

# Performance Analysis of Switched Capacitor Multilevel DC/AC Inverter using Solar PV Cells

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## ABSTRACT

The aim of this project is to propose a new inverter topology for a multilevel voltage output. This topology is designed based on a switched capacitor (SC) technicality, and the number of output levels is determined by the number of SC cells. Only one DC voltage source is needed, and the problem of capacitor voltage balancing is avoided as well. This structure is not only very simple and easy to be extended to a higher level, but also its gate driver circuits are simplified because the number of active switches is reduced. The operational principle of this inverter and the targeted modulation strategies are presented, and power losses are investigated. Finally, the performance of the proposed multilevel inverter is evaluated with the experimental results of an 11-level prototype inverter.

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## I. INTRODUCTION

DC/AC inverters convert DC source energy for AC users, and are a big category of power electronics. Power electronics is the technology to process and control the flow of electric energy by supplying voltages and currents in a form that is optimally suited for user loads. The input power can be AC and DC sources. A general example is that the AC input power is from the electric utility. The output power to the load can be AC and DC voltages. The power processor in the block diagram is usually called a converter. Conversion technologies are used to construct converters. Therefore, there are four categories of the converter:

- AC/DC converters/rectifiers (AC to DC)
- DC/DC converters (DC to DC)
- DC/AC inverters/converters (DC to AC)
- AC/AC converters (AC to AC)

We will use converter as a generic term to refer to a single power conversion stage that may perform

any of the functions listed above. To be more specific, in AC to DC and DC to AC conversion, rectifier refers to a converter when the average power flow is from the AC to the DC side. Inverting refers to the converter when the average power flow is from the DC to the AC side. In fact, the power flow through the converter may be reversible.

## II. MULTILEVEL DC/AC INVERTERS

Multilevel inverters use a different method to construct DC/AC inverters. This idea was published by Nabae in 1980 in an IEEE international conference, IEEE APEC'80 [1], and the same idea was published in 1981 in IEEE Transactions on Industry Applications. Actually, multilevel inverters employ a different technique from the PWM method, which vertically chops a reference waveform to achieve the similar output waveform (e.g., a sine wave). The multilevel inverting technique horizontally accumulates levels to achieve the waveform (e.g., a sine

wave).Although PWM inverters have been used in industrial applications, they have many drawbacks:

1. The carrier frequency must be very high. The  $mf > 21$ , which means  $f > 1$  kHz if the output waveform has frequency 50 Hz. Usually, in order to keep the THD small,  $f$  is selected as 2-20 kHz.
2. The pulse height is very high. In a normal PWM waveform (not multistage PWM), all pulse height is the DC linkage voltage. The output voltage of this PWM inverter has a large jumping span. For example, if the DC linkage voltage is 400 V, all pulses have the peak value 400 V. Usually, this causes large  $dv/dt$  and strong electromagnetic interference (EMI).
3. The pulse width would be very narrow when the output voltage has a low value. For example, if the DC linkage voltage is 400 V, the out-put is 10 V, and the corresponding pulse width should be 2.5% of the pulse period.
4. Terms 2 and 3 cause plenty of harmonics to produce poor THD.
5. Terms 2 and 3 result in a very rigorous switching condition. The switching devices experience large switching power losses.
6. The inverter control circuitry is complex, and the devices are costly. Therefore, the whole inverter is costly.

Multilevel inverters accumulate the output voltage to horizontal levels (layers). Therefore, using this technique overcomes the above drawbacks of the PWM technique:

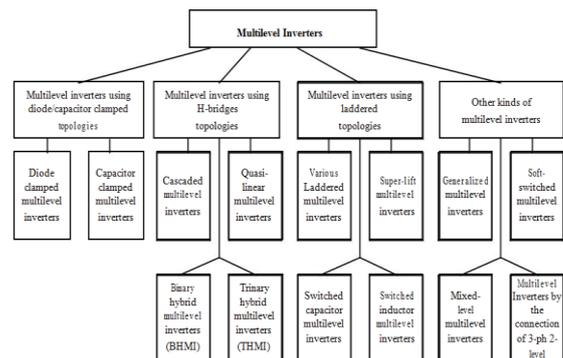
1. The switching frequencies of most switching devices are low, which are equal to or only a small multiple of the output signal frequency.
2. The pulse heights are quite low. For an  $m$ -level inverter with output amplitude  $V_m$ , the pulse heights are  $V_m/m$  or only a small multiple of it. Usually, it causes low  $dv/dt$  and ignorable electromagnetic interference (EMI).
3. The pulse widths of all pulses have reasonable values that are comparable to the output signal.
4. Terms 2 and 3 cannot cause plenty of harmonics producing lower THD.

5. Terms 2 and 3 offer smooth switching condition. The switching devices have small switching power losses.

6. Inverter control circuitry is relatively simple, and the devices are not costly. Therefore, the inverter is economical.

Multilevel inverters have been receiving increasing attention in recent decades, because of their many attractive features. Various kinds of multi-level inverters have been proposed, tested, and installed:

- Diode-clamped (neutral-clamped) multilevel inverters
- Capacitor-clamped (flying capacitors) multilevel inverters
- Cascaded multilevel inverters with separate DC sources
- H-bridge multilevel inverters
- Generalized multilevel inverters
- Mixed-level multilevel inverters
- Multilevel inverters by the connection of three-phase two-level inverters
- Soft-switched multilevel inverters
- Laddered inverters



The output voltage of the multilevel inverter has many levels synthesized from several DC voltage sources. The quality of the output voltage is improved as the number of voltage levels increases, so the effort of output filters can be decreased. The transformers can be eliminated due to reduced voltage that the life of the switch increases. Moreover, being cost-effective solutions, the application of multilevel inverters is also extended to medium- and low-power applications such as electrical vehicle propulsion systems, active power filters (APFs), voltage sag compensations, photovoltaic systems, and distributed power systems.

Multilevel inverter circuits have been investigated for three decades. Separate DC-sourced full-bridge cells are connected in series to synthesize a staircase AC output voltage.

The diode-clamped inverter, also called the neutral-point clamped (NPC) inverter, was presented in 1980 by Nabae. Because the NPC inverter effectively doubles the device voltage level without requiring precise voltage matching, this circuit topology prevailed in the 1980s. The capacitor-clamped (also called flying capacitor) multilevel inverter was introduced in the 1990s. Although the cascaded multilevel inverter was invented earlier, its application did not become widespread until the mid 1990s.

The advantages of cascaded multilevel inverters have been indicated for motor drives and utility applications. The cascaded inverter has drawn great interest due to the great demand for medium-voltage, high-power inverters. The cascaded inverter is also used in regenerative-type motor drive applications. Recently, some new topologies of multilevel inverters have emerged, such as generalized multilevel inverters, mixed multilevel inverters, hybrid multilevel inverters, and soft-switched multilevel inverters. Today, multilevel inverters are extensively used in high-power applications with medium voltage levels, such as laminates, mills, conveyors, pumps, fans, blowers, compressors, and so on.

Moreover, as a cost-effective solution, the applications of multilevel inverters are also extended to low-power applications such as photovoltaic systems, hybrid electrical vehicles, and voltage sags compensation, in which the effort of output filter components can be greatly decreased due to lower harmonic distortions of output voltages of the multilevel inverters.

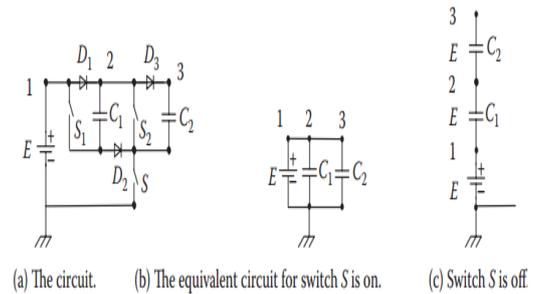
### III. SWITCHED-CAPACITOR MULTILEVEL DC/AC INVERTERS IN SOLAR PANEL ENERGY SYSTEMS

#### 3.1 Introduction

A switched capacitor (SC) is usually manufactured with a switch and a capacitor together. It has been used in DC/DC converters for many years. It can be integrated into power semiconductor IC chips. Hence, SC converters have small size and work at high switching frequencies. This technique opened the way to building converters with high power density and attracted the attention of research workers and manufacturers. We were the first to use switched capacitors in DC/AC inverters.

A switched-capacitor DC/DC converter is shown in Figure 1a. It contains two SCs ( $C_1$  and  $C_2$ ), main switch  $S$ , two slave switches ( $S_1$  and  $S_2$ ), and three diodes. The main switch  $S$  and the slave switches

are operated mutually exclusive; that is, when the main switch is on, the slave switches are off, and vice versa. When the main switch  $S$  is on, the slave switches are off, and all diodes conduct. The equivalent circuit is shown in Figure 1b. Both SCs are charged by the source voltage  $E$  in the steady state. When the main switch  $S$  is off, the slave switches are on, and all diodes are blocked. The equivalent circuit is shown in Figure 1c. The voltages at the points 1, 2, and 3 are  $E$ ,  $2E$ , and  $3E$ , respectively, in the steady state.



#### 3.2 Five-Level SC Inverter

A 5-level switched capacitor inverter is shown in Figure 2.

There is one DC voltage source  $E$ , one 3-position band-switch, and one changeover switch (2P2T) in the circuit. The slave switch  $S_1$  and the main switch  $S$  switch mutually exclusive; that is, when  $S$  is on,  $S_1$  is off, and vice versa. Capacitor  $C_1$  is a switched capacitor. When  $S$  is on and  $S_1$  is off, diode  $D_1$  conducts. Therefore, Capacitor  $C_1$  is charged to the voltage  $E$  in steady state. When  $S$  is off and  $S_1$  is on, diode  $D_1$  is blocked. The voltage at point 2 is  $V_2 = 2 \times E$  ( $V_1$  always equals  $E$ ). Therefore, the operating status is as follows:

- $V_{out} = 2E$ : 2P2T is on, the band switch is in position 2, and the main switch  $S$  is off.
- $V_{out} = E$ : 2P2T is on, the band switch is in position 1, and the main switch  $S$  is off.
- $V_{out} = 0$ : The band switch is at position 0 (i.e., N), and all switches can be on or off.

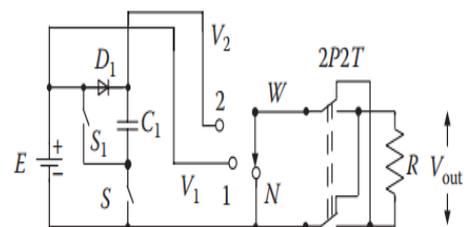


Fig 2.A five-level switched-capacitor inverter.

- $V_{out} = -E$ : 2P2T is off, the band switch is in position 1, and the main switch  $S$  is for.

- $V_{out} = -2E$ : 2P2T is off, the band switch is in position 2, and the main switch S is off.

We have obtained a five-level output AC voltage. The output voltage peak value is two times the input DC voltage E. The waveform is shown in Figure 3.

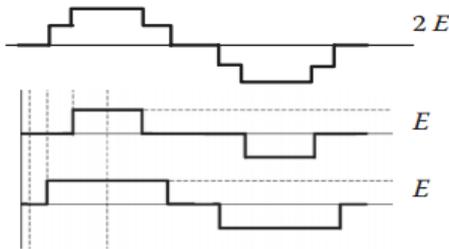


Fig 3: Waveform for five level inverter

### 3.3 Nine-Level SC Inverter

A nine-level switched-capacitor inverter is shown in Figure 4.

There is one DC voltage source E, one five-position band switch, and one changeover switch (2P2T) switches in the circuit. The slave switches  $S_{1-3}$  and the main switch S switches mutually exclusive; that is, when S is on, all slave switches are off, and vice versa. Capacitors  $C_{1-3}$  are the switched capacitors. When S is on, all diodes conduct. Therefore, all SCs charge to the voltage E in the steady state. When S is off and  $S_1$  is on, diode  $D_1$  is blocked. The voltage at point 2 is  $V_2 = 2 \times E$ ; the voltage at point 3 is  $V_3 = 3 \times E$ ; the voltage at point 4 is  $V_4 = 4 \times E$ ; ( $V_1$  has been always E). Therefore, the operating status is as follows:

- $V_{out} = 4E$ : 2P2T is on, the band switch is in position 4, and the main switch S is off.
- $V_{out} = 3E$ : 2P2T is on, the band switch is in position 3, and the main switch S is off.

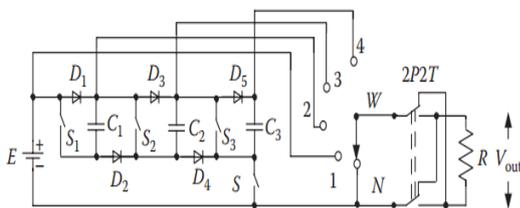


Figure 4:A nine-level switched-capacitor inverter.

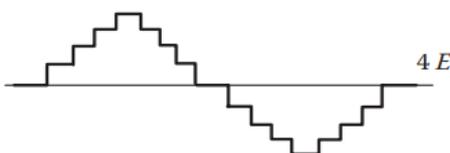


Figure 5: waveform for nine level inverter

- $V_{out} = 2E$ : 2P2T is on, the band switch is in position 2, and the main switch S is off.
- $V_{out} = E$ : 2P2T is on, the band switch is in position 1, and the main switch S is on.
- $V_{out} = 0$ : The band switch is at position 0 (i.e., N), and all switches can be on or off.
- $V_{out} = -E$ : 2P2T is off, the band switch is in position 1, and the main switch S is on.
- $V_{out} = -2E$ : 2P2T is off, the band switch is in position 2, and the main switch S is off.
- $V_{out} = -3E$ : 2P2T is off, the band switch is in position 3, and the main switch S is off.
- $V_{out} = -4E$ : 2P2T is off, the band switch is in position 4, and the main switch S is off.

We have obtained a nine-level output AC voltage. The output voltage peak value is four times the input DC voltage E. The waveform is shown in Figure 5.

### 3.4 Fifteen-Level SC Inverter

A 15-level switched-capacitor inverter is shown in Figure 6. There is one DC voltage source E, one 7-position band switch, and one changeover switch (2P2T) switch in the circuit. The slave switches  $S_{1-6}$  and the main switch S switch mutually exclusive; that is, when S is on, all slaves switches off, and vice versa. Capacitors  $C_{1-6}$  are SCs. When S is on and all slave switches are off, all diodes conduct. Therefore, all SCs are charged with

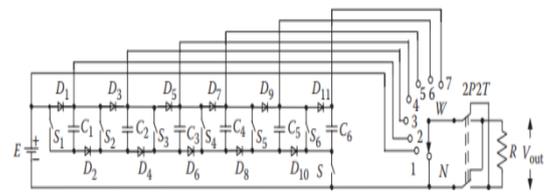


Figure 6:A fifteen level multilevel

The voltage E in the steady state. The voltage at point 2 is  $V_2 = 2 \times E$ ; the voltage at point 2 is  $V_3 = 3 \times E$ ; the voltage at point 4 is  $V_4 = 4 \times E$ , and so on, where  $V_1$  is always E. Therefore, the operating status is as follows:

- $V_{out} = 7E$ : 2P2T is on, the band switch is in position 7, and the main switch S is off.
- $V_{out} = 6E$ : 2P2T is on, the band switch is in position 6, and the main switch S is off.
- $V_{out} = 5E$ : 2P2T is on, the band switch is in position 5, and the main switch S is off.
- $V_{out} = 4E$ : 2P2T is on, the band switch is in position 4, and the main switch S is off.
- $V_{out} = 3E$ : 2P2T is on, the band switch is in position 3, and the main switch S is off.

- $V_{out} = 2E$ : 2P2T is on, the band switch is in position 2, and the main switch S is off.
- $V_{out} = E$ : 2P2T is on, the band switch is in position 1, and the main switch S is on.
- $V_{out} = 0$ : The band switch is at position 0 (i.e., N), and all switches are on.
- $V_{out} = -E$ : 2P2T is off, the band switch is in position 1, and the main switch S is on.
- $V_{out} = -2E$ : 2P2T is off, the band switch is in position 2, and the main switch S is off.
- $V_{out} = -3E$ : 2P2T is off, the band switch is in position 3, and the main switch S is off.
- $V_{out} = -4E$ : 2P2T is off, the band switch is in position 4, and the main switch S is off.
- $V_{out} = -5E$ : 2P2T is off, the band switch is in position 5, and the main switch S is off.
- $V_{out} = -6E$ : 2P2T is off, the band switch is in position 6, and the main switch S is off.
- $V_{out} = -7E$ : 2P2T is off, the band switch is in position 7, and the main switch S is off.

We have obtained a 15-level output AC voltage. The output voltage peak value is seven times the input DC voltage E. The waveform is shown in Figure 7.

### 3.5 Higher-Level SC Inverter

Repeatedly adding components ( $S_1-C_1-D_1-D_2$ ) as shown in Figure.6, we can obtain higher-level inverters. We believe that readers of this book have

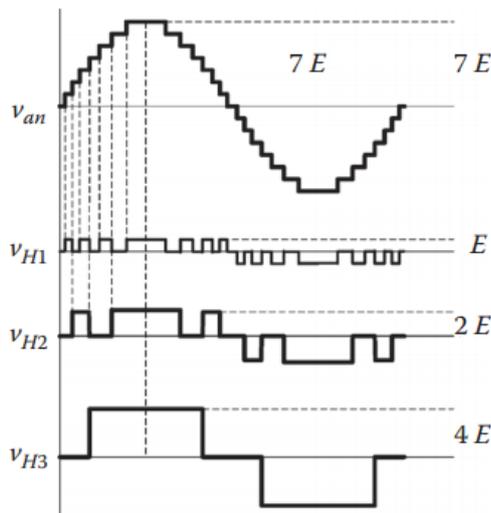


Figure 7: waveform for fifteen level inverter

understood how to construct higher-level inverters, for example, a 21-level SC inverter.

## IV. SIMULATION AND EXPERIMENTAL RESULTS

Switched- capacitor multilevel inverters in solar panel energy systems are examples for the

simulation. The 17-level inverter's simulation result is shown in Figure .8. Its corresponding experimental result is shown in Figure .9.

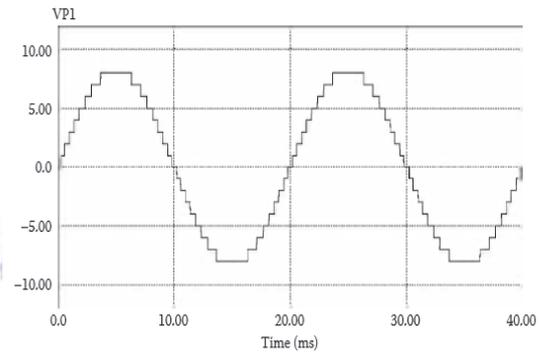


Figure 8: waveform for Seventeen level inverter

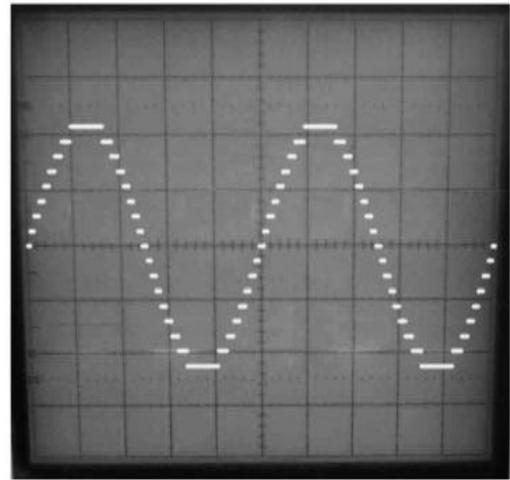


FIGURE 9:A seventeen-level experimental waveform

The 27-level inverter's simulation and corresponding experimental results can be seen in Figures10 and 11, respectively. Furthermore, we use the switched-capacitor technique to produce 37-level and 47-level SC inverters for the solar panel energy system. Their output voltages have 37 and 47 levels, respectively. Their simulation and experimental results are shown in Figures 12–15. We introduced switched-capacitor multilevel inverters in this chapter.

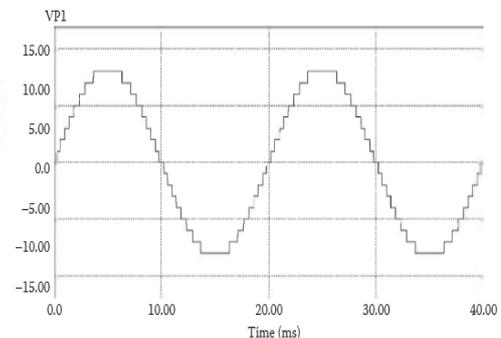


Figure 10:A 27-level simulation waveform.

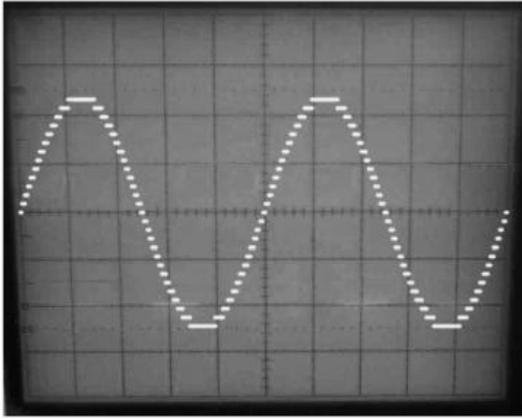


Figure 11:A 27-Level Experimental Waveform

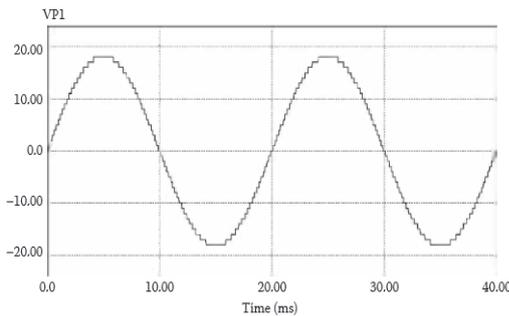


Figure 12:A 37-Level Simulation Waveform

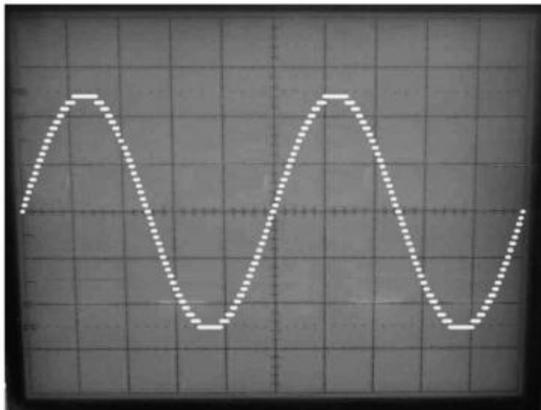


FIGURE 13:A 37-level experimental waveform.

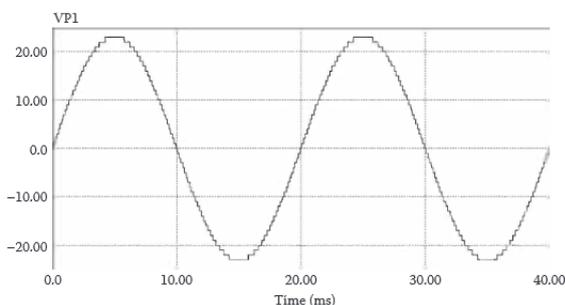


Figure 14:A 47-Level Simulation Waveform.

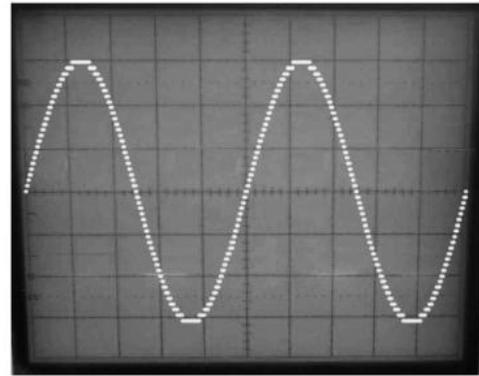


Figure 15:A 47-Level Experimental Waveform.

All SC multilevel inverters have relatively simple structure, straightforward operation procedure, easy control, and higher output voltage (compared with the input voltage). We can use fewer components to construct more levels of the output voltage. We applied four SCIs from 17-level to 47-level of output voltage to a solar panel energy system and obtained satisfactory simulation and experimental results that strongly supported our circuit design. These SC multilevel inverters can be used in other renewable energy systems and industrial applications.

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