DECOUPLED LIVELY AND REACTIVE CONTROL FOR GIANT SCALE GRID LINKED PHOTOVOLTAIC TECHNIQUES USING CASCADED MODULAR MULTISTAGE CONVERTERS

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ABSTRACT

Large-scale grid-connected photovoltaic (PV) sys-tems significantly contribute to worldwide renewable energy growth and penetration, which has inspired the application of cas-caded 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 volt-age over modulation when considering the varied and no 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 relation-ship between output voltage components of each module and power generation is analyzed with the help of a newly derived vector dia-gram which illustrates the proposed power distribution principle. On top of this, an effective control system including active and reactive components extraction, voltage distribution and synthe-sization, 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 cosimulation plat-form. A downscaled PV system including two cascaded 5-kW con-verters 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.

Index Terms—*Cascaded PV system, decoupled active and reac-tive power control, voltage distribution.*

INTRODUCTION

LOBAL energy crises and environmental concerns **G**[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 eas-ier to be harvested, converted, and delivered to grid by a va-riety 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 har-monic 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 seg-mented 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.

Several control strategies have been proposed for the cascaded PV system with direct connection between individual inverter module and segmented PV arrays [23]–[27]. But they did not consider the fact that PV arrays cannot be directly connected to the individual inverter module in high-voltage large-scale PV system application due to the PV insulation and leakage current issues. Even if there are low-frequency medium-voltage transformers between the PV converters and grid, there are still complicated ground leakage current loops among the PV con-verter modules [28]. Therefore, those methods in [23]–[27] are not qualified for a practical large-scale grid-connected cascaded PV system. Moreover, reactive power compensation was not achieved in [23]–[26], which largely limits the functions of the PV1

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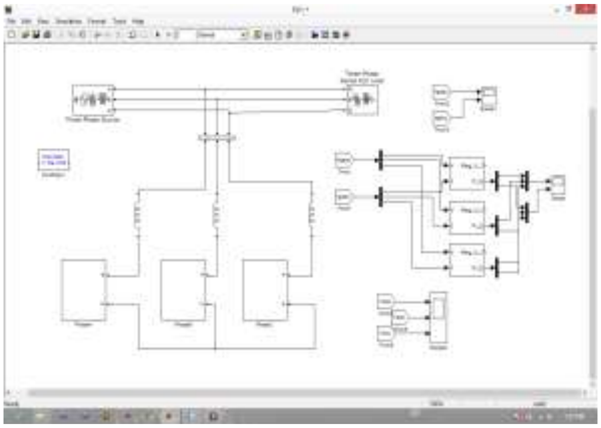

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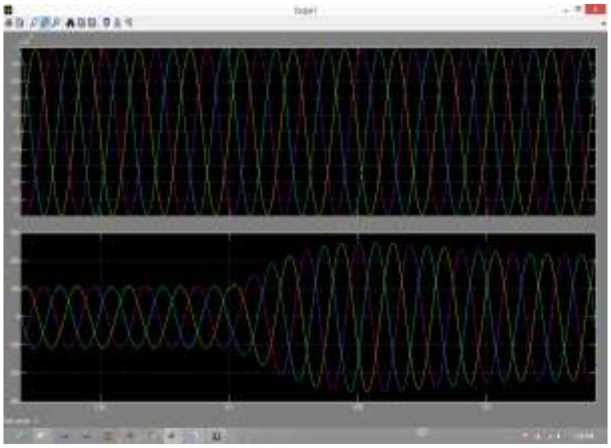

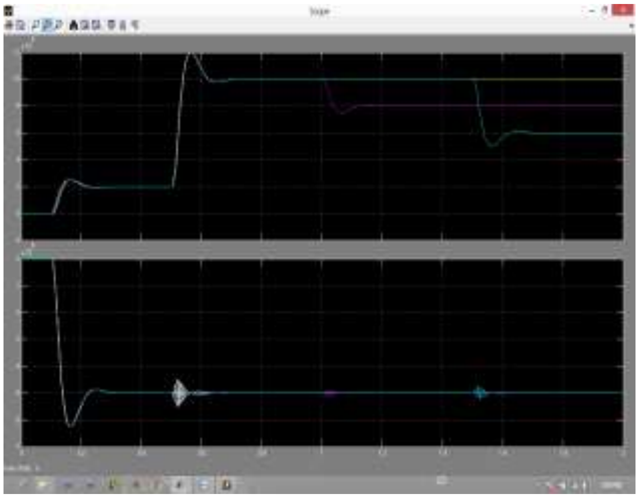

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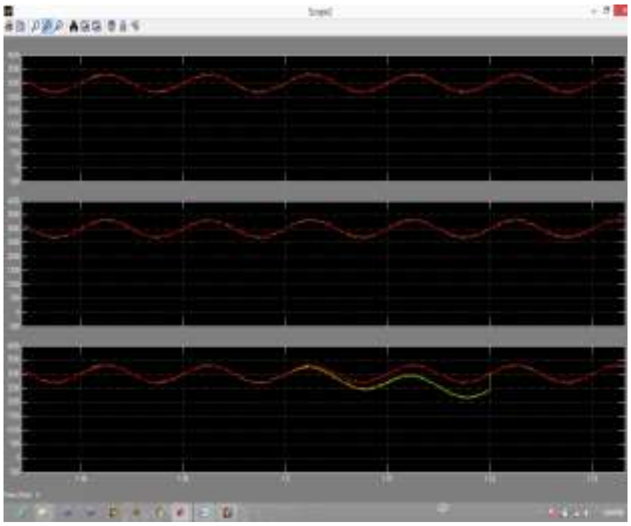


cascaded PV system to provide ancillary services. Proper reac-tive power compensation can significantly improve the system reliability, and in the meantime help the MPPT implementation for the cascaded module under unsymmetrical condition as well as comply with the system voltage requirement simulta-neously [29]. A reactive and active power control strategy has been applied in cascaded PV system with isolated dc–dc con-verters in [30] and [31]. If symmetrical active power comes from each module, active and reactive power can be equally distributed into these modules under traditional power control in [30] and [31]. However, if unsymmetrical active power is gen-erated from these modules, this control strategy will not be able to achieve decoupled active and reactive power control. Reactive power change is along with the active power change at the same direction, which may aggravate output voltage overmodulation during unsymmetrical active power outputs from segmented PV arrays.

In order to solve the aforementioned issues, this paper pro-poses a large-scale grid-connected cascaded PV system includ-ing current-fed dual-active-bridge (CF-DAB) dc–dc converters and cascaded multilevel inverters as shown in Fig. 1. A de-couple active and reactive power control system is developed to improve the system operation performance. Reactive power from each PV converter module is synchronously controlled to reduce the overmodulation of PV converter output voltage caused by unsymmetrical active power from PV arrays. In par-ticular, the proposed PV system allows a large low-frequency dc voltage ripple for each PV converter module, which will not affect MPPT achieved by CF-DAB dc–dc converters. As a re-sult, film capacitors can be applied to replace the conventional electrolytic capacitors, thereby enhancing system lifetime.

This paper is organized as follows: a two-stage large-scale grid-connected cascaded PV system topology and correspond- ing power flow distribution are first introduced in Section II. A vector method is derived to help illustrate the active and reactive power distribution principle between the cascaded PV inverter modules. In Section III, a comprehensive control system with CF-DAB dc–dc converters control and cascaded multilevel in-verter control is developed. The decoupled active and reactive power control including active and reactive components ex-traction, voltage distribution and synthesization, is executed in multilevel inverter control system to achieve independent active and reactive power distribution. A three-phase 3-MW/12-kV PV system including 12 cascaded PV inverter modules with the proposed decoupled active and reactive power control strat-egy is modeled in MATLAB/Simulink and PSIM cosimulation platform. A downscaled PV system prototype including two cascaded 5-kW inverter modules has also been built in the labo-ratory. Simulation and experiment results are presented to verify the validity of the proposed control strategy in Sections IV and V. Finally, conclusions are presented in Section VI.

SYSTEM CONFIGURATION AND POWER FLOW ANALYSIS

A System Configuration

The proposed large-scale grid-connected PV system is pre-sented in Fig. 1, which demonstrates a three-phase two-stage power conversion system. It includes *n* cascaded multilevel in-verter modules for each phase, where each inverter module is connected to *j* cascaded CF-DAB dc–dc converter modules with high voltage insulation [32].

Parameters		Symbol	Value
PV inverter modules in each phase	Number	n	4
	DC Capacitor voltage	V_{dcki} (k=1,2…n; i=a,b,c)	3000 V
	DC Capacitor size	C_{in}	400 uF
	Filter inductor	L_f	0.8 mH
	Switching frequency	f_{SW_AC}	5 kHz
CF-DAB DC-DC converter module	Number	j	5
	Capacitor voltage in low voltage capacitor	V_{LV}	300V
	Capacitor voltage in low voltage capacitor	V_{HV}	600V
	Transformer turn ratio	N	2
	PV arrays output voltage	V_{pvki_r} (k=1,2…n; i=a,b,c ; r=1,2…j)	100 V - 200 V
	Leakage inductor	L_s	2.5 µH
	DC inductor value	L_{dc1}, L_{dc2}	12.5 µH
	Capacitor in high voltage side	C_{HV}	2 mF
	Capacitor in low voltage side	C_{LV}	300 uF
	PV arrays output capacitor	C_{PV}	100 uF
	Switching frequency	f_{SW_DC}	50 kHz
Grid (three phase)	Rated real power	P_g	3 MW
	Rated reactive power	Q_g	1.5 MVAR
	Rated RMS line-line voltage	V_{gl-l}	12 kV

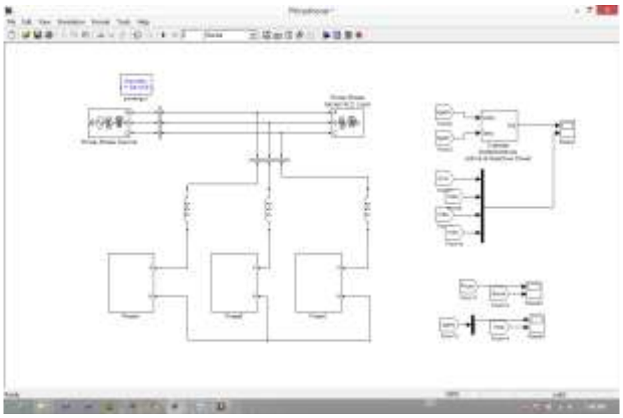
This configuration features many impressive advantages comparing with traditional PV systems with line-frequency transformer. The cascaded multilevel invert-ers are directly connected to the grid without big line-frequency transformer, and the synthesized output voltage from cascaded modules facilitates 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 en-ergy. Moreover, it is immune to the double-line-frequency power ripple propagation into PV arrays. Particularly, the ground leak-age 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 in-verter 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, C_{in} , is eligi-ble 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 carrier-based 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 trans-former 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.

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 Sec-tion II, which are not achieved in traditional control methods. 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. In the proposed control, individual voltage outer loop controls dc voltage of each inverter module to track the reference V_{dc}^*

SIMULATION VERIFICATION

The large-scale grid-connected cascaded PV system with the proposed control strategy is first validated in cosimulation platform with PSIM and MATLAB. The equivalent switching function model in phase *a* is shown in Fig. 5. The same model can be used in phases *b* and *c*. Considering the characteristics of PV arrays, the equivalent input current source i_{PV} and volt-age source V_{PV} are developed in this model. The duty cycle D determines the LVS voltage as shown in Fig. 3(a) and equiva-lent dc voltage in cascaded inverter side V_{dc} is controlled to be constant in Fig. 3(b). Therefore, the equivalent voltage source

PV Traditional



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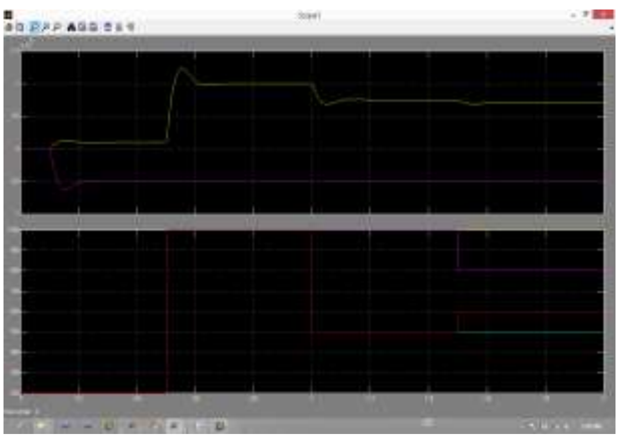
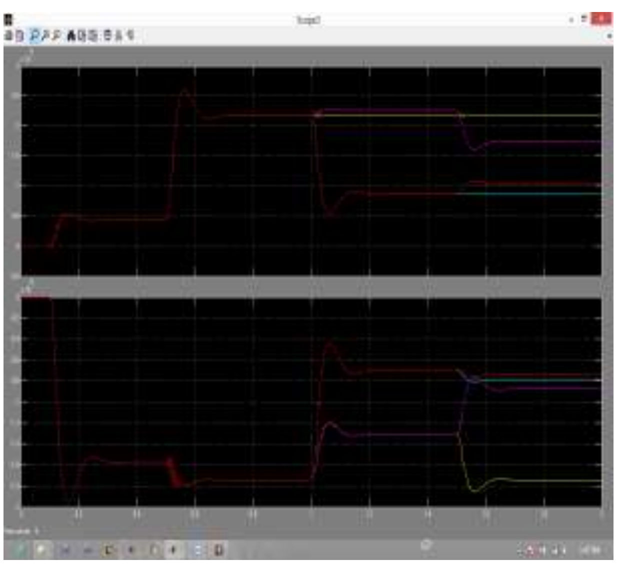
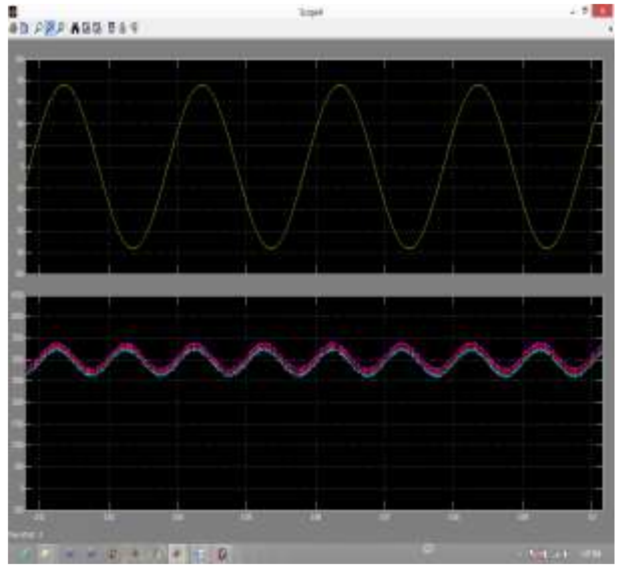
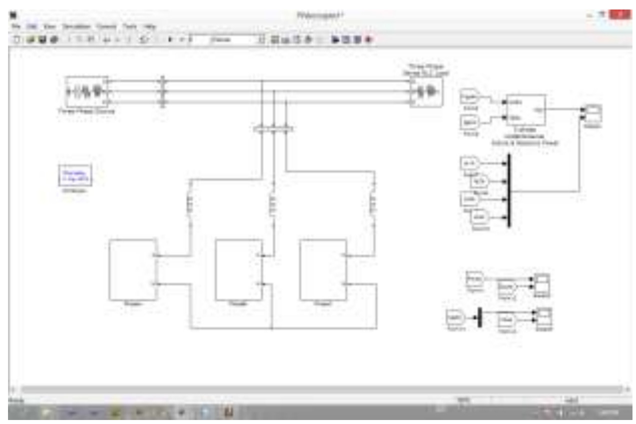






PV Decoupled



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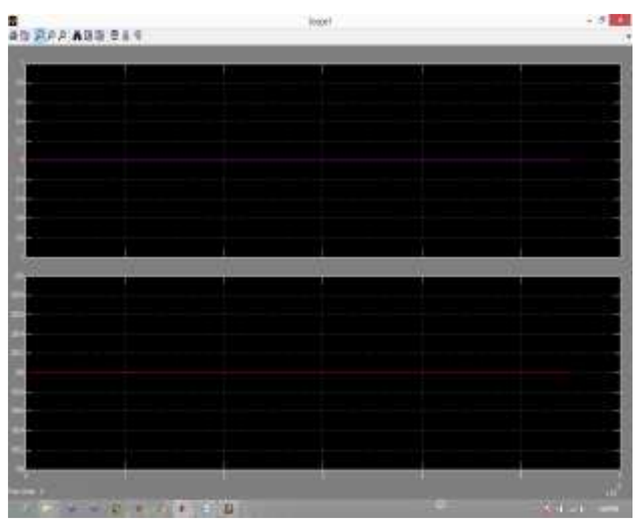

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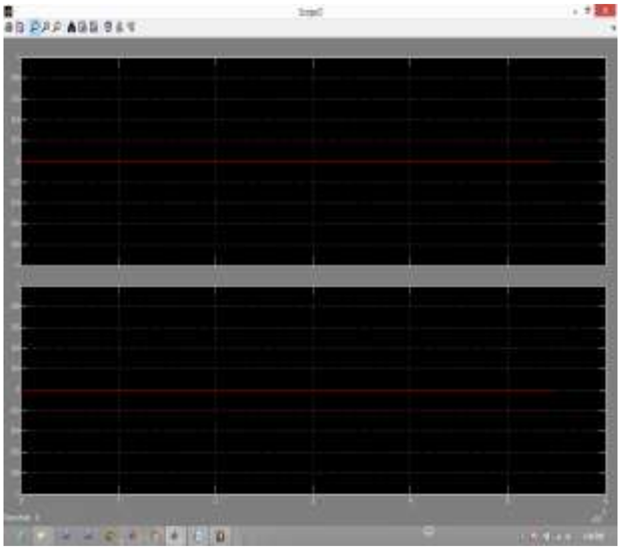

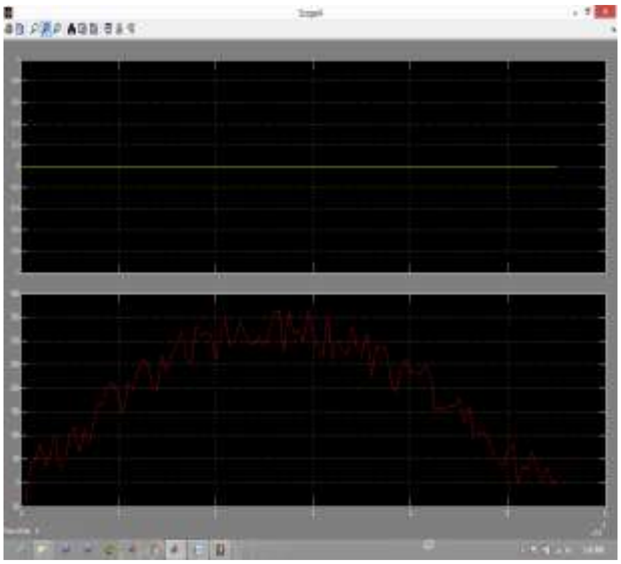

EXPERIMENTAL RESULTS

A downscaled PV system prototype including two cascaded 5-kW PV converter modules with SiC MOSFETs in phase *a* has been built in the laboratory as shown in Fig. 9. The proposed control strategy is implemented in DSP and FPGA cocontrol platform. The system circuit parameters are modified and listed in Table II considering power loss, actual line impedance, and grid equivalent impedance. The experimental results at 1.1 kVA have been recorded by Yokogawa scopecorder DL750 and car-ried out to demonstrate the performance of the proposed control system. The reactive power injected to grid Q_g is 740 VAR, which is less than the sum of Q_{pv1} and Q_{pv2} due to the reac-tive power loss on output filter and grid impedance as shown in Fig. 10(b). Subsequently, P_g increases from 150 to 770 W and Q_g varies slightly with the grid voltage change. The active and reactive power ratio of two modules is both 0.5:0.5. Afterward, the active power P_{pv1} from first module increases from 412.5 to 490 W and active power P_{pv2} generated by second module decreases from 412.5 to 330 W. Accordingly, the reactive power ratio of two modules changes from 0.5:0.5 to 0.6:0.4 with the active power change at the same direction, which causes the output overmodulation of first PV inverter module. As a result, the grid current i_g is distorted.

SYSTEM CIRCUIT PARAMETERS IN EXPERIMENT

Parameters		Symbol	Value
PV inverter modules in each phase	Number	n	2
	Capacitor Voltage	V_{dcj} (j=1,2...n)	100 V
	Capacitor size	C_{in}	400 uF
	Filter Inductor	L_f	2 mH
	Switching frequency	f_{SW}	10 kHz
Grid (each phase)	Rated real power	P_g	10 kW
	Rated reactive power	Q_g	10 kVAR
	Rated phase-ground voltage (RMS)	v_g	120 V

Fig. indicates active power distribution, reactive power distribution, grid voltage and current, and frequency spectrum with traditional proposed control strategy [30], Finally, $P_{p\,v\,1}$ decreases from 490 to 330 W and $P_{p\,v\,2}$ increases from 330 to 490 W. $Q_{p\,v\,1}$ decreases from 600 to 400 VAR and $Q_{p\,v\,2}$ increases from 600 to 400 W. The frequency spectrum of i_g is analyzed under symmetrical and unsymmetrical power distri-bution. It can be seen from Fig. 10(d) that THD is 8.61% with- equivalent reactive power is always distributed between the two modules as shown in Fig. 11(b). Because of active and reactive power loss, the sum of P_{PV1} and P_{PV2} is more than P_g , and the sum of Q_{PV1} and Q_{PV2} is greater than Q_g . The grid voltage and current waveform during different active power distribu-tion ratios are illustrated in Fig. 11(c). It can be seen that the grid current has good quality during different scenarios with the proposed control strategy. Furthermore, THD are the same re-gardless of the unsymmetrical active power distribution, which are only 3.98%.

CONCLUSION

This paper addressed the active and reactive power distribu-tion 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 pro-posed control strategy enabled the cascaded PV inverter modules to adequately embody their respective reactive power compen-sation capability regardless of their active power generation. Moreover, it was demonstrated that the risk of overmodulation of the output voltage from the cascaded PV inverter modules can be effectively reduced, which improves system power qual-ity and stability. Correspondingly, the simulation and experi-mental results confirmed the validity of the proposed control strategy.

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