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Power Control for Large-Scale Grid-Connected Photovoltaic Systems Using Cascaded Modular Multilevel Converters with MPPT

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Abstract:

Large-scalegrid-connectedphotovoltaic(PV)systemssignificantlycontributetoworldwiderenewableenergygrowth andpenetration,whichhasinspiredtheapplicationofcascadedmodularmultilevelconvertersduetotheiruniquefeaturessuchasmodularstructures,enhancedenergyharvestingcapability,scalabilityandsoon.The penetration of photovoltaic (PV) solar power generation in distributed generation (DG) systems is growing rapidly. This condition imposes new requirements to the operation and management of the distribution grid, especially when high penetration levels are achieved. Under this scenario, the power electronics technology plays a vital role in ensuring an effective grid integration of the PV system, since it is subject to requirements related not only to the variable source itself but also to its effects on the stability and operation of the electric grid. This paper proposes an enhanced interface for the grid connection of PV solar systems.

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 synthesization, 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 modelled and simulated in MATLAB. Simulation and experimental results are provided to demonstrate the effectiveness of the proposed control strategy for large-scale grid-connected cascaded PA full detailed model is described and its control scheme is designed. The dynamic performance of the designed architecture is verified by computer simulations and Further Extension can be done using Fuzzy Logic Controller.

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 ismuch 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 ofmodular 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,

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dirt, thermal gradients, etc. In a cascaded PV system, the total ac output volt- age 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 overmodulation 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 cur- rent 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 converter 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.

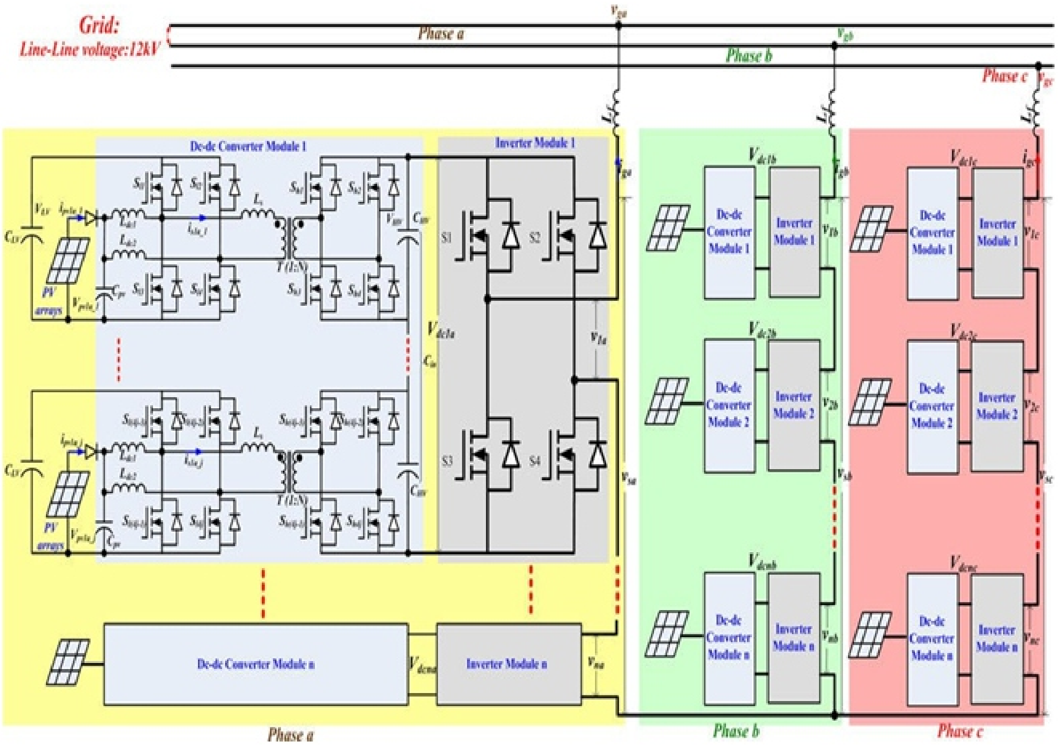

Fig.1.Proposed grid-connected PV system with cascaded multilevel converters at 3 MW.

Cascaded PV system to provide ancillary services. Proper reactive 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 simultaneously [29]. A reactive and active power control strategy has been applied in cascaded PV system with isolated dc–dc converters 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 generated 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 including 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.

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In particular, 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 result, 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 inverter 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 strategy is modeled in MATLAB/Simulink and PSIM co-simulation platform.

A downscaled PV system prototype including two cascaded 5-kW inverter modules has also been built in the laboratory. Simulation and experiment results are presented to verify the validity of the proposed control strategy in Sections IV andV. Finally, conclusions are presented in Section VI.

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.

TABLE I
SYSTEM CIRCUIT PARAMETERS IN SIMULATION

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	$V_{gL\text{-}L}$	12 kV

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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 eligibleto improve the system lifetime. In addition, the modularstructure enables the high-voltage high frequency Sic powerdevices for the HVHP PV application. The switching frequencyfor each power device is 5 kHz.

Due to the phase-shift carrier basedphase-width modulation (PWM) control, the PV inverterwill generate nine level output voltage and the equivalent outputPWM frequency is 40 kHz for each phase. The current ripple ofac inductor is selected to be less than 20% of the rated outputcurrent. Therefore, the ac inductor with 0.8 mH, Lf, is acted asthe filter. In each dc–dc converter module, Ldc1 and Ldc2 are dc inductors, and Ls is leakage inductor. CPV 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. CLV are LVS dc capacitor and CHV 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, vga 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 αβ stationary frame and dq rotating frame can be written in (1) and (2), respectively

$$\begin{cases} v_{ga\_\alpha} = V_{ga}\sin(\omega t) \\ v_{ga\_\beta} = -V_{ga}\cos(\omega t) \end{cases} \qquad (1)$$

$$\begin{bmatrix} v_{ga\_d} \\ v_{ga\_q} \end{bmatrix} = \begin{bmatrix} \sin(\omega t) & -\cos(\omega t) \\ \cos(\omega t) & \sin(\omega t) \end{bmatrix} \begin{bmatrix} v_{ga\_\alpha} \\ v_{ga\_\beta} \end{bmatrix} \qquad (2)$$

Where the ω is the system fundamental frequency, Vga is the amplitude of the grid voltage, vga d = Vga, vgz q = 0.The grid current is relatively stable to the grid voltage in steady state. Therefore, the new d-axis (d′) can be aligned with the grid current. It is obvious that the d′-axis component of the inverter output voltage vsa d′ determines the active power.

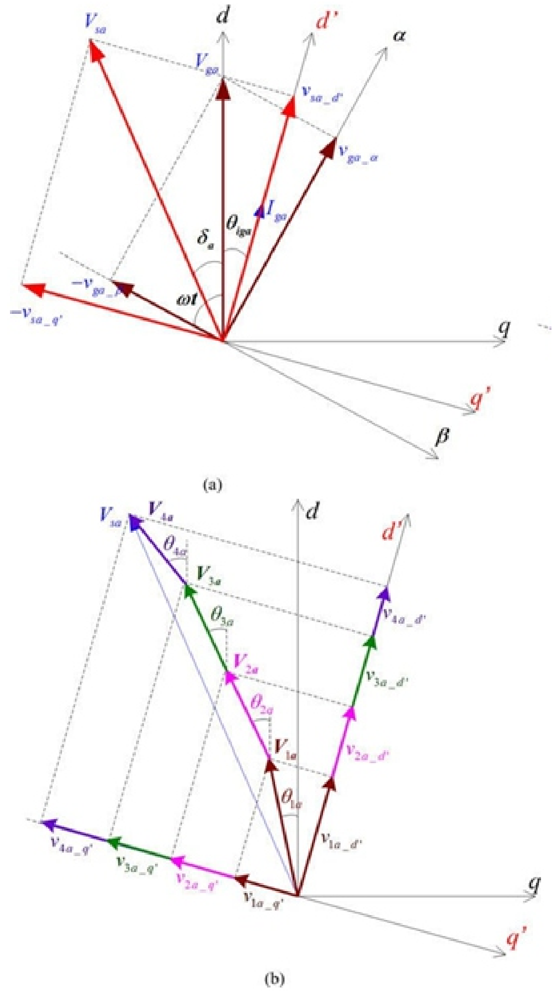

Fig.2.Vector diagrams showing relation between αβ frame, dq frame, and d′q′ frame. (a) The relationship between the grid current, grid voltage, and inverter output voltage in phase a. (b) The voltage distribution of PV inverter in phase a

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Generation and the q′-axis component vsa q ′ decides the reactive power output. Fig. 2(b) describes clearly the power distribution between four PV inverter modules under different active power generation. The output voltage of the total inverter Vsa is synthesized by the four inverter module output voltage with different amplitude and angles. In particular, the vka d′ and vka q ′ (k = 1, 2,. . .4) can be independently controlled to implement the decoupled active and reactive power control

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 oneunit of dc–dc converter module 1 in Fig. 1 [32]. The same controlcan be used to other units. Due to the dual-active-bridge structure,this control has two degrees of freedom: the duty cycle DAnd the phase shift angle ϕ, by which the PVvoltage Vpv1a 1 andLVS dc-link voltage VLV are controlled, respectively. Vpv1a 1 isdirectly controlled by the duty cycleD so that it can be well keptat the reference voltage V pv1a 1 which is generated from MPPTalgorithm [32].

Usually the bandwidth of the duty cycle loop isabout several kHz (e.g., 10 kHz in this paper), which is muchhigher than 120 Hz; thus, the double-frequency component inthe LVS or HVS is blocked and high utilization factor of MPPTis reached in the PV side. For simplicity, a simple high bandwidthPI controller is applied. The PV voltage and current areboth sensed for the calculation of Ppv1a 1, ipv1a 1 /vpv1a 1 , andΔipv /Δvpv which are used in MPPT algorithm.

The MPPT algorithmgenerates a reference voltage V pv1a 1 for the PV voltageregulation. Power transferred from LVS to HVS is determinedby the phase shift angle ϕ. By regulating LVS voltage throughϕ, the power generated from the PV arrays and the power deliveredto HVS are matched. To minimize the peak transformer, theLVS dc-link voltage VLV is controlled to follow the referenceVH-VN, that is HVS voltage divided by turn ratio N, so that theyare balanced. Proportional resonant (PR) controller is employedto obtain enough gain at double frequency to ensure the LVSvoltage 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 convertermodules is decided by the individual maximum poweravailable from PV arrays. Considering dc capacitors connectedwith cascaded multilevel inverter modules have the same capacitance,reactive power from each module can be synchronouslycontrolled to reduce the overmodulation risk regardless of activepower change. Therefore, the proposed control strategy can becalled decoupled active and reactive power distribution control.The double-loop dq control based on discrete Fourier transformPLL method [8] is applied to achieve the active and reactive-power distribution.

The unique features of this control strategyis that active and reactive power is decoupled in each moduleby synchronizing with the grid current as described in SectionII, which are not achieved in traditional control methodsin [30] and [31]. Due to the same grid current goes throughac side of each module, only grid voltage synchronization is-not able to perform the separation of active and reactive powerin each module under unsymmetrical active power generation.In the proposed control, individual voltage outer loop controlsdc voltage of each inverter module to track the reference V dc

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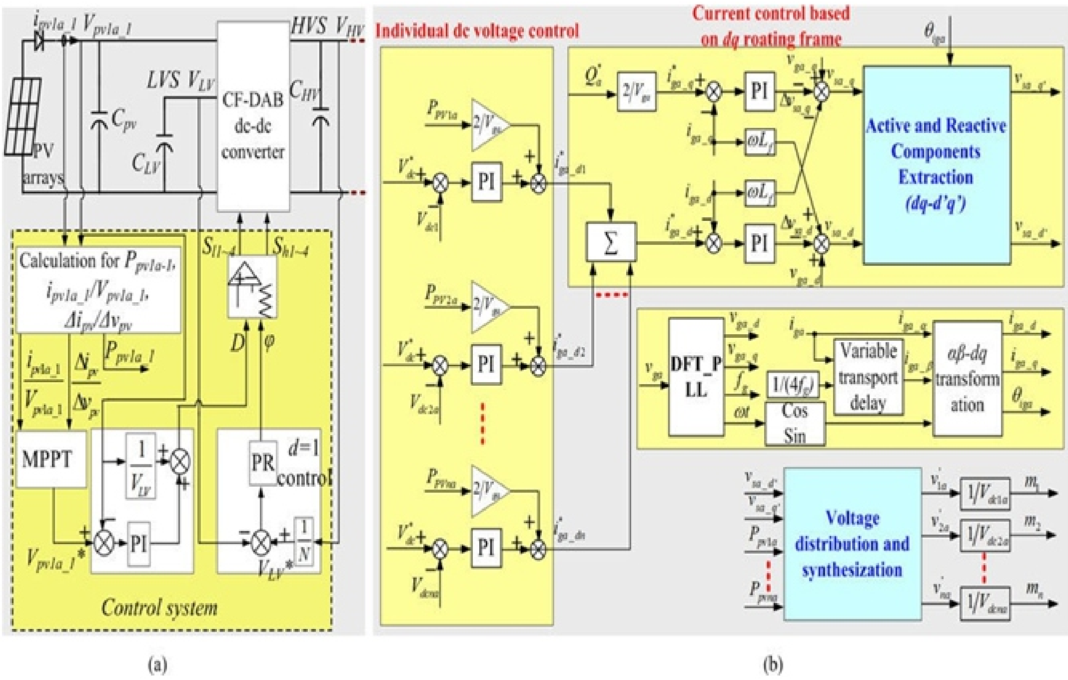

Fig. 3. Proposed control system of the grid-connected cascaded PV converters in phase a. (a) CF-DAB dc–dc converters control of one unit in module 1.(b) Cascaded multilevel inverters control.

by the PI controller. Therefore, the harvested maximum powerfrom j segmented PV arrays with CF-DAB dc–dc converterscontrol can be effectively delivered to grid. Afterward, the maximumpower is fed back to reduce the inner loop action. This allows the closed-loop compensators to have smaller gains andhence increased robustness [33]–[35]. The d-axis componentcommand of grid current i ga d is Synthesized by the multipleoutputs from the n individual voltage loops. The q-axiscomponent command of grid current iga q is obtained based on the desired reactive power Qa . The decoupled current loopcontrols the dq components of grid current iga d and iga q totrack the references iga d and i gaq , and then generates the totaloutput voltage regulation Δvsa d and Δvsa q , respectively. Thedq components of grid voltage, vga d and vgaq , are feedback tothe output voltage to improve the system dynamic performance,respectively [36]. The output voltage signal vsa d is synthesizedby Δvsa d, vga d and decoupled variable ωLfigaq . The outputvoltage signal vsa q is composed ofΔvsa q vga a and decoupledvariable ωLfigad . Subsequently, vsa d and vsa q are sent to the“active and reactive components extraction” module, which producesthe decisive active and reactive components, vsa d and vsa q , by synchronizing with iga . And then the “voltage distributionand synthesization” module divides the vsa d and vsa q into the n cascaded PV inverter modules according to their respectiveactive and reactive power contribution [29].

1) Active and Reactive Components Extraction: The “activeand reactive components extraction” module is used to transferthe outputs of inner loops vsa d and vsa q in dq frame tovsa d and vsa q in d q frame. The angle of grid current θigais the key to achieve the transformation. The grid current igacan be measured and act as the signal iga α in the α-axis. Theimaginary quadrature signal iga β of the grid current can begenerated by a variable transport delay block as shown in Fig. 3.

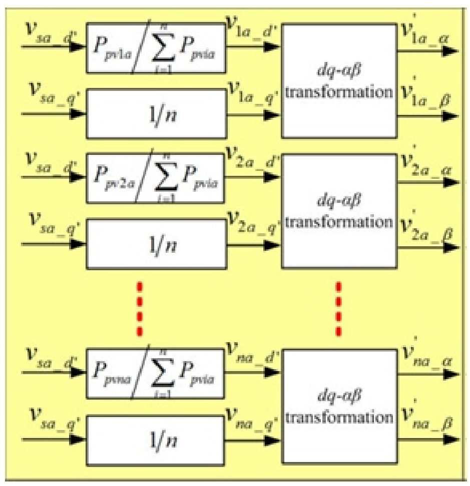

Fig.4. Proposed voltage distribution and synthesization of the cascaded PVinverters in phase a.

Therefore, θiga can be obtained based on the dq componentsof grid current iga d and iga q by the αβ–dq transformation asfollows:

$$\begin{bmatrix} i_{ga\_d} \\ i_{ga\_q} \end{bmatrix} = \begin{bmatrix} \sin\omega t & -\cos\omega t \\ \cos\omega t & \sin\omega t \end{bmatrix} \begin{bmatrix} i_{ga\_\alpha} \\ i_{ga\_\beta} \end{bmatrix} \quad (3)$$

whereθiga = tg−1(iga q/.iga d) is the grid current angle.Accordingly, the desired vsa d———————————— and vsa q ———————————— can be derived by

$$\begin{bmatrix} v_{sa\_d'} \\ v_{sa\_q'} \end{bmatrix} = \begin{bmatrix} \cos\theta_{iga} & \sin\theta_{iga} \\ -\sin\theta_{iga} & \cos\theta_{iga} \end{bmatrix} \begin{bmatrix} v_{sa\_d} \\ v_{sa\_q} \end{bmatrix}. \quad (4)$$

2) Voltage Distribution and Synthesization: The “voltage distribution and synthesization” module as shown in

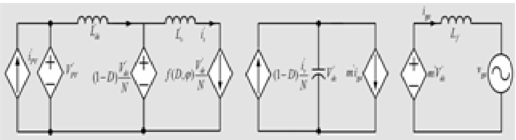

Fig. 5.Equivalent switching function model of the cascaded PV system in phase a.

Fig. 4 is developed to perform the active and reactive power distribution for each module. The active componentsvka d (k = 1, 2, ..., n) of each module output voltage is determinedby their respective active power contribution, which theratio is Ppvka /.Σni=1 Ppvia (k = 1, 2, ..., n). The reactive poweroutput from each module is controlled to be the same in orderto mitigate output voltage overmodulation caused by unsymmetricalactive power from segmented PV arrays [29]. Accordingly, the outputvoltage of each module can be expressed by

$$\begin{bmatrix} v'_{ka\_\alpha} \\ v'_{ka\_\beta} \end{bmatrix} = \begin{bmatrix} \sin(\omega t + \theta_{iga}) & \cos(\omega t + \theta_{iga}) \\ -\cos(\omega t + \theta_{iga}) & \sin(\omega t + \theta_{iga}) \end{bmatrix} \begin{bmatrix} v_{ka\_d'} \\ v_{ka\_q'} \end{bmatrix}$$

$$(k = 1, 2, ..., n) \quad (5)$$

Where v'ka = v'ka α is the desired output voltage of each module,v'ka β is the imaginary quadrature signal with v'ka and can be ignored in this control system.Therefore, the modulation index of respective outputvoltagecan be obtained by . $m_k = \frac{v'_{ka}}{V_{dcka}}$ as shown in Fig. 3(b). As aresult, the active and reactive power can be properly distributedin each module, which achieves the MPPT and augments the Security and stability of the cascaded PV system operationsimultaneously.

IV. SIMULATION VERIFICATION:

The large-scale grid-connected cascaded PV system withthe proposed control strategy is first validated in simulationplatform with PSIM and MATLAB. The equivalent switchingfunction model in phase a is shown in Fig. 5. The same modelcan be used in phases b and c. Considering the characteristicsof PV arrays, the equivalent input current source i’ PV and voltagesource V’PV are developed in this model. In this paper, the reactive power injection into grid (inductivereactive power) is defined as negative and reactive powerabsorption from grid (capacitive reactive power) is defined aspositive. The active power injection into grid is defined as positiveand active power absorption from grid is defined as negative.Figs. 6 and 7 show the system performance in phase awith traditional control strategy in [30] and [31] and with theproposed control strategy in Fig. 3 under different solar irradiation,respectively. In traditional control strategy, the vsa d andvsa q in Fig. 3 are divided by the module number, respectively,and equally distributed in the four cascaded inverter modulesin phase a. It does not consider the coupling between activepower and reactive power. As a result, the unsymmetrical activepower from these modules will affect the reactive power distributionbetween these modules.

The module with high active power generation is required to provide high reactive power,which will cause output voltage overmodulation of this module.However, the proposed decouple active and reactive power controlstrategy solve the aforementioned issue. vsa d and vsa q arereallocated based on the respective active power contributionof these modules. The equivalent reactive power can be generatedfrom these modules regardless of the unsymmetrical activepower. The following simulation results provide the verificationof the aforementioned analysis. Fig. 6 illustrates the system operationbehaviors with traditional control strategy. As shown inFig. 6(a), the solar irradiation for the four PV inverter modulesincreases from 200 to 1000 W/m2 at 0.5 s. The active power togrid, Pga , changes from 0.182 to 1 MW.The reactive power to grid, Qga , is controlled to be –0.5 MVAR. At 1 s, the solar irradiationon the third and fourth PV inverter modules decreasesto 500 W/m2 . Therefore, the active power from them, Pout 3aand Pout 4a , decreases from 0.25 to 0.12MW. Accordingly, thereactive power from them,Qout 3a andQout 4a , decreases from−0.125 MVAR to −0.085 MVAR.

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In this case, the unsymmetricalactive power generation may result in the output voltageovermodulation of the first and second inverter modules becausethey will be charged with the more voltage output to meet the system stability. On the other hand, the reactive power fromthe first and second PV inverter modules, Qout 1a and Qout2a , increases from −0.125 MVAR to −0.165 MVAR to keep the Qg to be constant. The increasing burden of reactive power generation exacerbates the output voltage overmodulation fromthe first and second inverter modules resulting in serious grid current distortion as shown in Fig. 6(b). The total harmonic distortion (THD) of grid current iga is 12.8%. After 1.5, the solar irradiation for the second–fourth PV inverter modules changes to 800, 600, and 500 W/m2 , respectively. The reactive power changes along with the active power in the same direction. The grid current quality is still poor. The dc voltages on the four modules, Vdc 1a –Vdc4a , have poor dynamic performance and deviate from the desired voltage.

Under the same conditions, the proposed control strategy can improve the system operation performance as shown in Fig. 7(a). The active and reactive power can be independently controlled. Although the solar irradiation on first and second inverter modules is different from one on third and fourth inverter modules after 1 s, the reactive power from them is controlled to be symmetrical. By this proper reactive power distribution, theovermodulation caused by the active power mismatch is eliminated. Even when different active power is generated from the four inverter modules after 1.5 s, the effective reactive power compensation can ensure the system with good power quality and stability as shown in Fig. 7(b). It can be seen that THD of iga is only 2.532%. The dc voltages on the four modules, Vdc 1a –Vdc4a , have good dynamic performance and are con- trolled to vary with 20% rated voltage but do not affect power quality.

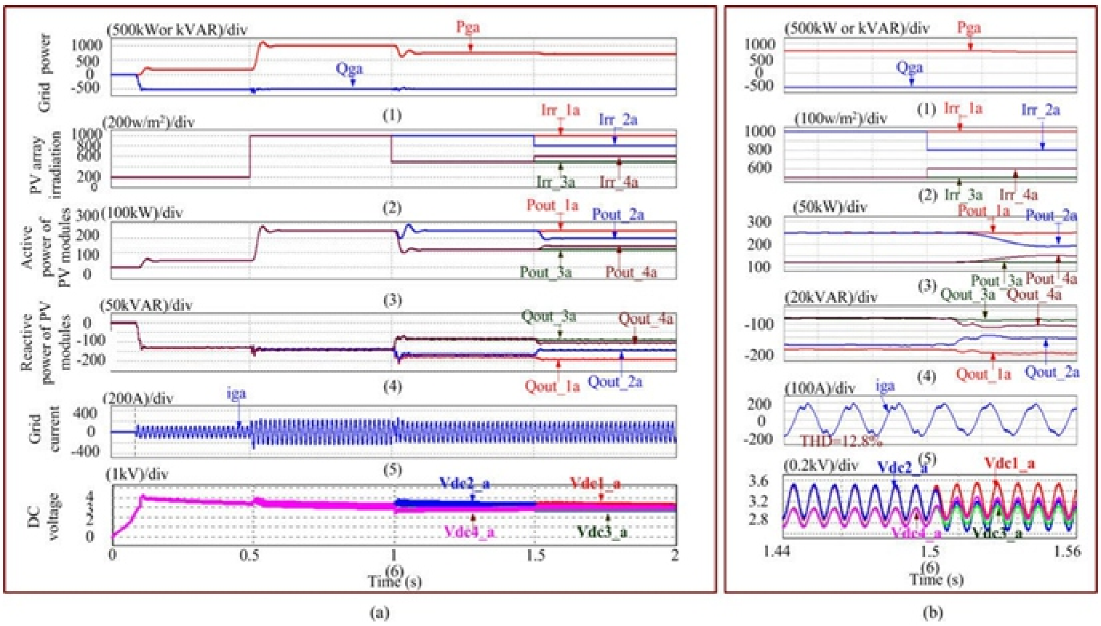

Fig.6. Simulation results of PV system with traditional active and reactive power control in phase a. (a) Power distribution. (b) Zoomed waveforms at 1.5 s.

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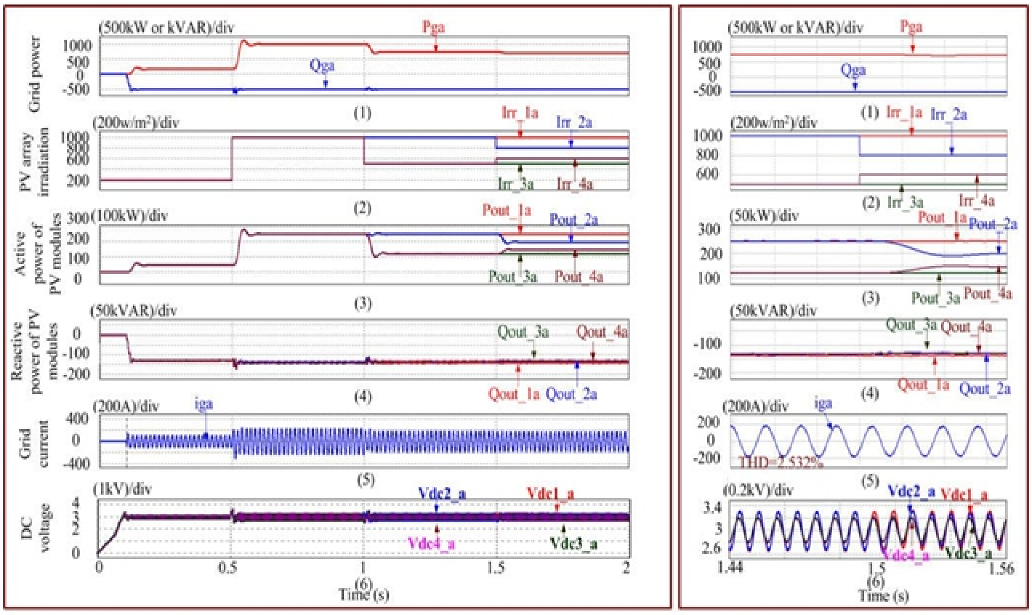
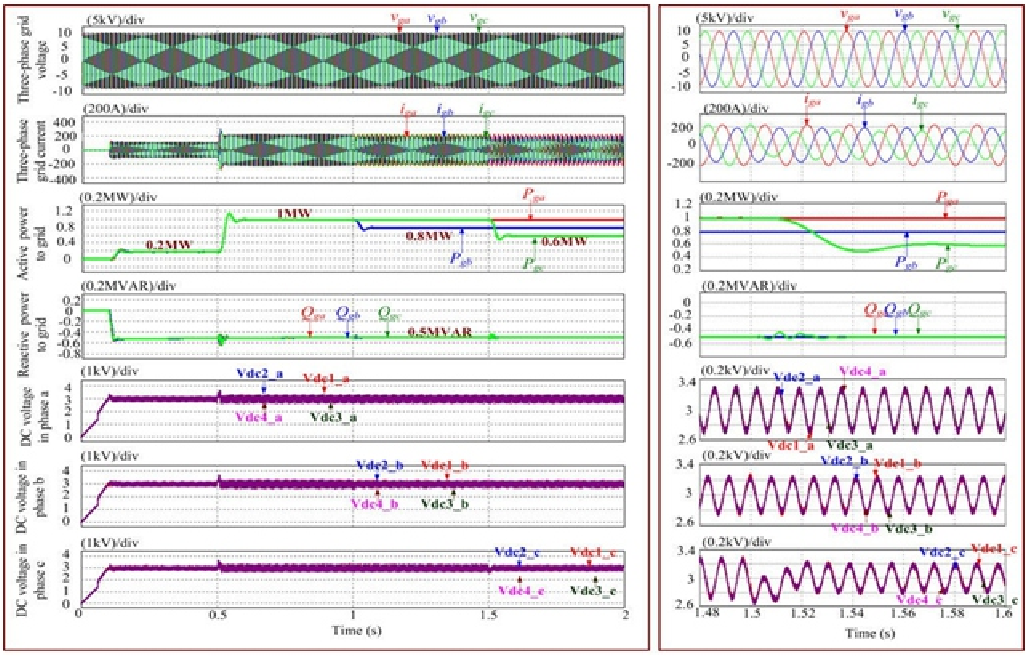


(a) (b)

Fig.7.SimulationresultsofPVsystemwithdecoupledactiveandreactivepowercontrolinphasea.(a)Powerdistribution. (b)Zoomedwaveformsat1.5s.



(a) (b)

Fig. 8. Simulation results of PV system with the proposed control in three phase. (a) Power distribution. (b) Zoomed waveforms during power transient at 1.5 s.

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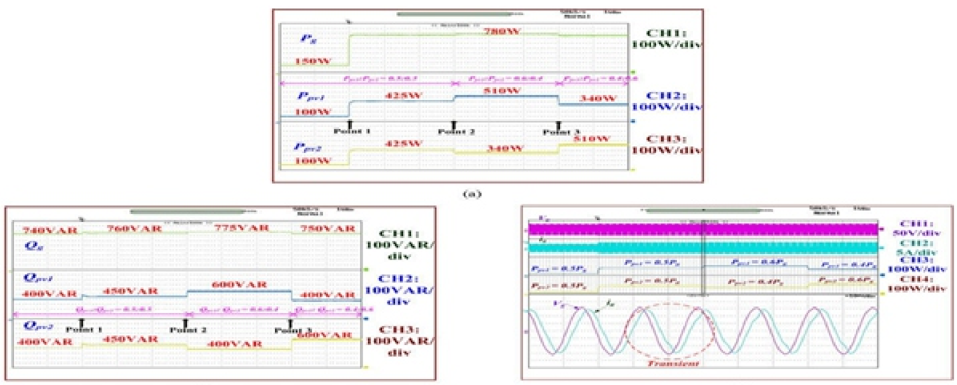
Fig. 8(a) shows the simulation results of three-phase cascaded PV system with the proposed control strategy. The solar irradiation for PV inverter modules changes from 200 to 1000 W/m2 at 0.5 s. The total active power to grid, Pg , increases from 0.6to 3 MW. The total reactive power to grid, Qg , is controlled to be −1.5 MVAR. At 1 s, solar irradiation appears on these PV inverter modules in phase b is different from ones in phasesa and c. Therefore, different active power is generated from three phase. At 1.5 s, different solar irradiations in the three- phase result in different active powers, Pga ,Pgb , and Pgc , with 1, 0.8, and 0.6 MW, respectively. Thanks to this effective control strategy, the reactive power in the three phases, Qga, Qgb, and Qgc, can be controlled to be same with 0.5 MVAR. In thiscase, although the grid currents are unbalanced, this system still has good power quality as shown in Fig. 8(b). The dc volt- ages on these modules, Vdc 1i –Vdc 4i (I = a, b, c), have good dynamic performance and are controlled to vary with 20% rated voltage.

V.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 carried out to demonstrate the performance of the proposed control system.Fig. 10 indicates active power distribution, reactive power distribution, grid voltage and current, and frequency spectrum with traditional proposed control strategy [30], [31], respectively. In the initial stage, two PV inverter modules generate the same active power, Ppv 1 = Ppv 2 = 100 W, and 150 W active power considering the loss is delivered to grid as shown in Fig. 10(a). The reactive power injected to grid Qg is 740 VAR, which is less than the sum of Qpv 1 and Qpv 2 due to the reactive power loss on output filter and grid impedance as shown in Fig. 10(b). Subsequently, Pg increases from 150 to 770 W and Qg 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 Ppv 1 from first module increases from 412.5 to 490 W and active power Ppv 2 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 ig is distorted as shown in Fig. 10(c). Finally, Ppv 1 decreases from 490 to 330 W and Ppv 2 increases from 330 to 490 W. Qpv 1 decreases from 600 to 400 VAR and Qpv 2 increases from 600 to 400 W. The frequency spectrum of ig is analyzed under symmetrical and unsymmetrical power distribution. It can be seen from Fig. 10(d) that THD is 8.61% with-out the proposed control strategy under unsymmetrical power distribution.Fig. 11 presents active power distribution, reactive power distribution, and grid voltage and current with the proposed control strategy, respectively. Similarly, Pg increases from 150 to 770 W at point 1. The active power from two modules is equalized be- fore point 2 as shown in Fig. 11(a). And then the active power distribution ratio of two modules is 0.6:0.4. After point 3, the ratio changes to 0.4:0.6. During the active power change, the



(a)
(b)
(c)

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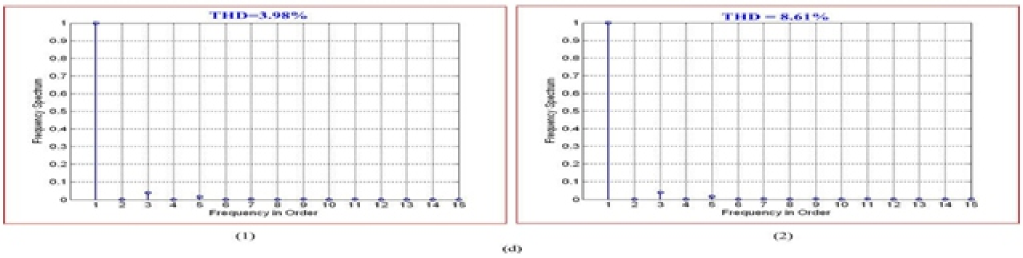

Fig. 10. Experimental results with traditional control strategy. (a) Active power distribution. (b) Reactive power distribution. (c) Grid voltage and current.(d) Frequency spectrum analysis—(1) symmetrical power distribution and (2) unsymmetrical power distribution

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 PPV 1 and PPV 2 is more than Pg , and the sum of QPV 1 and QPV 2 is greater than Qg . The grid voltage and current waveform during different active power distribution 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 regardless of the unsymmetrical active power distribution, which are only 3.98

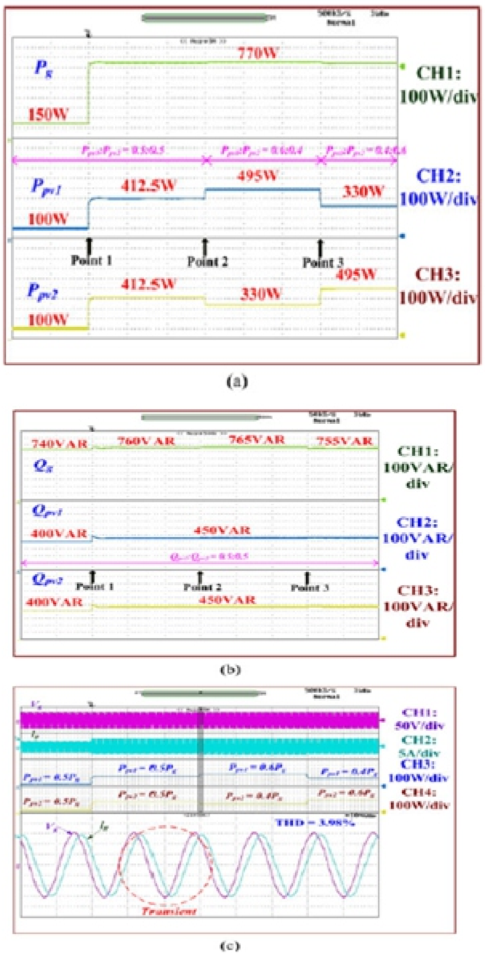

Fig.11. Experimental results with the proposed control strategy. (a) Active power distribution. (b) Reactive power distribution. (c) Grid voltage andcurrent

VI.CONCLUSION:

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 pro- posed control strategy enabled the cascaded

PV inverter modulesto adequately embody their respective reactive power compensation 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 qualityand stability. Correspondingly, the simulation and experimentalresults confirmed the validity of the proposed controlstrategy. Quality and stability. Correspondingly, the simulation and experimental results confirmed the validity of the proposed control strategy.

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