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Research paper

Modern control scheme for Z-Source inverter based PV power generation systems

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Abstract

Z-source inverter (ZSI) based photovoltaic power conversion system (PV-PCS) provides both the DC link voltage boost and DC-AC inversion in single stage with added features. Traditional maximum power point tracking (MPPT) control algorithm generates the required shoot-through interval to output maximum power to the Z-network. At this instant, the voltage across Z-source capacitor is equal to the MPP voltage of PV array. The capacitor voltage cannot be further increased if it is demanded by the load. This paper presents an improved MPPT control algorithm along with modified MPPT algorithm to achieve both the MPPT as well as capacitor voltage control at the same time. Development and implementation of the proposed algorithm has been carried out by Matlab/Simulink software and the results are provided.

Keywords: *Z-source inverter (ZSI); photovoltaic array (PVA); pulse width modulation (PWM); maximum power point tracking (MPPT); capacitor voltage control (CVC)*

1. Introduction

The photovoltaic power conversion system (PV-PCS) for converting solar energy into electricity is in general costly and is a vital way of electricity generation only if it can produce the maximum possible output for all weather conditions. Among the PCS's, two level converters were used to boost the PV voltage to the desired level and convert DC into AC for controlling the AC loads. The number of switching components, total volume of the system and overall cost of the system are increased while adapting the two stage converter based PCS. Z-source inverter (ZSI) has been proposed to overcome the disadvantages of the traditional inverters with unique impedance network [1]. A ZSI based PCS shown in Figure 1 created a center of attention for researchers since it offers DC boost and DC-AC inversion in one single stage. Due to its unique features and advantages, it is much suitable for various applications which are much sensitive for supply voltage sags/fluctuations [2-5].

Operating principle of ZSI based PV-PCS and their advantages over the traditional two stage converters have been discussed in [9]. Simple power feedback method is used to achieve MPPT in [9]. The same study has been extended for grid connected PV system in [10]. A simple control method for two-stage utility grid-connected PV-PCS is proposed in [10]. This approach enables maximum power point tracking (MPPT) control with post-stage inverter current information instead of calculating solar array power, which significantly simplifies the controller and the sensor. A power conversion circuit for a grid-connected PV system using a Quasi-ZSI was suggested and analyzed in [11]. A modified P&O method is used for MPPT control.

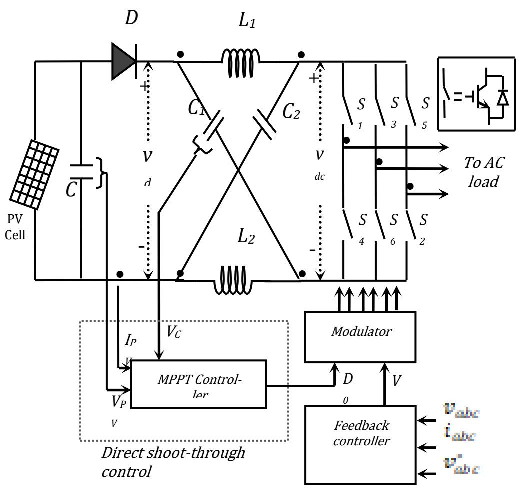
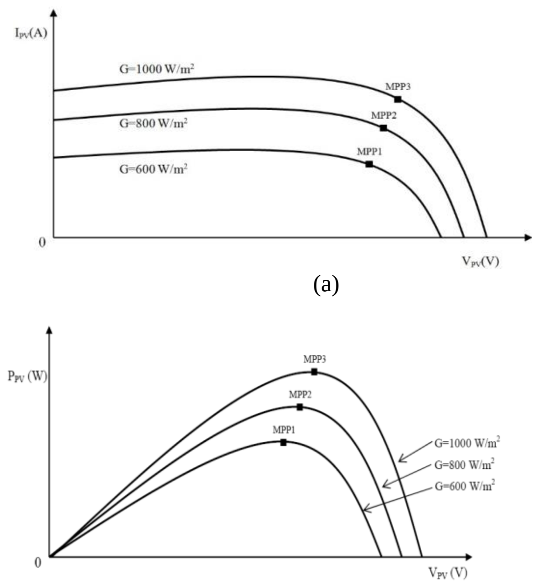


Figure 1. ZSI based PV-PCS

In the traditional algorithms, output of the MPPT controller is the reference signal for generating a shoot-through state to track the PV voltage at MPP. This is the reference voltage for the Z-source capacitor (V_C*) and the Z-source capacitor voltage is boosted to the PV voltage at MPP (V_{PV}*). To adjust further the DC link voltage, one has to increase/decrease the shoot-through time period according to the requirement by the load which is the limited value due to the MPPT algorithm. This paper presents an improved CVC to achieve the MPPT as well as capacitor voltage control beyond V_{PV}* simultaneously.

2. Capacitor Voltage Control

In the traditional control schemes of the ZSI based PCS, the shoot-through time period is calculated by the MPPT algorithm and accordingly two reference straight lines are generated to produce shoot-through pulses by simple boost control. The Z-source capacitor voltage can be boosted according to the shoot-through time periods calculated by the MPPT algorithm. If the reference voltage of the capacitor is relatively higher than the PV voltage at MPP, capacitor voltage cannot be increased further since the shoot-through states are generated solely to track the voltage at MPP. To control the capacitor voltage beyond V_{PV}* with retaining all the features of the traditional MPPT algorithm, this section presents a unified control algorithm which provides simultaneous control of MPPT and capacitor voltage.



(a)

(b)

Figure 2. I-V and P-V characteristics of PV array

2.1MPPT Algorithm

PV array has non-linear I-V and P-V characteristics as shown in Figure 2. According to the temperature and irradiation, the output voltage and current of the PV array varies. A variety of MPPT algorithms are used to extract maximum power from the PV array, since it has non linear characteristics. In this paper, perturbation and observation (P&O) algorithm is used to directly calculate the required shoot-through time periods. The input voltage of the Z-network is the output voltage of the PV array. The output voltage of the PV array can be controlled by controlling the Z-source capacitor or DC link voltage.

This could be achieved by imposing the simultaneous conduction of each or any phase leg switches of the inverter bridge. By adjusting the shoot-through time interval, one can get required amount of voltage across the DC link irrespective of the voltage supplied by the DC source. Figure 3 shows the P&O algorithm for direct shoot-through control. In this method, power is always measured and used as feedback to adjust shoot-through duty cycle to reach MPP. This is done by increasing/decreasing the shoot-through time period (T_0) with shoot-through perturbation (ΔT_0). Then two reference straight lines V_P and V_N to generate shoot-through states as shown in Figure 2 are generated as follows;

$$V_P = (1 - T_0)$$
$$V_N = -(1 - T_0) = -V_P \tag{1}$$

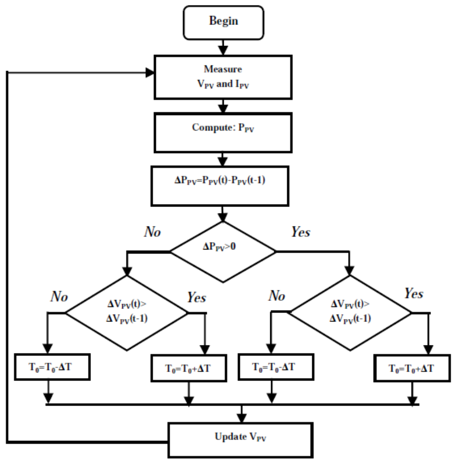


Figure 3. Flowchart of the traditional MPPT algorithm

These two straight lines (V_P and V_N) are compared with the high frequency triangular signal in order to generate the shoot-through pulses. The control block diagram of this traditional method is shown in Figure 5(a). In simple boost control, the shoot-through frequency is twice the switching frequency since two shoot-through pulses are generated in one switching cycle. The capacitor voltage/DC link voltage could be improved to the MPP voltage of a PV array (V_{PV}*) and hence maximum power from PV array could be extracted. Expression for DC link voltage can be;

$$v_{dc} = V_C = \frac{1-D_0}{1-2D_0} V_{PV} = V_{PV}^{\ *} \tag{2}$$

The AC load voltage can be controlled by the modulation index (M) and can be written as

$$\hat{v}_{ac} = M \frac{V_{PV}\ *}{2} \tag{3}$$

M can be varied from zero to V_P. As in the equation (10), MPPT algorithm controls the capacitor voltage until it reaches V_{PV}*, since the objective is to generate required shoot-through time (T_0) to maintain V_C to be equal to V_{PV}*.

2.2 Capacitor voltage control

MPPT algorithm generates shoot-through period (T_0) to boost the Z-source capacitor voltage to the PV array voltage at MPP. Further to boost the Z-source capacitor voltage beyond V_{pv}*, a capacitor voltage control (CVC) algorithm is

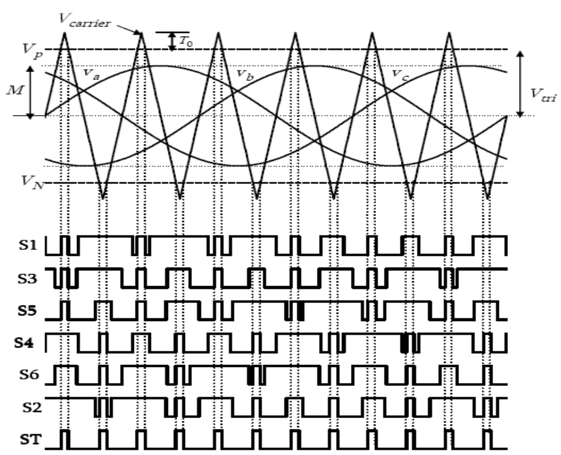


Figure 4. Modulation using P&O algorithm

presented in this section. The traditional capacitor voltage control scheme is shown in Figure 5 (a). As discussed in the previous section, the shoot-through duty period (T0) required to boost the capacitor voltage is directly calculated and the shoot-through reference straight lines are generated by the equation (1). No capacitor voltage control beyond the PV array voltage at MPP is facilitated here. Figure 5 (b) shows the proposed control scheme which felicitates the MPPT as well as capacitor voltage control simultaneously. Figure 6 shows the flowchart of the proposed MPPT algorithm which tracks the MPP voltage and also the reference capacitor voltage.

To track the reference capacitor voltage (VC*), proposed algorithm generates an additional shoot-through factor (T0'). The capacitor voltage is first set to the MPP voltage of the PV array for a particular solar irradiation and temperature level by the MPPT algorithm. Then the capacitor voltage is compared with the reference voltage which has to be maintained across the DC link of the inverter bridge. There is no additional shoot-through (T0') generated when the actual voltage of the capacitor is equal to the reference voltage. If the capacitor voltage is needed to be increased substantially, additional shoot-through period (T0') is generated and regulated according to the proposed algorithm shown in Figure 6. This additional shoot-through period could be added with the shoot-through time period (T0) generated by the MPPT to update VPV.

The new shoot-through time period (Tsh) to have simultaneous control of MPPT and capacitor voltage could be defined as follows

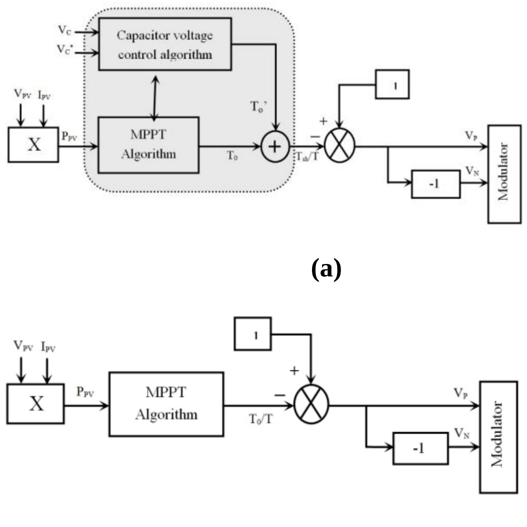


Figure 5. Traditional and proposed control schemes

$$T_{sh} = T_0 + T_0' \quad (4)$$

T_0 is used to track V_{PV}*, while T_0' is used to control the capacitor voltage beyond V_{PV}*.

Range of the new shoot-through time period T_{sh}, can be

$$T_{sh} \le (1 - M) \quad (5)$$

From equation (4) and (5), one could get

$$T_0' \le 1 - (M + T_0) \quad (6)$$

Maximum value of the shoot-through factor could be

$$(T_0')_{\max} \le 1 - (M + T_0) \quad (7)$$

Hence the modulation index and MPPT shoot-through periods limit the range of capacitor voltage control. Since the value of T_0 would be very small to track MPP voltage, the capacitor voltage boost factor (B_C) could be controlled as the traditional ZSI.

The reference straight lines to generate new shoot-through periods can be

$$\begin{aligned} V_P^* &= (1 - T_{sh}) \\ V_N^* &= -(1 - T_{sh}) = -V_P^* \end{aligned} \quad (8)$$

Figure 7 shows the generation of new shoot-through states (T_{sh}) by simple boost control method. In the first stage, the capacitor voltage is boosted to the MPP voltage of the PV array (V_{PV}*). This is done by regulating the shoot-through state (T_0) by using MPPT algorithm. When the DC link voltage of the inverter is needed to be increased beyond V_{PV}*, the new shoot-through time period (T_{sh}) could be generated by inserting an additional shoot-through time period (T_0'). It could be noted that, the two straight lines (V_P* and V_N*) are continuously regulated to maintain the Z-source capacitor to be equal to the reference capacitor voltage (V_C*). The shoot-through period is adjusted according to the changes in PV voltage at MPP. The minimum shoot-through period required to maintain the capacitor voltage as the PV voltage at MPP is generated by the MPPT algorithm and the supplementary shoot-through duty ratio is generated by the unified algorithm to provide additional boost in the capacitor voltage to track the reference value. By substituting (4) in to (2) one could get the average value of Z-source capacitor and DC link voltages as follows:

$$V_C = \frac{T - \left(\frac{T_0 + T_0'}{T}\right)}{T - 2\left(\frac{T_0 + T_0'}{T}\right)} V_{PV}^* = \frac{T - \frac{T_{sh}}{T}}{T - 2\frac{T_{sh}}{T}} V_{PV}^* = \frac{1 - D_{sh}}{1 - 2D_{sh}} V_{PV}^* = v_i \quad (9)$$

Peak value of the AC output voltage of the ZSI can be defined as

$$\hat{v}_{ac} = M \left(\frac{1 - D_{sh}}{1 - 2D_{sh}}\right) \frac{V_{PV}^*}{2} = M \frac{v_i}{2} \quad (10)$$

Shoot-through states are applied to all the legs simultaneously. This can significantly reduce the current stress on the each switch during shoot-through state. Figure 4 shows the PWM pulse generation for ZSI using simple boost control technique. It also shows the relation between the reference sinusoidal and reference shoot-through (V_P and V_N) signals and it holds true for V_P* and V_N* too. The shoot-through periods should be diminished from the traditional zero periods without altering the active time periods to produce less distorted AC output.

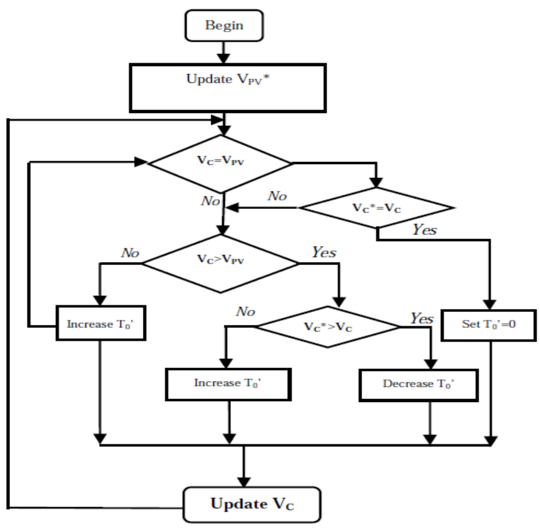


Figure 6. Flowchart of CVC algorithm

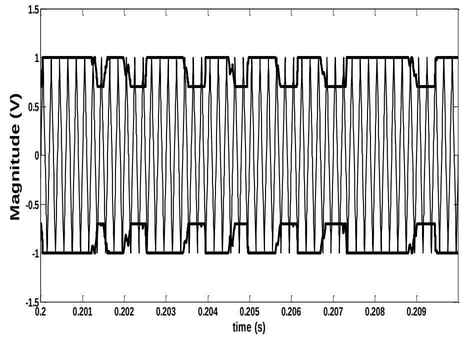


Figure 7. Simulation results of V_P and V_N to generate shoot-through period

3. Results and Discussion

Proposed CVC method is carried out for ZSI based PV system through Matlab/Simulink software and hardware set up. A simple boost control is used to generate the required shoot-through periods by the proposed algorithm. The Z-network is comprised of 1mH inductors and 1000µF. The PV array is modelled using the basic mathematical equations by considering the temperature and irradiation changes. LCL filter is inserted between the inverter bridge and three phase RL load (5kW with 0.9 power factor lagging). Figure 7 shows the simulated results of signal comparison to generate shoot-through periods by the proposed algorithm. It could be noted that, the two straight lines (V_P and V_N) are continuously regulated to maintain the Z-source capacitor to be equal to the reference capacitor voltage (V_C*). The shoot-through period is adjusted according to the changes in PV voltage at MPP. All paragraphs must be justified alignment. With justified alignment, both sides of the paragraph are straight.

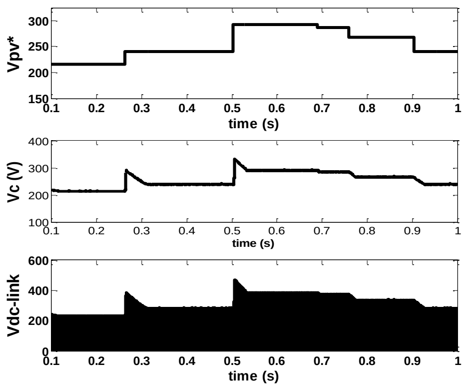


Figure 8. Simulation results of traditional MPPT control

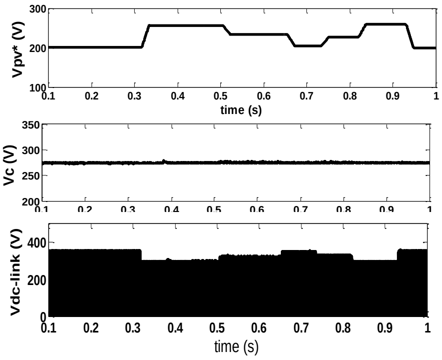


Figure 9. Simulation results of traditional MPPT with CVC algorithm to maintain V_c=275V

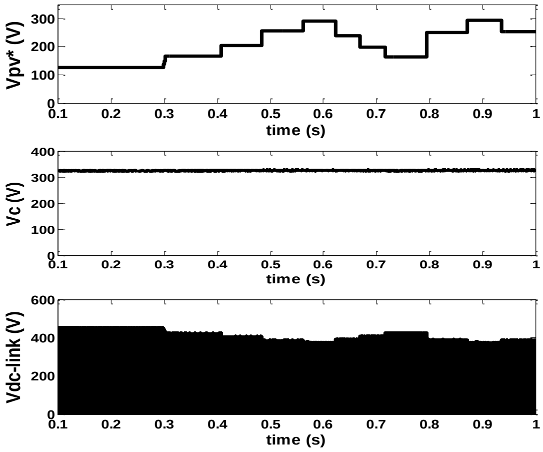
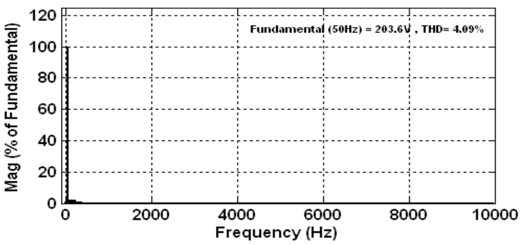
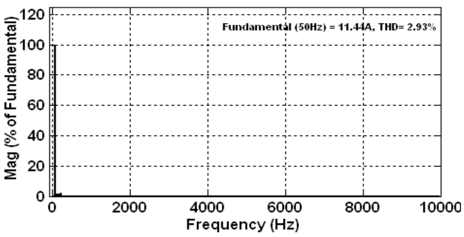


Figure 10. Simulation results of the proposed system to maintain Vc=315



(a)



(b)

Figure 11. THD of output parameters using proposed method (a) output voltage (b) output current

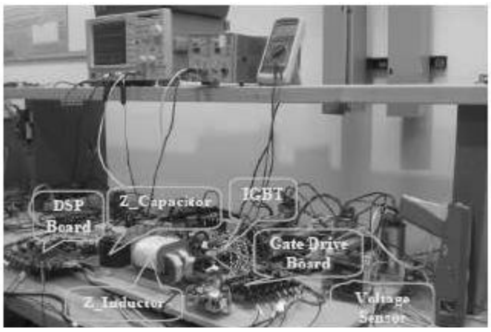


Figure 12. Experimental set up

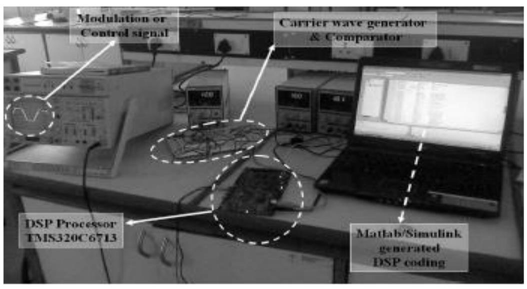


Figure 13. DSP Processor based Pulse Generation

The minimum shoot-through period required to maintain the capacitor voltage as the PV voltage at MPP is generated by the MPPT algorithm and the supplementary shoot-through duty ratio is generated by the proposed CVC algorithm to provide additional boost the capacitor voltage to track the reference value. Figure 8 shows the simulation results of the traditional MPPT algorithm, which maintains the Z-source capacitor voltage equal to the PV voltage at MPP. From this figure one can understand that, the capacitor voltage tracks the MPP voltage of the PV. The DC link voltage waveform for the above case is also shown in Figure 8. From this, it is evident that, there is no additional boost in the capacitor voltage is allowed since the traditional MPPT generates shoot-through periods to directly track the MPP voltage of the PV cell. The simulation results of the proposed CVC algorithm are shown in Figures 9-10. Figure 9 shows the results of the system, when the capacitor voltage reference is increased to 275V (greater than VPV*). Even though there are plenty of variations in the MPP voltage of the PV array, the voltage across Z-source capacitor is constantly maintained as 275V. This is because of the additional shoot-through period (T0') generation by the proposed CVC algorithm. The same response is obtained when the reference voltage of the capacitor is increased to 315V and it is shown in Figure 10. The harmonic profile of the output voltage/current waveforms of the proposed system is shown in Figure 11 and it confirms the improvement of THD. Experimental setup in the laboratory to analyse the ZSI-Hardware implementation with pulse generation using DSP processor are shown in Figure 12 and 13.

4. Conclusions

This paper has presented CVC algorithm for Z-source inverter based PV PCS along with MPPT control. It is shown that, by adapting CVC one can control the Z-source capacitor voltage beyond the voltage at MPP of the PV array. The whole system is experimentally verified and simulated using Matlab/Simulink software and the results of the traditional and proposed algorithms are presented. The advantage of the proposed algorithm is discussed for different operating conditions of the PV array.

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