Intelligent Cascaded Multilevel Inverter Topology For Large Scale Grid Connected PV Systems

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Abstract

Large-scale grid Connected photovoltaic (PV) systems significantly contribute to worldwide renewable energy growth and penetration, which has inspired the application of cascaded modular multilevel converters due to their unique features such as modular structures, enhanced energy harvesting capability, scalability and so on. However, power distribution and control in the cascaded PV system faces tough challenge on output voltage over modulation when considering the varied and non-uniform solar energy on segmented PV arrays. This paper addresses this issue and proposes a decoupled active and reactive power control strategy to enhance system operation performance. The relationship between output voltage components of each module and power generation is analyzed with the help of a newly derived vector diagram which illustrates the proposed power distribution principle. On top of this, an effective control system including active and reactive components extraction, voltage distribution and synthetization, is developed to achieve independent active and reactive power distribution and mitigate the aforementioned issue. Finally, a 3-MW, 12-kV PV system with the proposed control strategy is modeled and simulated in MATLAB and PSIM co simulation platform. A downscaled PV system including two cascaded 5-kW converters with proposed control strategy is also implemented in the laboratory. Simulation and experimental results are provided to demonstrate the effectiveness of the proposed control strategy for large-scale grid-connected cascaded PV systems.

Keywords— ANN, Grid, PV, CHB

I. INTRODUCTION

GLOBAL energy crises and environmental concerns [1]–[3] from conventional fossil fuels have attracted more and more renewable energy developments in the worldwide. Among of these renewable energy, solar energy is much easier to be harvested, converted, and delivered to grid by a variety of power converters [4]–[14]. In particular, large-scale grid-connected photovoltaic (PV) systems play a major role to achieve PV grid parity and have been put forward in high penetration renewable energy systems [15]. As one type of modular multilevel converters, cascaded multilevel converters share many merits of modular multilevel converters, e.g., lower electromagnetic interference, low device rating, improved harmonic spectra, modularity, etc., but also is very promising for the large-scale PV system due to its unique advantages such as independent maximum power point tracking (MPPT) for segmented PV arrays, high ac voltage capability, etc. [11]–[14]. However, cascaded multilevel converters in PV systems are different from their some successful application such as medium voltage motor drive, static synchronous compensator (STATCOM), harmonic compensator, solid state transformer, which are connected with symmetrical segmented dc sources [16]–[22]. PV systems with cascaded multilevel converters have to face tough challenges considering solar power variability and mismatch of maximum power point from each converter module due to manufacturing tolerances, partial shading, dirt, thermal gradients, etc. In a cascaded PV system, the total ac output voltage is synthesized by the output voltage from each converter module in one phase leg, which must fulfill grid codes or requirements. Because same grid current flows through ac side of each converter module, active power mismatch will result in unsymmetrical ac output voltage of these modules [14]. The converter module with higher active power generation will carry more portion of the whole ac output voltage, which may cause over modulation and degrade power quality if proper control system is not embedded into the cascaded PV system

II. SYSTEM CONFIGURATION AND POWER FLOW ANALYSIS

A. System Configuration

The proposed large-scale grid-connected PV system is presented in Fig. 1, which demonstrates a three-phase two-stage power conversion system. It includes *n* cascaded multilevel inverter modules for each phase, where each inverter module is connected to *j* cascaded CF-DAB dc–dc converter modules with high voltage insulation [32]. This configuration features many impressive advantages comparing with traditional PV systems with line-frequency transformer. The cascaded multilevel inverters are directly connected to the grid without big line-frequency transformer, and the synthesized output voltage from cascaded modules facilitates to be extended to meet high grid voltage requirement due to the modular structure. Each dc–dc converter module is interfaced with segmented PV arrays and therefore the independent MPPT can be achieved to harvest more solar energy. Moreover, it is immune to the double-line-frequency power ripple propagation into PV arrays. Particularly, the ground leakage current and PV insulation issues are effectively suppressed. In addition, flexible control strategies are able to be explored and applied in this topology owing to more control variables and control degree-of-freedom. Although there is no accurate number about the cost benefits comparing with the traditional PV system with line-frequency transformer, it is obvious that the proposed PV system will have lower cost due to high power density and modular structure, which will significantly reduce the cost of the power platform using to install the PV system. This paper is focused on active and reactive power distribution control of the cascaded multilevel inverters in the proposed PV system. The detailed dc–dc converter design has been provided in [32] and will not be repeated in this paper. The selected application is a 3-MW/12-kV PV system in this paper. The *n* is selected to be 4 considering the tradeoff among the cost, lifetime, passive components, switching devices and frequency selection, and power quality. As a result, power rating of each inverter module is 250 kW. The average dc voltage of each inverter module is 3000 V based on the requirement of inverter output voltage, power devices as well as power quality. The second-order voltage ripple on the dc side is allowed to 20% even higher. Hence, film capacitor with 400 μF, Cin , is eligible to improve the system lifetime. In addition, the modular structure enables the high-voltage high-frequency SiC power devices for the HVHP PV application. The switching frequency for each power device is 5 kHz. Due to the phase-shift carrierbased phase-width modulation (PWM) control, the PV inverter will generate nine level output voltage and the equivalent output PWM frequency is 40 kHz for each phase. The current ripple of ac inductor is selected to be less than 20% of the rated output current. Therefore, the ac inductor with 0.8 mH, L_f , is acted as the filter. In each dc–dc converter module, L_{dc1} and L_{dc2} are dc inductors, and L_s is leakage inductor. C_{PV} is high-frequency filter capacitor paralleled with PV arrays. High-frequency transformer with turn ration$N$ is connected between low-voltage side (LVS) converter and high-voltage side (HVS) converter.C_{LV} are LVS dc capacitor and C_{HV} are HVS dc capacitor. The detailed parameters have been provided in Table I.

B. Power Flow Analysis

In the cascaded PV system, power distribution between these modules is primarily dominated by their respective ac output voltage because the same grid current flows through these modules in each phase as shown in Fig. 1. Vector diagrams are derived in Fig. 2 to demonstrate the principle of power distribution between four PV inverter modules in phase *a*. The same analysis can be applied for phases *b* and *c*. Considering the relative stability of the grid voltage, v_{ga} is used for the synchronous signal. The α-axis is in phase with grid voltage and the β-axis lags the α-axis by 90◦ as shown in Fig. 2(a).The *d*-axis is aligned with the grid voltage by the phase-locked loop (PLL) control [8] and the *q*-axis lags the *d*-axis by 90◦. The components of grid voltage in $\alpha\beta$ stationary frame and *dq* rotating frame can be written in (1) and (2), respectively

III. CONTROL SYSTEM DESIGN

Fig. 3 shows the proposed control system of the grid connected cascaded PV converters including CF-DAB dc–dc converters control and cascaded multilevel inverters control in phase *a*. The same control system can be applied in phases *b* and *c*.

A. CF-DAB DC–DC Converters Control

Fig. 3(a) shows the CF-DAB dc–dc converters control for one unit of dc–dc converter module 1 in Fig. 1 [32]. The same control can be used to other units. Due to the dual-active-bridge structure, this control has two degrees of freedom: the duty cycle D and the phase shift angle ϕ, by which the PV voltage $V_{pv1a\ 1}$ and LVS dc-link voltage V_{LV} are controlled, respectively. $V_{pv1a\ 1}$ is directly controlled by the duty cycle D so that it can be well kept at the reference voltage $V*_{pv1a\ 1}$ which is generated from MPPT algorithm [32]. Usually the bandwidth of the duty cycle loop is about several kHz (e.g., 10 kHz in this paper), which is much higher than 120 Hz; thus, the double-frequency component in the LVS or HVS is blocked and high utilization factor of MPPT is reached in the PV side. For simplicity, a simple high bandwidth PI controller is applied. The PV voltage and current are both sensed for the calculation of $P_{pv1a\ 1}$, $i_{pv1a\ 1}/v_{pv1a\ 1}$, and $\Delta i_{pv}/\Delta v_{pv}$ which are used in MPPT algorithm. The MPPT algorithm generates a reference voltage $V*_{pv1a\ 1}$ for the PV voltage regulation. Power transferred from LVS to HVS is determined by the phase shift angle ϕ. By regulating LVS voltage through ϕ, the power generated from the PV arrays and the power delivered to HVS are matched. To minimize the peak transformer, the LVS dc-link voltage *V*LV is controlled to follow the reference *V*HV *N* , that is HVS voltage divided by turn ratio *N*, so that they are balanced. Proportional resonant (PR) controller is employed to obtain enough gain at double frequency to ensure the LVS voltage to dynamically follow the reference voltage.

B. Cascaded Multilevel Inverter Control

In the cascaded multilevel converter control showing in Fig. 3(b), active power distribution between cascaded PV converter modules is decided by the individual maximum power available from PV arrays. Considering dc capacitors connected with cascaded multilevel inverter modules have the same capacitance, reactive power from each module can be synchronously controlled to reduce the overmodulation risk regardless of active power change. Therefore, the proposed control strategy can be called decoupled active and reactive power distribution control. The double-loop *dq* control based on discrete Fourier transform PLL method [8] is applied to achieve the active and reactive power distribution. The unique features of this control strategy is that active and reactive power is decoupled in each module by synchronizing with the grid current as described in Section-II, which are not achieved in traditional control methods in [30] and [31]. Due to the same grid current goes through ac side of each module, only grid voltage synchronization is not able to perform the separation of active and reactive power in each module under unsymmetrical active power generation.

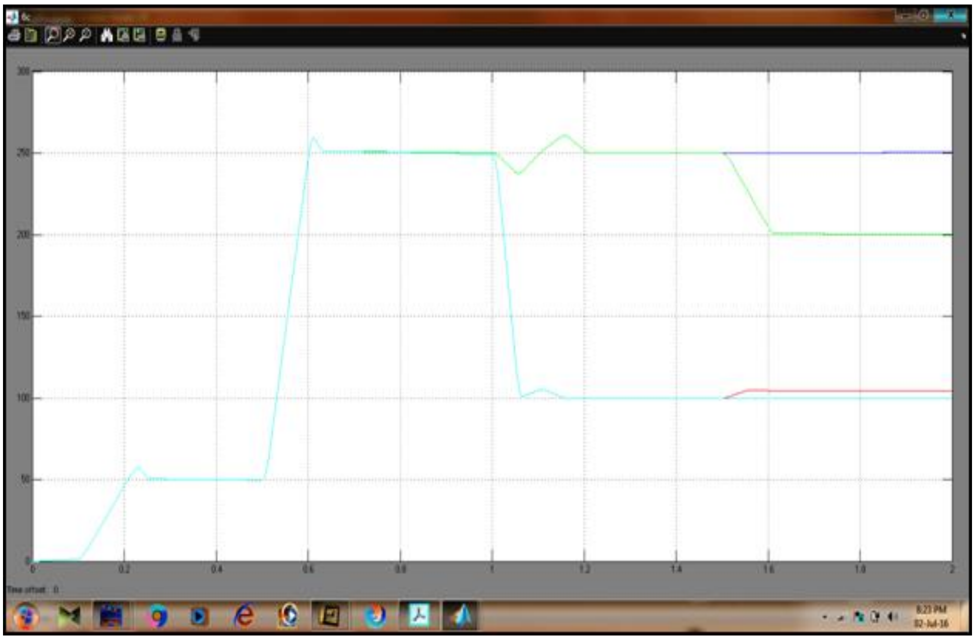
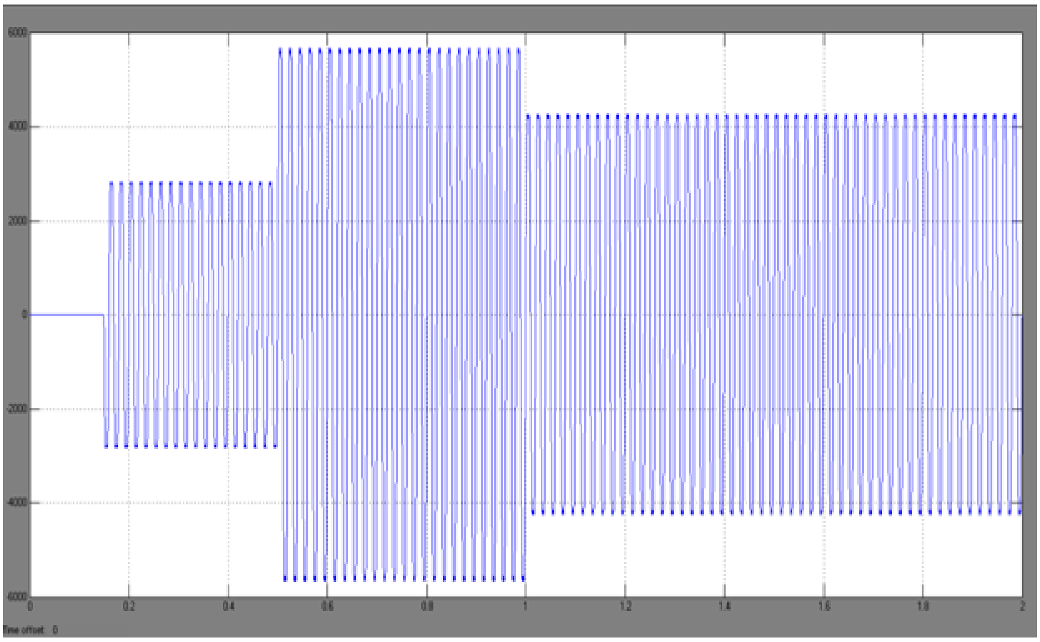


Fig. 1. Simulation results of PV system with traditional active and reactive power control in phase



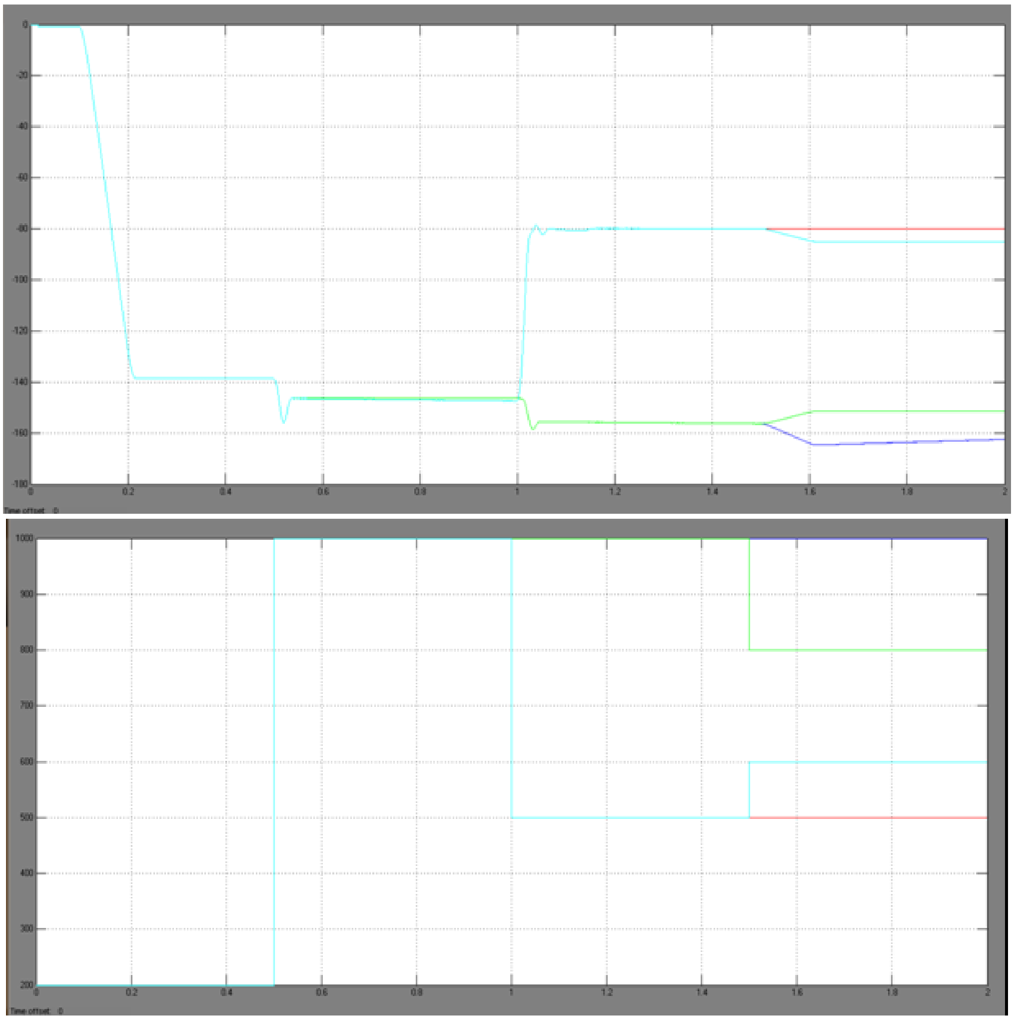


Fig. 2. Simulation results of PV system with decoupled active and reactive power control

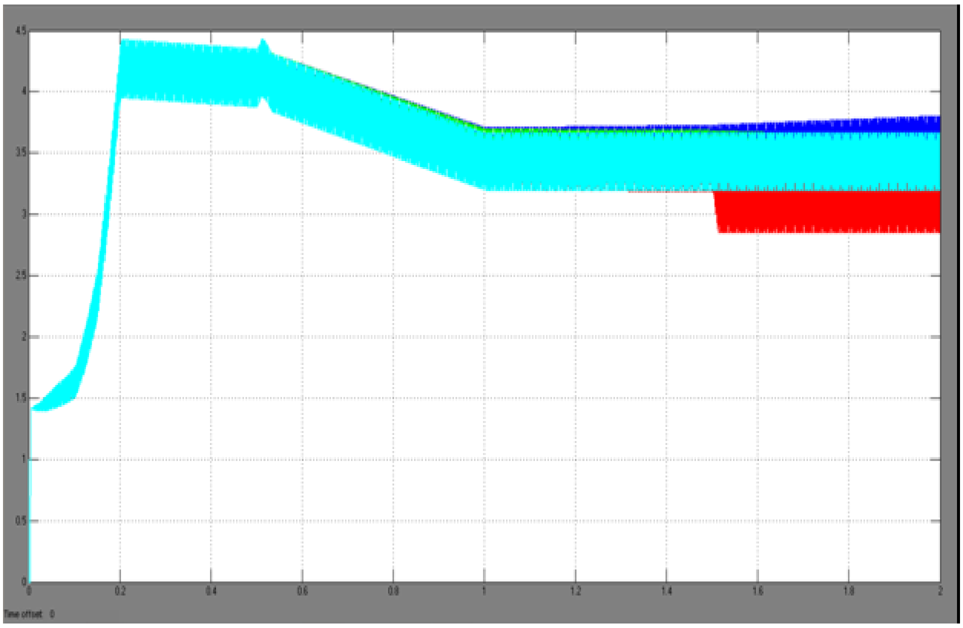


Fig. 3. Simulation results of PV system with the proposed control in three phase

Conclusion:

In this paper addressed the active and reactive power distribution among cascaded PV inverter modules and their impacts on power quality and system stability for the large-scale grid connected cascaded PV system. The output voltage for each module was separated based on grid current synchronization to achieve independent active and reactive power distribution. A decoupled active and reactive power control strategy was developed to enhance system operation performance. The proposed control strategy enabled the cascaded PV inverter modules and gives the enhanced performance. Simulation Results shows the validation for the above concept

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