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Reactive Power Compensation and Optimization Strategy for Grid-Interactive Cascaded Photovoltaic System

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ABSTRACT:

Cascaded multilevel converter structure can be appealing for high-power solar photovoltaic (PV) systems thanks to its modularity, scalability, and distributed maximum power point tracking (MPPT). However, the power mismatch from cascaded individual PV converter modules can bring in voltage and system operation issues. This paper addresses these issues, explores the effects of reactive power compensation and optimization on system reliability and power quality, and proposes coordinated active and reactive power distribution to mitigate this issue. A vector method is first developed to illustrate the principle of power distribution. Accordingly, the relationship between power and voltage is analyzed with a wide operation range.

Then, an optimized reactive power compensation algorithm (RPCA) is proposed to improve the system operation stability and reliability, and facilitate MPPT implementation for each converter module simultaneously. Furthermore, a comprehensive control system with the RPCA is designed to achieve effective power distribution and dynamic voltage regulation. Simulation and experimental results are presented to demonstrate the effectiveness of the proposed reactive power compensation approach in grid-interactive cascaded PV systems.

INTRODUCTION:

Worldwide renewable energy resources, especially solar energy, are growing dramatically in viewof energy shortage and environmental concerns. Large-scale solar photovoltaic (PV) systems are typically connected to medium voltage distribution grids, where power converters are required to convert solar energy into electricity in such a grid-interactive PV system . To achieve direct medium-voltage grid access without using bulky medium-voltage transformer, cascaded multilevel converters are attracting more and more attraction due to their unique advantages such as enhanced energy harvesting capability implemented by distributed maximum power point tracking (MPPT), improved energy efficiency, lower cost, higher power density, scalability and modularity, plug-N-power operation, etc.

Motivations are toward addressing the aforementioned issues and approaching to mitigate the negative effect of active power mismatch. In, MPPT is achieved for each module in these approaches to enhance energy harvesting. However, only unity power factor control was considered and the inherent reactive power compensation capability of the cascaded PV system is ignored. As a result, the PV system still surfers from the degraded power quality and system reliability. It is recognized that reactive power compensation is able to provide strong voltage support in a wide range. Proper reactive power compensation can significantly improve the system reliability, and in the meantime

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help the MPPT implementation for the cascaded module under unsymmetrical condition as well as comply with the system voltage requirement simultaneously. All of these have spurred growing interest in reactive power compensation for the cascaded PV system. A reactive power compensation strategy is integrated in the control system of the cascaded PV system in. However, this approach fails to consider the effect of voltage or current distortion caused by unsymmetrical active power on the power detection and distribution, and

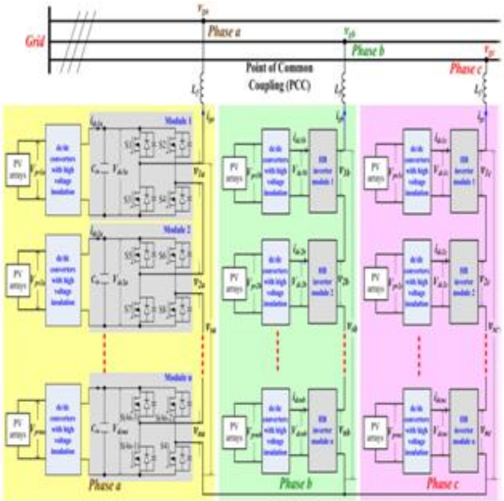

Fig.1Grid-interactive PV system with cascaded PV converters.

The converter module with high active power generation is not required to provide reactive power, which has limited the capability of reactive power compensation. Therefore, optimized solutions have yet to be found and it is very critical to develop an effective reactive power compensation strategy for the grid interactive cascaded PV system.

PROPOSED REACTIVE POWER COMPENSATION METHOD:

As aforementioned, appropriate reactive power compensation will enhance the cascaded PV system reliability and improve power quality, especially for unsymmetrical active power generation. Fig. 3 shows the proposed RPCA for the cascaded PV system in phase a.

The same algorithm can be used in phases b and c. The reactive power compensation requirement Q∗ gais associated with modulation index of output voltage from cascaded PV converter modules, PCC voltage, and MPPT control implementation which will determine the active power reference P∗ ga. In the initial state, MPPT control for each PV converter module is enabled and unity power factor is implemented considering symmetrical operation condition acts on these cascaded modules. In this scenario, Q∗ gais zero and P∗ gais derived from the sum of maximum active power from the individual PV

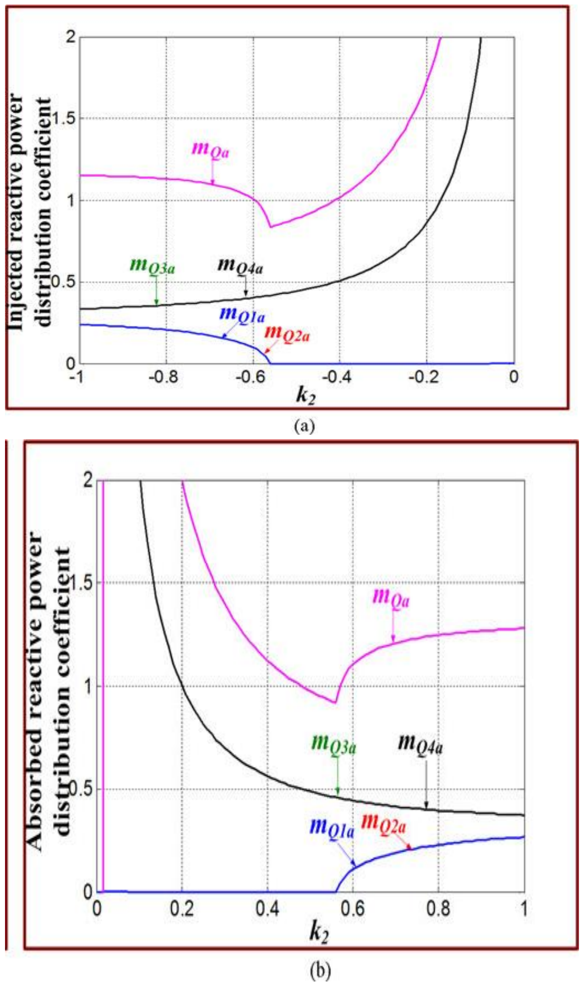

Fig. 2. Voltage distribution among four cascaded converter modules with k1 = 0.6 and k2 changes. (a) Reactive power injection. (b) Reactive power absorption.

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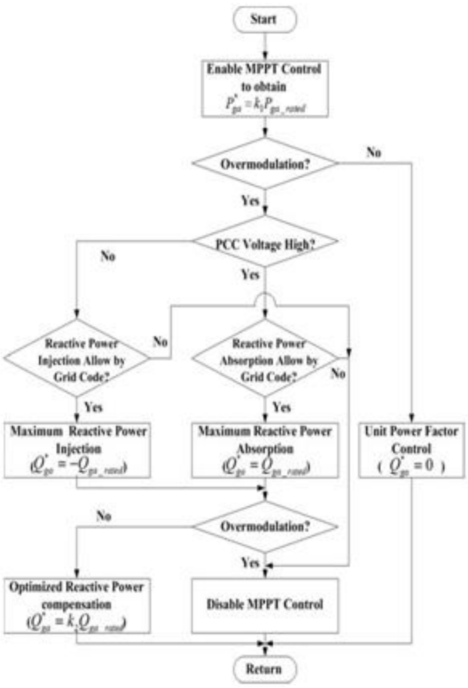

Fig. 3.Flowchart of the proposed RPCA.

arrays_nj=1 Ppvjasubtracting power loss, which is defined as k1Pga rated. Considering the known Pgarated, k1 can be calculated as P∗ ga/Pgarated. It is determined by the MPPT control and dc voltage control, which will be introduced in Section III-B. During the system operation, unsymmetrical active power may be generated from these modules due to PV module mismatch, orientation mismatch, partial shading, etc. As a result, over modulation may occur on the PV converters output voltage, especially for the converter module with higher active power output, which seriously impairs the MPPT of each module and system reliability. Once the over modulation is identified, the intentional reactive power compensation is activated to mitigate the over modulation with grid code authorization. If PCC voltage is high, maximum reactive power will be absorbed from grid to bring down the PCC voltage with the normal voltage range according to the IEEE Std. 1547, as well help possible MPPT implementation for each converter module simultaneously. k2 = 1 is designated to achieve the maximum reactive power absorption. The PV system operates like an inductor.

Otherwise, the maximum reactive power is injected into grid to provide the PCC voltage support. k2 = −1 is designated to execute the maximum reactive power injection. The PV system operates like a capacitor. If the maximum reactive power compensation still cannot eliminate the over modulation, MPPT control will be disabled to ensure the security and stability of the cascaded PV system. Instead, reactive power compensation can be optimized, that is the selection of k2 , to reduce the risk of overvoltage or under voltage caused by the maximum reactive power compensation. There are different ways to optimize reactive power distribution in the cascaded PV converter modules. In either way, the limited condition as shown in must be satisfied to avoid the over modulation. It is noted that the selected dc voltage and allowed voltage ripple will also impact on the reactive power compensation optimization. In this paper, the boundary condition in is selected to achieve the optimized reactive power distribution, which can limit the unity modulation voltage output for the converter module with high active power generation, even help to possible equivalent apparent power being extracted from each PV converter module. The selection of k2 is related to k1 and the level of unsymmetrical active power, which can be obtained based on . A specific example in Fig. 8 will be provided to demonstrate the proposed RPCA in Section II.

SIMULATION RESULTS:

In order to explore the performance of grid-interactive cascaded PV system with the proposed reactive power compensation approach, simulations were first conducted in a co simulation platform of MATLAB/Simulink and PSIM. A 3 MW/12 kV three-phase two-stage cascaded PV system as shown in Fig. 1 is applied in this paper. The system parameters in simulation are summarized in Table II. Figs. 4 and 5 illustrate the active and reactive power distribution, grid voltage and current change, voltage distribution among four cascaded PV converter modules with reactive power injection and absorption during different scenarios in phase a, respectively.

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Fig. 4(a) shows the power distribution with reactive power injection considering the low grid voltage. At the beginning, the MPPT control is enabled and each module harvests maximum power from the segmented PV arrays. At 0.5 s, the active power from four modules P1a−P4a , changes from50 kW to 250 kW. Active power to grid P gain creases from200 MW to 1 MW. The grid current magnitude I gain creases from 40 A to 200 A in Fig. 4(b). The system does not need the reactive power compensation because the symmetrical active power can equalize the output voltage from these modules. There is no over modulation, and grid current and PCC voltage have good quality as shown in Fig. 4(b) and (c). The modulation indices from our modules, m1a − m4a , are within [−1, 1].At 1 s, different active power is generated from the four modules due to the different irradiation. Modules 1 and 2 keep 250 kW active power output but the active power from modules 3 and 4reduces to 50 kW, which results in big power fluctuation during transient. Moreover, the over modulation caused by the unsymmetrical active power seriously distorts the grid current iganddegrades system operation performance as shown in Fig. 4(b)and (d). The module indices from modules 1 and 2, m1a andm2a , are in the range [−1, 1]. After 1.5 s, 1 MVAR reactive power Qgais injected to grid, which means that k2 = −1, and reactive power from four modulesQ1a−Q4a is controlled to the same first. It shows that the dynamic performance of reactive power is poor, which is caused by the distorted grid current and measurement module in PSIM. By the reactive power compensation, the system returns to the steady operation although active power distribution among the four modules is still unsymmetrical. Pgakeeps at 600 kW, which means that k1 = 0.6. Once the system operates in safety and steady status, the maximum active power output from the four modules can be accurately controlled and detected. The dynamic performance of grid current, PCC voltage Vga, and individual dc voltage, Vdc1a−Vdc4a , can be seen in Fig. 4(e). It takes 5 cycles to bring the system back to be stable.

At 2 s, the reactive power from the four modules is redistributed and optimized to reduce the risk of over voltage. Fig. 4(f) shows the voltage and current waveforms before and after reactive power compensation optimization. The reactive power injection can improve system reliability but also increase the grid voltage magnitude Vga from 9.7 to 10 kV. In order to limit the voltage rise, the optimized reactive power injection is reduced to −600 kVAR, that is, k2 = −0.6 which is obtained from Fig. 8. In this case, the unsymmetrical reactive power is arranged between the four modules, Q1a = Q2a = −95 kVAR and Q3a = Q4a = −220 kVAR. The filter inductor loss is also provided by the PV system. By the reactive power optimization, Vgadecreases from 10 to 9.9 kV; the grid current still has good quality and total harmonic distortion (THD) is less than 5%.The RPCA is verified in this simulation. Fig. 12(a) shows the power distribution with reactive power absorption considering the high grid voltage. The same active power as ones in Fig. 4 changes in each stage.

At 1.5 s, 1MVARreactive power Qga, that is, k2 = 1, is absorbed from grid to eliminate the over modulation andQ1a−Q4a is controlled to the same first. Pgakeeps at 600 kW, which means that k1 = 0.6. Once the maximum active power P1a−P4a is accurately captured at new steady system, Q1a−Q4a is rearranged to reduce the risk of under voltage at 2 s. The reactive power absorption can improve system reliability but also lower the grid voltage magnitude Vga from 9.9 to 9.7 kV as depicted in Fig. 5(b)–(f).In order to limit the voltage drop, the total reactive power injection is reduced to 700 kVAR, that is, k2 = 0.7 which is obtained from Fig. 8. In this case, optimized reactive power distribution can be derived based on (6): Q1a = Q2a = 100 kVAR and Q3a = Q4a = 230 kVAR. The filter inductor loss is provided by a grid. By the reactive power optimization, Vgain creases from 9.7 to 9.8 kV, good grid current is guaranteed, and THD is less than 5%.

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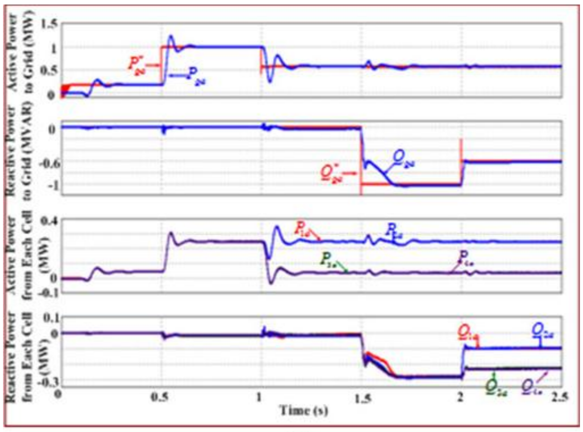
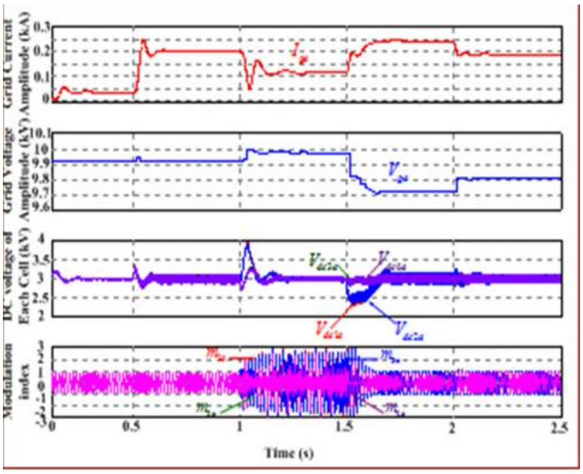


(a)



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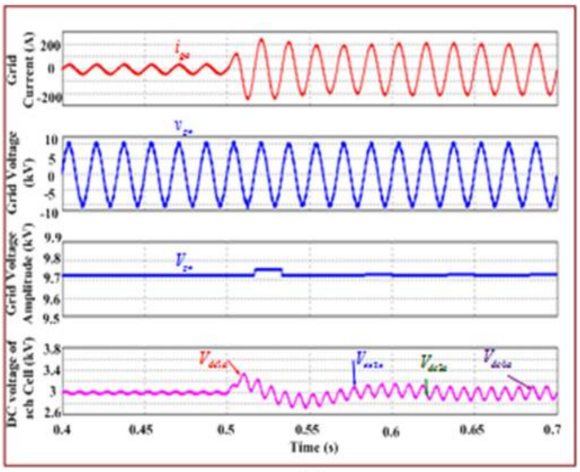

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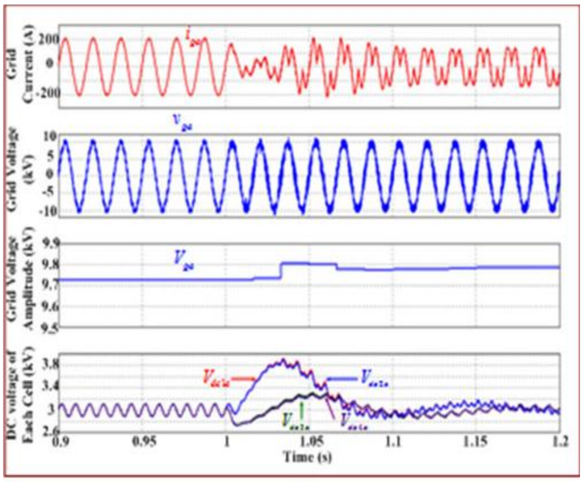

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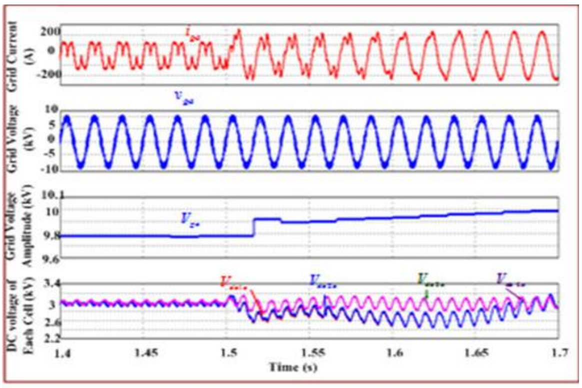

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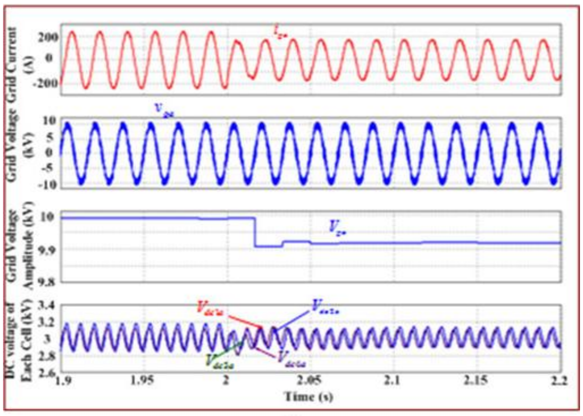

(f)

Fig. 4. Simulation results with the proposed approach in reactive power injection. (a) Active and reactive power distribution. (b) Voltage and current changes.(c) Zoomed voltage and current waveforms at 0.5 s. (d) Zoomed voltage and current waveforms at 1 s. (e) Zoomed voltage and current waveforms at 1.5 s.(f) Zoomed voltage and current waveforms at 2 s.

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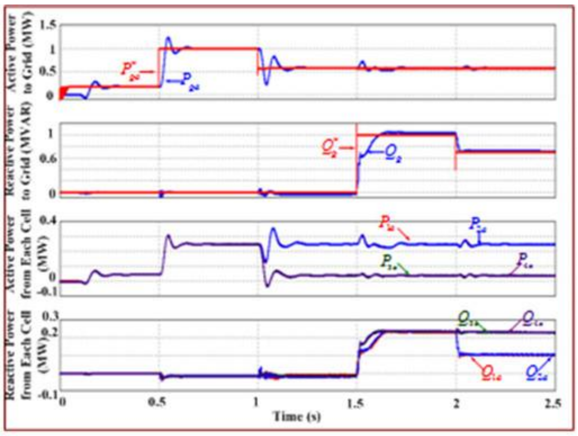
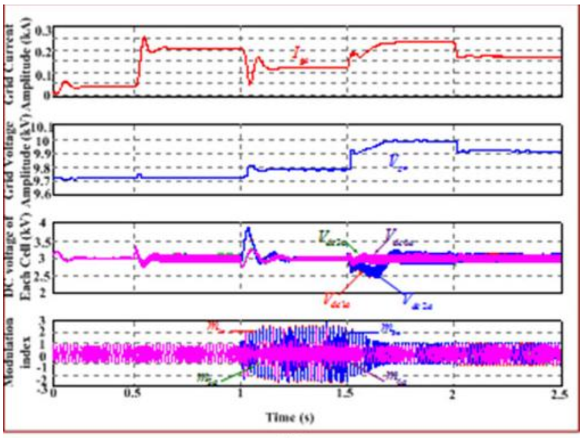


(a)



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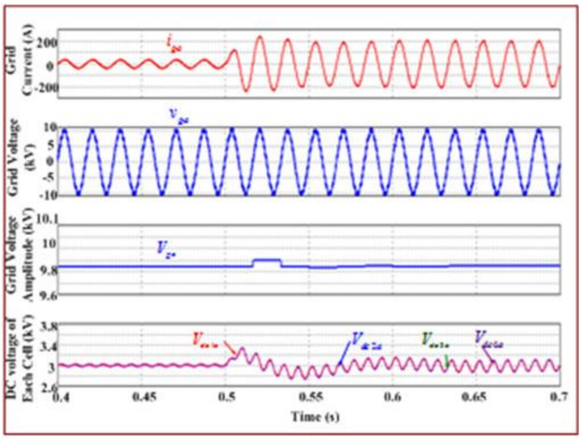

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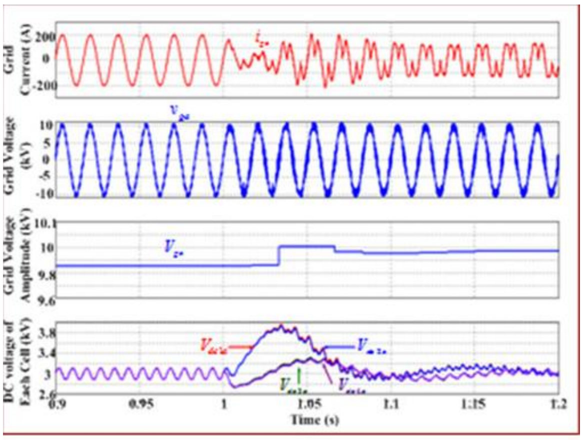

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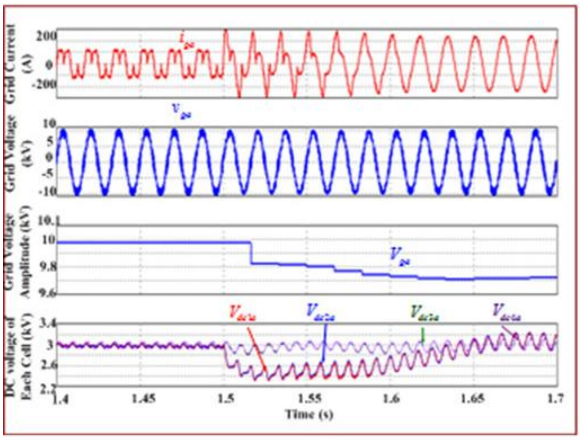

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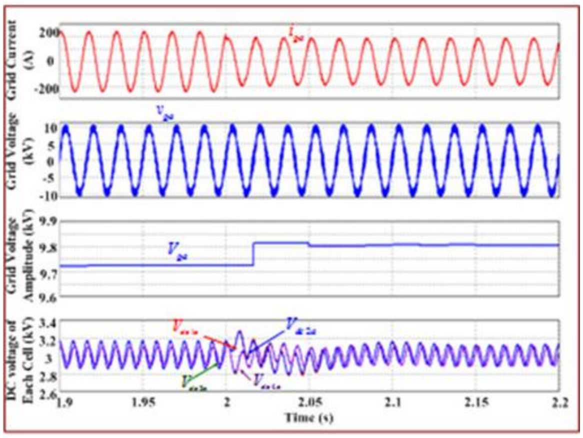

(f)

Fig. 5. Simulation results with the proposed approach in reactive power absorption. (a) Active and reactive power distribution. (b) Voltage and current changes.(c) Zoomed voltage and current waveforms at 0.5 s. (d) Zoomed voltage and current waveforms at 1 s. (e) Zoomed voltage and current waveforms at 1.5 s.(f) Zoomed voltage and current waveforms at 2 s.

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CONCLUSION:

This paper addressed the effect of reactive power compensation on system operation performance in grid-interactive cascadedPV systems. The system stability and reliability issue caused by unsymmetrical active power was specifically analyzed. Reactive power compensation and distribution was introduced to mitigate this issue. The output voltage of each module was verified to directly determine the power distribution. The relationship between voltage distribution and power distribution was illustrated with a wide power change range. An optimized RPCA was proposed considering the MPPT implementation, grid voltage, and over modulation. Moreover, the RPAC was eligible to be integrated into different types of the cascaded PV system. Correspondingly, the control system with MPPT control and optimized RPCA was developed and validated by the simulation and experimental results under different scenarios. The proposed approach was demonstrated to be able to effectively enhance system operation stability and reliability, and improve power quality.

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