Application of Trans Z-source Inverter in Photovoltaic Systems

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Abstract: In this paper a new photovoltaic system based on trans Z-source inverter (Trans-ZSI) is proposed. This inverter has been derived from quasi Z-source inverter recently. Trans Z-source network consists of one transformer and one capacitor. While maintaining all prominent features of pervious Z-source inverters, Trans Z-source inverter has several unique advantages such as increased voltage gain, reduced voltage stress and reduced components of impedance network. Due to these features, using trans Z-source inverter as a single stage converter in photovoltaic systems gives satisfactory results. In this paper the application of trans-ZSI in photovoltaic systems in both stand alone mode and grid connected mode has been investigated. By using the dynamic model of trans ZSI, the proper controllers for both stand alone mode and grid connected mode is designed. By controlling the shoot through duty ratio and modulation index, output voltage control has been performed in stand alone mode. Maximum power delivering and unity power factor is achieved through the use of controller in grid connected mode. Simulation results are presented to verify the ability of proposed system.

Keywords: Trans Z-source inverter (Trans-ZSI), Photovoltaic (PV) system, stand alone mode, grid connected mode, Maximum power point tracking.

1. Introduction

In recent years, the use of renewable energy sources especially photovoltaic energy has been increased due to exhaustion of fossil fuels and their high costs and harmful influences on environment. Despite all advantages of photovoltaic energy, there are some limitations confront it. These limitations include high cost of PV modules and interference converter system and variant power of PV cells. With changing irradiance and temperature, the output voltage of PV arrays varies widely. Hence, in order to use PV system in stand alone mode or grid connected mode, it is necessary to use an interference DC/DC converter. This converter increases the cost and complexity of the system and results in a lower efficiency.

Since introduction of Z-source inverter, many researches have been performed in using the Z-source inverters as a single stage converter in PV systems. In [1,2,3] Z-source inverter is used to connect the PV system to the grid. In [4, 5] a PV system based on quasi Z-source inverter which has more advantages comparing with traditional Z-source inverters, has been proposed. In [6] by using the dynamic model of quasi ZSI, controller for both stand alone and grid connected modes has been designed.

Recently a new structure of Z-source inverters which is named Trans Z-source inverter, has been introduced. This inverter has been derived from quasi Z-source inverter. Trans ZSI has all prominent features of pervious Z-source inverters. Moreover this inverter has some unique privileges such as increased voltage gain, reduced voltage stress on switching devices and reduced components of impedance network. Trans Z-source network consists of a transformer and one capacitor. For transformer turns ratio (n) more than 1, voltage gain of trans Z-source inverter can be increased noticeably than that of traditional Z-source/quasi Z-source inverters. Due to the prominent features of trans ZSI, it is suitable as a single stage converter for PV systems. In this paper a PV system based on trans ZSI which is connected to a local load and a three phase grid, is proposed. The proper controllers for both stand alone mode and grid connected mode is designed. In both modes the control of dc side and ac side is executed separately. In stand alone mode, the controller parameters of dc side is determined by using the dynamic model of trans ZSI. By designing a proper controller in grid connected mode, maximum power delivering and unity power factor is achieved.

Simulation results are presented to corroborate the performance of proposed systems.

2. Trans Z-source Inverter

The structure of the quasi ZSI and the trans ZSI are shown in figures 1 and 2 respectively. In structure of the trans ZSI, two inductors L₁ and L₂ are replaced with one transformer. Hence either C₁ or C₂ can be removed.

![Fig.1. Quasi Z-source inverter](image-url)
With assuming $T_1$, $T_0$ and $T_0$ are switching period, non-shoot through interval and shoot through interval in a switching period, respectively and $D_0$ is shoot through duty cycle, the trans Z-source network capacitor voltage can be calculated as follows:

$$V_C = \frac{1 - D_0}{1 - (1 + n)D_0}V_{in} \quad (1)$$

The peak dc link voltage across the inverter bridge is:

$$v_{peak} = \frac{1}{1 - (1 + n)D_0}V_{in} \quad (2)$$

It can be seen for $n = 1$, the trans ZSI equations are same with those of the traditional Z-source/quasi Z-source inverters. But for turns ratio $(n)$ more than 1, the inverter dc link voltage boost can be higher given the same modulation index. In other words, it needs a smaller shoot through duty ratio (accordingly, a larger modulation index) to produce the same ac output than the traditional Z-source/quasi Z-source inverters do[7]. In PV generation which may has a low dc output voltage, this feature of trans ZSI can be very efficient.

### 3. Control Methodology

The main purposes of controller design in both stand alone mode and grid connected mode are expressed respectively as follows:

1) Output voltage control with a valid magnitude and frequency.

2) Maximum power delivering with a desired power factor and low THD content.

### 3.1 Controller design for stand alone mode

Fig.3 shows overall configuration of the PV system based on the trans ZSI and the control system in the stand alone mode. $L$, $R$, $L_m$, $C$ and $R$ are stray inductance of transformer, stray resistance of transformer, magnetic inductance of transformer, trans Z-source network capacitor and equivalent series resistance of capacitor, respectively. $C_f$, $L_f$ and $R_f$ are filter capacitor, filter inductance and stray resistance of filter inductor, respectively.

The present system is a multi-input and multi-output system. Both the control parameters are dependent each other as change in one parameter imposes a limitation on the freedom of the other. This limitation imposes some problems and complexities in system control. By executing the control of the dc side and ac side of trans ZSI separately, the system complexity is reduced [8].

By dynamic modeling of trans ZSI and small signal analysis, the transfer function of shoot through duty ratio ($d_0$) to trans Z-source network capacitor voltage can be obtained, which is expressed via (3), where $I_{load}$, $V_C$, $D_0$, $I_{load}$ and $V_{in}$ are presented an operating point. By bode plot of open loop transfer function of dc side controller, PI parameters ($K_p$, $K_i$) can be determined based on this principle that to avoid clashes between dynamics of the dc side and the ac side, bandwidth of the dc side should be much lower than that of the ac side, but fast response of the dc side is necessary for a good reference tracking.

$$G_{d0}^V = \frac{A(s)}{B(s)} \quad (3)$$

Where

$$A(s) = (1 + n)(L_m + L)(L_m + n^2L)(I_{load} - I_m)s + (1 + n)(R + r)((n^2 - 1)D_0 + 1)L_m + n^2L)$$

$$+ (1 + n)(R + r)((n^2 - 1)D_0 + 1)L_m + n^2L)$$

$$+ (I_{load} - nI_m) - (1 - (1 + n)D_0)[n(n^2 - 1)$$

$$+ (L_m + n^2L)nV_{in} + (r + (1 + n)R)I_{load}$$

and

$$B(s) = n\{C(L_m + L)(L_m + n^2L)s^2 + C(R + r)$$

$$+ (((n^2 - 1)D_0 + 1)L_m + n^2L)s + (1 - (1 + n)D_0)$$

$$+ ((1 - D_0)(L_m + n^2L) - nD_0)(L_m + L)]$$

The feed forward $d_0$ can be determined according to relevant equations for the trans ZSI as follows:

$$d_0 = \frac{V_C^* - V_{in}}{(1 + n)V_C^* - V_{in}} \quad (4)$$

Voltage control of ac side is performed by changing the modulation index. In this paper ac side controller
is designed in synchronous frame. In Fig. 5, the structure of controller is shown which consists of two loops: inner current loop and outer voltage loop. For good performance of control system, a proportional-integral (PI) controller and a proportional controller are used in outer loop and inner loop, respectively. The controllers parameters ($K_{pv}$, $K_{iv}$ and $K_{ip}$) can be selected by using the bode plots of system open loop and closed loop transfer functions.

3.2 Controller design for grid connected mode

As the same of stand alone mode, the dc side control and the ac side control are executed separately. The main objectives of the dc side controller and the ac side controller are maximum power point tracking and controlling the injection power to the grid with desired power factor, respectively. Fig. 4 shows the control system in the grid connected mode.

In the dc side controller, maximum power point tracking (MPPT) is performed by adjusting the shoot through duty ratio. The output voltage of PV arrays is fed back and controlled through a PI controller which assisted with a feed forward $d_0$. The feed forward $d_0$ can be calculated from $V_{MPP}$ as follows:

$$d_0 = \frac{V_C - V_{MPP}}{(1 + n)V_C - V_{MPP}} \tag{5}$$

The input voltage of trans Z-source network (or output voltage of PV arrays) can be obtained as follows:

$$V_{in} = V_{PV} = \frac{T_1 - nT_0}{T_1} V_C \tag{6}$$

According to above equation if the trans Z-source capacitor voltage is kept constant, the input voltage of trans Z-source network is increased as the shoot through interval decreases, or vice versa. Since the trans Z-source capacitor voltage has a direct relation with the output voltage of PV arrays, the output power control can be achieved by the capacitor voltage control. Assuming the synchronously rotating d-axis is aligned to the capacitor voltage space vector, the d-axis current reference is produced through a PI controller proportionate to the capacitor voltage error. If the error is positive, to maintain a constant capacitor voltage, the active power injected to the grid should be decreased.

If the synchronous reference is synchronized with the grid voltage, injected active and reactive powers can be expressed as follows:

$$P = \frac{3}{2} V_d I_d \tag{7}$$

$$Q = -\frac{3}{2} V_d I_q \tag{8}$$

![Fig. 3. Configuration of the PV system based on the trans ZSI and control system in the stand alone mode](image-url)
The q-axis current reference is determined dependent on the desired amount of injection reactive power. In case that unity power factor is desired, the q-axis current reference is considered zero.

3. Simulation Results

In order to verify the performance of the proposed system, several simulations in both stand alone and grid connected modes have been carried out. Constant boost control was used in simulations. Specifications of the proposed system are presented in Table I.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_m$</td>
<td>828</td>
<td>μH</td>
</tr>
<tr>
<td>$L$</td>
<td>0.1</td>
<td>μH</td>
</tr>
<tr>
<td>$r$</td>
<td>0.01</td>
<td>Ω</td>
</tr>
<tr>
<td>$C$</td>
<td>400</td>
<td>μF</td>
</tr>
<tr>
<td>$R$</td>
<td>0.1</td>
<td>Ω</td>
</tr>
<tr>
<td>$V_{in}$</td>
<td>130</td>
<td>V</td>
</tr>
<tr>
<td>$D_0$</td>
<td>0.25</td>
<td>-</td>
</tr>
<tr>
<td>$I_{load}$</td>
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<td>A</td>
</tr>
<tr>
<td>$V_C$</td>
<td>359</td>
<td>V</td>
</tr>
<tr>
<td>$I_m$</td>
<td>45</td>
<td>A</td>
</tr>
<tr>
<td>$n$</td>
<td>2</td>
<td>-</td>
</tr>
</tbody>
</table>

### 3.1 Simulation results for stand alone mode

In stand alone mode, the simulation was performed in two cases. At the first case, the input voltage (output voltage of PV arrays) is decreased from 260 V to 200 V at $t=0.25$ sec. In this mode, the output voltage of PV arrays was simulated by a dc voltage source. The controller parameters of dc side was selected by using bode diagram of open loop transfer function of dc side controller. With $K_{p,dc} = 3e-5$ and $K_{i,dc} = 0.05$, the crossover frequency and phase margin of dc side controller are set to 32 Hz and 73.7 deg, respectively.

With proper selection of capacitor voltage reference, the overlap of shoot through duty ratio and modulation index can be avoided. According to the equation obtained in [9], the capacitor voltage reference was selected to be 310 V.

When the input voltage is reduced, dc side controller increases shoot through duty ratio to maintain a constant output voltage of trans Z-source network. The waveforms of input voltage, capacitor voltage, load voltage and current are shown in figures 6 and 7.

At the second case, the output load is changed from 1 kW to 2 kW at $t=0.25$ sec. The input voltage is 200 V. The simulation results in this case are shown in Fig. 8. The simulation results in two cases verify good transient performance of the proposed
system. It can be seen output voltage has a good disturbance rejection characteristic.

3.2 Simulation results for grid connected mode

The PV arrays specification at standard conditions (1000 W/m², 25°C) are presented in Table II. The perturbation and observation (P&O) method was used for maximum power point tracking and determination of MPP voltage (\(V_{\text{MPP}}\)). The following figures show simulation results when the solar irradiation is reduced from 1000 W/m² to 800 W/m² at \(t = 0.15\) sec.

TABLE II: Specifications of PV arrays and grid

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>(V_{\text{OC}})</td>
<td>192.5 V</td>
</tr>
<tr>
<td>(I_{\text{SC}})</td>
<td>59.6 A</td>
</tr>
<tr>
<td>(V_{\text{MPP}})</td>
<td>170 V</td>
</tr>
<tr>
<td>(I_{\text{MPP}})</td>
<td>53.7 A</td>
</tr>
<tr>
<td>(P_{\text{MPP}})</td>
<td>9129 W</td>
</tr>
<tr>
<td>(V_{\text{grid(ph)}})</td>
<td>110 V (rms)</td>
</tr>
<tr>
<td>Grid Frequency</td>
<td>50 Hz</td>
</tr>
</tbody>
</table>

Fig. 9 shows the output voltage of PV arrays follows the MPP voltage properly at two conditions (when solar irradiance is 1000 W/m² or 800 W/m²).

Capacitor voltage was kept constant by ac controller during whole circumstances. The capacitor voltage is demonstrated in Fig. 10.

Output power of PV arrays is shown in Fig. 11 which verifies the ability of the system in delivering maximum power to the grid. By setting the q-axis current reference to 0, unity power factor is achieved. Injected current into the grid and voltage are shown in Fig. 12.
4. Conclusion

This paper proposes a new photovoltaic system based on trans Z-source inverter which has been introduced recently. This inverter has a higher voltage gain compared to traditional Z-source/quasi Z-source inverters which is suitable for PV generation.

The control system for both stand alone and grid connected modes are presented. In both modes, dc side and ac side control are executed independently. With proper selection of the controller system parameters in stand alone mode, output voltage control is achieved. By presented dc side controller in grid connected mode, MPPT is carried out. In the ac side, by regulating the trans Z-source network capacitor voltage, the injected power to grid with desired power factor is controlled.

The ability of the proposed system is validated through several simulations.

References


