Topological Comparison and Analysis of Medium-voltage and High-power Direct-linked PV Inverter

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***Abstract*—Among all the renewable energy sources, the installed capacity of solar power generation is the fastest growing in recent years, so photovoltaic (PV) power generation still has great market potential. Compared with low-power systems, large-scale PV systems are more commercially attractive, because they can reduce the cost of the system per watt. The PV inverters with centralized and string structure have been applied in large-scale PV plant, but it is difficult to further increase the voltage and power levels for a single converter. In addition, the line-frequency isolation transformer requires a large amount of materials and has a large volume and weight. Therefore, it is a current trend for large-scale PV system to increase the voltage and power levels to directly connect to the medium-voltage power grid. Based on this, this paper investigates and compares several topologies of PV inverters without line-frequency transformer, including the MMC structure and the three-phase cascaded H-bridge (CHB) structure, which are able to directly connect to the 35kV medium-voltage power grid, and can not only make the voltage and power levels higher, but also further reduce the cost and volume of the whole system.**

***Index Terms*—Direct-linked PV inverter, large-scale PV system, MMC structure, three-phase CHB structure.**

I. INTRODUCTION

In recent years, renewable energy resources have become an increasingly important part of electricity generation. Aside from contributing to reducing greenhouse gas emissions, they also increase the flexibility in energy source mix by lowering the dependence on fossil fuels [1]-[4]. According to the Global Status Report of Renewable Energy in 2019, the share of renewables in annual additions of power generation capacity is on the rise, which has surpassed non-renewable energy since 2012, shown in Fig. 1 [5]. Among different types of renewable energy sources, solar energy has become the fastest growing in terms of installed capacity. As could be seen from Fig. 2, in 2018, the new installed capacity of PV power generation reached about 100GW, accounting for 55.25% of the new installed capacity of renewable energy, which is greater than the sum of the new installed capacity of other renewable energy sources [5]. In addition, considering the simple installation, easy maintenance and cost reduction year by year, PV grid-connected power generation still has great market potential [6]-[7].

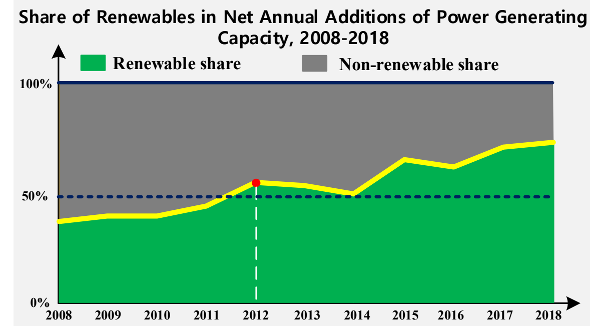

Fig. 1. Share of renewables in net annual additions of power generating capacity, 2008-2018.

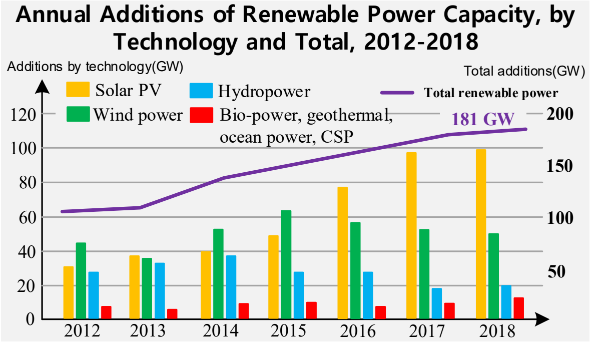

Fig. 2. Annual additions of renewable power capacity, 2012-1018.

PV grid-connected power generation mainly includes household PV power generation system (PVPGS), buildings distributed PVPGS, and large-scale PVPGS on the ground or water. For adapting to different application scenarios, the topologies of inverters are enriched continuously. Nowadays, inverters are mainly classified into the following categories: micro-inverters and the structure of power optimizers, string inverters, and centralized inverters.

Micro-inverters and power optimizers are mostly used for household PV power generation. These inverters have the advantages of panel-level monitoring, panel-level MPPT, which is conducive to the intellectual development of inverters. Other topologies with similar functions also include

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single-phase CHB PV inverters and sinusoidal cascaded PV inverters, which are developing rapidly [8]-[10]. For centralized structures, a large number of PV modules are connected to a centralized inverter through several DC combiner boxes, which has the advantages of high-power level, high efficiency, high system reliability, and maintenance cost. The development orientation of centralized inverters is the higher power, voltage, and integration. According to the data released by each manufacturer, SUNGROW released SG3400HV centralized inverter at Intersolar Europe 2018, using 1500 Vdc system and three-level technology, which achieved a maximum output power up to 3.593 MVA for a single inverter. In order to meet the high-power demand of large-scale utility plants, majofig.r inverter manufacturers have also launched integrated power plant products based on centralized structure. ABB's PVS980-CS turnkey solution uses two 1500V centralized inverters in parallel, realizing the maximum output power of 4.6 MVA; TBEA and SMA have also introduced 1500V centralized integrated power plant products with maximum output power of 5.5 MVA and 3 MVA; SUNGROW's 6.8 MVA Turnkey Station power plant solution achieves the maximum output power at present. It uses two SG3400HV centralized inverters in parallel and achieves the highest output power of 6.8 MVA. For string structures, multiple PV modules are series connected to form a PV string, each PV string connects to a string inverter. It can realize multi-channel MPPT and has a wide MPPT voltage range. String inverters are currently developing in the direction of the higher power, higher voltage, and more intelligent. At present, the high-power-level string inverter is implemented in the 1500V power system. The latest Huawei's PV string inverter SUN2000-185KTL has a maximum DC input voltage of 1500V and a maximum output power of 185kVA, it could realize 9 independent MPPT channels. The TBEA's PV string inverter TS208KTL has a higher maximum output power of 208kVA, and it can realize 12 independent MPPT channels. SUNGROW's SG250HX PV string inverter has the maximum output power of 250kVA, which is the maximum output power of all the PV string inverters at present, and it can realize 12 independent MPPT channels.

Based on the IHS Markit latest data, Fig. 3 presents the global PV inverter shipments by system type, it shows that the utility-scale installations (>5 MW) will be the largest system type for PV inverter shipments in 2023. Compared with low-power systems, large-scale PV systems are more commercially attractive, because they can reduce the cost of the system per watt, which is more helpful for the PV generation to connect to the grid at an equal price [8],[11],[12]. The PV inverters with centralized and string structure introduced above have been applied in large-scale PV plant. However, it is difficult to further increase the power level of a single inverter due to the limitation of switching devices. In addition, due to the low voltage level on the AC-side of the inverter, it must be boosted by the line-frequency isolation transformer before it can be connected to the 35kV medium-voltage power grid, which requires a large amount of materials such as copper and iron, and has a large volume and weight. Therefore, it is a current trend for large-scale PV system to increase the voltage and power levels to directly connect to the medium-voltage power grid. This paper investigates and compares several topologies of PV inverters without line-frequency transformer, including the MMC structure and the three-phase CHB structure, which are able to directly connect to the 35kV medium-voltage power grid, and can not only make the voltage and power levels higher, but also further reduce the cost and volume of the whole system.

The rest of this paper is organized as follows: the current technical status, topologies, advantages, and disadvantages of inverters based on the MMC structure is presented in Section II. The current technical status, topologies, advantages, and disadvantages of inverters based on the three-phase CHB structure is covered in section III. The last part is the conclusions in Section IV.

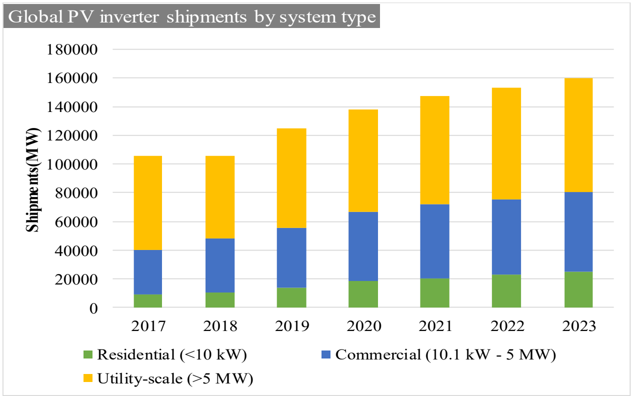

Fig. 3. Global PV inverter shipments by system type.

II. PV INVERTERS BASED ON MMC STRUCTURE

PV inverters based on MMC structure can be divided into two types of topology: non-isolated and isolated. For the non-isolated topology, the PV output is directly connected to the input of the inverter, while for the isolated topology, the PV output connected to the input of the inverter through an isolated DC/DC converter.

(1) The non-isolated MMC-based PV inverter topology 1 as shown in Fig. 4 was proposed in [13]-[14], and the non-isolated MMC-based PV inverter topology 2 as shown in Fig. 5 was proposed in [15]-[16]. In topology 1, the PV sub-module (PM) of MMC is connected in parallel with the PV module through the dc-side capacitor. The upper and lower bridge arms of each phase contain one redundant sub-module (SM) respectively, and the capacitor on the dc-side is not connected to the PV module. By controlling the capacitor voltage of PM, MPPT of PV module is realized, and SM is controlled to adjust the bridge arm voltage to ensure the stable operation of the system. The topology adopts a modular structure, with multi-level output from ac-side, it can realize grid connection with higher voltage, and the filter on the grid side is small. The main problem is that the redundant control of SM is coupled with the MPPT control of PM, which makes the system control more complex and less stable. Because the output power of each PM could be different, there is inter-bridge and inter-phase power imbalance. Since the three-phase bridge arm is connected in parallel in the dc-side,

and the instantaneous energy of MMC is stored in the suspended independent dc capacitor, the imbalance of energy distribution between each phase will lead to the circulating current in the inverter, increasing the system loss [17]-[18]. In topology 2, The PV modules are directly connected to the sub-module of MMC, and they are connected in series to form the dc-link for each phase. The dc-link voltage is unipolar and multilevel in nature, which is converted to AC voltage by a low-frequency converter (LFC). In this topology, the three-phase bridge arms are independent of each other, so there is no circulating current, and the output voltage level is more compared with topology 1 when the modules are the same. However, the LFC converters in each phase increase the hardware cost and volume, and the switching modulation is more complex, and the power balance problem still exists. Additionally, the low-frequency converter in Fig.5 has to withstand the phase voltage of the inverter, so it needs the high voltage switches when applied in the large-scale PV plant. But there are no practical solutions to handle this problem so far, making this topology not suitable in the high-voltage PV plant. The above two topologies do not require DC/DC converters, and the system has low cost, small size, and high efficiency, but it is easy to inject DC components into the grid, and there is a common mode leakage current problem. When applied to large-scale PV power stations, it is likely to cause over-voltage breakdown of PV modules, so it has a low system safety performance.

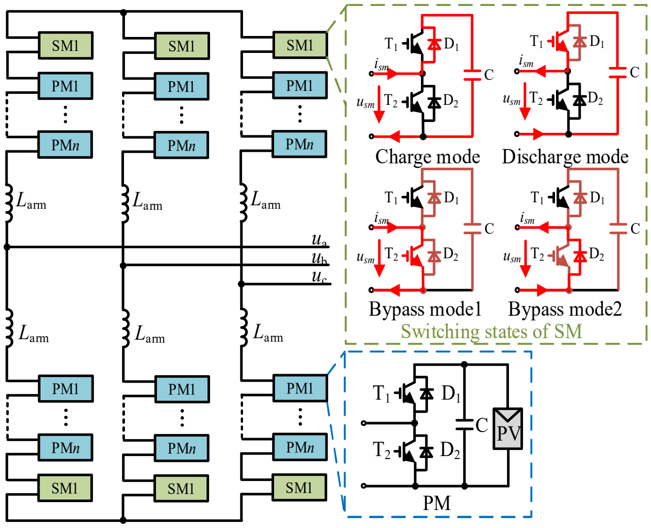

Fig. 4. Non-isolated MMC-based PV inverter topology 1.

(2) The isolated MMC-based PV inverter topology 1 as shown in Fig. 6 was proposed in [19]-[22], and the isolated MMC-based PV inverter topology 2 as shown in Fig. 7 was proposed in [23]-[25].In topology 1, each PV module is connected in series to form a PV string, which is connected to the total dc-side of MMC through a DC/DC converter, and the capacitor of each submodule of MMC is suspended on the dc-side. In topology 2, each PV module is connected to each sub-module of MMC through a DC/DC converter. In the above two topologies, the power level of the inverter can be expanded by increasing the number of sub-modules of each phase, and the DC/DC converter has the isolation function, making it suitable

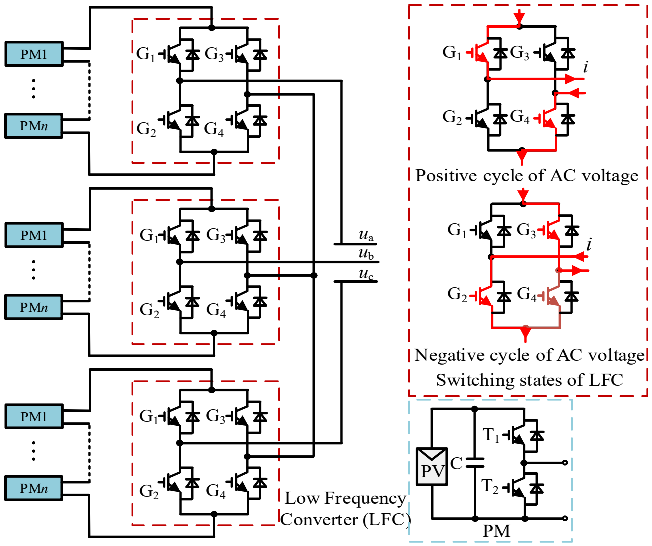

Fig. 5. Non-isolated MMC-based PV inverter topology 2.

for large-scale PV plants. In topology 1, the PV strings are connected to the common dc-bus, and there is no power imbalance, but it cannot realize the independent MPPT of each PV module, resulting in the low PV efficiency. It needs a lot of PV panels series-connected when applied in the large-scale PV plant, which is a shortcoming of this topology. The isolation problem of the high voltage DC/DC converter in Fig. 6 is also a big challenge when applied in large-scale PV plants. In topology 2, PV modules connected to each MMC sub-module can be independently controlled by MPPT through DC/DC converter, which has high PV efficiency. However, each sub-module is equipped with DC/DC converter. When applied to large-scale PV plants, the number of DC/DC converters is huge, and the hardware cost and volume are large. In addition, there is power imbalance problem existed. Because the two topologies are three-phase common dc-bus structure, there are circulating currents in the inverter.

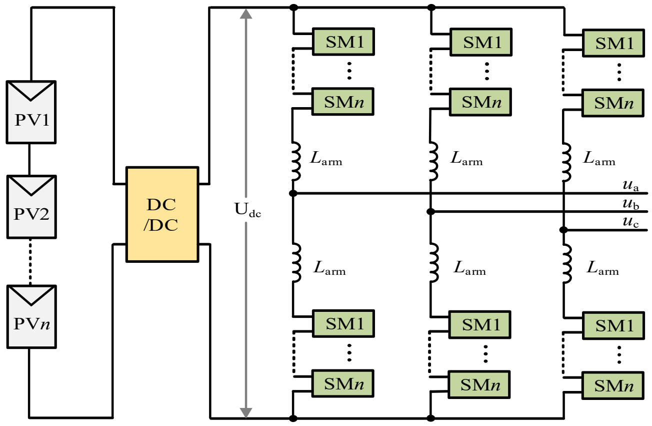

Fig. 6. Isolated MMC-based PV inverter topology 1.

To sum up, in the non-isolated MMC-based PV inverter, there is no need for DC/DC converter. The system has low cost, small size, and high efficiency, but it is likely to inject DC components into the grid, and there is a common mode leakage current problem. When applied to large-scale PV plants, it is likely to cause over-voltage breakdown of PV modules and low

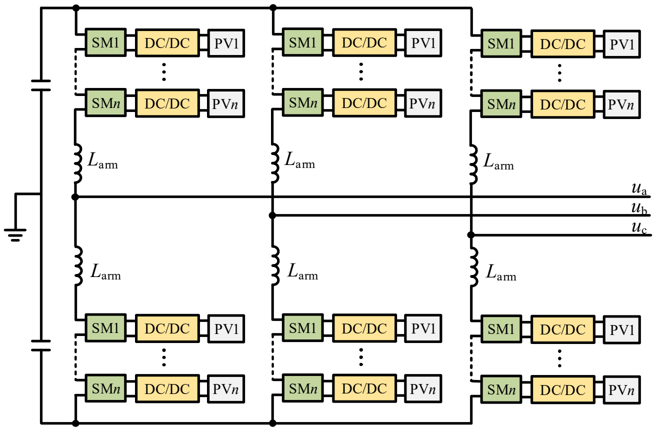

Fig. 7. Isolated MMC-based PV inverter topology 2.

system safety performance. In the isolated MMC-based PV inverter, the power level of the inverter can be expanded by increasing the number of sub-modules of each phase, and the DC/DC converter has the isolation function, making it suitable for large-scale PV plants.

III. THREE-PHASE CHB PV GRID-CONNECTED INVERTERS

A. Independent DC-bus Structure

There are two types of three-phase CHB inverters based on the independent DC-bus structure. One is the three-phase non-isolated CHB inverters [26]-[28], whose topology is shown in Fig. 8, and the other is the three-phase isolated CHB inverters [29]-[32]. Considering that the voltage withstands of commercial PV panels does not exceed 1500V, three-phase non-isolated CHB inverters are not suitable for medium-voltage and high-power applications [12]. Fig. 9 shows the schematic diagram of three-phase isolated CHB PV inverters, where each phase of the converter has N same modules, and each module includes PV arrays, an isolated DC/DC converter, and an H-bridge (HB) converter. The modular structure allows the easy extension to reach higher voltage and power levels with low voltage switching devices (1200V) available in the market [29]-[32]. The converter is capable of directly connecting to the medium voltage grid without bulky and heavy line-frequency transformer since high-frequency transformers have provided galvanic isolation in isolated DC/DC converters, which also frees the system from leakage current problem. Besides, the input port of isolated DC/DC converter is powered by PV arrays independently, so that it can implement multiple MPPT control. However, there are still some problems in the application of this topology in commercialization.

Since the power generated by each PV array may be unequal because of non-uniform solar irradiance, unequal ambient temperature, and even partial shading, the active power of all modules cannot be precisely the same, leading to power imbalance problem. The power imbalance can be divided into two categories: inter-module power imbalance and inter-phase imbalance [29]-[32]. The inter-module power imbalance will lead to over-modulation of HBs with larger power, which will result in a distorted grid current [33]-[41]. The inter-phase power imbalance will result in the unbalanced three-phase grid currents, unable to meet the grid-connected code [31].

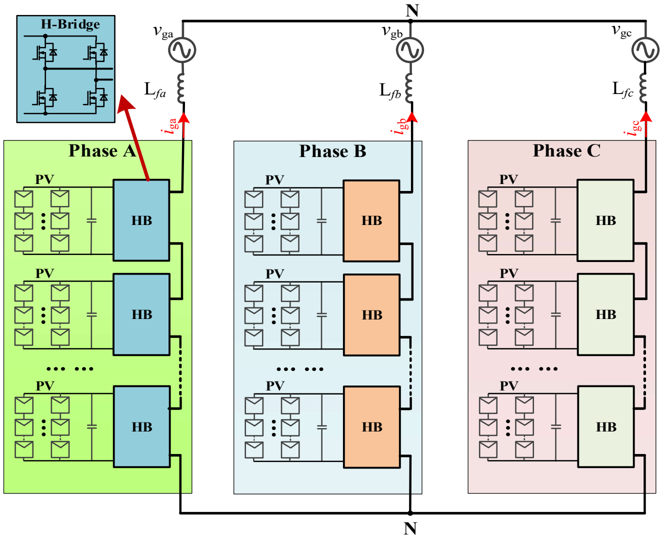

Fig. 8. Three-phase non-isolated CHB PV grid-connected inverter topology.

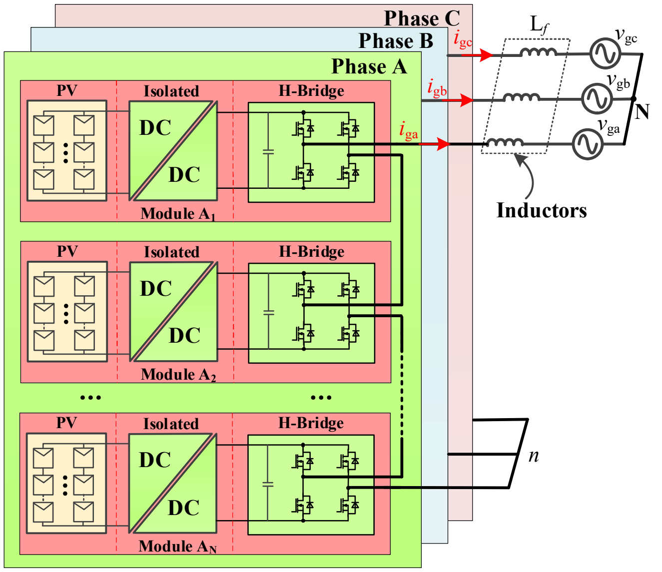

Fig. 9. Three-phase isolated CHB PV grid-connected inverter topology.

(1) Several control methods have been proposed to deal with the inter-module power imbalance. A reactive power compensation strategy is described in [33]–[35], which can deal with serious power imbalance. However, the lower power factor may limit its application. A hybrid modulation strategy is presented in [36]-[38]. It can extend the linear modulation range to about 4/π, but it will aggravate the voltage fluctuation on the dc-bus. A third harmonic compensation strategy (THCS) is presented in [39], [40]. This method can overcome the shortcomings of the above methods, but it can only extend the modulation of HB to 1.155. A harmonic compensation control strategy (HCS) is proposed in [41], which retains all the advantages of THCS and can further extend the modulation degree of HBs to 4/π. The overall performance of this method is optimal. However, when the active powers among HBs are further unbalanced, HCS will also fail. Therefore, the only method to balance modules power is to make some PV arrays exit the maximum power point, but this will result in low

energy harvesting.

(2) For star-connected converters, the inter-phase power imbalance problem can be solved by injecting zero-sequence voltage. A fundamental frequency zero-sequence injection method was derived through instantaneous power theory [42] and phasor diagrams [43], respectively. A weighted min–max zero-sequence injection method was proposed in [44]. Furthermore, three methods, namely, double 1/6 third harmonic injection, reduced third harmonic injection, and double min–max zero-sequence injection, were also proposed in [31]. In addition, the optimal zero-sequence injection (OZSI) and simplified OZSI, were presented in [32]. Among all the control methods, OZSI has the strongest capacity to cope with inter-phase power imbalance. However, when the inter-phase is further unbalanced, even OZSI cannot balance the three-phase grid currents. The inter-phase powers can only be balanced by reducing the power of the phase with higher power. Similarly, this will reduce the power generation of the system.

(3) According to the above analysis, the power transmitted among HBs may be different. Therefore, when the carrier phase shift SPWM (CPS-SPWM) modulation strategy is adopted, the ideal multi-level step wave cannot be synthesized even if the DC voltage of all HBs is the same. That is, the multi-level step wave will contain harmonics whose frequency is twice the switching frequency of HB. For making the THD of the grid current meet requirement, the switching frequency of a single HB cannot be too low, which will increase the switching loss of HB and reduce the system efficiency. Besides, although the input voltage of isolated DC/DC converter can be controlled separately to ensure all PV arrays work at their maximum power points, this will lead to a wider voltage range of DC/DC converter, which is not beneficial to the efficiency of isolated DC/DC converter, and thus lowering the efficiency of the whole system.

In summary, the three-phase isolated CHB PV inverter can be connected directly to a 35kV medium voltage grid without the line-frequency transformer by reasonably configuring the number of modules, and the voltage and power levels can also be higher. Meanwhile, this topology can achieve multiple MPPT control, which is conducive to obtaining more energy. However, inter-module and inter-phase power imbalance is an inherent problem of the topology, which is difficult to be entirely solved by control strategy alone. Also, the higher switching frequency of HBs and the wider voltage range of isolated DC/DC converters will reduce the efficiency of the topology.

B. Common DC-bus Structure

From the above analysis, three-phase CHB inverters based on independent DC-bus structure will inevitably suffer from inter-module power imbalance and inter-phase power imbalance. The proposed methods can only alleviate rather than solve these problems. Therefore, the three-phase CHB inverter topology based on the common DC-bus structure is proposed to make up for the shortcomings of the inverters based on independent DC-bus structure.

Fig. 10 shows the topology 1 of the three-phase CHB inverter based on the common DC-bus structure. Compared with the structure in Fig. 9, this topology parallels the input side of the isolated DC/DC converter of each phase to form a common DC-bus. Therefore, the three-phase structure consists of three DC-buses, and each DC-bus is connected to the corresponding PV array. This structure completely solves the inter-phase power imbalance problem, and the isolated DC/DC converter in the topology also solves the problem of leakage current, but this topology still has the inter-phase power imbalance problem. Besides, since each phase is connected to the corresponding PV array with the common DC-bus, each phase can only achieve independent MPPT control. For three-phase inverters, this structure can only achieve three channels MPPT control.

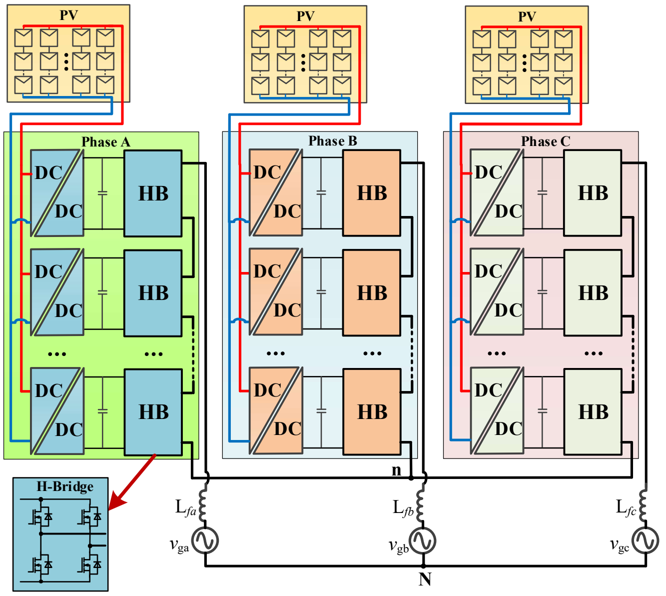

Fig. 10. Common DC-bus topology 1.

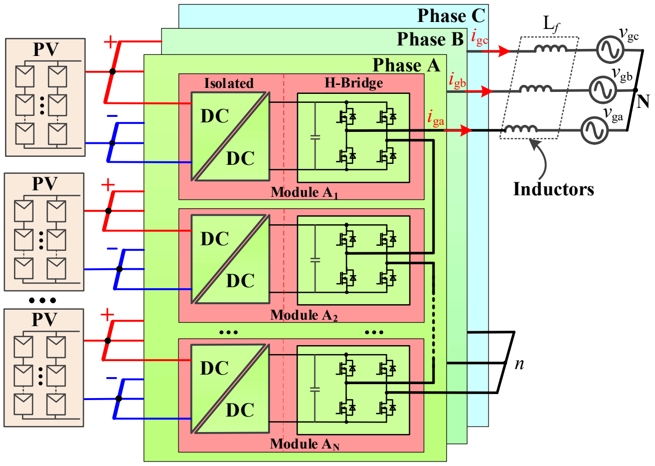

Fig. 11. Common DC-bus topology 2.

Fig. 11 shows the second topology of the three-phase CHB inverters based on common DC-bus structure. Compared with topology 1, topology 2 parallels the input side of the nth isolated DC/DC converter in each phase of the three-phase converter and connects it to the corresponding PV array. Therefore, the input power of each phase in this topology can be kept consistent, which avoids the problem of the inter-phase power imbalance problem. Also, topology 2 can effectively expand the number of MPPT channels, which can achieve N-channels MPPT control (N is the number of HBs in each phase), and there is also no leakage current problem. However, this structure cannot solve the inter-module power imbalance problem.

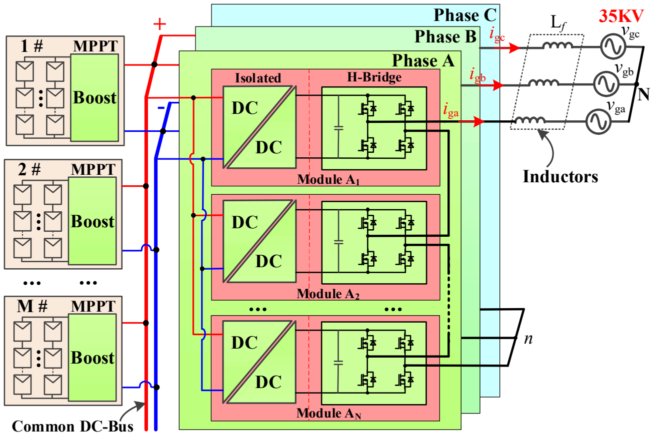

Fig. 12. Common DC-bus topology 3.

To overcome the shortcomings of the above two topologies, the third topology of three-phase CHB inverter topology based on common DC-bus is given, as shown in Fig. 12. In topology 3, the input sides of all isolated DC/DC converters are connected in parallel to form a common DC-bus. For achieving multi-MPPT control, the common DC-bus needs to connect multiple Boost converters, and each Boost converter has a PV array in parallel at its input. This topology has all the advantages of three-phase isolated CHB PV inverters. That is, it can realize high voltage and high-power conversion, can be connected to the medium-voltage power grid without power-frequency transformer, and also avoids the leakage current problem [45],[46]. Besides, this topology also overcomes the shortcomings of the above two topologies as follows:

(1) In topology 3, the input terminals of all isolated DC/DC converters are connected in parallel to form a common DC-bus. Similar with traditional three-phase inverters, the inter-phase power will be automatically balanced. Therefore, there is no inter-phase power imbalance problem in this topology. Also, after using the control strategy proposed in [45], the power of all HBs in the each phase can be equally distributed, so that the active power of all HBs can be the same. Therefore, there is also no inter-module power imbalance problem.

(2) Using the control strategy proposed in [45], the DC-bus voltage of all three-phase HBs can be controlled to the same value. Besides, the active power transmitted by all three-phase HBs is the same. Therefore, when CPS-SPWM is adopted, the output voltage of the HB AC side can synthesize an ideal step wave [46]-[48]. So, the switching frequency of HB can be set to a lower value, and a higher equivalent switching frequency can be obtained. For example, each phase in a three-phase system contains N HBs (in order to achieve a higher output voltage, N is generally larger). If the switching frequency of each HB is 500Hz, the equivalent switching frequency of the output voltage of HB on the AC side is (1000*N) Hz.

(3) MPPT control is completed by the Boost converter in the former stage of this topology, so the common DC-bus voltage can also be controlled to a fixed value. Also, the output voltage of the isolated DC/DC converter (HB DC-bus voltage) can also be controlled to a fixed value. Therefore, the gain of the isolated DC/DC converter is relatively fixed. Compared with the topology shown in Fig.9, efficiency can also be relatively high.

However, compared with the topologies shown in Fig. 9, Fig. 10, and Fig. 11, Boost converters are added in this topology to form a three-stage structure, which is the disadvantage of this topology. Usually, the Boost converter is relatively efficient, so the overall efficiency of this topology will not be too low.

IV. CONCLUSIONS

In this article, several inverter topologies without line-frequency transformers for large-scale PV power stations are investigated and compared. One is the PV inverters based on MMC structure, and the other is the three-phase CHB PV inverters. With the above analysis, the following conclusions are as follows:

(1) The PV inverters based on MMC structure can be directly connected to the higher voltage power grid without power-frequency transformer, and the power level is high, so this topology is suitable for large-scale PV power stations. There is no inter-phase and inter-module power imbalance problem in the topology of the PV module connected to the DC-bus, but its efficiency is low. The topology of each sub-module connected to the PV array can realize independent MPPT, but its control is complex, and there are the inter-phase and inter-module power imbalance problem. The topology with the low-frequency converter avoids the circulation problem and improves the levels of the output voltage, but its cost is high, and its control is involved.

(2) Three-phase isolated CHB PV inverter based on independent DC-bus structure effectively solves the leakage current problem, can be connected to the 35kV medium-voltage power grid and can realize multi-MPPT. However, the inter-phase and inter-module power imbalance problems are difficult to solve thoroughly in this topology. Besides, the higher switching frequency of HB and the wider voltage range of DC/DC converter limit the improvement of efficiency.

(3) Among all of common DC-bus topology, the third topology not only can also solve the inter-module and inter-phase power imbalance problems, but also achieve lower HB switching frequency and higher isolation DC/DC converter efficiency. Although the three-stage structure will affect system efficiency, the efficiency of the Boost converter is relatively high, so the overall efficiency of this topology will not be too low.

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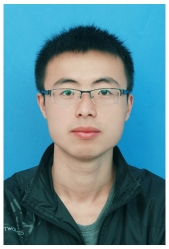

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