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Decoupled Active and Reactive Power Control for Large-Scale Grid-Connected Photovoltaic Systems Using Cascaded Modular Multilevel Converters

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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 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 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.

INTRODUCTION:

Global energy crises and environmental concerns 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. 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. 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. 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.

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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. 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. 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 converter modules. Therefore, those methods in are not qualified for a practical large-scale grid-connected cascaded PV system. Moreover, reactive power compensation was not achieved in, which largely limits the functions of the 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. A reactive and active power control strategy has been applied in cascaded PV system with isolated dc–dc converters in and.

If symmetrical active power comes from each module, active and reactive power can be equally distributed into these modules under traditional power control in and. 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 over modulation during unsymmetrical active power outputs from segmented PV arrays. In order to solve the aforementioned issues, this paper proposes 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 decouple 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 over modulation of PV converter output voltage caused by unsymmetrical active power from PV arrays. 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 corresponding power flow distribution. A vector method is derived to help illustrate the active and reactive power distribution principle between the cascaded PV inverter modules. 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 extraction, voltage distribution and synthesization, is executed in multilevel inverter control system to achieve independent active and reactive power distribution.

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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.

MULTI-LEVEL INVERTER:

Numerous industrial applications have begun to require higher power apparatus in recent years. Some medium voltage motor drives and utility applications require medium voltage and megawatt power level. For a medium voltage grid, it is troublesome to connect only one power semiconductor switch directly. As a result, a multilevel power converter structure has been introduced as an alternative in high power and medium voltage situations. A multilevel converter not only achieves high power ratings, but also enables the use of renewable energy sources. Renewable energy sources such as photovoltaic, wind, and fuel cells can be easily interfaced to a multilevel converter system for a high power application. The concept of multilevel converters has been introduced since 1975. The term multilevel began with the three-level converter . Subsequently, several multilevel converter topologies have been developed.

However, the elementary concept of a multilevel converter to achieve higher power is to use a series of power semiconductor switches with several lower voltage dc sources to perform the power conversion by synthesizing a staircase voltage waveform. Capacitors, batteries, and renewable energy voltage sources can be used as the multiple dc voltage sources. The commutation of the power switches aggregate these multiple dc sources in order to achieve high voltage at the output; however, the rated voltage of the power semiconductor switches depends only upon the rating of the dc voltage sources to which they are connected.

ADVANTAGES & DISADVANTAGES:

A multilevel converter has several advantages over a conventional two-level converter that uses high switching frequency pulse width modulation (PWM). The attractive features of a multilevel converter can be briefly summarized as follows.

• Staircase waveform quality: Multilevel converters not only can generate the output voltages with very low distortion, but also can reduce the dv/dt stresses; therefore electromagnetic compatibility (EMC) problems can be reduced.

• Common-mode (CM) voltage: Multilevel converters produce smaller CM voltage; therefore, the stress in the bearings of a motor connected to a multilevel motor drive can be reduced. Furthermore, CM voltage can be eliminated by using advanced modulation strategies

• Input current: Multilevel converters can draw input current with low distortion.

Diode-Clamped (DC) Topology

The diode-clamped (DC), also called neutral-point clamped (NPC), topology is based on the utilization of a number of diodes in order to block small DC sources. The configuration of a single-phase 3-level and 5-level diode-clamped inverter is shown in Figure 2.2.

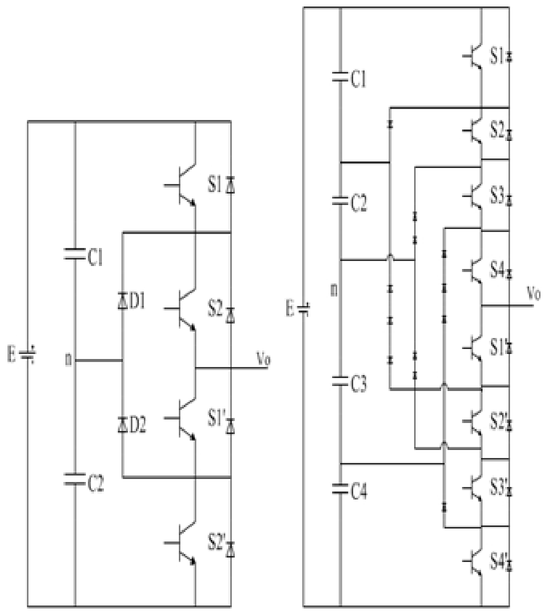

Figure 2.2 Single-phase 3-level and 5-level DC topology

The DC topology can easily be extended to a generic n-level configuration.

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In a 3-level diode-clamped inverter, the DC bus voltage is divided by capacitor banks into two equal steps. Operation of the inverter is simple. The name of the DC topology originates from the fact that the voltage between two switches is clamped through the clamping diodes. When switches are(s1,s2) on and are(s1′s2′) off, output voltage of the inverter is equal to the voltage of , which is equal to ⁄. Likewise, when switches (s1,s2) are off and(s1′s2′) are on, output voltage of the inverter is equal to the voltage of , which is equal to-E/2. When are on and are off, output voltage of the inverter is equal to 0. In a 5-level diode-clamped inverter, the DC bus voltage is split into four equal voltage steps. In this case, the number of diodes required to clamp the voltage changes point by point. Each diode is sized to provide voltage blocking for the voltage across one capacitor.

For instance,D1 is represented only by one diode, while D1'is represented by three diodes equal toD1 , which are in series because it must block voltage across capacitors c2, c3, and c4, meaning that it is allowed to use one diode with higher blocking capability or three diodes in series with equal blocking capability toD1 . Considering the diode reverse voltage for an n-level inverter, calculated by vr=E/n-1 , the diode reverse voltage for a 5-level inverter is equal toE /4, thus demonstrating that increasing the number of levels results in decreased voltage stress on thecomponents. Operation of 3- and 5-level NPC topology is shown in Table 2.1 and 2.2, respectively.

Table 2.1 Switching table for the 3-level DC topology

Switches				Output Voltage
S1	S2	S1'	S2'	Vo
1	1	0	0	$+E/2$
0	1	1	0	0
0	0	1	1	$-E/2$
1	0	0	1	N/A

Flying Capacitor (FC) topology

This topology is similar to diode-clamped topology in which diodes are replaced by capacitors in order to maintain voltage levels across DC link capacitors. Figure 2.3 shows the structure of a single-phase 3-level and 5-level flying-capacitor inverter. The topology has a ladder structure of DC dice capacitors, in which, the voltage on each capacitor differs from voltage of the next capacitor. FC topology can easily be extended to higher levels. Voltage across each capacitor is given by: vc=E/n. This voltage is the reverse voltage drop each switch can withstand when all capacitors are fully charged. These capacitors are known as clamping capacitors because their function of them is similar to the clamping diodes in diode-clamped topology because they maintain the voltage drop between the buses to which they are connected.

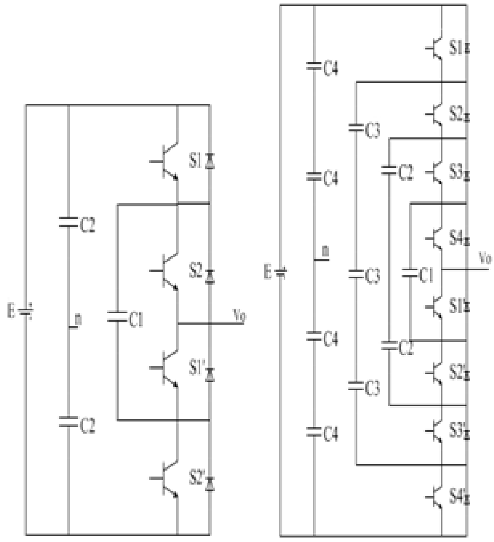

Figure 2.3 Single-phase 3-level and 5-level FC topology

The operation of a 3-level flying-capacitor is similar to the 3-level diode-clamped inverter. When switches(s1,s2) are on and(s1′s2′)are off, output voltage of the inverter is equal to+E ⁄2, and when switches (s1,s2) are off and (s1′s2′)are on, output voltage of the inverter is equal to-E⁄2. When(s1,s1′) are on and(s2 s2′) are off, voltage of the capacitor c1is increased and when(s2 s2′) are on and s1,s1′) are off, the capacitor c1 is in discharging mode.

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In the latter two cases, output voltage of the inverter is equal to 0. By switching between these two states, charge on the capacitor c1 maintains balanced. These two switching states are called intra-phase redundant states. In the 3-level inverter, various switch configurations cannot occur. Si andsi′ , where the number of switches is, should be switched in a complimentary way. Possible configurations for a single-phase n-level flying-capacitor inverter are as:

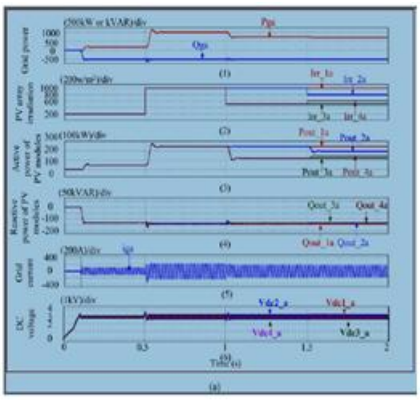
N= $2^{(n-1)}$For this topology the number of possible configurations is greater than the number of possible output voltage levels. The total number of possible switching states for a 5-level flying-capacitor inverter is 16 whereas the possible number of output voltage levels is 5, while creating 11 redundancies. Therefore, maintaining voltage balancing for this inverter is complicated. Table 2.3 and 2.4 show switching states for 3- and 5-level FC topology, respectively

Table 2.3 Switching table for the 3-level FC topology

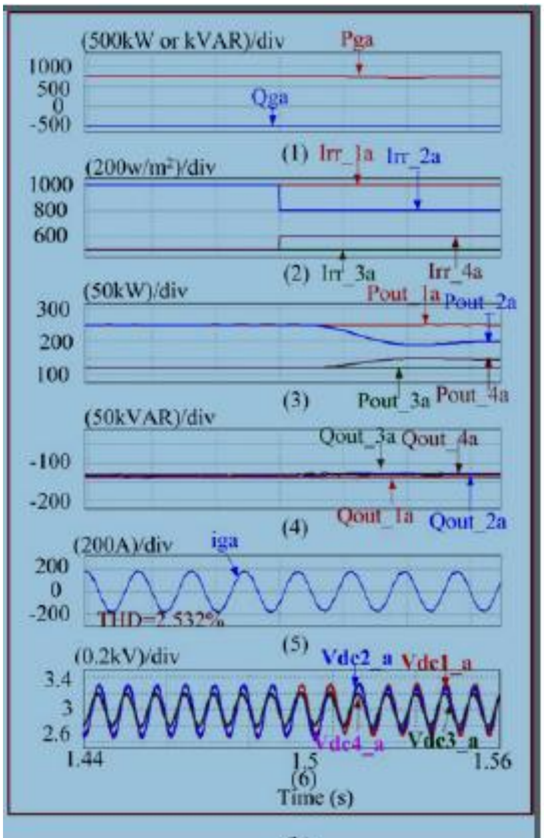
Switches				Output Voltage
S1	S2	S1'	S2'	Vo
1	1	0	0	$+E/2$
1	0	0	1	0
0	1	1	0	0
0	0	1	1	$-E/2$

Table 2.4 Switching table for the 5-level FC topology

SIMULATION RESULT



(a)



(b)

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 proposed control strategy enabled the cascaded PV inverter modules to adequately embody their respective reactive power compensation capability regardless of their active power generation. Moreover, it was demonstrated that the risk of over modulation of the output voltage from the cascaded PV inverter modules can be effectively reduced, which improves system power quality and stability.

Correspondingly, the simulation and experimental results confirmed the validity of the proposed control strategy.

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