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# Five-Level Inverter for PV Power Generation System

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**ABSTRACT—*A five-level inverter is introduced and applied for injecting the real power of the photovoltaic 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. The experimental studies show that the developed photovoltaic power generation system is better than the conventional system.***

**Keywords—** Harmonic distortion, Electromagnetic interference, Single phase five-level inverter, PV system

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## 1. INTRODUCTION

Demand for renewable energy has increased significantly over the years because of ever increasing energy consumption, shortage of fossil fuels and greenhouse effect. The definition of renewable energy includes any type of energy generated from natural resources that is infinite or constantly renewed. Examples of renewable energy include solar, wind, and hydropower. Renewable energy, due to its free availability and its clean and renewable character, play a key role in solving the worldwide energy crisis. Among various types of renewable energy sources, solar energy and wind energy have become very popular and demanding due to advancement in power electronics techniques. PV (Photovoltaic) sources are used today in many applications as they have the advantages of effective maintenance and pollution free. Due to high cost, historically PV system have used to supply satellites, but with the invention of low cost thin film panels, solar electric energy demand has grown consistently which is mainly due to its decreasing cost [1]. The solar will provide the electricity up to 64% of the total energy by the end of this century [2]. This decline has been driven by the following factors.

1) An increasing efficiency of solar cells
2) Manufacturing technology improvements
3) Economies of scale.

Renewable power sources are difficult to be directly connected to the power grid due to their variable and intermittent nature. Power electronic converters technology plays an important role in integrating and utilizing these alternative energy sources into the electricity grid, and is widely used and rapidly expanding as these applications become more integrated with the grid-based systems. PV inverter, which is the heart of a PV system, is used to convert dc power obtained from PV modules into ac power to be fed into the grid. A single-phase grid-connected inverter is usually used for residential or low-power applications of power ranges that are less than 10 kW. The conventional single-phase inverter topologies for grid connection include half-bridge and full bridge. But, the switching power loss, harmonic distortion, and EMI (Electromagnetic interference) caused by the switching operation of the power electronic devices in the conventional inverters are high [3].

Multilevel inverter topologies have drawn a large research interest over the last two decades due to their inherent merits compared with their conventional counterpart especially for medium or high-power applications. They synthesize the ac output voltage from several levels of voltage, hence generate low distortion waveforms and reduced amplitude of harmonics in the output. On the other hand, for low-power systems, multilevel inverters have been also competing with high frequency pulse width-modulation inverters in applications where high efficiency is of major importance. Moreover, the lower prices and rapid growth of power switches and new semiconductor technologies, as well as the current demand on high-performance inverters required by renewable energy systems have extended the applications of multilevel inverters [4].

In this proposed method, a five-level inverter is introduced and applied for injecting the real power of the renewable power into the grid. Hence improves its output waveform, reduces its harmonic content and, hence, also reduces the size of the filter used and the level of EMI generated by the inverter's switching operation. Switching losses are lower than those of conventional two-level inverters.  All of these advantages make the proposed model cheaper, lighter, and more compact.

## 2. CONVENTIONAL SINGLE PHASE INVERTER TOPOLOGIES

Nowadays, most photovoltaic inverters include an isolating transformer, which has large volume, high cost, and especially great loss, thus it decreases the efficiency of whole system. The line frequency transformer configuration is shown in fig. 2.1.Where the transformer is used to step up the voltage, because PV system power generation is less than 10 kW. One of the trends of the photovoltaic power generation system is transformer less one. This is achieved by the advanced power electronic technologies. The transformer less configuration is shown in fig. 2.2. [5].Where the dc-dc converter is a boost converter, which step up the output voltage of the solar cell array and hence eliminate the transformer from the converter configuration and get an efficient system with reduced cost as compared to the configuration shown in fig. 2.1.

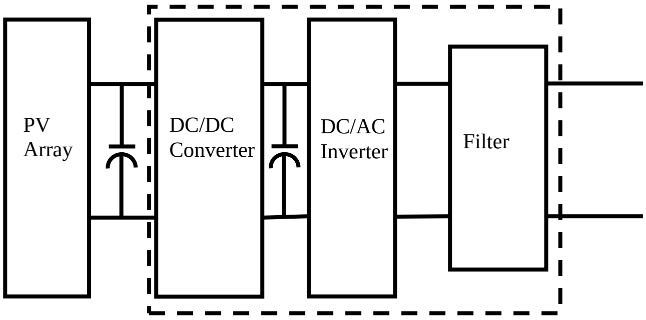

Figure 1: Line frequency transformer configuration [5]

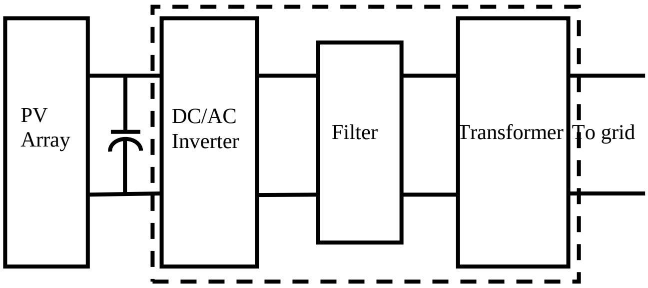

Figure 2: Transformer less configuration [5]

The conventional single-phase inverter topologies for grid connection include half-bridge and full bridge [6]. They are transformer less configuration. The half-bridge inverter is configured by one capacitor arm and one power electronic arm. The output ac voltage of the half-bridge inverter is two levels. 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 [7]. The output ac voltage of the full-bridge inverter is two levels if the bipolar modulation is used and three levels if the unipolar modulation is used. Bipolar modulation has less leakage current, but causes more harmonics and more losses. In order to reduce the losses, unipolar PWM (Pulse width modulation) is commonly 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, 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. These limitations of the conventional inverters for grid connected PV power generation system lead to the invention of the multilevel inverter.

Multilevel inverter topologies have drawn a large research interest over the last two decades due to their inherent merits compared with their conventional counterpart especially for medium and high power applications. They synthesize the ac output voltage from several levels of voltage, hence generate low distortion voltage and current waveforms and reduced amplitude of harmonics in the output. On the other hand, for low power systems (<10kW), multilevel inverters have been also competing with high frequency PWM inverters in applications where high efficiency is of major importance. Multilevel inverter can effectively 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. 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. Moreover, the semiconductor technologies, as well as the current demand on high-performance inverters required by renewable energy systems have extended the applications of multilevel inverters. The conventional single-phase multilevel inverter topologies are listed below and they are shown in fig. 2.3 [8].

a) Diode-clamped multilevel inverter
b) Flying capacitor multilevel inverter
c) Cascade H-bridge multilevel inverter

The basic configuration of a diode-clamped multilevel inverter is shown in fig. 2.3(a). 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 $V_{dc}/2$ (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 in controlling the diode-clamped multilevel inverter, and it is very hard under the light load. If the five-level output voltage is expected, extra two diodes and four power electronic switches are required.

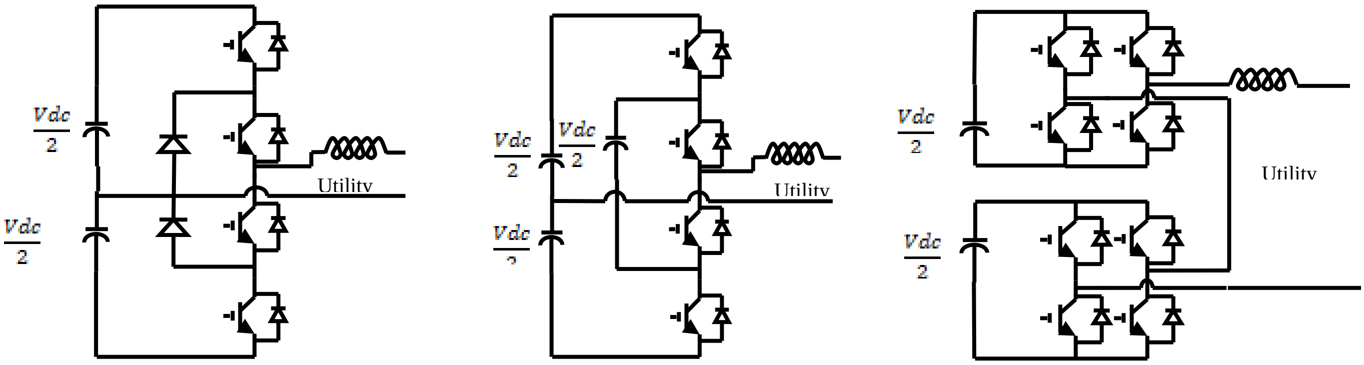

Figure 3: Circuit configuration of conventional single-phase multilevel inverter (a) Diode clamped. (b) Flying capacitor.(c) Cascade H-bridge. [8]

The circuit configuration of a basic flying capacitor multilevel inverter is shown in fig. 2.3(b). 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 $V_{dc}/2$. 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.

The circuit configuration of the basic cascade H-bridge multilevel inverter is shown in fig. 2.3(c). 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. Hence this topology appears to be superior to other multilevel inverters in applications at high power rating due to its modular nature, ease of control, flexibility of application and robustness. However, this topology has the disadvantages that two independent dc voltage sources are required.

In the proposed method of PV power generation system, a five-level inverter is developed and applied for injecting the real power of the photovoltaic 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. The five-level inverter generates an output voltage with five levels and applies in the output stage of the photovoltaic 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 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.

## 3. FIVE LEVEL INVERTER

A better strategy for power electronic interface for photovoltaic power generation system to overcome all the limitations of conventional technique is required. For this purpose a five-level inverter is introduced. This five-level inverter is used for injecting the real power of the photovoltaic power into the grid.

### *3.1 Circuit Configuration*

The circuit configuration of the five-level inverter applied to a photovoltaic power generation system is shown in fig. 3.1. As can be seen, it is configured by a solar cell array, a dc–dc converter, a five-level inverter, two switches, and a DSP (Digital signal processor)-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.

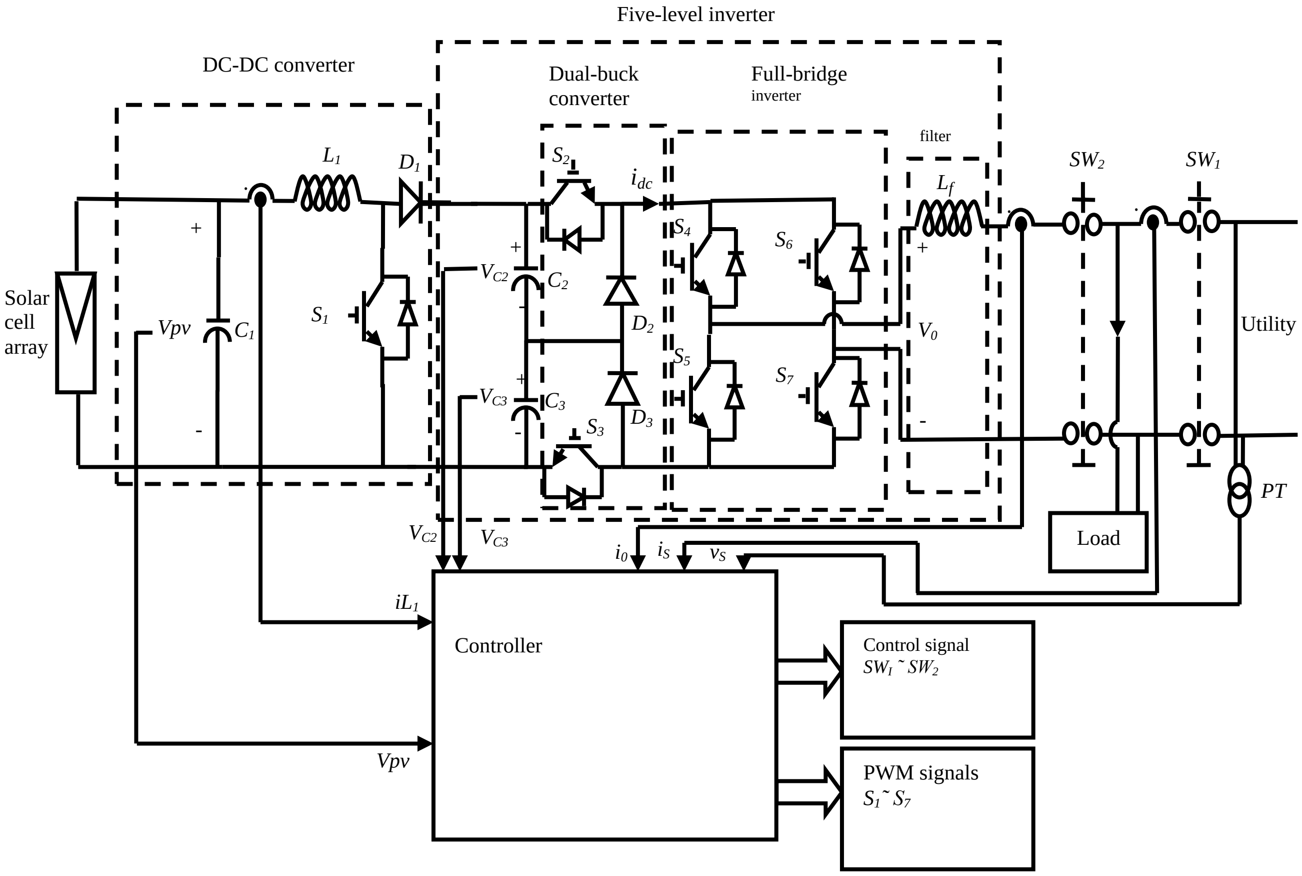

Figure 4: Circuit configuration of the developed photovoltaic power generation system.

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 MPPT (Maximum power point tracking) and boosting the output voltage of the solar cell array [9]. 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 ac voltage. An inductor is placed at the output of the full bridge inverter to form as a filter inductor for filtering out the high-frequency switching harmonic generated by the dual-buck converter.

### *3.2 Operation Principle of Five-level Inverter*

The operation of this five-level inverter can be divided into eight modes. These eight modes of operation of the five-level inverter explain the way of obtaining five level output voltage. Modes 1–4 are for the positive half-cycle, and modes 5–8 are for the negative half-cycle. The operation modes of five-level inverter are shown in fig. 3.2. 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. 3.2 (a) to 3.2 (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:

*Mode 1:* The operation circuit of mode 1 is shown in fig. 3.2 (a). 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 discharged 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 $V_{dc}/2$.

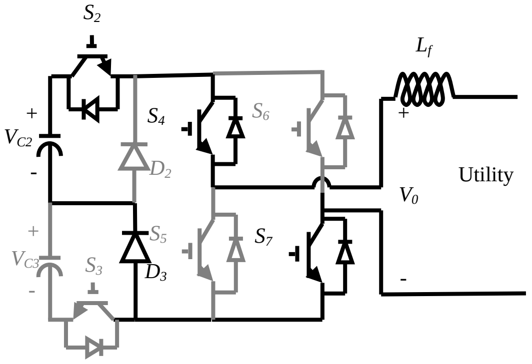

Fig. 3.2 (a) mode-1 operation of five-level

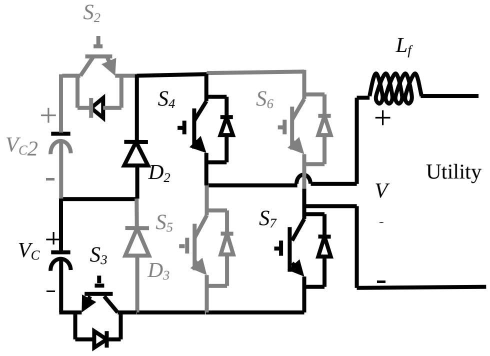

Fig. 3.2 (b) mode-2 operation of five-level

*Mode 2:* The operation circuit of mode 2 is shown in fig. 3.2 (b). 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 $S_3$ to form a loop. Both output voltages of the dual-buck converter and five-level inverter are $V_{dc}/2$.

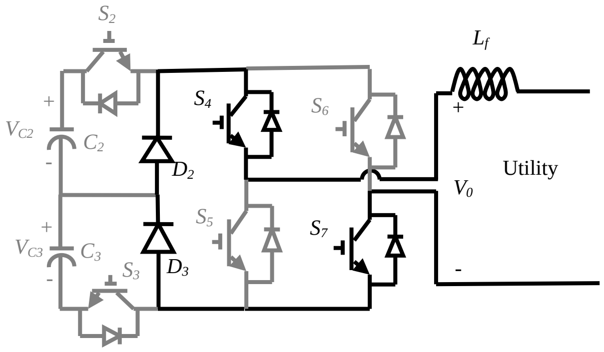

Fig. 3.2 (c) mode-3 operation of five-level

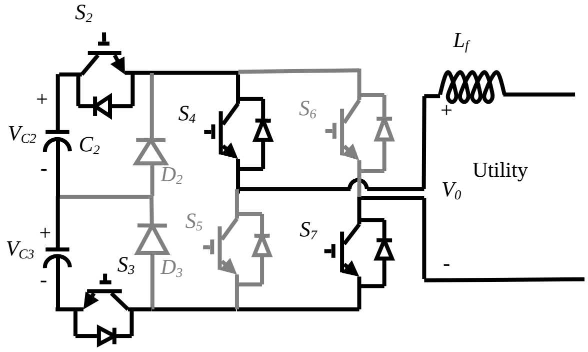

Fig. 3.2 (d) mode-4 operation of five-level

*Mode 3:* fig. 3.2.3 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:* The operation circuit of mode 4 is shown in fig. 3.2 (d). Both power electronic switches $S_2$ and $S_3$ of the dual-buck converter are turned ON.DCcapacitors$C_2$ 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 $V_{dc}$.

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.

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 electronic switches $S_2$ and $S_3$ is in the OFF state and the other is switched in high frequency during one PWM period. The switching operation of the power electronic switches in the eight modes of operation of the five-level inverter can be summarized as shown in table 3.1.

Table 1: Switching operation of power electronic switches of five-level inverter

| Modes | Switching mode of power electronic switches | | | | | | Vout |
|---|---|---|---|---|---|---|---|
| | S2 | S3 | S4 | S5 | S6 | S7 | |
| Mode 1 | On | Off | On | Off | Off | On | $V_{dc}/2$ |
| Mode 2 | Off | On | On | Off | Off | On | $V_{dc}/2$ |
| Mode 3 | Off | Off | On | Off | Off | On | 0 |
| Mode 4 | On | On | On | Off | Off | On | $V_{dc}$ |
| Mode 5 | On | Off | Off | On | On | Off | $V_{dc}/2$ |
| Mode 6 | Off | On | Off | On | On | Off | $V_{dc}/2$ |
| Mode 7 | Off | Off | Off | On | On | Off | 0 |
| Mode 8 | On | On | Off | On | On | Off | $V_{dc}$ |

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. Hence balancing the voltages of dc capacitors is very important in controlling the multilevel inverter. The voltage balance of dc capacitor voltages $V_{C2}$ and $V_{C3}$ can be controlled by the power electronic switches $S_2$ and $S_3$ easily. The easiness of balancing the dc capacitor is one of the reasons for five-level inverter better than the conventional inverters. When the absolute of the utility voltage is smaller than $V_{dc}/2$, one power electronic switch either $S_2$ or $S_3$ is switched in high frequency and the other is still in the OFF state. Which power electronic switch is switched in high frequency depends on the dc capacitor voltages $V_{C2}$ and $V_{C3}$. If dc capacitor voltage $V_{C2}$ is higher than dc capacitor voltage $V_{C3}$, power electronic switch $S_2$ is switched in high frequency. In this situation, the voltage source $V_{Cx}$ in fig. 3.4 (a) is $V_{C2}$, and $C_2$ will be discharged. Thus, the dc capacitor voltages $V_{C2}$ decreases and $V_{C3}$ does not change. On the contrary, power electronic switch $S_3$ is switched in high frequency when voltage $V_{C3}$ is higher than voltage $V_{C2}$. In this situation, the voltage source $V_{Cx}$ in fig. 3.4 (b) is $V_{C3}$. Thus, the dc capacitor voltages $V_{C3}$ decreases and $V_{C2}$ does not change. In this way, the voltage balance of $C_2$ and $C_3$ can be achieved.

When the absolute of the utility voltage is higher than $V_{dc}/2$, one power electronic switch either $S_2$ or $S_3$ is switched in high frequency and the other is still in the ON state. Which power electronic switch is switched in high frequency depends on the dc capacitor voltages $V_{C2}$ and $V_{C3}$. If dc capacitor voltage $V_{C2}$ is higher than dc capacitor voltage $V_{C3}$, the power electronic switch $S_3$ is switched in high frequency. The voltage source $V_{Cx}$ in fig. 3.4 (b) is dc capacitor voltage $V_{C2}$. When the power electronic switch $S_3$ is turned ON, both $C_2$ and $C_3$ are discharged. However, only $C_2$ supplies the power when the power electronic switch $S_3$ is turned OFF. Thus, $C_2$ will discharge more power than that of $C_3$. On the contrary, the power electronic switch $S_2$ is switched in high frequency when dc capacitor voltage $V_{C3}$ is higher than dc capacitor voltage $V_{C2}$. The voltage source $V_{Cx}$ in fig. 3.4 (b) is dc capacitor voltage $V_{C3}$. When the power electronic switch $S_2$ is turned ON, both $C_2$ and $C_3$ are discharged. However, only $C_3$ supplies the power when the power electronic switch $S_2$ is turned OFF. Thus, $C_3$ will discharge more power than that of $C_2$. In this way, the voltage balance of $C_2$ and $C_3$ can be achieved.

As mentioned earlier, the operation of power electronic switches $S_2$ and $S_3$ for the balancing of capacitor voltage can be summarized as Table 3.2. The voltages of capacitors $C_2$ and $C_3$ can be easily balanced compared with the conventional multilevel inverter. This helps to obtain the output voltage and current with reduced harmonic distortion and also the control circuit becomes less complicated compared to the conventional multilevel inverters. This balancing of capacitor voltage is the main factor that makes the proposed five-level inverter best among the already existing multilevel inverter topologies.

Table 3.2 ON/OFF state of $S_2$ and $S_3$

| | | $\|V_S\| < V_{dc}/2$ | $\|V_S\| > V_{dc}/2$ |
|---|---|---|---|
| $V_{C2}>V_{C3}$ | $S_2$ | PWM | on |
| | $S_3$ | off | PWM |
| $V_{C2}<V_{C3}$ | $S_2$ | off | PWM |
| | $S_3$ | PWM | on |

Table 4.1 shows the comparison of the proposed five-level inverter with the conventional five-level inverters (diode-clamped five level inverter, flying capacitor five-level inverter, and cascade H-bridge five -level inverter). Comparison is based on the number of power electronic switches, number of balancing capacitors, high frequency switching switches and the complexity of balancing each capacitor. The detailed study and the comparison show that five-level inverter proposed is superior to the conventional five-level inverters on the basis of above mentioned factors [10]. These are the main advantages of proposed five level multilevel inverter.

Table 4.1 Comparison of five-level inverters

| | Diode-clamped | Flying capacitor | Cascade H-bridge | Developed inverter |
|---|---|---|---|---|
| Power electronic switches | 8 | 8 | 8 | 6 |
| Capacitors | 2 | 4 | 2 | 2 |
| Balancing voltages of capacitors | hard | hard | hard | easier |
| High frequency switching switches | 8 | 8 | 8 | 2 |

## 4. CONCLUSION

A photovoltaic power generation system with a five-level inverter is introduced. 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 hence overcome the main limitations of the conventional power electronic interface for photovoltaic power generation system. Main advantages of proposed five level grid connected PV inverter are,

- Less switching power loss
- Reduced harmonic distortion
- Reduced EMI
- Simplified control circuit
- Capacitor voltages can be easily balanced
- Better power efficiency
- Capacity of output filter can be reduced
- Cheaper, lighter and more compact

If the five-level inverter must supply reactive power to the utility, two power electronic switches must replace the diodes *D*2 and *D*3. 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.

## 5. ACKNOWLEDGEMENT

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