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Performance Analysis of Quasi-Z-Source Inverter using Model Predictive Controller for Photovoltaic Power Generation Systems

[1]M.Sivaramaselvi, [2]P.S.Manoharan and [3]M.Senthil Kumar,
[1]Student, [2]Associate Professor, [3] Research Scholar,
[1,2,3]Electrical and Electronics Engineering Department, Thiagarajar College of Engineering, Madurai, TamilNadu, India

Abstract-- This paper presents the performance analysis of Quasi-Z-Source Inverter (QZSI) using Model Predictive Controller (MPC) for Photovoltaic (PV) generation system. This QZSI employs a unique impedance network to couple the inverter main circuit to the power source. It's providing unique features that cannot be obtained in the conventional Voltage Source Inverter (VSI) and Current Source Inverter (CSI). The main aim of MPC is predicting the future values of output variables using a dynamic model of the process. Using a cost function optimization the error should be minimized and the best switching state is selected. QZSI inductor current and capacitor voltage are changed based on the same cost function. The MATLAB simulation results show the performance analysis of QZSI using MPC.

Keywords-- Photovoltaic (PV) power generation, Quasi-Z-SourceInverter (QZSI), Model Predictive Control (MPC).

I. INTRODUCTION

The single phase Quasi-Z-Source Inverter (QZSI) is widely used for the application of solar photovoltaic (PV) power generation systems. PV cell's voltage varies with respect to temperature and irradiation compared with conventional voltage source inverter (VSI) the QZSI have the capability of handling a wide input voltage range. It also has some other features like lower component rating, increased efficiency, reduce the cost and reduce the harmonics. From the theoretical analysis and simulation results shows that QZSI can realize voltage buck or boost and dc-ac inversion in a single stage with high reliability and efficiency. In most applications, Proportional-Integral (PI) controller has been employed to control current and voltage etc… It is easy to implement but it has some drawbacks. This controller requires a modulator such as Sinusoidal Pulse Width Modulation (SPWM) to generate PWM signals.

MPC is a simple and robust method, where it doesn't need other modulation techniques. Proportional Integral Derivative (PID) controller and Linear Quadratic Regulator (LQR) controller doesn't provide guaranteed control due to the uncertainties and disturbances present in the system to overcome this MPC is used. It provides the better performance than conventional modulation techniques attain and makes it easy to apply linearity and nonlinearity constraints even in the multi variable system. To implement this the calculation time must be smaller than the sampling time, to avoid the overrun problems.

II. CIRCUIT ANALYSIS OF THE QUASI-Z-SOURCE INVERTER

Fig.1 shows the equivalent circuit of single- phase QZSI.

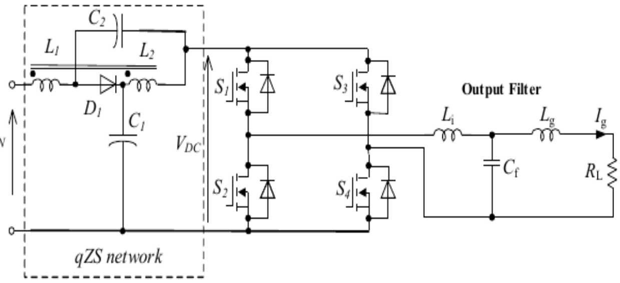


Figure 1: Equivalent circuit of single- phase QZSI

Figure. 2a and 2b show the equivalent circuit of QZSI in non-shoot through state and shoot through state respectively. It has two types of operating states at the dc side.

A. Non Shoot through state

During the non-shoot through state, the QZSI model is represented by a constant current source are shown in Fig. 2.

By applying Kirchhoff's voltage law to Fig.2, the inductor voltages (v_{L1} andv_{L2}), dc link voltage(v_{PN}) and diode voltage (v_{diode}) are given by,

$$v_{L1} = v_{in} - v_{C1}, v_{L2} = -v_{C2} \quad (1)$$

$$v_{PN} = v_{C1} - v_{L2} = v_{C1} + v_{C2}, v_{diode} = 0 \quad (2)$$

B. Shoot through state

During the shoot through state, the QZSI model is represented by short circuit as shown in Fig. 3.

By applying Kirchhoff's voltage law to Fig.3, the inductor voltages (v_{L1} andv_{L2}), dc link voltage(v_{PN}) and diode voltage (v_{diode}) are given by,

$$v_{L1} = v_{C2} + v_{in}, v_{L2} = v_{C1} \quad (3)$$

$$v_{PN} = 0, v_{diode} = v_{C1} + v_{C2} \quad (4)$$

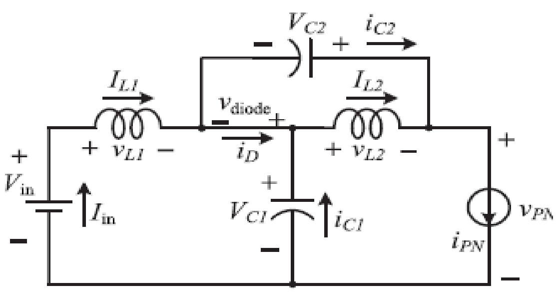


Figure 2: Equivalent circuit of QZSI in Non-shoot through state

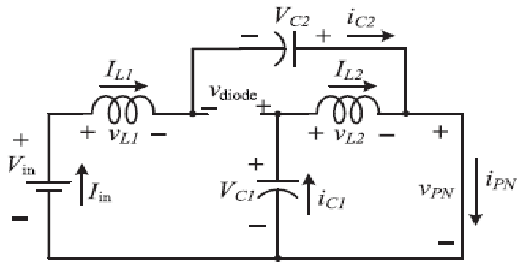


Figure 3: Equivalent Circuit of QZSI in Shoot through State

Under steady state conditions, the average voltage of the inductors over one switching cycle is given by,

$$v_{C1} = \frac{T_1}{T_1 - T_0} v_{in} \qquad (5)$$

Where T_0 the duration of Shoot through state is, T_1 is the duration of the Non-shoot through state and v_{in} is input dc voltage.

By using (2), (4) and (5) the peak dc link voltage across the inverter bridge is given by,

$$v_{PN} = v_{C1} + v_{C2} = \frac{T}{T_1 - T_0} v_{in} = B v_{in} \qquad (6)$$

Where T is the switching cycle ($T_0 + T_1$) and B is the boost factor of QZSI.

The average current of the inductor L_1, L_2 can be calculated by the system power rating P is given by,

$$I_{L1} = I_{L2} = I_{in} = \frac{P}{v_{in}} \qquad (7)$$

By applying Kirchhoff's current law in equation (7) we can get,

$$i_{C1} = i_{C2} = i_{PN} - i_{L1} \qquad (8)$$

The voltage gain (G) of the QZSI is given by,

$$G = \frac{v_{in}}{0.5\, v_{PN}} = MB \qquad (9)$$

Where M is modulation index, v_{in} is the peak ac phase voltage. Assuming that during one switching cycle, T, the interval of the shoot through state is T_0; the interval of non-shoot through states is T_1; thus one has $T = T_0 + T_1$ and the shoot-through duty ratio, $D = \frac{T_0}{T}$.

The boost factor is given by,

$$B = \frac{1}{1-2D} \qquad (10)$$

Where B is the boost factor of QZSI.

III. PROPOSED MPC SCHEME

The block diagram of MPC is shown in Fig.4. It has two main layers,

1. Predictive model
2. Cost function optimization.

The dynamic model of the system is used to predict the future behavior of the control variables. Using the cost function optimization the error should be minimized in the next sampling time. The major advantages of MPC are easy to apply in both linear and non-linear system. It has very small steady state error and fast dynamic response. It is described by the following 4 steps:

1. Find the reference value
2. Predict the future behavior of control variables
3. Using cost function
4. Applying control algorithm

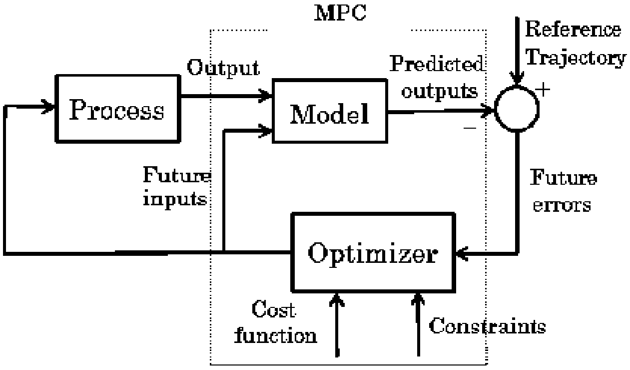


Figure 4: Block diagram of MPC

The flowchart of MPC is shown in Fig. 5.

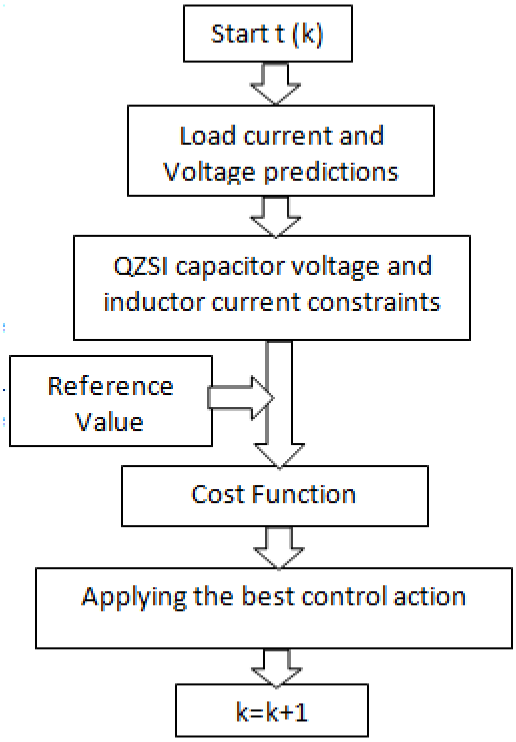


Figure 5: MPC Flowchart

Initially, at sampling time t(k) the load current and voltage are measured and saved, then at time t(k+1) this model is used to predict future behavior of the current and voltage values. After that, the reference values compared with the predicted values and appropriate control action is applied. This process is repeated again and again.

Predicted values of output current of this model is given by,

$$i(k+1) = \left(1 - \frac{r_L}{L} T_s\right) i(k) + \frac{T_s}{L}(v(k+1) - e \qquad (11)$$

Where L is the load inductance and r_L is the inductor resistance, T_s is the sampling period. Where e(k+1) is the grid voltage at next sampling time.

By using the equivalent circuit of the QZSI to predict the capacitor voltage and inductor current for the next sampling time. It can be expressed according to switching state.

In Shoot through state:

$$v_c(k+1) = v_c(k) - \frac{T_s}{C} i_L(k+1) \quad (12)$$

$$i_L(k+1) = i_L(k) + \frac{T_s}{L} v_{c(k+1)} \quad (13)$$

In Non-shoot through state:

$$v_c(k+1) = v_c(k) - \frac{T_s}{C}(i_L(k+1) - i_{inv}(k+1) \quad (14)$$

$$i_L(k+1) = i_L(k) + \frac{T_s}{L}(v_{c(k+1)} - v_{c(k+1)}) \quad (15)$$

By using cost function optimization to minimize the difference between the reference and the predicted value. The output current can be controlled. The output current cost function is given by,

$$g = \sqrt[2]{(i_{\alpha}^* - i_{\alpha(k+!)})^2 + (i_{\beta}^* - i_{\beta(k+!)})^2} \quad (16)$$

Where i_α^* and i_β^* are the real and imaginary parts of the reference current and $i_{\alpha(k+!)}$ and $i_{\beta(k+!)}$ are the predicted current for next sampling time.

The cost function has two other terms to controlling the capacitor voltage and inductor current is given by,

$$g = \sqrt[2]{(i_{\alpha}^* - i_{\alpha(k+!)})^2 + (i_{\beta}^* - i_{\beta(k+!)})^2} + \lambda_c |v_c^* - v_{c(k+!)}| + \lambda_L |i_L^* - i_{L(k+!)}| \quad (17)$$

Where v_c^* and i_L^* are the reference values of the capacitor voltage and inductor current of the QZSI. $v_{c(k+!)}$ and $i_{L(k+!)}$are the next sampling time predicted values.λ_c and $\lambda_L$are the weighing factor. The reference capacitor voltage doubled the output peak voltage in order to improve the inverter performance. The reference inductor current is given by,

$$i_L^* = \frac{\text{Output power}}{v_{in}} \quad (18)$$

IV. SIMULATION RESULTS AND DISCUSSION

The MPC is designed and applied to the QZSI. The ultimate goal of this MPC controller is to achieve a fast dynamic performance and stability in presence of error to reduce the effect of noise and disturbance present in the real control system MPC control is used. The test system is simulated by using MATLAB.

Table 1: Simulation Parameters

Symbol	Description	Values
v_{in}	Input dc voltage	50V
L_1, L_2	QZSI inductance	500µH
C_1, C_2	QZSI capacitance	400µF
F_{sw}	Switching frequency	1000Hz
L	Load inductance	12mH
R	Load resistance	10ohm
T_s	Sampling time	1µs

Table 2: PV Array Specifications

Maximum power (W)	40
Cells per module	12
Open circuit voltage(V)	21.6
Short circuit current(A)	2.62
Voltage at maximum power point(V)	17.2
Current at maximum power point(A)	2.32

A single phase seven levels QZSI based dc source system was simulated in MATLAB/Simulink. Where the sampling time T_s=1µs; the input voltage is set to be $V_{in} = 50$ V in each bridge which is 150 V is boosted to 300 V in output. The corresponding input voltage and output voltage waveform are shown in Fig.6 and 7 respectively.

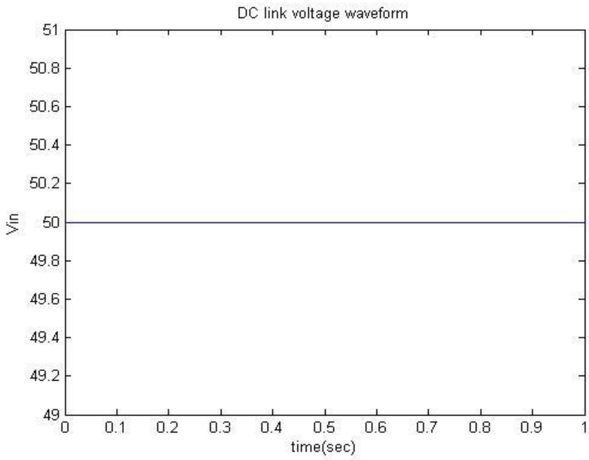


Figure 6: Input voltage waveform

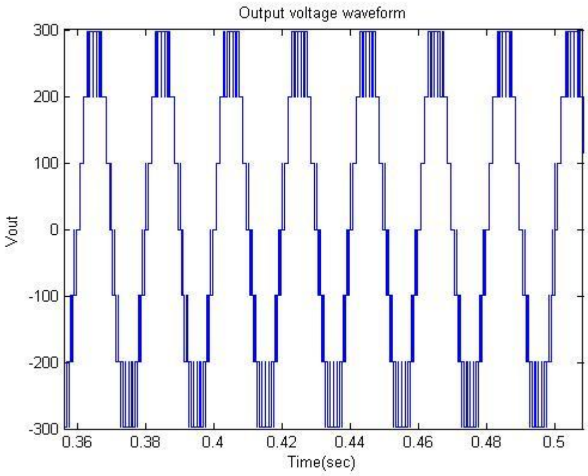
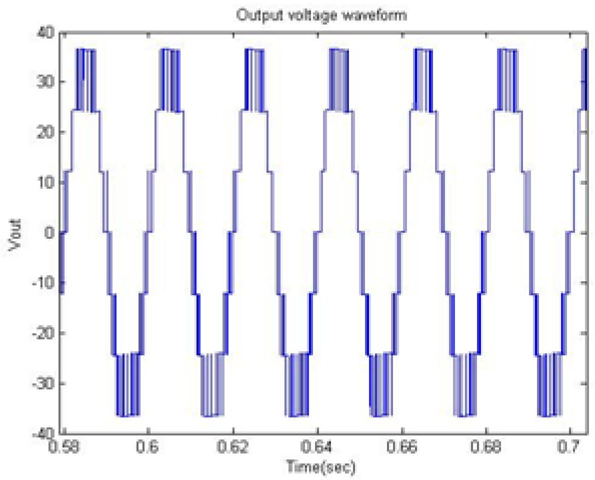


Figure 7: Output voltage waveform

A single phase seven level QZSI based PV power generation system was simulated in MATLAB/Simulink. The PV panel output voltage is connected to the input of the inverter. The rating of PV panel is 6V in each bridge. Hence, the input voltage is set to be 18V is boosted to 36V in output is shown in Fig.8.



The total harmonic distortion results were analysed for both with and without Model Predictive Controller are shown in Fig.9 and10 respectively. Here the THD level without controller is 15.88% has been reduced to 13.83% while using MPC.

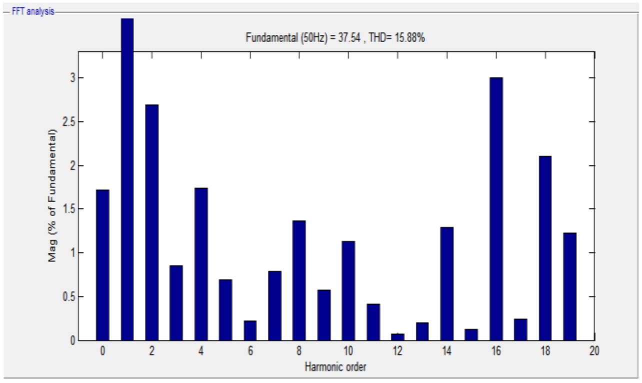


Figure 9: THD for seven-level inverter without MPC

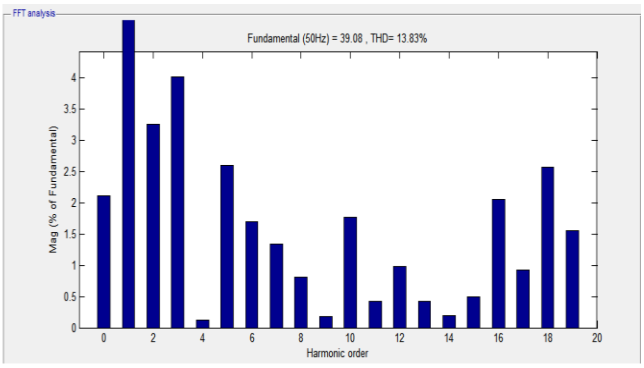


Figure 10: THD for seven-level inverter with MPC

V. CONCLUSION AND FUTURE WORK

This work analyses' the performance of Quasi-Z-Source inverter (QZSI) using model predictive controller (MPC) on photovoltaic power generation system. By using MPC to reduce the effect of noise and disturbance present in the system. A developed algorithm for QZSI was discussed. MPC has the merits of high performance in tracking the set values of the reference for the controlled variable. THD level has been reduced to 13.83% using MPC controller. The simulation was carried out on the seven-level Quasi-Z-Source Inverter. The Quasi-Z-Source Inverter based PV system was tested. Simulations were performed to verify the performance of the proposed inverter topology and its control strategy. The simulation results will be confirmed by the experimental results in future work.

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