Research on the Module Power Equalization Control Strategy of Three-Phase Common DC-Bus Cascaded H-Bridge Multilevel Inverter for Large-Scale PV Power Plants

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ABSTRACT Featured with the characteristics of expandable modular structure, no need for line-frequency transformer directly connected to medium voltage grid and the same active power of each phase, three-phase common dc-bus cascaded H-bridge multilevel inverter has great advantages in high-voltage and high-power photovoltaic (PV) power generation application. However, if the number of modules in three phases is different, the active power of each module in the phase with fewer modules will be higher, and the active power transmitted by each module in the phase with more modules will be lower. Unbalanced active powers among modules lead to different heat dissipation requirements, which does not contribute to the modular design of the system. Aiming at this problem, this paper proposes an active power equalization control strategy based on zero-sequence voltage compensation. According to the actual number of modules in three phases and power factor of inverter, the compensated zero-sequence voltage can be calculated, by which all modules are capable of transmitting the almost same active power no matter whether the number of modules in three phases are same or not, and whether the inverter operates at unit power factor or not. The effectiveness of the proposed strategy is verified by simulation and experimental results.

INDEX TERMS Multilevel, cascaded H-bridge, three-phase common dc-bus PV inverter, module power equalization.

I. INTRODUCTION

Compared with the low-voltage and low-power photovoltaic (PV) system, large-scale PV power plants are capable of delivering further reductions in cost per watt of the system, which is help for the PV power generation on the grid at parity, with greater commercial value [1]–[4]. One way to realize high-voltage and high-power PV grid-tied power generation is to adopt three-phase isolated PV inverter based on cascaded H-bridge (CHB) topology [5]–[12]. Its modular structure can use low-voltage devices to expand the system to a higher voltage and power level, and be directly connected to medium voltage power grid without heavy line-frequency transformer. In addition, the multilevel output voltage allows each H-bridge (HB) to work at a lower switching frequency, improving the overall efficiency of the inverter. Among the high-voltage and high-power PV inverters based on CHB structure, the following two types of topologies have attracted much attention. One is the independent dc-bus CHB (IDB-CHB) PV inverter [5]–[9] shown in Fig. 1 and another is common dc-bus CHB (CDB-CHB) PV inverter [10]–[12] shown in Fig. 2. In contrast, due to no inter-module and inter-phase power imbalance problems, simple control, and more energy harvesting, the advantages of CDB-CHB inverter in large-scale PV grid-connected power generation applications are more prominent [1], [2].

Similar to the traditional three-phase PV inverter, when grid voltages are balanced, phase A, B and C of CDB-CHB PV inverter are capable of transmitting the same active power. Generally, each phase of the three-phase CDB-CHB PV inverter is designed to be the same number of modules, so all modules have the same active power, and their voltage stress,
current stress, and thermal stress keep consistent. However, under the conditions of fault redundancy, the number of modules in the fault phase will be less than that in the normal phase, resulting in that all modules in the fault phase need to bear more active power. The unequalization of active powers among all modules will cause different heat dissipation requirements, which is against the modular design, and long-term operation will affect the life of the modules with higher power. Therefore, it is necessary to carry out module power equalization control for CDB-CHB PV inverter.

For the power balance control of three-phase isolated CHB PV inverter, IDB-CHB structure has been studied more. The power balance control strategies proposed in [2], [5]–[9], [13] can effectively deal with the inter-phase power imbalance problem of IDB-CHB PV inverter by compensating zero-sequence voltage. In [14]–[17], several control strategies are studied for IDB-CHB PV inverter under fault conditions, which all can inject balanced three-phase currents into the grid. Although [2], [5]–[9], [13]–[17] have studied inter-phase power balance and fault redundancy control strategies of IDB-CHB PV inverter, the topology is different from that of this paper, and the problems to be solved are also different. For the IDB-CHB PV inverter, the dc-bus of each module is connected with a PV array, and all PV arrays all can operate at their own maximum power point. Because the characteristics of each PV array are not exactly the same (such as different light intensity, different surface dust accumulation and partial occlusion), it will result in inter-module and inter-phase power imbalance problems. However, CDB-CHB structure is similar to the traditional three-phase PV inverter, and the active powers transmitted by phase A, B, and C are automatically balanced [4]. If the number of modules in phase A, B, and C are the same, each module can also transmit the same active power, which is the biggest difference between IDB-CHB and CDB-CHB structures. The purpose of this paper is that all modules in the CDB-CHB PV inverter can transmit the same active power when the number of modules in each phase is different (usually caused by fault) and the inverter operates in non-unit power factor. Several control strategies have been proposed in [10]–[12], [18] for CDB-CHB PV inverter, which can ensure all modules to transmit the same active power, but these methods only consider the scenario that phase A, B, and C have the same number of modules. In [19], a method of system degradation is proposed to balance the active power of all modules, by which if the modules in phase A fail, not only the fault modules in phase A need to be bypassed, but also the corresponding position modules in phase B and C also are bypassed to ensure that the number of modules in each phase are the same. Then, the strategies in [10]–[12] are used to equalize the active power of all modules. However, this method will lower the module utilization. Inspired by [2], [5]–[9], [13] to solve the inter-phase power imbalance of IDB-CHB PV inverter, zero-sequence voltage compensation also can be used to equalize the modules power when the number of modules in each phase of CDB-CHB is different. Relying on the power redistribution capability of zero-sequence voltage, the original balanced three-phase powers can be adjusted to imbalance, that is, the phase with more modules transmits higher active power, and the phase with less modules delivers lower active power, so as to achieve the purpose that all modules have the same active power. In addition, PV power plant will produce a certain amount of reactive power consumption, mainly including high-voltage transformer and transmission lines. Especially in large-scale power plant, the losses of reactive power cannot be ignored. To avoid injecting reactive power into the grid, CDB-CHB PV inverter can operate at a non-unit power factor to compensate for reactive power consumption of the whole power station. Therefore, considering the actual working scenario, a module power equalization control strategy based on zero-sequence voltage compensation is proposed in this paper. Based on the actual number of modules in three phases and the power factor of CDB-CHB inverter, an appropriate zero-sequence voltage can be calculated and be compensated to the system, which ensures that all modules in three-phase inverter are capable of transmitting the same active power no matter whether the number of modules in three phases are same or not, and whether the inverter operates at unit power factor or not.

This paper is organized as follows: the system configuration and redundancy design are presented in Section II.
Modules active power unequalization problem under fault redundancy condition is analyzed in detail, and a control strategy based on zero-sequence voltage compensation to equalize the active power of all modules is proposed in Section III. Simulation and experimental results are respectively given in Sections IV and V to validate the performance of the suggested method. The last part is the conclusions provided in Section VI.

II. SYSTEM CONFIGURATION AND REDUNDANCY DESIGN

A. SYSTEM CONFIGURATION

The recommended three-phase CDB-CHB PV inverter is shown in Fig. 3, where LLC converters are adopted as the isolated DC/DC converter for a higher total efficiency and power density [20]. In addition, to reduce the system size and save on insulation costs of transformer, LLC converter adopts one-input-four-outputs structure [4], that is, one LLC converter connects four HBs, which is also called a module. For the studied topology in Fig. 3, the number of modules in phase A, B, and C are denoted by $n_A$, $n_B$, and $n_C$, respectively. Normally, $n_A = n_B = n_C$. To adapt the 1500V PV system, both boost converters and LLC converters need to adopt three-level structure so that 1200V switching devices (market mainstream and cheap) can be used. The LLC converter contains a high-frequency transformer with a ratio of $N_T:1:1:1:1$. If $N_T$ is designed to a suitable value greater than 1, HBs can still use 1200V switching devices.

When the common dc-bus voltage is stabilized at a certain value, boost converter is able to achieve the maximum power point tracking of corresponding PV array by controlling its input voltage. There are lots of literature on this issue [21], [22], so boost converters are not the focus in this paper due to their independent operation. Considering that all modules in Fig. 3 have the same structure, the $i$th module in phase A is taken for analysis, and detailed circuit structure is shown in Fig. 4. Switches $Q_{A1} \sim Q_{A4}$ (including their body diodes and equivalent capacitors $C_{eq}$), the input capacitors $C_{dA1}$ and $C_{dA2}$, free-wheeling diodes $D_{A1}$ and $D_{A2}$, and flying capacitor $C_{SA1}$ form the left leg of three-level LLC, and $Q_{A5} \sim Q_{A8}$, $C_{dA1}$ and $C_{dA2}$, $D_{A3}$ and $D_{A4}$, and $C_{SA2}$ form the right leg. The resonant inductor $L_{R_{A1}}$, the magnetizing inductor $L_{m_{A1}}$, and the resonant capacitor $C_{R_{A1}}$ form the resonant tank. $T_{RA1}$ is the high-frequency isolated transformer. $D_{RA1} \sim D_{RA4}$ ($j = 1, 2, 3, 4$) are the output rectifier diodes. Four HB inverters are composed of $T_{A1} \sim T_{A4}$ ($j = 1, 2, 3, 4$), respectively, and $C_{A1} \sim C_{A4}$ are the dc-bus capacitors of four HBs. In addition, $U_{dc_{A1}}$ denotes the common dc-bus voltage; $U_{HA1} \sim U_{HA4}$ denote the HB dc-bus voltages of $i$th module in phase A; $i_{A}$ denotes the output current of HBs in phase A, which is also the grid current of phase A.

B. REDUNDANCY DESIGN

To achieve higher voltage (35kV) and higher power level (>5WM), the CDB-CHB PV grid-connected inverter need to have more modules in practical application. Therefore, redundancy design is usually adopted to improve the reliability of cascaded modular topology and avoid economic loss caused by shutdown [19]. That is to say, when some modules fault, they are bypassed to ensure the normal operation of the system.

The minimum number of modules for phase X ($X = A, B, C$) of three-phase CDB-CHB PV inverter is denoted by $N_{min}$. Due to mass production, the process of each module is the same. Assuming that the reliability of each module is $P_M$ ($0 < P_M < 1$), the reliability of the entire system is analyzed as below.

1) Each phase of three-phase CDB-CHB PV inverter is designed to have $N_{min}$ modules, that is, there are no redundant modules in each phase. Then, the reliability of the system can be calculated as follows:

$$P_{R,0} = (P_M)^{N_{min}} \quad (1)$$

2) Three phases are all designed to have ($N_{min} + 1$) modules, that is, each phase is redundant with one module. Then, the reliability of the system can be calculated as:

$$P_{R,1} = (P_M)^{N_{min}+1} + C_{N_{min}+1}^1 (1 - P_M) (P_M)^{N_{min}} \quad (2)$$

3) Three phases are all designed to have ($N_{min} + 2$) modules, that is, each phase is redundant with two modules. Then, the reliability of the system can be calculated as:

$$P_{R,2} = (P_M)^{N_{min}+2} + C_{N_{min}+2}^1 (1 - P_M) (P_M)^{N_{min}+1} + C_{N_{min}+2}^2 (1 - P_M)^2 (P_M)^{N_{min}} \quad (3)$$

4) Three phases are all designed to have ($N_{min} + 3$) modules, that is, each phase is redundant with three modules. Then, the reliability of the system can be calculated as:

$$P_{R,3} = (P_M)^{N_{min}+3} + C_{N_{min}+3}^1 (1 - P_M) (P_M)^{N_{min}+2} + C_{N_{min}+3}^2 (1 - P_M)^2 (P_M)^{N_{min}+1} + C_{N_{min}+3}^3 (1 - P_M)^3 (P_M)^{N_{min}} \quad (4)$$

FIGURE 3. Schematic diagram of three-phase CDB-CHB PV inverter with one-input-four-outputs isolated DC/DC converters.
Taking the dc 1500V and ac 35kV system as an example, the redundancy design of the CDB-CHB PV inverter in Fig. 3 is introduced. The steady-state value of the common dc-bus voltage $U_{dcT}$ must be greater than the open circuit voltage of the PV arrays connected to boost converters but less than 1500V, and here is set to be 1425V. If the turns ratio of primary winding to secondary windings of high-frequency transformer is set to 1.5, the dc-bus voltages of all HBs can be controlled to 950V under normal conditions.

For ac voltage rated at 35kV (generally refers to the root mean square value of line-to-line voltage), the peak value of phase voltage can be calculated as follows:

$$U_{PP} = \left(35000 \times \sqrt{2}\right) / \sqrt{3} \approx 28577V \quad (5)$$

The upper limit voltage of the conventional centralized inverter is 1.15 times of the grid phase voltage, so the maximum value of the grid phase voltage can be calculated as follows:

$$U_{PPMax} = 1.15 \times V_{PP} \approx 32864V \quad (6)$$

Under normal working conditions, the total HB dc-bus voltage of one module is $U_{HT} = 3800V$ (950 x 4 = 3800), so the minimum number of modules in each phase is obtained as:

$$N_{min} = U_{PPMax} / U_{HT} \approx 8.65 \quad (7)$$

From the above analysis, if it is to be directly connected to the 35kV medium voltage grid, the number of modules in each phase should not be less than 9 ($N_{min} = 9$). Assuming that the reliability of a single module is $P_{M} = 99\%$, the relationship between system reliability and the number of modules in each phase is shown in Fig. 5. If redundancy design is not adopted, the reliability of the system is only 91.352\%, which is obviously lower than that of single module. In other words, as the number of modules increases, the reliability of the whole system will decrease. If one module is redundant in each phase, the reliability of the system is greatly improved, and the value is 99.573\%, which is greater than the reliability of a single module. Therefore, it is necessary to adopt redundancy design for cascaded topology. When the number of redundant modules is 3, the reliability of the system has reached 99.999\%. At this time, under the premise of meeting the power conversion, if the number of redundant modules continues to increase, the reliability will not increase significantly, but increase the cost of the whole system. To sum up, the three-phase CDB-CHB PV inverter must adopt redundancy design, and the number of redundant modules should be between 1 and 3.
III. MODULE POWER EQUALIZATION CONTROL BASED ON ZERO-SEQUENCE VOLTAGE COMPENSATION

From the above analysis, for the three-phase CDB-CHB PV inverter, using redundancy design can greatly improve the system reliability, and avoid effectively system shutdown caused by the module failure. The implementation method is that when the Y-th module in phase X faults, the system will bypass this module by closing the switch SWXY to ensure the normal operation of the system. However, when the system operates in fault redundancy mode, the number of modules of each phase will no longer remain the same. Similar to the traditional three-phase PV inverter, each phase of three-phase CDB-CHB PV inverter can still transmit the same active power when using voltage oriented control. Since the number of modules in the fault phase is less than that in the normal phase, all modules in the fault phase will bear more active power.

Generally, PV power station will have a certain amount of reactive power consumption mainly caused by line-frequency transformer and transmission line. For the CDB-CHB PV inverter connected to 35kV grid, it mainly refers to the 35kV/110kV line-frequency transformer in the post stage, as shown in Fig. 6. To avoid injecting reactive power into the grid, the PV inverter can adjust its own power factor to compensate the reactive power consumption of the power station. To make the phase angle of grid voltage and current at port 1 must not be in phase, that is, the three-phase CDB-CHB PV inverter operates at non-unit power factor. Therefore, considering the actual working scenario, the main work of this paper is that all modules in the three-phase CDB-CHB PV inverter can still transmit the same active power when the system operates in fault redundancy mode and non-unit power factor.

A. ZERO-SEQUENCE VOLTAGE COMPENSATION METHOD

Assuming that three-phase grid voltages are balanced, their expressions are as follows:

\[
\begin{align*}
    u_{gA} &= U_g \cos(\omega t) \\
    u_{gB} &= U_g \cos(\omega t - 2\pi/3) \\
    u_{gC} &= U_g \cos(\omega t + 2\pi/3)
\end{align*}
\]

(8)

where \(U_g\) and \(\omega t\) are the amplitude and phase angle of the three-phase grid voltages.

Then, the fundamental component of ac output voltages of three-phase CDB-CHB inverter can be expressed as follows:

\[
\begin{align*}
    u_{cA} &= U_c \cos(\omega t + \alpha) \\
    u_{cB} &= U_c \cos(\omega t - 2\pi/3 + \alpha) \\
    u_{cC} &= U_c \cos(\omega t + 2\pi/3 + \alpha)
\end{align*}
\]

(9)

where \(U_c\) denotes the amplitude of \(u_{cA}\), \(u_{cB}\), and \(u_{cC}\), and \(\alpha\) denotes the angle between \(u_{gA}\) and \(u_{gB}\).

When the three-phase CDB-CHB PV inverter operates at non-unit power factor, the three-phase grid currents can be expressed as follows:

\[
\begin{align*}
    i_{gA} &= I_g \cos(\omega t + \varphi) \\
    i_{gB} &= I_g \cos(\omega t - 2\pi/3 + \varphi) \\
    i_{gC} &= I_g \cos(\omega t + 2\pi/3 + \varphi)
\end{align*}
\]

(10)

where \(I_g\) denotes the amplitude of the grid currents, and \(\varphi\) denotes the power factor angle of the inverter.

Therefore, considering the actual working scenario, the main work of this paper is that all modules in the three-phase CDB-CHB PV inverter can still transmit the same active power when the system operates in fault redundancy mode and non-unit power factor.

According to equations (11)-(13), the active power \(P_A\), \(P_B\), and \(P_C\) transmitted by each phase, and the total active power \(P_{sum}\) transmitted by the three-phase converter are as follows:

\[
P_A = P_B = P_C = \frac{3U_g I_g}{2} \cos(\varphi - \alpha)
\]

(14)

\[
P_{sum} = P_A + P_B + P_C = \frac{3U_g I_g}{2} \cos(\varphi - \alpha)
\]

(15)

As could be seen, no matter whether the number of modules in the three-phase converter is the same or not, the active power transmitted by each phase of the three-phase converter is the same, which is the advantage of the common dc-bus structure. To enable all modules to transmit the same active power when using voltage oriented control.
power under the conditions of different number of modules in each phase, zero-sequence voltage injection is adopted for the three-phase star-connected inverter, so that three-phase transmission active powers are redistributed. It is assumed that the compensated zero-sequence voltage is as follows:

\[ u_0 = U_0 \cos(\omega t + \beta) \]  

where \( U_0 \) and \( \beta \) denotes the amplitude and phase angle of \( u_0 \), respectively.

The instantaneous power produced by zero-sequence voltage \( u_0 \) on three phases A, B and C are as follows:

\[
p_{A0} = u_0 I_{gA} = \frac{U_0}{2} I_{g} \left(\cos(\omega t + \phi) \right) \\
= \frac{U_0}{2} \left(\cos(\phi - \beta) + \frac{U_0}{2} \cos(2\omega t + \phi + \beta) \right) \tag{17}
\]

\[
p_{B0} = u_0 I_{gB} = \frac{U_0}{2} I_{g} \left(\cos(\omega t + \phi + \frac{2\pi}{3}) \right) \\
= \frac{U_0}{2} \left(\cos(\phi - \frac{2\pi}{3} - \beta) + \frac{U_0}{2} \cos(2\omega t + \phi + \frac{2\pi}{3}) \right) \tag{18}
\]

\[
p_{C0} = u_0 I_{gC} = \frac{U_0}{2} I_{g} \left(\cos(\omega t + \phi) \right) \\
= \frac{U_0}{2} \left(\cos(\phi + \frac{2\pi}{3} - \beta) + \frac{U_0}{2} \cos(2\omega t + \phi + \frac{2\pi}{3}) \right) \tag{19}
\]

Then, the active powers produced by zero-sequence voltage \( u_0 \) on phase A, B and C are as follows:

\[
\begin{align*}
P_{A0} &= \frac{U_0 I_{g}}{2} \cos(\phi - \beta) \\
P_{B0} &= \frac{U_0 I_{g}}{2} \cos(\phi + \frac{2\pi}{3} - \beta) \\
P_{C0} &= \frac{U_0 I_{g}}{2} \cos(\phi + \frac{2\pi}{3} - \beta)
\end{align*} \tag{20}
\]

According to (14) and (20), after compensating zero-sequence voltage, the three-phase transmission active powers \( P_{A^*}, P_{B^*}, \) and \( P_{C^*} \) are calculated as follows:

\[
\begin{align*}
P_{A}^* &= P_{A0} + P_{A} = \frac{U_0 I_{g}}{2} \cos(\phi - \alpha) + \frac{U_0 I_{g}}{2} \cos(\phi - \beta) \\
P_{B}^* &= P_{B0} + P_{B} = \frac{U_0 I_{g}}{2} \cos(\phi + \frac{2\pi}{3} - \alpha) + \frac{U_0 I_{g}}{2} \cos(\phi + \frac{2\pi}{3} - \beta) \\
P_{C}^* &= P_{C0} + P_{C} = \frac{U_0 I_{g}}{2} \cos(\phi + \frac{2\pi}{3} - \alpha) + \frac{U_0 I_{g}}{2} \cos(\phi + \frac{2\pi}{3} - \beta)
\end{align*} \tag{21}
\]

According to (15), (21), and (22), (23) can be calculated as follows:

\[
\begin{align*}
U_0 \cos(\beta - \varphi) &= \frac{2n_A - n_B - n_C}{n_A + n_B + n_C} U_c \cos(\alpha - \varphi) \\
U_0 \sin(\beta - \varphi) &= \frac{\sqrt{3}(n_C - n_B)}{n_A + n_B + n_C} U_c \cos(\alpha - \varphi)
\end{align*} \tag{23}
\]

According to the control principle of three-phase converter, formula (24) can be obtained as follows:

\[
U_c \cos(\alpha - \varphi) = U_c \cos \alpha \cos \varphi + U_c \sin \alpha \sin \varphi \\
= u_d \cos \varphi + u_q \sin \varphi \tag{24}
\]

where \( u_d \) and \( u_q \) represent the amplitudes of active power modulation voltage and reactive power modulation voltage, respectively.

By introducing (23) and (24) into (16), the compensated zero-sequence voltage can be calculated as follows:

\[
u_0 = U_0 \cos(\omega t + \beta) \\
= U_0 \cos[(\omega t + \beta - \varphi) + \varphi] \\
= U_0 \cos[(\omega t + \beta - \varphi)] \cos \varphi - U_0 \sin[(\omega t + \beta - \varphi)] \sin \varphi \\
= [U_0 \cos(\omega t) \cos(\beta - \varphi) - U_0 \sin(\omega t) \sin(\beta - \varphi)] \cos \varphi \\
- [U_0 \sin(\omega t) \cos(\beta - \varphi) + U_0 \cos(\omega t) \sin(\beta - \varphi)] \sin \varphi \\
= (u_d \cos \varphi + u_q \sin \varphi) \left[ k_1 \cos(\omega t - k_2 \sin(\omega t)) \cos \varphi - k_1 \sin(\omega t) + k_2 \cos(\omega t) \right] \sin \varphi \tag{25}
\]

where,

\[
\begin{align*}
k_1 &= \frac{2n_A - n_B - n_C}{n_A + n_B + n_C} \\
k_2 &= \frac{n_A + n_B + n_C}{\sqrt{3} (n_C - n_B)} \\
\sin(\varphi) &= \frac{i_q}{\sqrt{i_d^2 + i_q^2}} \\
\cos(\varphi) &= \frac{i_d}{\sqrt{i_d^2 + i_q^2}} \tag{26}
\end{align*}
\]

To sum up, injecting the zero-sequence voltage calculated by (25) is able to make all the modules in three-phase CDB-CHB PV inverter transmit the same active power even if the number of modules in each phase of three-phase CDB-CHB is different and the system operates at non-unit power factor.

**B. SYSTEM CONTROL STRATEGY**

As shown in Fig. 7, the proposed module active power equalization control strategy for three-phase CDB-CHB PV inverter is composed of main controller, HB controllers, and DC/DC controllers, which interact with each other through communication.

The main controller is mainly responsible for average voltage control of all HBs, active current and reactive current control, zero-sequence voltage calculation, inter-phase
power redistribution, and inter-module power equalization. Firstly, the phase angle $\omega t$ of $u_{gA}$, $u_{gB}$, $u_{gC}$ can be obtained by a digital phase-locked loop [23]. Then, Clark and Park transformations are used for $u_{gA}$, $u_{gB}$, $u_{gC}$ and $i_{gA}$, $i_{gB}$, $i_{gC}$, respectively, and $e_{d}$, $e_{q}$, $i_{d}$, $i_{q}$ are obtained. Secondly, average voltage control of all HBs is achieved. The average value of all HBs dc-bus voltage $U_{Haver}$ is obtained by dividing $U_{SUM}$, the total sum of $U_{HAy}$, $U_{HBy}$ and $U_{HCky}$ by $(4n_{A} + 4n_{B} + 4n_{C})$, and then $U_{Haver}$ is controlled to $U_{ref}$ by a PI regulator, whose output is the active power reference current $i_{d*}$. Thirdly, the reactive power reference current $i_{q*}$ can be calculated based on the actual reactive power consumption of the whole PV power plant. $i_{d}$ and $i_{q}$ have been calculated and can be controlled to $i_{d*}$ and $i_{q*}$ by two PI regulators. Then, the amplitudes of active power modulation voltage $u_{d}$ and reactive power modulation voltage $u_{q}$ can be calculated based on the outputs of two current regulators. The $dq/abc$ transformation is used for $u_{d}$ and $u_{q}$ to obtain the three-phase modulation voltages $u_{A}$, $u_{B}$, $u_{C}$, which are also the fundamental component of ac output voltage of three-phase CDB-CHB inverter. Fourthly, judge whether the number of actual operation modules of each phase, $n_{A}$, $n_{B}$, and $n_{C}$, are not less than the minimum number of modules $N_{min}$. That is, if $n_{A} \geq N_{min}$, $n_{B} \geq N_{min}$, and $n_{C} \geq N_{min}$ do not work, the system will be shut down for maintenance. Otherwise, zero-sequence voltage $u_{0}$ is calculated based on (25), and compensated to $u_{d}$, $u_{q}$ to obtain the three-phase modulation voltages $u_{A}$, $u_{B}$, $u_{C}$, which can achieve the active power modulation of each phase. Finally, the modulation voltages of each HB, $u_{AH}$, $u_{BH}$, $u_{CH}$, are obtained by dividing the $u_{A}$, $u_{B}$, $u_{C}$ by $4n_{A}$, $4n_{B}$, and $4n_{C}$, respectively, which achieves inter-module power equalization of each phase.

Each three-level LLC converter has a DC/DC controller, which is responsible for controlling the dc-bus average voltage of four HBs in its post stage. The output average voltages of LLC converters, $U_{HX}$, obtained by dividing the sum of $U_{HX1}$, $U_{HX2}$, $U_{HX3}$, $U_{HX4}$ by 4, $X = A, i = 1, 2, \ldots, n_{A}, X = B, i = 1, 2, \ldots, n_{B}, X = C, i = 1, 2, \ldots, n_{C}$, can be controlled to $1/N_{T}$ of common dc-bus voltage $U_{dcT}$ with zero steady-state error through PI regulators whose outputs are the frequencies $f_{DX}$ of LLC converters. Then, the switching driving signals of three-level LLC converter can be obtained by variable frequency modulation (VFM) [24].

Four HBs in the post stage of LLC converter use one HB controller together, which are mainly responsible for generating switching signals for each HB. The modulation waveforms of all HBs, $m_{Aij}$, $m_{Bij}$, $m_{Cij}$, are calculated by dividing the $u_{AH}$, $u_{BH}$, $u_{CH}$ by $U_{HAy}$, $U_{HBy}$ and $U_{HCky}$, respectively, and then carrier phase-shifted sinusoidal pulse width modulation (CPS-SPWM) is employed to generate switching signals [25].

IV. SIMULATION RESULTS

To verify the performance of the proposed method, a simulation model of three-phase CDB-CHB PV grid-connected inverter is built in MATLAB/Simulink. Each phase is designed to have four modules and one module redundancy is allowed. Due to the complexity of the system and the high switching frequency of LLC converter, the simulation step size should not be too large (500ns). If each LLC converter adopts the one-input-four-outputs structure, the whole system will include 12 three-level LLC converters and 48 HBs in normal operation, so the simulation time is relatively long. Therefore, the LLC converter in Fig. 3 can use one-input-one-output structure in simulation model, which will not affect the effectiveness verification of the control strategy, but also simplify the simulation model and save simulation time. In addition, the turns ratio of high-frequency transformer of LLC converter is set to 1:5:1 and the reference voltage of HB dc-bus is set to 950V, so the common dc-bus voltage (that is, all LLC converters input voltage) finally can be stabilized at about 1425V. The rated power of the simulation system is about 0.65MW, and other parameters are given in Table 1.

The first simulation has been carried out under the condition that three-phase CDB-CHB PV inverter outputs inductive reactive power (the phase of grid voltage ahead of grid
current). It is set that one module in phase C faults, and the number of normal operation modules in three-phase inverter is $n_A = 4, n_B = 4, n_C = 3$. Before $t = 0.4s$, the zero-sequence voltage $u_0$ calculated by (25) is not compensated, and the grid current $i_gA, i_gB$ and $i_gC$ are balanced, but the active power $P_{C1}$ transmitted by the module in phase C is significantly higher than the active powers $P_{A1}$ and $P_{B1}$ transmitted by the modules in phase A and B, as shown in Fig. 8(a) and Fig. 8(d). After compensating $u_0$ since $t = 0.4s$, the waveforms of three-phase modulation voltage $u_{cA}^*, u_{cB}^*, u_{cC}^*$ and zero sequence voltage $u_0$ are shown in Fig. 8(b). As could be seen, the amplitude of $u_{cA}^*$ and $u_{cB}^*$ increases, while the amplitude of $u_{cC}^*$ decreases. Accordingly, the output voltage of CDB-CHB PV inverter $u_{HAT}, u_{HBT}$ and $u_{HCT}$ will also change, shown in Fig. 8(c). Since the total active power of the system has not changed, the amplitude of $i_gA, i_gB$ and $i_gC$ will not change. However, due to the active power redistribution, $P_{C1}$ decreases from 66.67kW to about 54.56kW, while $P_{A1}$ and $P_{B1}$ increases from 50kW to about 54.55kW and 54.548kW, respectively. Therefore, the proposed control method can make the active powers of the modules in each phase almost the same under the condition of inductive reactive power output and module fault redundancy.

The second simulation operates under the conditions that three-phase CDB-CHB PV inverter outputs capacitive reactive power and the number of normal operation modules in three-phase inverter is $n_A = 3, n_B = 4, n_C = 3$. That is, one module in phase A and phase C fault. Fig. 9(a) shows the waveforms of $u_{gA}$ and $i_gA, i_gB, i_gC$. Fig. 9(b) shows the waveforms of $u_{cA}^*, u_{cB}^*, u_{cC}^*$ and $u_0$. Fig. 9(c) shows the waveforms of $u_{HAT}, u_{HBT}$ and $u_{HTC}$. Fig. 9(d) shows the waveforms of $P_{A1}, P_{B1}$ and $P_{C1}$. Before $t = 0.4s$, the zero-sequence voltage $u_0$ calculated by (25) is not compensated. $i_gA, i_gB$ and $i_gC$ are balanced, but the power relationship of modules in phase A, B, and C is $P_{A1} \approx P_{C1} > P_{B1}$. After $t = 0.4s, u_0$ calculated by (25) is compensated, and the active powers of the first module in phase A, B, and C are: $P_{A1} = 60.006kW, P_{B1} = 59.993kW, P_{C1} = 60.001kW$, respectively. Therefore, the proposed control method can make the active power of the modules in each phase almost the same under the condition of capacitive reactive power output and module fault redundancy.

### V. EXPERIMENTAL RESULTS

A low-voltage and low-power experimental prototype of three-phase CDB-CHB PV grid-connected inverter is made to verify the effectiveness of the proposed control strategy, shown in Fig. 10, where each phase consists of four modules under normal case (four LLC converters and sixteen HBs in total). A Chroma62150H-1000S PV simulator is connected to the common dc bus to power the whole system. All HB dc-bus voltage are controlled to 17V and the turn ratio of LLC transformer is 21:1:1:1:1, so the common dc-bus voltage is about 357V in steady state. In addition, a Chroma61860 grid simulator with the phase voltage output of RMS 110V is used to simulate ac grid. Although the power and voltage levels of the prototype in our laboratory are relatively low, the structure of the whole system is the same as that in Fig. 3 and Fig. 4, and does not affect the validation of the control method. Other principal parameters are given in Table 2.

The first experiment has been done in the case that three-phase CDB-CHB PV inverter outputs inductive reactive power. The waveforms of three-phase modulation voltage $u_{cA}^*, u_{cB}^*, u_{cC}^*$ and zero sequence voltage $u_0$ are shown in Fig. 8(b). As could be seen, the amplitude of $u_{cA}^*$ and $u_{cB}^*$ increases, while the amplitude of $u_{cC}^*$ decreases. Accordingly, the output voltage of CDB-CHB PV inverter $u_{HAT}, u_{HBT}$ and $u_{HCT}$ will also change, shown in Fig. 8(c). Since the total active power of the system has not changed, the amplitude of $i_gA, i_gB$ and $i_gC$ will not change. However, due to the active power redistribution, $P_{C1}$ decreases from 66.67kW to about 54.56kW, while $P_{A1}$ and $P_{B1}$ increases from 50kW to about 54.55kW and 54.548kW, respectively. Therefore, the proposed control method can make the active powers of the modules in each phase almost the same under the condition of inductive reactive power output and module fault redundancy.

### TABLE 1. Simulation parameters.

| Symbol | Parameter | Value |
|--------|-----------|-------|
| $U_g$ | Grid phase voltage amplitude | 2500V |
| $L_s$ | Grid side filter inductance | 2mH |
| $f_s$ | HB switching frequency | 2000Hz |
| $C_M$ | HB dc-bus capacitance | 10mF |
| $L_{res}$ | Resonant inductance of LLC converter | 15μH |
| $C_{res}$ | Resonant capacitance of LLC converter | 675μF |
| $L_{m}$ | Magnetizing inductance of LLC converter | 100μH |
| $C_{sw}$ | LLC switching equivalent capacitor | 10μF |
| $f_{LCC}$ | Rated switching frequency of LLC | 50000Hz |

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FIGURE 8. Simulation results when one module in phase C faults and inverter outputs inductive reactive power. (a) Grid voltage and grid currents. (b) Modulation voltages and zero-sequence voltage. (c) Output phase voltages of CHB inverter. (d) Module active powers in phases A, B, and C. 

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TABLE 2. Experimental parameters.

| Symbol | Parameter                         | Value          |
|--------|-----------------------------------|----------------|
| $U_{ph}$ | Grid phase voltage/amplitude/frequency | 155.56V/50Hz  |
| $L_f$  | Grid side filter inductance       | 2mH           |
| $f_u$  | HB switching frequency            | 500Hz         |
| $C_{st}$ | HB de-bus capacitance            | 4700μF×4      |
| $V_{nr}$ | HB de-bus reference voltage     | 17V           |
| $L_{st}$ | Resonant inductance               | 180μH         |
| $C_{st}$ | Resonant capacitance             | 56nF          |
| $L_{mst}$ | Magnetizing inductance          | 2mH           |
| $N_T$  | Turn ratio of LLC transformer     | 21            |
| $T_c$  | LLC converter dead-time          | 1μs           |
| $f_{LLC}$ | Rated switching frequency of LLC | 50000Hz       |

power and one module in phase C faults ($n_A = 4$, $n_B = 4$, $n_C = 3$). Three-phase grid currents, $i_{gA}$, $i_{gB}$, and $i_{gC}$, are shown in Fig. 11(a), where the line voltage of phase A and B, $u_{AB}$, with 1.6667ms delay is used to indicate the phase angle of $u_{gA}$. As could be seen, the phase of $u_{gA}$ is ahead of $i_{gA}$, so the inverter outputs inductive reactive power. At the beginning of system operation, zero-sequence voltage is not compensated. At a certain time, the zero-sequence voltage calculated by (25) is injected. From Fig. 11(a), before and after compensating $u_0$, the grid currents hardly change, since the total power of the system has not changed. However, due to the compensation of $u_0$, the amplitudes of $u_{HAT}$ and $u_{HBT}$ will increase, while the amplitude of $u_{HCT}$ will decreases, shown in Fig. 11(b), which can redistribute the active power among three phases. Active powers of three phases, $P_A$, $P_B$, $P_C$, and module active powers $P_{A1}$, $P_{B1}$, $P_{C1}$ are measured by a YOKOGAWA WT3000E power analyzer, and the results are presented in Fig. 11(c) and Fig. 11(d). After the compensation of $u_0$, the active powers of three phases are $P_A = 1625.04W$, $P_B = 1622.26W$, $P_C = 1220.75W$ ($P_A \approx P_B > P_C$), respectively, and the powers of single module in three phases are $P_{A1} = 406.89W$, $P_{B1} = 404.19W$, $P_{C1} = 407.44W$ ($P_{A1} \approx P_{B1} \approx P_{C1}$), respectively. That is to say, after compensating $u_0$, the total active powers of phase A and B are higher because of the larger number of modules, and that of phase C is lower due to less number of modules, thus ensuring that all modules transmit almost the same active power. In addition, the THD of grid currents are all less than 1.8% in two measurements.

For comparison, the second experiment is carried out under the same conditions as that in first experiment, and the control strategy in [10] is used. The test results of three phases active powers $P_A$, $P_B$, $P_C$ and module active powers $P_{A1}$, $P_{B1}$, $P_{C1}$ are demonstrated in Fig. 12(a) and Fig. 12(b). The total powers of three phases are $P_A = 1490.74W$, $P_B = 1494.41W$, $P_C = 1494.51W$ ($P_A \approx P_B \approx P_C$), respectively, and the powers of single module in three phases are $P_{A1} = 372.13W$, $P_{B1} = 372.18W$, $P_{C1} = 501.32W$ ($P_{A1} \approx P_{B1} < P_{C1}$), respectively.
respectively. As could be seen, when outputting inductive reactive power and module fault redundancy, the method in [10] cannot equalize the active power of all modules.

The feasibility of the proposed method is validated by the third experiment under the conditions that three-phase CDB-CHB PV inverter outputs capacitive power and one module in phase A and C fault ($n_A = 3$, $n_B = 4$, $n_C = 3$). At some point, $u_0$ calculated by (25) is superimposed on the three-phase modulation voltages. From Fig. 13(a), before and after compensating $u_0$, the grid currents hardly change, since the total power of the system has not changed. However, due to the compensation of $u_0$, the amplitude of $u_{HBT}$ will increases, while the amplitudes of $u_{HAT}$ and $u_{HCT}$ will decrease, shown in Fig. 13(b). The test results of active powers in three phases, $P_A$, $P_B$, $P_C$, and module active powers $P_{A1}$, $P_{B1}$, $P_{C1}$ are demonstrated in Fig. 13(c) and Fig. 13(d). The total powers of three phases are $P_A = 1353.56W$, $P_B = 1789.77W$, $P_C = 1344.48W$ ($P_A \approx P_C < P_B$), respectively, and the powers of single module in three phases are $P_{A1} = 448.82W$, $P_{B1} = 448.40W$, $P_{C1} = 448.13W$ ($P_{A1} \approx P_{B1} \approx P_{C1}$), respectively. That is to say, after compensating $u_0$, the total active powers of phase A and B are higher because of the larger number of modules, and that of phase C is lower due to less number of modules, thus ensuring that all modules
transmit almost the same active power. In addition, the THD of grid currents are all less than 2.1% in two measurements.

For comparison, the fourth experiment is carried out under the same conditions as that in third experiment, and the method in [10] is adopted. The test results of active powers in three phases, \( P_A, P_B, P_C \) and module active powers, \( P_{A1}, P_{B1}, P_{C1} \) are demonstrated in Fig. 14(a) and Fig. 14(b). The total powers of three phases are \( P_A = 1409.74 \text{W}, P_B = 1489.41 \text{W}, P_C = 1494.51 \text{W} \approx P_A \approx P_C \), respectively, and the powers of single module in three phases are \( P_{A1} = 501.06 \text{W}, P_{B1} = 370.34 \text{W}, P_{C1} = 501.80 \text{W} \approx P_{C1} > P_{B1} \), respectively. As could be seen, when outputting capacitive reactive power and module fault redundancy, the method in [10] cannot balance the active power of all modules.

VI. CONCLUSION

In this paper, a power equalization control strategy for three-phase CDB-CHB PV grid-connected inverter based on one-input-four-outputs LLC converter is mainly studied. Firstly, the relationship between the number of redundant modules and the reliability of the whole system is analyzed. The results show that system reliability can be greatly improved with the redundancy design, and the more redundant modules, the higher the reliability. Considering the cost and reliability, the number of redundant modules should be set to 1~3. In addition, aiming at the problem of module active power unequalization caused by fault redundancy condition, a zero-sequence voltage compensation strategy is proposed based on the actual number of modules in three phases and the power factor of the inverter, which can ensure that all modules in three-phase inverter are capable of transmitting the same active power no matter whether the number of modules in three phases are same or not, and whether the inverter operates at unit power factor or not.

REFERENCES

[1] X. Zhang, T. Zhao, W. Mao, D. Tan, and L. Chang, “Multilevel inverters for grid-connected photovoltaic applications: Examining emerging trends,” IEEE Power Electron. Mag., vol. 5, no. 4, pp. 32–41, Dec. 2018.

[2] X. Zhang, M. Wang, T. Zhao, W. Mao, Y. Hu, and R. Cao, “Topological comparison and analysis of medium-voltage and high-power direct-linked PV inverter,” CES Trans. Electr. Mach. Syst., vol. 3, no. 4, pp. 327–334, Dec. 2019.

[3] Y. Yu, G. Konstantinou, B. Hredzak, and V. G. Agelidis, “On extending the energy balancing limit of multilevel cascaded H-bridge converters for large-scale photovoltaic farms,” in Proc. Australas. Universities Power Eng. Conf. (AUPEC), Hobart, TAS, Australia, vol. 3, Sep. 2013, pp. 1–6.

[4] T. Zhao, X. Zhang, M. Wang, W. Mao, M. Ma, F. Wang, and X. Wang, “Analysis and suppression of resonant current envelope ripple of LLC converter in cascaded modular PV solid state transformer,” IEEE J. Emerg. Sel. Topics Power Electron., early access, Apr. 2020, doi: 10.1109/JESTPE.2020.2988989.

[5] S. Rivera, S. Kouro, B. Wu, J. I. Leon, J. Rodriguez, and L. G. Franquelo, “Cascaded H-bridge multilevel converter multistring topology for large scale photovoltaic systems,” in Proc. IEEE Int. Symp. Ind. Electron., Gdansk, Poland, Jun. 2011, pp. 1837–1844.

[6] S. Rivera, B. Wu, S. Kouro, H. Wang, and D. Zhang, “Cascaded H-bridge multilevel converter topology and three-phase balance control for large scale photovoltaic systems,” in Proc. 3rd IEEE Int. Symp. Power Electron. Distrib. Syst. (PEDES), Aalborg, Denmark, Jul. 2012, pp. 690–697.

[7] Y. Yu, G. Konstantinou, C. D. Townsend, R. P. Aguiler, and V. G. Agelidis, “Delta-connected cascaded H-bridge multilevel converters for large-scale photovoltaic grid integration,” IEEE Trans. Ind. Electron., vol. 64, no. 11, pp. 8877–8886, Nov. 2017.

[8] S. Essakiapan, H. S. Krishnamoorthy, P. Enjeti, R. S. Balog, and S. Ahmed, “Multilevel medium-frequency link inverter for utility scale photovoltaic integration,” IEEE Trans. Power Electron., vol. 30, no. 7, pp. 3674–3684, Jul. 2015.

[9] Y. Yu, G. Konstantinou, B. Hredzak, and V. G. Agelidis, “Optimal zero sequence injection in multilevel cascaded H-bridge converter under unbalanced photovoltaic power generation,” in Proc. Int. Power Electron. Conf. (IPEC-Hiroshima-ECCE ASIA), Hiroshima, Japan, May 2014, pp. 1458–1465.

[10] X. Ma, X. Yang, F. Zhang, L. Huang, Z. Li, and H. Song, “A control scheme of three phase solid state transformer for PV generation based on improved voltage-tracking method of DC links,” in Proc. IEEE Appl. Power Electron. Conf. Expo. (APEC), Tampa, FL, USA, Mar. 2017, pp. 474–479.

[11] J. Shi, W. Gou, H. Yuan, T. Zhao, and A. Q. Huang, “Research on voltage and power balance control for cascaded modular solid-state transformer,” IEEE Trans. Power Electron., vol. 26, no. 4, pp. 1154–1166, Apr. 2011.

[12] F. Zhang, X. Ma, L. Huang, F. Xu, Y. Xuan, X. Yang, X. Hao, and Z. Li, “Design and demonstration of a SiC-based 800-V/10-kV 1-MW solid-state transformer for grid-connected photovoltaic systems,” in Proc. IEEE 3rd Int. Future Energy Electron. Conf. ECCE Asia (IFEEC-ECCE Asia), Kaohsiung, Taiwan, Jun. 2017, pp. 1987–1990.

[13] Y. Yu, G. Konstantinou, C. D. Townsend, and V. G. Agelidis, “Comparison of zero-sequence injection methods in cascaded H-bridge multilevel converters for large-scale photovoltaic integration,” IET Renew. Power Gener., vol. 11, no. 5, pp. 603–613, Apr. 2017.

[14] B. Mirafzal, “Survey of fault-tolerance techniques for three-phase voltage source inverters,” IEEE Trans. Ind. Electron., vol. 61, no. 10, pp. 5192–5202, Oct. 2014.

[15] L. Maharjan, T. Yamagishi, H. Akagi, and J. Asakura, “Fault-tolerant operation of a battery-energy-storage system based on a multilevel cascade PWM converter with star configuration,” IEEE Trans. Power Electron., vol. 30, no. 9, pp. 5223–5235, Sep. 2015.

[16] M. Alleenjad, S. Farhangi, and H. Iman-Eini, “Modified space vector modulation for fault-tolerant operation of multilevel cascaded H-bridge inverters,” IET Power Electron., vol. 6, no. 4, pp. 742–751, Apr. 2013.

[17] H. Salimian and H. Iman-Eini, “Fault-tolerant operation of three-phase cascaded H-Bridge converters using an auxiliary module,” IEEE Trans. Ind. Electron., vol. 64, no. 2, pp. 1018–1027, Feb. 2017.

[18] L. Wang, D. Zhang, Y. Wang, B. Wu, and H. S. Azad, “Power and voltage balance control of a novel three-phase solid-state transformer using multilevel cascaded H-Bridge inverters for microgrid applications,” IEEE Trans. Power Electron., vol. 31, no. 4, pp. 3289–3301, Apr. 2016.

[19] W. Song and A. Q. Huang, “Fault-tolerant design and control strategy for cascaded H-bridge multilevel converter-based STATCOM,” IEEE Trans. Ind. Electron., vol. 57, no. 8, pp. 2700–2708, Aug. 2010.

[20] Y. Gu, Z. Lu, L. Hang, Z. Qian, and G. Huang, “Three-level LLC series resonant DC/DC converter,” IEEE Trans. Power Electron., vol. 20, no. 4, pp. 781–789, Jul. 2005.

[21] J.-M. Kwon, B.-H. Kwon, and K.-H. Nam, “Three-phase photovoltaic system with three-level boosting MPPT control,” IEEE Trans. Power Electron., vol. 23, no. 5, pp. 2319–2327, Sep. 2008.

[22] H.-C. Chen and W.-J. Lin, “MPPT and voltage balancing control with sensing only inductor current for photovoltaic-fed, three-level, boost-type converter,” IEEE Trans. Power Electron., vol. 29, no. 1, pp. 29–35, Jan. 2014.
[23] P. Rodriguez, J. Pou, J. Bergas, J. I. Candela, R. P. Burgos, and D. Boroyevich, “Decoupled double synchronous reference frame PLL for power converters control,” IEEE Trans. Power Electron., vol. 22, no. 2, pp. 584–592, Mar. 2007.

[24] A. Tsunoda, Y. Hinago, and H. Koizumi, “Level- and phase-shifted PWM for seven-level switched-capacitor inverter using series/parallel conversion,” IEEE Trans. Ind. Electron., vol. 61, no. 8, pp. 4011–4021, Aug. 2014.

[25] W. Chen, Y. Gu, and Z. Lu, “A novel three level full bridge resonant DC-DC converter suitable for high power wide range input applications,” in Proc. APEC 22nd Annu. IEEE Appl. Power Electron. Conf. Expo., Anaheim, CA, USA, vol. 1, Feb. 2007, pp. 373–379.

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