Five-Level Inverter for Renewable Power Generation System

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Abstract—In this paper, a five-level inverter is developed and applied for injecting the real power of the renewable power into the grid to reduce the switching power loss, harmonic distortion, and electromagnetic interference caused by the switching operation of power electronic devices. Two dc capacitors, a dual-buck converter, a full-bridge inverter, and a filter configure the five-level inverter. The input of the dual-buck converter is two dc capacitor voltage sources. The dual-buck converter converts two dc capacitor voltage sources to a dc output voltage with three levels and balances these two dc capacitor voltages. The output voltage of the dual-buck converter supplies to the full-bridge inverter. The power electronic switches of the full-bridge inverter are switched in low frequency synchronous with the utility voltage to convert the output voltage of the dual-buck converter to a five-level ac voltage. The output current of the five-level inverter is controlled to generate a sinusoidal current in phase with the utility voltage to inject into the grid. A hardware prototype is developed to verify the performance of the developed renewable power generation system. The experimental results show that the developed renewable power generation system reaches the expected performance.

Index Terms—Harmonic distortion, inverters, power electronics.

I. INTRODUCTION

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HE conventional single-phase inverter topologies for grid-connection include half-bridge and full bridge [1]–[4]. The half-bridge inverter is configured by one capacitor arm and one power electronic arm. The dc bus voltage of the half-bridge inverter must be higher than double of the peak voltage of the output ac voltage. The output ac voltage of the half-bridge inverter is two levels. The voltage jump of each switching is the dc bus voltage of the inverter. The full-bridge inverter is configured by two power electronic arms. The popular modulation strategies for the full-bridge inverter are bipolar modulation and unipolar modulation [3], [5]–[7]. The dc bus voltage of the full-bridge inverter must be higher than the peak voltage of the output ac voltage. The output ac voltage of the full-bridge inverter is two levels if the bipolar modulation is used two levels if the unipolar modulation is used. The voltage jump of each switching is double the dc bus voltage of the inverter if the bipolar modulation is used, and it is the dc bus voltage of the inverter if the unipolar modulation is used. All power electronic switches operate in high switching frequency in both half-bridge and full-bridge inverters. The switching operation will result in switching loss. The loss of power electronic switch includes the switching loss and the conduction loss. The conduction loss depends on the handling power of power electronic switch. The switching loss is proportional to the switching frequency, voltage jump of each switching, and the current of the power electronic switches. The power efficiency can be advanced if the switching loss of the dc–ac inverter is reduced.

Multilevel inverter can effectively reduce the voltage jump of each switching operation to reduce the switching loss and increase power efficiency. The number of power electronic switches used in the multilevel inverter is larger than that used in the conventional half-bridge and full-bridge inverters. Moreover, its control circuit is more complicated. Thus, both the performance and complexity should be considered in designing the multilevel inverter [8], [9]. However, interest in the multilevel inverter has been aroused due to its advantages of better power efficiency, lower switching harmonics, and a smaller filter inductor compared with the conventional half-bridge and full-bridge inverters.

The conventional single-phase multilevel inverter topologies include the diode-clamped, the flying capacitor, and the cascade H-bridge types [10]–[15], as shown in Fig. 1. Fig. 1(a) shows the basic configuration of a diode-clamped multilevel inverter. As can be seen, it is configured by two dc capacitors, two diodes, and four power electronic switches. Two diodes are used to conduct the current loop, and four power electronic switches are used to control the voltage levels. The output voltage of the basic diode-clamped multilevel inverter has three levels. The voltage difference of each level is $V_d/2$ (the voltage on a capacitor). Since the voltages of two dc capacitors are used to form the voltage level of the multilevel inverter, the voltages of these two dc capacitors must be controlled to be equal. The control for balancing these two dc capacitors is very important.

![Fig. 1. Circuit configuration of conventional single-phase multilevel inverter. (a) Diode clamped. (b) Flying capacitor. (c) Cascade H-bridge.](image-url)
in controlling the diode-clamped multilevel inverter, and it is very hard under the light load [16]–[19]. If the five-level output voltage is expected, extra two diodes and four power electronic switches are required [11], [20]. Fig. 1(b) shows the circuit configuration of a basic flying capacitor multilevel inverter. As can be seen, it is configured by three dc capacitors and four power electronic switches. The voltage on each dc capacitor is controlled to be $V_{dc}/2$, and the output voltage of the basic flying capacitor multilevel inverter has three levels. The voltage difference of each level is also $V_{dc}/2$ (the voltage on a dc capacitor). These three dc capacitors must be controlled for maintaining their voltages to be $V_{dc}/2$ in the charge and discharge processes. Therefore, its control circuit is more complicated. If five-level output voltage is required, an extra dc capacitor and four power electronic switches are required [11], [13], [14]. Fig. 1(c) shows the circuit configuration of the basic cascade H-bridge multilevel inverter [8]–[11], [15], [21]. As can be seen, it is configured by two full-bridge inverters connected in cascade. The dc bus voltage of each full-bridge inverter is $V_{dc}/2$, and the output voltage of each full-bridge inverter can be controlled to be $V_{dc}/2$, 0, and $-V_{dc}/2$. Thus, the voltage levels of the output voltage of the cascade full-bridge multilevel inverter are $V_{dc}$, $V_{dc}/2$, 0, $-V_{dc}/2$, and $-V_{dc}$. This topology has advantages of fewer components being required compared with other multilevel inverters under the output voltage with the same levels, and its hardware circuit can be modularized because the configuration of each full bridge is the same. However, this topology has the disadvantages that two independent dc voltage sources are required.

In this paper, a five-level inverter is developed and applied for injecting the real power of the renewable power into the grid. This five-level inverter is configured by two dc capacitors, a dual-buck converter, a full-bridge inverter, and a filter [22]. The five-level inverter generates an output voltage with five levels and applies in the output stage of the renewable power generation system to generate a sinusoidal current in phase with the utility voltage to inject into the grid. The power electronic switches of the dual-buck converter are switched in high frequency to generate a three-level voltage and balance the two input dc voltages. The power electronic switches of the full-bridge inverter are switched in low frequency synchronous with the utility to convert the output voltage of the dual-buck converter to a five-level ac voltage. Therefore, the switching power loss, harmonic distortion, and electromagnetic interference (EMI) caused by the switching operation of power electronic devices can be reduced, and the control circuit is simplified. Besides, the capacity of output filter can be reduced. A hardware prototype is developed to verify the performance of the developed renewable power generation system.

II. CIRCUIT CONFIGURATION

Fig. 2 shows the circuit configuration of the five-level inverter applied to a photovoltaic power generation system. As can be seen, it is configured by a solar cell array, a dc–dc converter, a five-level inverter, two switches, and a digital signal processor (DSP)-based controller. Switches $SW_1$ and $SW_2$ are placed between the five-level inverter and the utility, and they are used to disconnect the photovoltaic power generation system from the utility when islanding operation occurs. The load is placed between switches $SW_1$ and $SW_2$. The output of the solar cell array is connected to the input port of the dc–dc converter. The output port of the dc–dc converter is connected to the five-level inverter. The dc–dc converter is a boost converter, and it performs the functions of maximum power point tracking (MPPT) and boosting the output voltage of the solar cell array. This five-level inverter is configured by two dc capacitors, a dual-buck converter, a full-bridge inverter, and a filter. The dual-buck converter is configured by two buck converters. The two dc capacitors perform as energy buffers between the dc–dc converter and the five-level inverter. The output of the dual-buck converter is connected to the full-bridge inverter to convert the dc voltage to the grid. An inductor is placed at the output of the full-bridge inverter to form a filter inductor for filtering out the high-frequency switching harmonic generated by the dual-buck converter.

III. OPERATION PRINCIPLE OF FIVE-LEVEL INVERTER

The operation of this five-level inverter can be divided into eight modes. Modes 1–4 are for the positive half-cycle, and modes 5–8 are for the negative half-cycle. Fig. 3 shows the operation modes of five-level inverter. As can be seen, the power electronic switches of the full-bridge inverter are switched in low frequency and synchronously with the utility voltage to convert the dc power into ac power for commutating. As seen in Fig. 3(a)–(d), the power electronic switches $S_4$ and $S_7$ are in the ON state, and the power electronic switches $S_5$ and $S_6$ are in the OFF state during the positive half-cycle. On the contrary, the power electronic switches $S_4$ and $S_7$ are in the OFF state, and the power electronic switches $S_5$ and $S_6$ are in the ON state during the negative half-cycle. Since the dc capacitor voltages $V_{C2}$ and $V_{C3}$ are balanced by controlling the five-level inverter, the dc capacitor voltages $V_{C2}$ and $V_{C3}$ can be represented as follows:

$$V_{C2} = V_{C3} = \frac{1}{2}V_{dc}. \quad (1)$$

The operation modes of this five-level inverter are stated as follows.

Mode 1: Fig. 3(a) shows the operation circuit of mode 1. The power electronic switch of the dual-buck converter $S_2$ is turned ON and $S_3$ is turned OFF. DC capacitor $C_2$ is charged through $S_2$, $S_4$, the filter inductor, the utility, $S_7$, and $D_3$ to form a loop. Both output voltages of the dual-buck converter and five-level inverter are $V_{dc}/2$.

Mode 2: Fig. 3(b) shows the operation circuit of mode 2. The power electronic switch of the dual-buck converter $S_2$ is turned OFF and $S_3$ is turned ON. DC capacitor $C_3$ is discharged through $D_2$, $S_4$, the filter inductor, the utility, $S_7$, and $S_4$ to form a loop. Both output voltages of the dual-buck converter and five-level inverter are $V_{dc}/2$.

Mode 3: Fig. 3(c) shows the operation circuit of mode 3. Both power electronic switches $S_2$ and $S_3$ of the dual-buck converter
are turned OFF. The current of the filter inductor flows through the utility, \( S_7, D_3, D_2, \) and \( S_4. \) Both output voltages of the dual-buck converter and five-level inverter are 0.

**Mode 4:** Fig. 3(d) shows the operation circuit of mode 4. Both power electronic switches \( S_2 \) and \( S_3 \) of the dual-buck converter are turned ON. DC capacitors \( C_2 \) and \( C_3 \) are discharged together through \( S_2, S_4, \) the filter inductor, the utility, \( S_7, \) and \( S_3 \) to form a loop. Both output voltages of the dual-buck converter and five-level inverter are \( V_{dc}. \)

Modes 5–8 are the operation modes for the negative half-cycle. The operations of the dual-buck converter under modes 5–8 are similar to that under modes 1–4, and the dual-buck converter can also generate three voltage levels \( V_{dc}/2, \) \( V_{dc}/2, \) 0, and \( V_{dc}, \) respectively. However, the operation of the full-bridge inverter is the opposite. The power electronic switches \( S_1 \) and \( S_7 \) are in the OFF state, and the power electronic switches \( S_5 \) and \( S_6 \) are in the ON state during the negative half-cycle. Therefore, the output voltage of the five-level inverter for modes 5–8 will be \( -V_{dc}/2, -V_{dc}/2, 0, \) and \( -V_{dc}, \) respectively.

Considering operation modes 1–8, the full-bridge inverter converts the dc output voltage of the dual-buck converter with three levels to an ac output voltage with five levels which are \( V_{dc}, V_{dc}/2, 0, -V_{dc}/2, \) and \( -V_{dc}. \)

The operation of power electronic switches \( S_2 \) and \( S_3 \) should guarantee the output voltage of the dual-buck converter is higher than the absolute of the utility voltage. The waveforms of output voltage of five-level inverter and utility voltage are shown in Fig. 4.

Due to the operation of full-bridge inverter, the voltage and current in the dc side of full-bridge inverter are their absolute values of the utility voltage and the output current of the five-level inverter. When the absolute of the utility voltage is smaller than \( V_{dc}/2, \) the output voltage of the dual-buck converter should change between \( V_{dc}/2 \) and 0. Accordingly, the power electronics of five-level inverter is switched between modes 1 or 2, and mode 3 during the positive half-cycle. On the contrary, the power electronics of five-level inverter is switched between modes 5 or 6, and mode 7 during the negative half-cycle. One of the power
The switching operations of the replaced power electronic switches are complementary to those of power electronic switches $S_2$ and $S_3$, respectively. Accordingly, the five-level inverter can supply active power and reactive power simultaneously.

**VII. CONCLUSION**

A photovoltaic power generation system with a five-level inverter is developed in this paper. The five-level inverter can perform the functions of regulating the dc bus voltage, converting solar power to ac power with sinusoidal current and in phase with the utility voltage, balancing the two dc capacitor voltages, and detecting islanding operation. The experimental results verify the developed photovoltaic power generation system, and the five-level inverter achieves the expected performance.

**REFERENCES**


