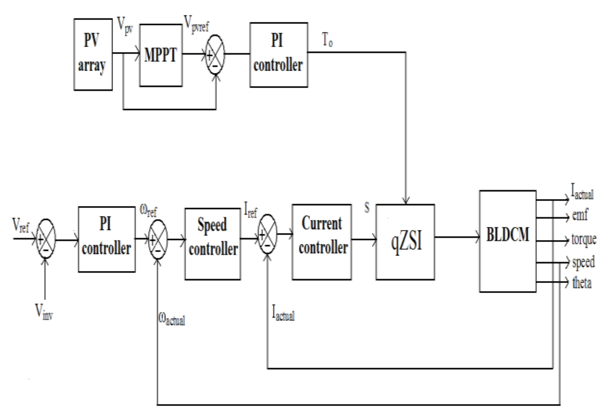

Fig.8 Block Diagram of the Control System

The blocks of the control system are PV array, MPPT controller, qZSI, BLDC motor, PI controllers and hysteresis current controllers and this is shown in Fig.8.

In this the output voltage of the PV array is compared with that of the maximum voltage from the MPPT, which acts as the reference voltage for the PV array. The error signal is then given to the PI controller where it is processed to obtain $T_{0,}$ which regulates the shoot through interval time of qZSI, thus regulating the input dc voltage of the inverter (V_{inv}). The inverter input voltage (V_{inv}) is compared with the reference voltage at which the motor can operate and the error signal is given to the PI controller where it is processed to produce the reference speed. The reference speed and the actual speed of the motor are compared and fed to a PI speed controller. The output of this

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is considered as the reference torque or reference current (I_{ref}). The motor currents are compared with the reference current. The hysteresis current controller regulates the output of this within the hysteresis band around the reference current and is given as the switching signals to the inverter.

VII. SIMULATION RESULTS

A solar panel of about 2kw rating is used. The control system is simulated in Matlab/Simulink. The simulation of the proposed system is shown in Fig.9. The motor speed, torque, motor phase current and back emf waveforms are shown in the Fig.10 [(a)-(d)].

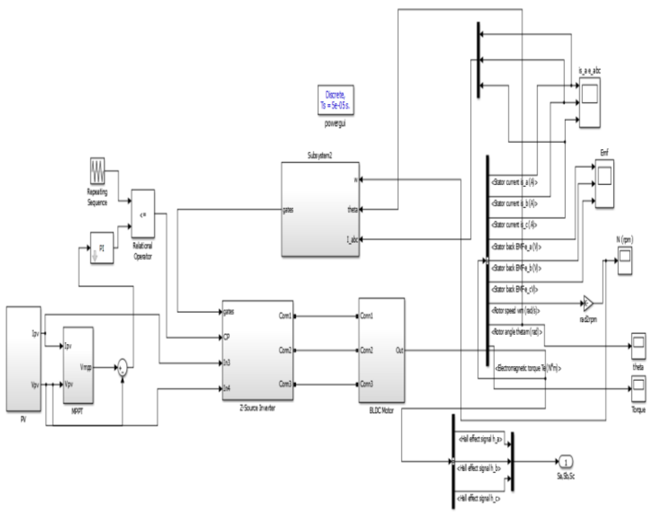

Fig.9 Simulation of Proposed System

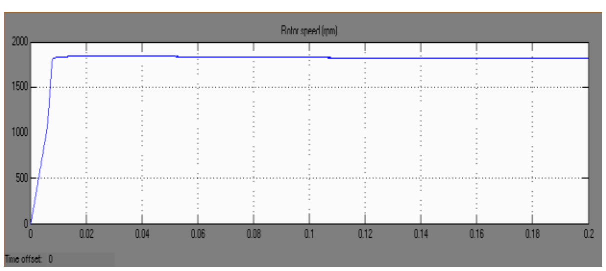

Fig.10 (a) Speed Waveform

Analyzing the speed waveform, it is seen that, it took very less time to reach the constant value and is almost ripple free.

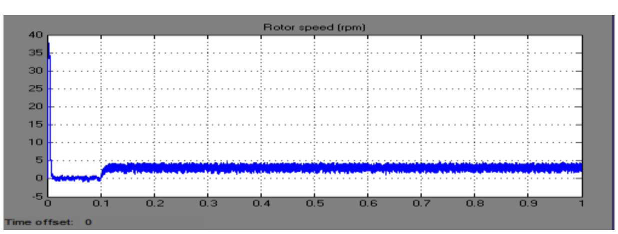

Fig.10 (b) Torque Waveform

In the torque waveform, initially there is a rise in magnitude this is due to the fact that initially back emf developed will be very small and since torque is proportional to the current, the initial torque will be high. There after the torque settles almost near to the load torque applied and the small ripples corresponds to the commutation ripple in the current waveform. Anyways the there is a considerable reduction in torque ripple by placing a hysteresis current controller.

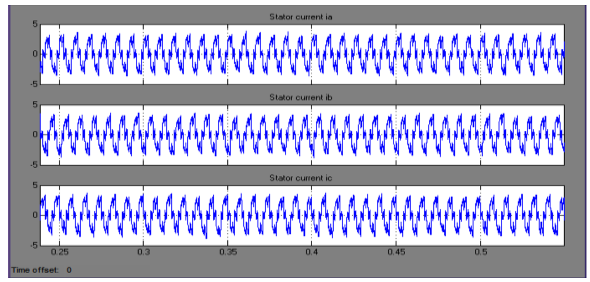

Fig.10 (c) Current Waveform

Current waveform obtained will be a quasi square waveform. Similar to torque waveform, there will be an initial rise in the current due to the lack of back emf generation.

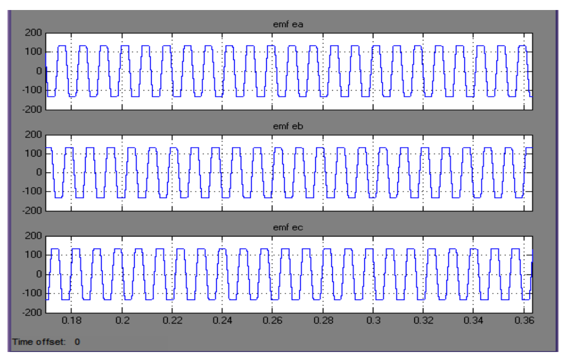

Fig.10 (d) Back Emf Waveforms

Back emf waveform, obtained will be of trapezoidal in shape. Each phase emf will be displaced by 120 degree phase shift.

VIII. CONCLUSION

The paper proposes the modeling of solar powered MPPT based qZSI to drive a BLDC motor for water pumping application. Solar panel is used as the power source in remote areas where the accessibility of grid is difficult. With the use of MPPT, maximum power from the PV array can be obtained all the time. The qZSI uses single energy conversion stage for both boosting as well as inversion of the input voltage. Thus reduces the number of switches and the associated switching losses. BLDC

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motor has greater advantages than other types of motors. Simulation model of each section is done in Matlab/Simulink.

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BIOGRAPHIES

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