CHAPTER 2

EVOLUTION OF MULTILEVEL INVERTERS AND LITERATURE SURVEY

2.1 Inverter

The Inverter is an electrical device that converts direct current (DC) to alternate current (AC). The inverter is used for backup power in a home. The AC power is used mostly for electrical devices like lights, radar, radio, motor, and other devices.

2.2 Multilevel inverter

J. Rodriguez, J. S. Lai, and F. Z. Peng (2002) was proposed a Multilevel inverter technology has emerged recently as a very important alternative in the area of high-power medium-voltage energy control. J. Rodriguez, J. S. Lai, and F. Z. Peng presents the most important topologies like diode-clamped inverter (neutral-point clamped), capacitor-clamped (flying capacitor), and cascaded multicell with separate dc sources. Emerging topologies like asymmetric hybrid cells and soft-switched multilevel inverters are also discussed. And also presents the most relevant control and modulation methods developed for this family of converters: multilevel sinusoidal pulse width modulation, multilevel selective harmonic elimination, and space-vector modulation. Special attention is dedicated to the latest and more relevant applications of these converters such as laminators, conveyor belts, and unified power-flow controllers. The need of an active front end at the input side for those inverters supplying regenerative loads is also discussed, and the circuit topology options are also presented. Finally, the peripherally developing areas such as high-voltage high-power devices and optical sensors and other opportunities for future development are addressed.

F. S. Kang et al. (2005) was proposed a new multilevel pulse width-modulation (PWM) inverter scheme for the use of stand-alone photovoltaic systems. It consists of a PWM inverter, an assembly of LEVEL inverters, generating staircase output voltages, and cascaded transformers. To produce high-quality output voltage waves, it synthesizes a large number of output voltage levels using cascaded transformers, which have a series-connected secondary. By a suitable selection of the secondary turn-ratio of the transformer, the amplitude of an output voltage appears at the rate of an integer to an input dc source. Operational principles and analysis are illustrated in depth. The validity of the proposed system is verified through computer-aided simulations and experimental results using prototypes generating output voltages of an 11 level and a 29 level, respectively, and their results are compared with conventional counterparts

B. P. McGrath and D. G. Holmes (2002) was proposed an analytical solutions of pulse width-modulation (PWM) strategies for multilevel inverters are used to identify that alternative phase opposition disposition PWM for diode-clamped inverters produces the same harmonic performance as phase-shifted carrier PWM for cascaded inverters, and hybrid PWM for hybrid inverters, when the carrier frequencies are set to achieve the same number of inverter switch transitions over each fundamental cycle. Using this understanding, a PWM method is then developed for cascaded and hybrid inverters to achieve the same harmonic gains as phase disposition PWM achieves for diode-clamped inverters

Now a day's numerous industrial applications have started to involve high power appliances in the industries, still, they require medium or low power for their process. Using a high-power source for all industrial loads may show advantageous to some motors demanding high power, while it may harm the other loads. Some medium voltage motor and home applications need medium voltage. The multilevel inverter has been introduced since 1975 as a substitute in high power and medium voltage situations. The Multilevel inverter is similar to an inverter and it is used for industrial applications as a substitute in high power and medium voltage conditions.

The need for the multilevel converter is to give high output power from a medium-voltage source. Sources like batteries, supercapacitors, the solar panels are medium voltage sources. The multilevel inverter consists of several switches. In the multilevel inverter, the arrangement switches' angles are very important.

Multilevel inverters are three types.

- Diode clamped multilevel inverter
- Flying capacitors multilevel inverter
- Cascaded multilevel inverter

2.2.1 Diode clamped multilevel inverter

The key perception of this inverter is to use diodes and sends the multiple voltage levels through the different phases to the capacitor banks which are in series. A diode allows a limited amount of voltage, so dipping the stress on other electrical devices. The diode clamped multilevel inverter topology as shown in Fig. 2.1. The applied DC voltage is divided into various levels via capacitors, for *N* level inverter *N-1* capacitors are essential. Diodes are used to clamp the output voltages.

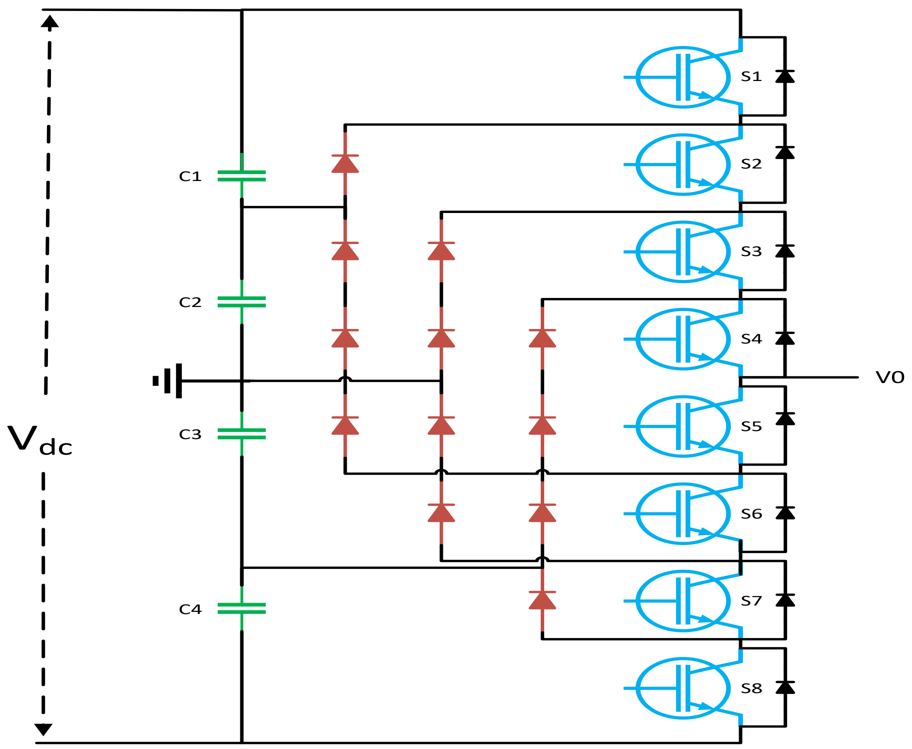

Fig. 2.1 Diode clamped multilevel inverter

Table.2.1 Modes of operation of diode clamped multilevel inverter

V0	S1	S2	S3	S4	S5	S6	S7	S8
$V_{dc}/2$	1	1	1	1	0	0	0	0
$V_{dc}/4$	0	1	1	1	1	0	0	0
0	0	0	1	1	1	1	0	0
$-V_{dc}/4$	0	0	0	1	1	1	1	0
$-V_{dc}/2$	0	0	0	0	1	1	1	1

This type of multilevel inverter is used in

- Static var compensation
- Variable speed motor drives
- High voltage system interconnections
- High voltage DC and AC transmission lines

The main advantages of using this multilevel inverter are:

- More efficiency for switching at the fundamental frequency.
- Pre charging of capacitors is done in groups.
- Efficient for back to back high-power connections.
- Lesser number of components.
- Low cost.

Disadvantages of using this multilevel inverter are:

Quadratic relation between the number of diodes and the number of levels is difficult to calculate, especially when the number of levels gets higher it becomes stressful and you would surely want to avoid it.

- Maintaining certain charging and discharging is difficult.
- Charge equilibrium gets disturbed for more than three levels.
- Limited output voltage.

2.2.2 Flying capacitors multilevel inverter

The main perception of this inverter is to use capacitors. It is of a series connection of capacitor clamped switching cells. The capacitors allow a limited amount of voltage to electrical devices. In this inverter switching states are similar in the diode clamped inverter. Clamping diodes are not needed in this type of multilevel inverters. Each leg consists of switching devices which are normally transistors. Every inverter limb contains cells connected in inward nested series. Every single cell has a single capacitor and two power switches. The power switch is a combination of a transistor connected with an anti-parallel diode. Like diode clamped inverter, this topology uses capacitors for clamping. An inverter with N cell will have $2N$ switches and $N+1$ different voltage level including zero. We can also have negative voltage levels, and so, all in all, we can say that N cell multilevel inverter can give a $2N+1$ voltage level. Capacitors nearer to the load have lower voltage Capacitors nearer to the source voltage (V_{dc}) have a higher voltage. The number of levels depends upon the number of conducting switches in each limb. They are called Flying Capacitor Multilevel Inverter because the capacitors float concerning to earth's potential. The main advantage of this multilevel inverter is each branch can be analysed separately and individually. The flying capacitor multilevel inverter topology is shown in Fig. 2.2.

Voltage balancing of capacitors:

One of the main advantages of using a Flying capacitor multilevel inverter is it's able to work at voltages higher than the blocking ranges of each power cell consisting of a diode and switching elements. Current co-efficient of an individual limb is equal and opposite in polarity. So, there is no net change in charge of capacitors. The cell and capacitor voltage

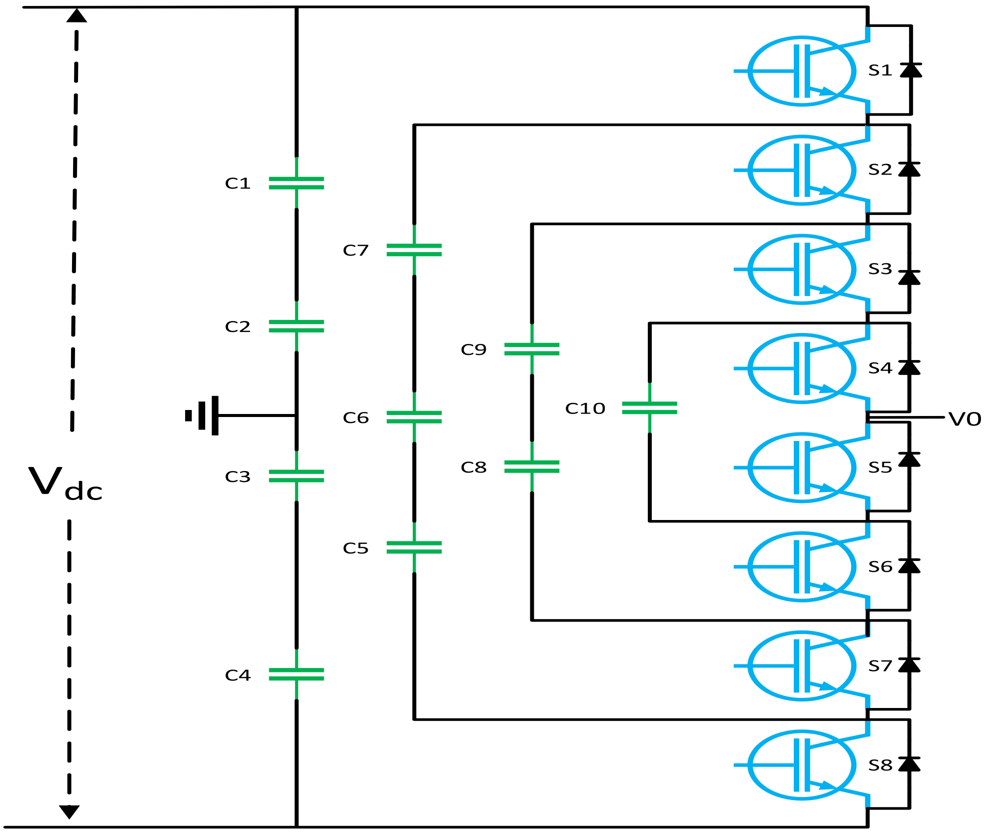

Fig.2.2 Flying capacitor multilevel inverter

Difference is sustained within a safe range and hence there is no chance of unbalancing the capacitor voltages.

Table.2.2 modes of operation of flying capacitor multilevel inverter

V_0	S1	S2	S3	S4	S5	S6	S7	S8
$V_{dc}/2$	1	1	1	1	0	0	0	0
$V_{dc}/4$	1	1	1	1	1	0	0	0
0	1	1	0	0	1	1	0	0
$-V_{dc}/4$	1	0	0	0	1	1	1	0
$-V_{dc}/2$	0	0	0	0	1	1	1	1

Switching strategy:

To synthesize a sinusoidal waveform at the output, the switching strategy needs to be defined. It is quite simple. Every voltage is applied at the output with a certain electrical angle. Careful application of the angle gives low harmonic distortion an requires amplitude at the output

More than one switching strategies are existing for a single voltage level. Three conditions should be shadowed for the right choice:

- For every change in the state, only one switch shift should be allowed.
- The capacitor's voltage balance should be maintained.
- All the switching devices are used equally.

The disadvantages of using this multilevel inverter is pre charging of capacitors is necessary and difficult

This multilevel inverter is used in:

- Induction motor control with DTC (Direct Torque Control) circuit
- Static var generation
- Both AC-DC and DC-AC conversion applications
- Converters with Harmonic distortion capability
- Sinusoidal current rectifiers

2.2.3 Cascaded multilevel inverter

Cascaded multilevel inverters are classified into

a) Cascaded H-Bridge multilevel inverter
b) Cascade Half-Bridge multilevel inverter
c) Cascaded switched Diode multilevel inverter

a) Cascaded H-Bridge multilevel inverter

The cascaded H-bride multilevel inverter is to use capacitors and switches and requires a smaller number of components at each level. This topology consists of a series of power conversion cells and power can be easily scaled. The mixture of capacitors and switches pair is called an H-bridge and gives the distinct input DC voltage for each H-bridge. It consists of H-bridge cells and each cell can deliver the three different voltages like zero, positive DC and negative DC voltages. One of the advantages of this type of multilevel inverter is that it needs a smaller number of components compared with diode clamped and flying capacitor inverters. The cost and mass of the inverter are less than those of the two inverters. Soft-switching is possible by some of the new switching methods.

Multilevel cascade inverters are used to eradicate the bulky transformer required in case of conventional multi-phase inverters, clamping diodes required in case of diode clamped inverters and flying capacitors required in case of flying capacitor inverters. But these require a large number of isolated voltages to supply each cell.

The cascaded H-bridge inverter has drawn tremendous interest due to the greater demand for medium-voltage high-power inverters. The cascaded inverter uses series strings of single-phase full-bridge inverters to build multilevel phase legs with separate dc sources. A single H-bridge is shown in Fig. 2.3. The output of individual H-bridge can have three discrete levels, in a staircase waveform that is closely sinusoidal even without filtering. A single H-bridge is a three-level inverter. individual single-phase full-bridge inverter generates three voltages at the output: V_{dc}, *0*, $-V_{dc}$. The four switches *S1, S2, S3,* and *S4* are controlled to generate three discrete outputs V_{out} with levels *0,* V_{dc} and $-V_{dc}$. When *S1* and *S2* are on, the output is V_{dc}. when *S3* and *S4* are turned on, the output is $-V_{dc}$; when either pair *S1* and *S3* or *S2* and *S4* are on, the output is 0. Fig. 2.4 shows a single-phase, five-level cascaded H-bridge cell inverter realized by connecting two three-level conventional full-bridge inverters in series was presented in Tolbert et al (1999). The switch sets *S1* and *S3* and *S2* and *S4* are opposite

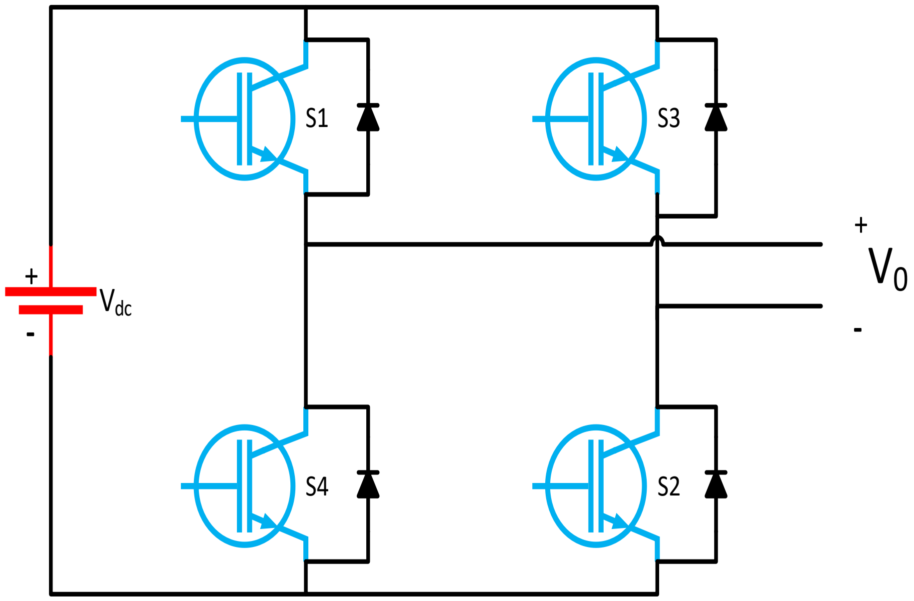

Fig. 2.3 Single H-Bridge Topology

to each other. The different voltage levels that can be obtained at the output terminals are *0*, V_{dc}, $-V_{dc}$, $2V_{dc}$, $-2V_{dc}$. If the dc voltage sources in both the inverter circuits associated in series

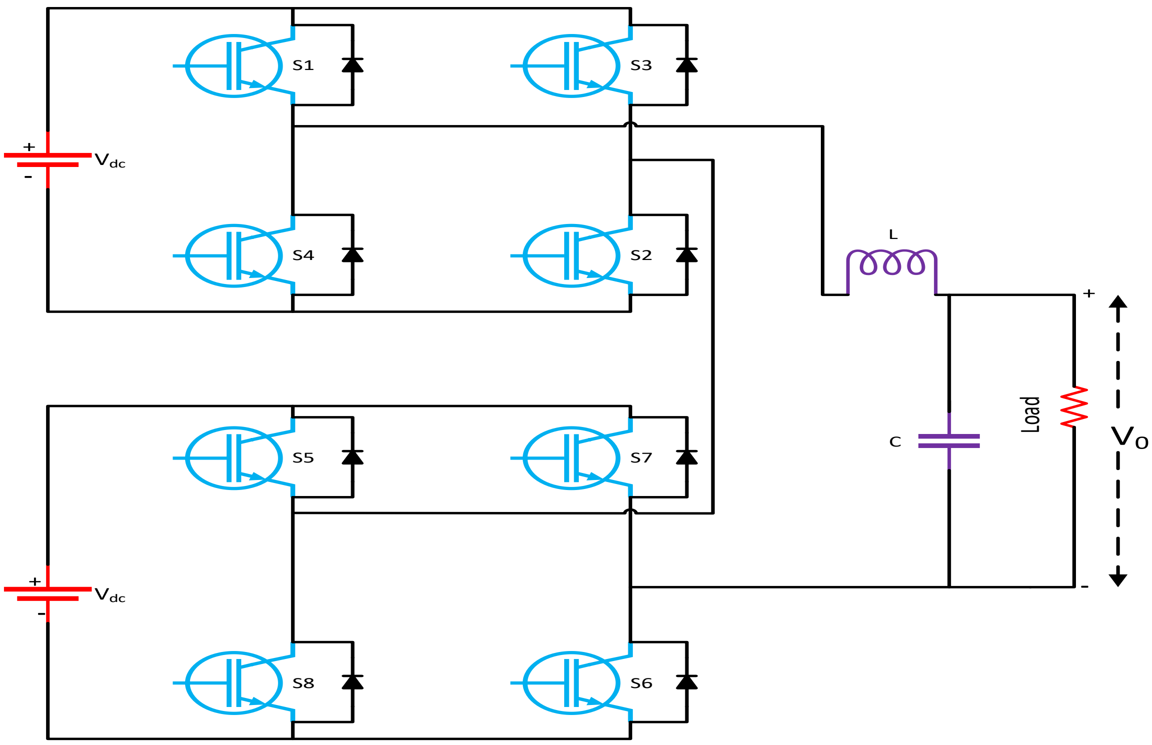

Fig. 2.4 5 Level Cascaded H-Bridge multilevel Inverter

are not equal to each other, then nine levels can be obtained at the output terminals. The number of levels in the output voltage can be amplified by two by adding a similar inverter in series. The *n* number of output phase voltage levels in a cascaded inverter with *s* separate dc sources is *2s-1* possible levels. Cascaded H-bridge cell inverters use the smallest number of power electronic devices when compared to any other topology. However, they require remote power sources in each cell which in turn needs a large isolating transformer. When the switches S_{a1}, S_{a2}, S_{b3}, and S_{b4} are on and S_{a3}, S_{a4}, S_{b1}, and S_{b2} are turned off, the corresponding output voltage of the cascaded H- bridge multilevel inverter is zero. The switches S_{a1}, S_{a2}, S_{b1}, and S_{b2} are turned on and S_{a3}, S_{a4}, S_{b3}, and S_{b4} are turned off, the corresponding output voltage of the cascaded H-bridge multilevel inverter is $2V_{dc}$. Similarly, the output voltages for additional switching stages are shown in Table 2.1.

Table 2.3 Switching States for 5 Level Cascaded H-Bridge

V_0	S1	S2	S3	S4	S5	S6	S7	S8
V_{dc}	1	1	0	0	0	1	0	0
$2V_{dc}$	1	1	0	0	1	1	0	0
0	0	0	0	0	0	0	0	0
$-V_{dc}$	0	0	0	1	0	0	1	1
$-2V_{dc}$	0	0	1	1	0	0	1	1

The advantages of cascaded multilevel H-bridge inverter are the following:

- The series construction permits a scalable, modularized circuit layout and packaging due to the identical structure of each H-bridge.
- No additional clamping diodes or voltage balancing capacitors are necessary.
- Switching unnecessary usage for inner voltage levels is possible because the phase voltage is the sum of the output of each bridge.

The disadvantage of cascaded multilevel H-bridge inverter is the following:

- Needs separate DC sources.
- It requires more switching devices.

b) Cascaded Half-Bridge multilevel inverter

The basic unit of novel cascaded multilevel inverter is half-bridge. Fig. 2.6 shows the configuration of the half-bridge cascaded multilevel inverter. The maximum output voltage of the multilevel inverter is given by (1)

$$V_0 = V_{01} + V_{02} + \cdots + V_{0n} \tag{2.1}$$

In the topology of Fig. 2.6, assuming that in each half-bridge unit the DC voltage is equal to *E*. the half-bridge only generates two kinds of voltage levels: *E*, *0*; and all voltage levels generated by the half-bridge are synthesized before the H-bridge, therefore, the synthesized voltage levels become nE, $(n-1)E$, $\cdots$, 0. The function of the H-bridge is flipping the polarity of the output voltage at the negative half, it means that, at the negative half cycle, the H-bridge turns synthesized voltage levels from positive to negative. Therefore, output voltage levels become $nE, (n-1)E, \cdots, 0, \cdots, -(n-1)E, -nE$.

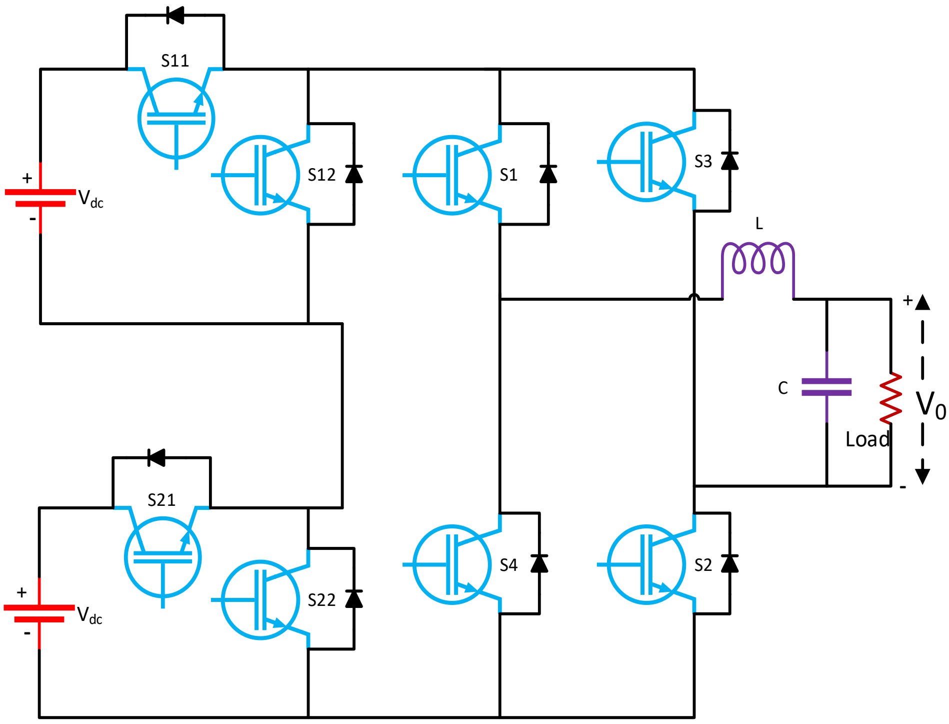

Fig.2.5 Cascaded Half-Bridge Multilevel Inverter

If all the DC voltage sources in Fig. 2.5 are equal to *E*, the inverter can also be called the symmetric multilevel inverter. The number of maximum output voltage steps of the *N* series basic units can be evaluated by (2) and the maximum output voltage is given by (3).

$$N_{step} = 2N + 1 \tag{2.2}$$

$$V_{omax} = NE \tag{2.3}$$

the novel topology of cascaded multilevel inverter reduces the number of devices without affecting the function of the electronic system. In Fig. 2.5, based on the same DC sources, the topology needs $2N+4$ semiconductor devices to realize the N_{step} staircase output waveform and in Fig. 2.4, the topology needs $4N$ semiconductor devices to realize the N_{step} staircase output waveform. With the increase of the number of cascaded units, the novel topology needs fewer semiconductor devices compared with cascaded H-bridge multilevel inverter. It compared the novel topology with the conventional cascaded multilevel inverter topology at the power component requirements, the standing voltage of switches, and the number of switches. Through the comparison, the novel topology needs fewer switches to realize the same output voltage, reduces the installation area and the number of gate drivers, so the cost is less.