DC Voltage Utilization Improvement to Enlarge Power Balance Constraint Range for Photovoltaic Cascaded Inverter

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ABSTRACT In the three-phase photovoltaic (PV) cascaded inverter, the output power of PV arrays is not equal due to the difference of solar radiation, temperature and other factors, which leads to the over modulation of PV cascaded inverter. In order to solve the above problems, the carrier phase-shifted PWM (CPS-PWM) control strategy based on third harmonic injection is proposed in this paper, taking a single-stage high-frequency-link isolated cascaded PV inverter topology with clamping circuits as an example. It can not only improve the utilization of DC voltage, but also enlarge the power balance constraint range between the units in the phase of cascaded PV inverter, so as to ensure that all units can avoid over modulation under some serious power imbalance cases, and will not increase the third harmonic component injection of grid current. Firstly, the topology and working principle of the proposed inverter based on CPS-PWM control strategy are introduced. Then, the improved CPS-PWM control strategy which can improve the DC voltage utilization of the PV cascaded inverter is analyzed, and the control strategy of intra-phase power balance is emphatically analyzed in the overall control strategy of PV cascaded inverter system, and it is discussed that the proposed control strategy can also enlarge the power balance constraint range between the units of the cascaded inverter. Finally, the effectiveness of the proposed PV cascaded inverter based on the improved CPS-PWM control strategy is verified by the simulation and experimental results.

INDEX TERMS PV cascaded inverter, DC voltage utilization, power balance constraint.

I. INTRODUCTION

Solar energy has made great strides in the past decade. By the end of 2019, the total installed capacity of solar energy in the world has reached 651GW, which has become the fourth largest power source. Solar energy as a representative of renewable energy, its production growth rate far exceeds that of other energy sources [1], [2]. To choose the appropriate inverter structure based on grid connected PV system and modulation strategy has become a research hotspot, which helps to improve the efficiency and dynamic stability of grid connected PV system [3]–[5].

At present, most of the PV inverters in large-scale PV power stations are centralized PV inverters, because of their advantages of lower cost, easier maintenance [6]. Generally, the centralized PV power station is boosted to medium voltage level by DC/AC converter and low-voltage power frequency transformer. The power of multiple lines is collected to the medium voltage power grid and finally transmitted to the remote load center, as shown in Fig. 1. However, the power frequency transformer has a series of problems such as large volume, heavy quality and large investment in the early stage, which leads to high maintenance cost and the difficulty of installation in remote areas. Therefore, it is of great value to study the application of the PV medium voltage grid connected power system without power frequency transformer [7]–[9].

Due to its small size and light weight, high frequency isolated inverter (HFII) can replace power frequency transformer to construct medium voltage PV grid connected power generation system. According to the power conversion level, the structure of HFII can be divided into two types: two-stage
and single-stage [10]. The cascaded H-bridge (CHB) multilevel inverter structure in Fig. 2 can realize two-stage power conversion, which has the advantages of easy modular expansion and direct access to high-voltage power grid without transformer [11]. However, the two-stage inverter has a large volume of independent capacitor, which leads to the complex control of voltage and current sharing between cascaded units, and reduces the reliability and power density of the system.

Therefore, the single-stage isolated PV inverter based on common DC bus can eliminate the large volume independent capacitor of two-stage converter and avoid the complex control of voltage and current sharing between cascaded units, so as to meet the requirements of grid connected PV system for high reliability, light weight and low cost [12]. The half bridge buck boost PV inverter proposed in [13] used a pair of PV sources, and only one of them had a given grid voltage in half a cycle, so each PV source needed an additional high value filter capacitor. A single-stage cascaded medium voltage grid connected PV system structure was constructed by combining the common DC bus and cascaded DC-AC converter in [14]. However, due to the difficulties in engineering design and complex manufacturing process of multi winding transformer, it is not easy to be applied in engineering [15].

In this paper, a single-stage high-frequency-link isolated cascaded PV inverter structure with clamping circuits is proposed, which inherits the advantages of modularization, high power density and simple control of the isolated modular multilevel converter (I-M^2C) topology based on high-frequency link concept proposed in [16], [17].

The modules of PV cascaded inverter will be short of energy supply due to external factors such as uneven illumination, different temperature or aging of PV panels, resulting in two types of power imbalance: inter-phase imbalance and intra-phase imbalance [18]. Because the proposed cascaded PV inverter based on multi-bus DC collection can avoid inter-phase power imbalance, and only need to overcome the intra-phase power imbalance, so as to avoid the over modulation caused by the different output power of modules in a phase.

In order to solve the power imbalance problem, some control methods have been proposed. An improved maximum power point tracking (MPPT) algorithm was proposed in [24], which balanced the power by taking the PV arrays with larger output power out of MPPT operation, but it reduced the power generation. A reactive power compensation strategy was proposed in [25], which had the disadvantage of reducing the power factor of system. Therefore, if the current DC voltage is used to obtain higher AC output voltage through reasonable modulation strategy, the steady-state output capability of the system will be greatly improved [19]–[22]. A hybrid modulation strategy combining low-frequency square wave and high-frequency PWM wave was proposed in [26]. It extended the linear modulation range of the inverter to $4/\pi$, but this method aggravated the DC voltage fluctuation. The PV cascaded inverter in [23] adopted CPS-PWM control strategy to improve the output voltage level and reduce the filter volume. However, the DC voltage utilization of conventional CPS-PWM control strategy is not high (only 0.866), and it was easy to cause over modulation of the modules with larger output power under uneven irradiance and temperature conditions.

However, the improved control strategy proposed in this paper based on the third harmonic injection can overcome the above shortcomings, and enlarge the power balance constraint range between the units in the phase of cascaded PV inverter to avoid the inherent over modulation and expand the safety margin of grid connected PV system.

The detailed contributions of this study are summarized as follows:

1) Develops an improved CPS-PWM control strategy, which can improve the DC voltage utilization can be increased by 15% without reducing the power generation.
2) Presents an intra-phase power balance control of cascaded PV inverter which can avoid over modulation of the units with larger output power under uneven irradiance and temperature conditions.
3) Proposes an improved DC voltage utilization method which can enlarge the power balance constraint range
between units, so as to improve the stability margin of grid connected PV system.

The paper is arranged as follows. The topology and working principle of the proposed cascaded PV inverter based on conventional CPS-PWM control strategy are described in section II. The improved CPS-PWM control strategy which can improve the DC voltage utilization and the intra-power balance control strategy are introduced in section III. The power balance constraint of the proposed PV cascaded inverter system with the proposed control strategy is derived in section IV. The effectiveness of the proposed inverter based on the proposed control strategy is verified by simulation and experimental results in Section V and Section VI. Finally, the conclusions are highlighted in Section VII.

II. STRUCTURE OF SINGLE STAGE PHOTOVOLTAIC MEDIUM VOLTAGE GRID CONNECTED POWER GENERATION SYSTEM

In this paper, a single-stage high-frequency-link isolated cascaded PV inverter topology with clamping circuits is presented in Fig. 3. The PV side of the inverter adopts centralized structure, and each PV array corresponds to a three-phase single-stage power converter unit (power converter unit A\(_n\), power converter unit B\(_n\), power converter unit C\(_n\)) in parallel, and independent MPPT for each unit to ensure the maximum power extraction from each PV array.

Compared with the conventional three-phase cascaded PV inverter, the proposed inverter based on multi-bus DC collection has the advantage of eliminating second-harmonic voltage ripple by DC link capacitor, which does not need additional control strategy to suppress the voltage fluctuation.

A. A SINGLE-STAGE HIGH-FREQUENCY-LINK ISOLATED CASCADED PV INVERTER TOPOLOGY

As shown in Fig. 3, the input ports of the power converter units of each phase are connected in parallel with the corresponding capacitors, and the output ports of units are connected in series with the medium voltage power grid. The circuit topology and key voltage port waveforms of the power converter unit are shown in Fig. 4. Each power converter unit is composed of two high-frequency isolated bridge cells (I-BCs) connected in input parallel output series (IPOS). Each I-BC consists of two sub-modules (SMs) based on the bidirectional PSFB converter, which are called upper SM and lower SM respectively. The upper and lower modules in each unit are connected in parallel at the front stage and in reverse series at the back stage, and each SM consists of a dual active H-bridge, a high frequency transformer (HFT), a voltage clamping circuit and a DC-link capacitor \(C_{dc}\).

The voltage clamping circuit is composed of four diodes, a clamping resistance \(R_c\) and a clamping capacitor \(C_v\), which is used to suppress the voltage spike caused by the resonance between the leakage inductance of HFT and the parasitic capacitance of secondary switches, so as to improve the reliability of the inverter. In a SM, the upper SM only outputs positive high-frequency square waves, while the lower SM outputs negative ones, and the output voltage \(v_u\) (\(v_l\)) of the upper (lower) SM can be expressed as follows:

\[
\begin{align*}
\text{\(v_u\)} &= \frac{V_{dc}}{k} \times d_u = \frac{V_{dc}}{k} \times (D + d) \\
\text{\(v_l\)} &= \frac{V_{dc}}{k} \times d_l = -\frac{V_{dc}}{k} \times (D - d)
\end{align*}
\]

(1)

where \(V_{dc}\) is DC voltage, and the ratio of HFT is assumed to be \(k\), and \(d_u(d_l)\) is the modulation index of upper (lower) SM, which can be expressed as follows:

\[
\begin{align*}
\text{\(d_u\)} &= D + d = 0.5 + d_m \sin(\omega t + \theta) \\
\text{\(d_l\)} &= -D + d = -0.5 + d_m \sin(\omega t + \theta) \quad (0 \leq d_u, d_l \leq 1)
\end{align*}
\]

(2)

where the DC modulation index \(D\) can be set at 0.5, and \(d_m\) should satisfy \(0 \leq d_m \leq 0.5\) to ensure the maximum value of AC modulation index \(d\) is 0.5, and AC side voltage \(v_{ac}\) of I-BC is the sum of the voltages of the upper and lower SM port. Therefore, according to (1) and (2), \(v_{ac}\) can be derived as (3).

\[
v_{ac} = v_u + v_l = \frac{V_{dc}}{k} \times (d_u + d_l) = 2d \times \frac{V_{dc}}{k}
\]

(3)
It is assumed that a power converter unit is composed of m I-BCs in series. The input DC voltage of power converter unit is taken as \( V_{dc_i} \), and the relationship between the total output voltage \( v_{gm} \) of a single-phase inverter and the output voltage \( v_{gmi} \) of a power converter unit is as follows:

\[
v_{gm} = \sum_{i=1}^{n} v_{gmi} = 2mnd \times \frac{V_{dc}}{k} \quad (4)
\]

**B. CPS-PWM STRATEGY OF THE PV CASCaded INVERTER**

The conventional CPS-PWM control strategy in Fig. 5 is adopted in the proposed PV cascaded inverter, which can achieve a higher equivalent switching frequency with lower switching frequency. Moreover, the modulation strategy can improve the harmonic performance of the output voltage, thus reducing the volume and cost of the filter.

Reference [23] described the modulation strategy of the novel cascaded PV inverter in detail, so this article does not describe it too much. And the working principle of CPS-PWM strategy applied to the power converter unit with two cascaded I-BC is shown in Fig. 5, and the carrier \( u_{cl1} \) and \( u_{cl2} \) generate controlling pulses for two I-BCs respectively. Because monopolar phase shift control is chosen as the modulation strategy, the phase shift between \( u_{cl2} \) and \( u_{cl1} \) is \( T_f/4 \), that is, the carrier phase shift angle is 90°. Comparing the modulation wave \( (d_{clp}, d_{clm}, d_{clb}, d_{clin}) \) with the carriers \( (u_{cl1} \) and \( u_{cl2} \) ), the output voltages \( (v_{ac1} \) and \( v_{ac2} \) ) of the I-BCs are obtained, and \( v_{ac} \) is the sum of \( v_{ac1} \) and \( v_{ac2} \).

**III. THE CONTROL STRATEGY FOR IMPROVING VOLTAGE UTILIZATION**

**A. THE MODULATION STRATEGY OF THIRD HARMONIC COMPONENT INJECTION**

The DC voltage utilization of conventional CPS-PWM control strategy is not high (only 0.866), and the inverter is prone to cause over modulation of the modules with larger output power under uneven irradiance and temperature conditions. Therefore, an improved CPS-PWM control strategy based on the third harmonic component injection is proposed in this paper, which can improve the amplitude of output AC voltage so as to improve the utilization of DC voltage. Meanwhile, it can also enlarge the power balance constraint range of proposed PV cascaded inverter, and improve the stability margin of the inverter, which will be described in detail in the Section IV.

Since the proposed inverter adopts the star connection mode at the grid side, the third harmonic components with the same amplitude in each phase can directly offset each other, and there is no need to add additional harmonic suppression strategy. In the proposed strategy, the third harmonic component is injected into the 50 Hz fundamental index after adding third harmonic component into 50 Hz sine waveform.

**FIGURE 5.** The working principle of CPS-PWM modulation strategy applied to a single-stage power converter unit.

**FIGURE 6.** The modulation waveform after adding third harmonic component into 50 Hz sine waveform.
It can be solved by (6): $\theta = 60^\circ$, so the peak value of the hybrid AC index ($d_{jm}$) can be obtained as (7).

$$d_{jm} = d_{jm} \sin \theta + \frac{1}{6}d_{jm} \sin 3\theta = 0.866d_{jm}$$

(7)

Therefore, the waveform coefficient $\alpha$ after the third harmonic component injection can be expressed as:

$$\alpha = \frac{d_{jm}}{d_{jm}} = 1.15$$

(8)

In conclusion, $d_{jm}$ can reach 0.575 after adding the third harmonic component, and the DC voltage utilization can be increased by 15%.

B. THE INTRA-PHASE POWER BALANCE CONTROL STRATEGY OF THE PROPOSED PV CASCADED INVERTER

The overall control strategy of the proposed cascaded PV inverter includes three loop control strategy, intra-phase power balance control strategy, and proposed improved CPS-PWM control strategy, as shown in Fig. 8. And the three control loops contain outer MPPT loop, middle DC-link voltage control loop, and inner grid current control loop.

The intra-phase power balance control strategy can control the output active power and reactive power of the cascaded units effectively, and ensure that the input voltage of each inverter unit is always kept at the reference voltage controlled by MPPT to guarantee its maximum power output (MPO).

It is assumed that each power converter unit contains two I-BCs, and $m = 2$, according to (4), the equivalent average model for the three-phase PV inverter system composed of $n$ units can be obtained in Fig. 9. Furthermore, $\beta_i$ is the dynamic equilibrium index, which satisfies $\beta_1 + \beta_2 + \ldots + \beta_n = 1$. As shown in (9), the filter inductance $L$ and line resistance $r$ are equally divided into $n$ parts, and the PV array corresponding to each unit is equivalent to the controlled current source $i_{dci}$ ($i = 1, 2, \ldots, n; j = a, b, c$).

$$\begin{aligned}
    i_{dci} &= i_{dcia} + i_{dicib} + i_{dicich} \\
    r &= r_1 + r_2 + \ldots + r_n \\
    L &= L_1 + L_2 + \ldots + L_n
\end{aligned}$$

(9)

As shown in Fig. 9, $v_{ij}$ and $i_{ij}$ ($j = a, b, c$) are the voltage and current of three-phase PV inverter system respectively, and the output voltage of each power converter unit is $v_{gmi}$, which depends on the DC input voltage ($v_{dci}$) and hybrid modulation index ($d_{ij}$), and meets the following requirements:

$$\begin{aligned}
    V_{dce} &= V_{dce1} + V_{dce2} + \ldots + V_{dce n} \\
    v_g &= v_{gm} \sin(ot) \\
    i_g &= i_{gm} \sin(ot) \\
    v_{gm} &= L \frac{d i_d}{dt} + r_i g + v_g = 4d_E V_{dce} / k
\end{aligned}$$

(10)

Since the proposed PV cascaded inverter is based on multi-bus DC collection, the difference among the output voltages of units of the single-phase inverter is small except for their phase angles. The three-phase variables are expressed as the same variable in order to simplify the analysis, and the equivalent structure of the three-phase inverter is as shown in Fig. 10. Meanwhile, $d_E$ represents the equivalent modulation index of single-phase inverter, and $v_{dce}$ represents the equivalent DC input voltage, and $i_{dce}$ represents equivalent DC side current, and $v_{gm}$ represents the total output voltage of the single-phase inverter, and they satisfy (11) and (12).

$$\begin{aligned}
    V_{dce} &= V_{dce1} + V_{dce2} + \ldots + V_{dce n} \\
    v_g &= v_{gm} \sin(ot) \\
    i_g &= i_{gm} \sin(ot) \\
    v_{gm} &= L \frac{d i_d}{dt} + r_i g + v_g = 4d_E V_{dce} / k
\end{aligned}$$

(11)

(12)

Combined with (11) and (12), the equivalent modulation index ($d_E$) can be derived as follows:

$$\begin{aligned}
    d_E &= d_E \sin(ot + \phi_E) = \frac{k\sqrt{a^2 + b^2}}{4V_{dce}} \sin(ot + \phi_E) \\
    a &= v_g + r_i g \approx v_g \\
    b &= i_{gm} \omega L \\
    \phi_E &= \arctan(\frac{b}{a})
\end{aligned}$$

(13)

The phase angle ($\phi_E$) of the output voltage of the inverter unit can be approximately 0, according to (13), so $d_E$ can be reduced as:

$$d_E \approx d_{Ep} \sin(ot) \approx \frac{k v_g}{4V_{dce}} \sin(ot)$$

(14)

Then, according to the Kirchhoff’s Voltage Law, the output voltage ($v_{gmi}$) of a power converter unit of single-phase cascaded inverter in Fig. 9 is expressed as follows:

$$v_{gmi} = L \frac{d i_d}{dt} + r_i g + v_g = 4d_i V_{dci} / k$$

(15)

Since $\beta_i$ can be regarded as a constant in the steady state of the inverter, according to (15) and the derivation of $d_E$, the expression of the hybrid modulation index ($d_i$) of single-phase inverter can be deduced as:

$$d_i \approx d_{ip} \sin(ot) \approx \frac{k \beta_i v_g}{4V_{dci}} \sin(ot)$$

(16)

Compared with $n$ power converter units in series, the units in parallel can independently control power balance.
Therefore, the output power of units in series can be decoupled and the PV cascaded inverter system can be decomposed into $n$ subsystems in parallel by energy conservation relationship, as shown in Fig. 11, and $\beta_i$ can be deduced as (17) and (18).

$$\frac{1}{2} I_{geip} V_{dc} \approx \frac{1}{2} I_{gp} V_{gp}$$  (17)

$$\beta_i \approx V_{dc} \sum_{j=1}^{n} I_{geip} V_{dc}$$  (18)

Each power converter unit corresponds to its hybrid modulation index ($d_i$). Therefore, the transmission power of each unit can be controlled by $d_i$ to realize the intra phase power balance of the PV cascaded inverter system, and units with the same $d_i$ have the same power conversion. The different output voltage of each unit can be used to represent the power conversion relationship between the units, and combining (14), (16) and (18), $d_i$ can be expressed by $d_E$ as:

$$d_i = \frac{I_{geip} \sum_{j=1}^{n} I_{geip} V_{dcj} d_E}{I_{gp}}$$  (19)

Therefore, the compensation strategy in (19) is adopted for the modulation index ($d_i$), and the intra-phase power balance of the inverter is shown in Fig. 8. Furthermore, the constraint range based on the proposed control is analyzed in Section IV, and it is also verified that the proposed control strategy can enlarge the power constraint range, so as to improve the stability of the PV cascaded inverter system.
The DC voltage utilization improvement method proposed in this paper can enlarge the power balance constraint range of cascaded inverters, so as to avoid over modulation of the units with larger output power under uneven irradiance and temperature conditions. Therefore, power balance constraint range of \( n \)-cascaded inverter will be discussed in this section.

It is assumed that the inverter system works at unity power factor. The three-phase power is balanced in steady state of the inverter system, the three-phase grid voltage is \( v_{g}\), the three-phase grid current is \( i_{g}\), the grid voltage of each phase is \( v_{gj}\) (\( j = a, b, c \)), and \( v_{ge} = v_{gb} = v_{gc} \); the inductance voltage is expressed as \( v_{li} \).

The equivalent average model for the grid connected power generation system based on the PV cascaded inverter is shown in Fig. 12. Due to the proposed control strategy, the output voltage of the PV cascaded inverter is divided into two parts: one is the output voltage of fundamental frequency component \( (v_{gmfi}) \), and the other is the output voltage of third harmonic component \( (v_{gmi}) \).

Since the third harmonic component of the output voltage of the cascaded PV inverter cancel each other in the line voltage, according to the superposition theorem, the common-mode voltage \( v_{no} \) of the three-phase inverter to the ground can be expressed as:

\[
v_{no} = v_{gm} = \sum_{i=1}^{n} \frac{2md_i V_{dci}}{k}
\]  

(20)

Assuming that the direction of \( v_{gm} \) is the same as that of \( d \)-axis, the following relationship can be obtained:

\[
\begin{align*}
    v_{gm} & = v_g + v_L + v_{no} = v_{gmfi} + v_{gmi} \\
    v_L & = j\omega L_i g
\end{align*}
\]

(21)

Therefore, the relationship for a power converter unit among output voltage \( v_{gm} \), fundamental frequency component \( v_{gmfi} \) and third harmonic component \( v_{gmi} \) is as (22).

\[
v_{gm} = v_{gmfi} + v_{gmi}
\]

(22)

The projection of modulation index \( d_i \) on \( d \)-axis and \( q \)-axis is \( d_{di} \) and \( d_{qi} \), respectively. The projection of the fundamental frequency component \( v_{gmfi} \) on \( d \)-axis is \( v_{gmfi}d \), which is also known as active component. The projection of \( v_{gmi} \) on the \( q \)-axis is \( v_{gmi}q \), which is also known as reactive power component. The relationship among \( v_{gmfi} \), \( v_{gmfi}d \) and \( v_{gmi}q \) is expressed as (23).

\[
v_{gmfi} = \frac{2m(d_{di} + j d_{qi}) V_{dci}}{k} = v_{gmfi}d + v_{gmi}q
\]

(23)

Therefore, combing (20), (21), (22) and (23), \( v_{g} \) and \( i_{g} \) can be derived as:

\[
    v_{g} = \sum_{i=1}^{3} \frac{2md_{di} V_{dci}}{k}
\]

(24)

\[
    \omega L_i g = \sum_{i=1}^{3} \frac{2md_{qi} V_{dci}}{k}
\]

(25)

Since the intra-phase power balance control in the power converter unit does not affect \( d_{gi} \) of the three-phase inverter, \( d_{qi} \) in power converter unit is evenly distributed, which can be obtained as (26) by using (25).

\[
    d_{qi} = \frac{\omega L_i g}{2m V_{dci}}
\]

(26)

If the loss of the inverter is ignored, the total output power \( P_{o} \) of the DC side of the inverter is equal to the output power of the AC side of the inverter, and the output power \( P_{i} \) of each PV array is equal to the active power output by the power converter unit, and \( P_{o} \) and \( P_{i} \) can be derived as (27).

\[
\begin{align*}
    P_{o} & = \sum_{i=1}^{n} V_{dci} i_{dci} = 3 v_{g} I_{g} \\
    P_{i} & = 3 v_{gmfi} I_{g}
\end{align*}
\]

(27)

Therefore, the power constraint can be obtained as follows:

\[
    \frac{P_{i}}{P_{o}} = \frac{v_{gmfi} v_{g}}{v_{g}} = \frac{2md_{di} V_{dci}}{k v_{g}}
\]

(28)

If the third harmonic component is not added to the CPS-PWM strategy, the maximum fundamental value of AC
modulation index \((d_{fjm})\) is 0.5, which meets the following requirements:

\[
d_i^2 + d_q^2 \leq 0.25
\]  \hspace{1cm} (29)

Assuming that each input DC bus voltage of the PV inverter is basically equal, \(U_{dc}\) is used to represent the DC bus voltage values, and \(v_{di} = U_{dc}\) \((i = 1 \ldots n)\). According to (28) and (29), power constraint of system can be deduced as:

\[
P_i \leq \frac{2mU_{dc}}{kV_r} \sqrt{0.25 - \left(\frac{\omega L_{k}k}{2mnU_{dc}}\right)^2} \hspace{1cm} (30)
\]

According to (8), \(d_{fjm} = 0.5\alpha\) after adopting the improved control strategy. Therefore, the following conditions should be met:

\[
d_i^2 + d_q^2 \leq 0.25\alpha^2
\]  \hspace{1cm} (31)

The power constraint range after adding the third harmonic component can be derived as:

\[
P_i \leq \frac{2mU_{dc}}{kV_r} \sqrt{0.25 - \left(\frac{\omega L_{k}k}{2mnU_{dc}}\right)^2} \hspace{1cm} (32)
\]

By comparing (30) and (32), it can be seen that after adopting the improved control strategy, the power balance interface range of each unit of the inverter has been enlarged. Because the waveform coefficient \(\alpha\) is 1.15 after injecting the third harmonic component, when the output power of the PV array does not meet (32), \(d_{fjm}\) will be greater than 0.575, which will lead to over-modulation of inverter unit.

According to (30) and (32), the power constraint relational graphs with and without the third harmonic component injection as shown in Fig. 13 are obtained. It is assumed that \(m = n = 2\), HFT ratio \(k = 2.5\), voltage level of three-phase power grid is 10kV, the rest of the simulation parameters refer to Table 1. As shown in Fig. 13, the points on the two 3D surfaces are the critical ones for the power balance of the units in the PV cascaded inverter.

The critical points in Fig. 13 before adding the third harmonic component constitute the Power Balance Interface I, after adding the third harmonic component, it has changed to the Power Balance Interface II, and the region between the two interfaces is the expansion range of power balance constraint. When the output power \(P_i\) of the PV array is below the 3D surface, the power balance constraint condition is not satisfied, and the over-modulation phenomenon will occur. On the contrary, when the output power \(P_i\) of the PV array is above the 3D surface, the power balance constraint condition is satisfied, and the system will remain balanced.

V. SIMULATION RESULTS

The 1.5MW three-phase medium voltage grid connected system based on a single-stage high-frequency-link isolated cascaded PV inverter was simulated in Matlab/Simulink software. The output voltage of AC side of the PV inverter system was 10kV. The PV simulation array uses a total of 10 \(\times\) 33 PV modules for series and parallel connection, and the output voltage of an array has reached 500V, and the parameters of the selected PV array are shown in Table 1.

The output AC voltage and current waveforms of the proposed PV cascaded inverter system are shown in Fig. 14. According to (4), the theoretical amplitude and the effective value of output phase voltage is 8kV and 5.66kV. And the effective value in simulation results is 5.60kV, which is lower than the theoretical effective value because of the leakage inductance of the transformer.

Fig. 15 shows the simulation waveforms of AC duty cycle \(d_j\) and its fundamental wave \(d_j\) and third-order harmonic \(d_j\). The simulation results show that the amplitude range of the fundamental \(d_j\) has increased to 0.575 after adding the third harmonic \(d_j\). Therefore, the utilization of DC voltage has been improved, and the correctness of (5) is verified.
has increased by 1.15 times to 9.122kV, so the utilization of DC voltage has increased by 15%. The discussion of total harmonic distortion (THD) is based on the first 20 harmonic components (50 Hz-1000 Hz) in the system. In Fig. 16(c), the THD of output phase voltage of the inverter after adding the zero sequence component is 17.74%, and the third harmonic component is much higher than other harmonics (even more than 15% of the total harmonics). In Fig. 16(d), the THD of output line voltage of the inverter is 1.37% after the third harmonic injection, and the third harmonic component has dropped to less than 0.02%, so it can be considered that there is almost no third harmonic component in output line voltage, and it is also verified that the third harmonic injection has no effect on the output line voltage.

B. THE POWER BALANCE CONTROL STRATEGY BETWEEN CASCADED INVERTER UNITS

The paper proposes an intra-phase power balance control based on the improved CPS-PWM strategy in order to avoid the over modulation problem. Assuming that the ambient temperature of the selected PV array is maintained at 25°C, the power imbalance condition can be divided into three stages: ① First stage (0-0.15s): the two PV arrays are under the same irradiance (S₁ = S₂ = 1000W/m²); ② Second stage (0.15s-0.35s): the irradiance of array 1 decreases to 800W/m², while that of array 2 remains at 1000W/m²; ③ Third stage (0.35s-0.6s): the irradiance of array 1 increases to 1000W/m², the two arrays are under the same irradiance again (S₁ = S₂ = 1000W/m²). The irradiance change of arrays in the above three stages is shown in Fig. 17.

The MPPT control shows that the MPO can be guaranteed when the terminal voltage of the selected PV array is maintained at 547V under the irradiance of 1000W/m² and at 541V under the irradiance of 800W/m². In Fig. 18(a), the terminal voltages of the two PV arrays are maintained at
547V in the first stage. In the second stage, as the terminal voltage of array1 decreases to 500V with the decrease of irradiance, while that of array2 is greatly increased to 591V after being affected. And as the irradiance of array1 increases to 1000W/m², the two voltages are maintained at 547V again after a short time (about 0.1s). So, the voltages of PV arrays without the proposed control fluctuate greatly with the change of irradiance, which makes the PV modules with high output power prone to over modulation.

After adding the intra-phase power balance control, the terminal voltage of array2 still maintains 547V in the second stage in Fig. 18(b), while the voltage of array1 decreases slightly to 541V, making the bus voltage of PV array maintain at its maximum power output voltage, and the two PV arrays maintain their MPO voltage at this time. Fig. 19 shows the comparison of output power of PV array1 in three stages with and without control strategy, and the voltage fluctuation of PV array 1 deviates from the maximum power point (MMP) without the proposed control, resulting in the loss of power generation \( \Delta P = 3kW/s \). Therefore, the intra-phase power balance control proposed in this paper can avoid the over modulation problems caused by the aging and partial occlusion of PV modules, and can also adjust the output voltage of PV array in real time according to the ambient changes, so as to maximize the use of solar energy.

### VI. EXPERIMENTAL RESULTS

Combined with the simulation results of PV grid connected system based on an isolated cascaded inverter, in order to further verify the feasibility of the structure in practical engineering application and the correctness of the modulation control strategy. Then, the steady and transient performance of the PV cascaded inverter and the effectiveness of the third harmonic injection method to improve DC voltage utilization are verified by a small prototype built in the laboratory.

The experimental schematic diagram of the PV grid connected system is shown in Fig. 20, the hardware experimental device diagram is shown in Fig. 21, and the experimental parameters of the overall system of three-phase PV inverter are shown in Tab. 2, and the experimental parameters of the overall system of three-phase PV inverter are shown in Tab. 2.
shown in Tab. 3, and the PV arrays were replaced by DC voltage sources.

The experimental prototype of the PV grid connected system is composed of a DC voltage source, an isolated cascaded inverter, a signal control device and a pure resistive load. The DC voltage source can simulate the characteristics of PV arrays and transmit DC power to three-phase PV inverter. The isolated cascaded inverter mainly includes three power converter units. Each power converter unit is cascaded by two I-BCs. DSP central controller and FPGA independent controller are connected by optical fiber to form control system. The steady-state and transient performance of the inverter is verified when $v_{dc}$ is 50V, and then the DC voltage utilization improvement method based on third harmonic injection is verified when $v_{dc}$ is 30V.

### A. WORKING PRINCIPLE AND MODULATION STRATEGY VERIFICATION OF PV INVERTER ($V_{dc} = 50V$)

Fig. 22 shows the three-phase AC output phase voltage waveform and phase current waveform when the PV inverter works in a steady-state. When $V_{dc}$ is 50V, $d_m = 0.45$, the theoretical peak value of output phase voltage of PV inverter can be derived as 90V by (4), and the actual effective value is 85.9V. Therefore, the theoretical value is basically consistent with the actual one, which verifies the correctness of (4), and the lower actual value is due to the voltage drop caused by the leakage inductance of HFT.

Fig. 23 shows the transient waveform of three-phase current when the load is changed from $\infty$ to 160Ω. The output current of the three-phase inverter increases rapidly from 0A at no-load to 613mA, and the inverter transits to a new steady-state, which has good transient performance.

Fig. 24 shows the output port voltage waveforms of three power converter units. The experimental results show that the number of output voltage levels of the three-phase inverter unit increases to five after using CPS-PWM strategy, which verifies the feasibility and effectiveness of the modulation strategy.

Fig. 25 shows the output voltage waveforms of the two I-BCs of the power converter unit in phase B and the detailed waveforms of their partial amplification. In Fig. 25, the output voltage $v_{gmb}$ of B-phase power converter unit is the sum of two cascaded I-BCs output voltages $v_{ac1}$ and $v_{ac2}$. Since the equivalent switching frequency ($f_e$) is 4 times of the carrier frequency ($f_c$), the correctness of CPS-PWM strategy based on single-phase power converter unit in section II is verified.

### B. VERIFICATION OF DC VOLTAGE UTILIZATION IMPROVEMENT METHOD BASED ON PHI-PWM ($V_{dc} = 30V$)

Fig. 26(b) and Fig. 26(a) shows the output phase voltage waveform of the proposed inverter with and without adding the third harmonic component with an amplitude of $1/6d_m$, so as to compare the DC voltage utilization under the two conditions.

When $V_{dc} = 30V$ and $d_m = 0.5$, the output phase voltage of the three-phase inverter is 60V. Compared with the output phase voltage without DC voltage utilization improvement method, the new output phase voltage amplitude has been
1) The proposed improved modulation strategy can increase the utilization of DC side voltage to 15%, and greatly improve the power output capacity of grid connected PV system.

2) The proposed intra-phase power balance control of cascaded PV inverter can avoid the over modulation problems caused by the aging and partial occlusion of PV modules;

3) The proposed improved control strategy can enlarge the power balance constraint range between units, and ensure the stability of the three-phase inverter system under serious unbalanced conditions.

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VOLUME 9, 2021