A Novel Control Technique for PV System Integration by Using Z Source Inverter

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Abstract—A novel control method, including system-level control and SVPWM for quasi-Z-source multilevel cascade inverter (QZS-CMI) based photovoltaic (PV) power system integration is proposed. The control achieves current injection, independent maximum power point tracking (MPPT) for every PV panels, and balanced dc-link voltage for all H-bridge quasi-Z-source inverter (qZS-HBI) modules. A multilevel space vector modulation (SVM) for the single-phase qZS-CMI is proposed to synthesize the step-like voltage waveforms. Simulations based on a seven-level converter are carried out to validate the proposed methods.

Index Terms—Cascade multilevel inverter (CMI), photovoltaic (PV) power system, quasi-Z-source inverter, space vector Pulse width modulation (SVPWM).

I. INTRODUCTION

A recent upsurge in the study of photovoltaic (PV) power generation emerges, since they directly convert the solar radiation into electric power without hampering the environment. However, the stochastic fluctuation of solar power is inconsistent with the desired stable power injected to the grid, owing to variations of solar irradiation and temperature. To fully exploit the solar energy, extracting the PV panels’ maximum power and feeding them into grids at unity power factor become the most important. The contributions have been made by the cascade multilevel inverter (CMI). Nevertheless, the H-bridge inverter (HBI) module lacks boost function so that the inverter KVA rating requirement has to be increased twice with a PV voltage range of 1:2; and the different PV panel output voltages result in imbalanced dc-link voltages. The extra dc–dc boost converters were coupled to PV panel and HBI of the CMI to implement separate maximum power point tracking (MPPT) and dc-link voltage balance. However, each HBI module is a two-stage inverter, and many extra dc–dc converters not only increase the complexity of the power circuit and control and the system cost, but also decrease the efficiency.

Recently, the Z-source/quasi-Z-source cascade multilevel inverter (ZS/qZS-CMI)-based PV systems. They possess the advantages of both traditional CMI and Z-source topologies. For example, the ZS/qZS-CMI: 1) has high-quality staircase output voltage waveforms with lower harmonic distortions, and reduces/eliminates output filter requirements for the compliance of grid harmonic standards; 2) requires power semiconductors with a lower rating, and greatly saves the costs; 3) shows modular topology that each inverter has the same circuit topology, control structure and modulation; 4) most important of all, has independent dc-link voltage compensation with the special voltage step-up/down function in a single-stage power conversion of Z-source/quasi-Z-source network, which allows an independent control of the power delivery with high reliability; and 5) can fulfill the distributed MPPT.

In order to properly operate the ZS/qZS-CMI, the power injection, independent control of dc-link voltages, and the pulsewidth modulation (PWM) are necessary. The work in [5] and [7] focused on the parameter design of the ZS/qZS networks and the analysis of efficiency. The work in [8] presented the whole control algorithm, i.e., the MPPT control of separate quasi-Z-source H-bridge inverter (qZS-HBI) module, and the grid-
injected power control, whereas the phase-shifted sine wave PWM (PS-SPWM) is the only existing PWM technique for the single-phase ZS/qZS-CMI. The PS-SPWM consumes more resources to achieve the shoot-through states because two more references are compared with the carrier waveform. Additionally, the ZS/qZS-CMI based grid-tie PV system has never been modeled in detail to design the controllers.

The main contributions of this paper include: 1) a novel multilevel space vector modulation (SVM) technique for the singlephase qZS-CMI is proposed, which is implemented without additional resources; 2) a grid-connected control for the qZS-CMI based PV system is proposed, where the all PV panel voltage references from their independent MPPTs are used to control the grid-tie current; the dual-loop dc-link peak voltage control is employed in every qZS-HBI module to balance the dc-link voltages; 3) the design process of regulators is completely presented to achieve fast response and good stability; and 4) simulation and experimental results verify the proposed PWM algorithm and control scheme.

This paper is organized as follows. An overview of the whole system with control strategy is presented in Section II. Section III focuses on the system modeling and grid-connected control. Section IV addresses the proposed multilevel SVM technique. Section V designs the regulators; the proposed strategy is verified by simulation and experimental results in Section VI. Finally, a conclusion is given in Section VII. Note that, in the derivations of the paper, all of the symbols with “ ” denote the amplitude, and those with “ ” denote the average.

II. DESCRIPTION OF QZS-CMI-BASED GRID-TIE PV POWER SYSTEM

Fig. 1 shows the discussed qZS-CMI-based grid-tie PV power system. The total output voltage of the inverter is a series summation of qZS-HBI cell voltages. Each cell is fed by an independent PV panel. The individual PV power source is an array composed of identical PV panels in parallel and series. A typical PV model is performed by considering both the solar irradiation and the PV panel temperature. A. qZS-CMI The qZS-CMI combines the qZS network into each HBI module. When the th qZS-HBI is in nonshoot-through states, it will work as a traditional HBI. There are

\[ \hat{v}_{DClk} = \frac{1}{1 - 2D_k} v_{PVk} = B_k v_{PVk} \quad v_{Hk} = S_k \hat{v}_{DClk} \quad (1) \]

while in shoot-through states, the qZS-HBI module does not contribute voltage. There are

\[ \hat{v}_{DClk} = 0 \quad v_{Hk} = 0. \quad (2) \]

For the qZS-CMI, the synthesized voltage is

\[ v_H = \sum_{k=1}^{n} v_{Hk} = \sum_{k=1}^{n} S_k \hat{v}_{DClk} \quad (3) \]

where is the output voltage of the th PV array; is the dc-link voltage of the th qZS-HBI module; and represent the shoot-through duty ratio and boost factor of the th qZS-HBI, respectively, is the output voltage of the th module, and is the switching function of the th qZS-HBI.
B. Control Strategy

The control objectives of the qZS-CMI based grid-tie PV system are: 1) the distributed MPPT to ensure the maximum power extraction from each PV array; 2) the power injection to the grid at unity power factor with low harmonic distortion; 3) the same dc-link peak voltage for all qZS-HBI modules. The overall control scheme of Fig. 1 is proposed to fulfill these purposes. For achieving the first two goals, the closed loops are employed. 1) Total PV array voltage loop adjusts the sum of PV array voltages tracking the sum of PV array voltage references by using a proportional and integral (PI) regulator. Each PV array voltage reference is from its MPPT control independently. 2) Grid-tie current loop ensures a sinusoidal grid-injected current in phase with the grid voltage. The total PV array voltage loop outputs the desired amplitude of grid-injected current. A Proportional + Resonant (PR) regulator enforces the actual grid current to track the desired grid-injected reference. The current loop output’s total modulation signal subtracts the modulation signal sum of the second, third, , and th qZS-HBI modules to get the first qZS-HBI module’s modulation signal. 3) The separate PV array voltage loops regulate the other PV array voltages to achieve their own MPPTs through the PI regulators, such as to , respectively. With the total PV array voltage loop control, the PV arrays fulfill the distributed MPPT. In addition, the voltage feed forward control is used to generate each qZS-HBI module’s modulation signal, which will reduce the regulators’ burden, achieve the fast dynamic response, and minimize the grid voltage’s impact on the grid-tie current.

For the third goal, the dc-link peak voltage is adjusted in terms of its shoot-through duty ratio for each qZS-HBI module. A proportional regulator is employed in the inductor current loop to improve the dynamic response, and a PI regulator of the dc-link voltage loop ensures the dc-link peak voltage tracking the reference. Finally, the independent modulation signals and shoot through duty ratios of the qZS-CMI , are combined into the proposed multilevel SVM to achieve the desired purposes.

III. SYSTEM MODELING AND CONTROL

Fig. 2 shows block diagram of the proposed grid-tie control with the system model for the qZS-CMI based PV power system. The details will be explained as follows.

![Fig.2 Simulink model of schematic diagram](image)

where is the current of qZS inductor, is the th PV array’s current, and is the capacitance of PV array terminal capacitor. The qZS-CMI based grid-tie PV system has

\[ v_H = v_g + L_f \frac{di}{dt} + r_f i_s \]  \hspace{1cm} (5)

where is the grid voltage, is the grid-injected current, is the filter inductance, and is its parasitic resistance. The transfer function of the grid-injected current can be

\[ G_f(s) = \frac{I_s(s)}{V_H(s) - V_g(s)} = \frac{1}{L_f s + r_f}. \]  \hspace{1cm} (6)

\[ G_{PRI}(s) = k_{iP} \left( k_{iR} \omega_0 \right) \frac{s^2 + \omega_0^2}{s^2 + \omega_0^2} \]  \hspace{1cm} (7)

With the compensation of the PR regulator, the transfer function becomes

\[ G_{iicom}(s) = G_{PRI}(s) G_{io}(s) \frac{v_{DC}}{L_f s^3 + r_f s^2 + L_f \omega_0 s + r_f \omega_0^2}. \]  \hspace{1cm} (14)

![Fig.4. Simplified block diagram of the grid-current closed loop](image)
Consequently, the closed-loop transfer function of grid-tie current control can be obtained in (15), shown at the bottom of the page.

### B. PV Voltage Loop

From (4), we have

$$V_{PVk}(s) = \frac{1}{C_p}\left[I_{PVk}(s) - I_{L1k}(s)\right].$$

In addition, the output power of each qZS-HBI module equals its input power in the nonshoot-through state, the the qZS-HBI module has the power equation

$$\frac{\dot{i}_s \dot{V}_{Hk}}{2} = \dot{v}_{DCk} \dot{i}_{DCk} = v_{PVk} \dot{i}_{L1k,nsh}$$

### IV. PROPOSED MULTILEVEL SVM FOR QZS-CMI

As the qZS network is embedded to the HBI module, the SVM for each qZS-HBI can be achieved by modifying the SVM technique for the traditional single-phase inverter [15]. Using the first qZS-HBI module of Fig. 1 as an example, the voltage vector reference is created through the two vectors and , by

$$\ddot{v}_{L1k,nsh} = \frac{\dot{i}_s \dot{V}_{Hk}}{2 \dot{v}_{DCk}(1 - 2D_k)}.$$  \hspace{1cm} (18)

where is the carrier frequency; the time interval is the duration of active vectors, and is the duration of traditional zero voltage space vectors. Thus, the switching times for the left and right bridge legs in traditional HBI are . However, the shoot-through states are required for the independent qZS-HBI module. For this purpose, a delay of the switching times for upper switches or leads of the switching times for lower switches are employed at the transition moments. During each control cycle, the total time of shoot-through zero state is equally divided into four parts. The time intervals of and remain unchanged; and are the modified times to generate the shoot-through states; and are the switching control signals for the upper switches, and are that for the lower switches,. In this way, the shoot-through states are distributed into the qZS-HBI module without additional switching actions, losses, and resources. To generate the step-like ac output voltage waveform from the qZS-CMI, a phase difference, in which is the number of reference voltage vectors in each cycle, is employed between any two adjacent voltage vectors. The total voltage vector is composed of reference vectors from the qZS-HBI modules.

### V. CONTROL PARAMETER DESIGN

The prototype specifications of qZS-CMI based PV power system are shown in Table I. For the grid-connected current loop, the PR regulator parameters are designed to get a fast dynamic and zero-steady state error at the grid frequency. The fast dynamic response and stable steady-state performance are taken into account to design the control parameters for total PV voltage control loop, separate PV voltage control loop, and dc-link voltage control loop. The design results are shown in Table II, and all of the Bode plots are shown in Figs. 8–10.

Fig. 8 shows the Bode plots of the grid-tie current loop transfer functions and , which are before and after compensation, respectively. The symbol is the corner frequency of , which equals from (6); is the resonant frequency of the PR regulator, i.e., grid frequency of 314 rad/s. After compensation, provides a large gain inside its bandpass region, making the crossover frequency almost tenfold the corner frequency . Thus, the grid-connected fast response is greatly enhanced without loss of stability, which can be obtained from the bode diagram of closed-loop transfer function .

### VI. SIMULATION

A seven-level qZS-CMI for grid-connected PV power system is prototyped. Two Agilent E4360A Solar Array Simulators (SAS) are used to emulate the electrical behavior of PV arrays. Each SAS has two channel outputs, and each channel is with maximum 120-V maximum power point (MPP) voltage and 5-A MPP current. Simulation results are shown in Figs. 5.

#### A. DC-Link Voltage Balance Test

The different PV array voltages are performed for the three qZS-HBI modules. The second module’s PV voltage is set to 70 V and the others are at 90 V. A 50- resistor is used as ac
load in this test. All of the voltages in experimental results are 100 V/div.

From (1), the 136-V dc-link voltage of qZS-HBI module is required to support the 230-V grid. Fig. 11 shows the simulation results, where the second module’s dc-link peak voltage is boosted to the same voltage value when compared with other modules, but with a longer shoot-through time interval. Also, the qZS-CMI outputs the seven-level voltage with equal voltage step from one level to another level.

We can find that the same qZS-CMI output voltages and currents are achieved, which is derived from the designed dc-link peak voltage control.

Fig.5 Output results for proposed converter (a) Grid voltage and current (b) Converter voltage (c),(d),(e) and (f) PV voltages and references

B. Grid-Tie Investigation

The qZS-CMI is connected to the grid in order to test the proposed grid-tie control. Fig. 13 shows the PV array’s powervoltage characteristics. The measured PV array voltage and current of each module are used to calculate the actual PV power and the MPPT algorithm searches for the PV voltage reference at the MPP, which is refreshed every 0.05 s. Here, the perturbation and observation (P&O) MPPT strategy is applied in considering the excellent tracking efficiency and easy implementation.

At first, the three modules are all working at 900 W/m², and all of the initial voltage references of MPPT algorithms are given at 105 V. The second module’s irradiation decreases to 700 W/m² from 1 to 2 s in simulation. Fig. 14 shows the simulation results. In the experiments, the same test conditions of irradiation and
temperature can be implemented by setting the
curves of Agilent SAS. Fig. 5(a) shows the total
PV voltage (sum of three PV panel voltages) and
reference, PV panel voltages and references of
modules 2 and 3, respectively. It can be seen that
the excellent tracking performance is achieved
during 0–1 s; even though the second module’s
PV irradiation changes after 1 s, the still tracks the
reference very well after a very short transient.

VII. CONCLUSION

This paper proposed a control method for
qZS-CMI based single-phase grid-tie PV system.
The grid-injected power was fulfilled at unity
power factor, all qZS-HBI modules separately
achieved their own maximum power points
tracking even if some modules’ PV panels had
different conditions. Moreover, the independent
dc-link voltage closed-loop control ensured all
qZS-HBI modules have the balanced voltage,
which provided the high quality output voltage
waveform to the grid. The control parameters
were well designed to ensure system stability and
fast response. A multilevel SVM integrating with
shootthrough states was proposed to synthesize
the staircase voltage waveform of the single-phase
qZS-CMI.

The simulation and experiment were
carried out on the seven-level qZS-CMI
prototype. The qZS-CMI based grid-tie PV
system was tested. The simulation and experimental results verified the proposed qZS-
CMI based grid-tie PV power system and the
proposed control method. In principle, the
proposed system can work with the weak grid,
even though this paper did not address this topic.

In future work, we will focus on the
application to the weak grid, and the detailed
analysis and experimental results will be disclosed
in the next paper.

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