# Review of Multilevel Inverter Topologies and Its Applications

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***Abstract*—Nowadays, multilevel inverter technologies have attracted attention as a convenient solution in many industrial applications. There are a few interesting features of using this configuration, where less component count, less switching losses, and improved output voltage/current waveform. The most significant criteria in multilevel inverter is the minimization of harmonic components in the inverter output voltage/current. The evolution of multilevel inverter technologies and the commercial products based on a multilevel inverter topology has shown tremendous developments due to the many advantages. In this paper, a review of the classical multilevel inverters and the recently introduced topologies are presented. They are trending as the most preferable power electronics device that have been widely used in the applications like motor-drive applications up to MegaWatt (MW) power levels, renewable energy (solar/wind power inverters) and reactive power compensation (i.e. STATCOM). This paper provides a general comparisons for various type of multilevel inverters and their suitable applications with useful references.**

***Index Terms*—Multilevel Inverter; High-Power Applications; Power Electronics Devices.**

## I. INTRODUCTION

Recently, a demand for a high voltage, higher power converters which are capable of producing the high quality waveforms, whilst utilizing low voltage devices and reduced switching frequencies has led to the multilevel inverter development. As a result of high efficiency, they have been benefitting the applications which require medium voltage levels with high power in comparison to the traditional inverters with two levels. It must be noted that high power ranges from 1 - 50 MW, while medium ranged voltage from 2.3 - 6.6 kV [1]. Over the past decades, there are various multilevel inverter topologies which have been successfully developed as a substitute for high power and medium voltage applications, and they offer better approaches than series connection and single switch. Following are the advantages of utilising multilevel inverters:

1. The efficiency is very high due to the minimum switching frequency.
2. They can improve power quality and dynamic stability of the utility systems.
3. The switching stress and electromagnetic interference (EMI) are low.

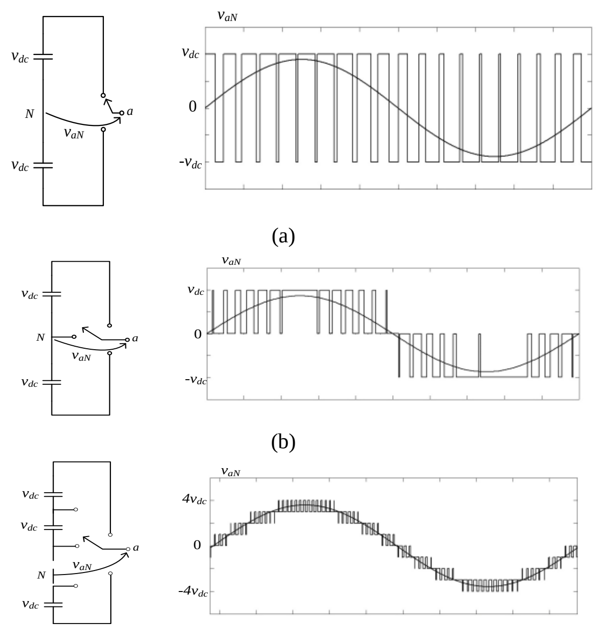


Figure 1: Basic concepts of inverters (a) Two-level (b) Three-level (c) Nine-level

4. Due to their modular and simple structure, they can be stacked up to an almost unlimited number of levels.
5. They are an ideal interface between the utility and renewable energy sources (i.e. PV or fuel cells).

This paper is aimed at presenting a comprehensive and detailed investigation about the categories of multilevel inverter topologies available. In addition to this, brief explanations and accounts of various topologies and their applications have been furnished in the paper.

This paper is structured in following sections. Section 2 discussed about the technology used in multilevel inverters. Subsequently, in section 3, the description of eight types of multilevel inverter topologies has been discussed. Finally, the conclusion has presented in section 4 of this paper.

## II. MULTILEVEL INVERTER TECHNOLOGY

The origin of multilevel inverter idea is from the power semiconductors array with several sources of DC voltage producing waveforms of multiple step voltage with controllable and variable amplitude, frequency and phase when it is controlled properly [2].

The major difference between two level voltage source inverter (VSI) and the multilevel inverter is the quantity of voltage levels which have been illustrated in Figure 1. With two-level VSI producing only two levels of voltage, multilevel inverters are capable of producing an unlimited quantity of voltage levels, theoretically. The multilevel inverters have a minimum of three voltage levels.

The quality of a power converter is judged by the quality of its voltage and current waveforms. The measurement of harmonic spectra can be expressed in terms of total harmonic distortion (THD). In the case of multilevel inverter system, the most significant criterion is the minimization of harmonic components in the inverter output voltage/current. The THD could be decreased by increasing the number of levels in the voltage output by either using certain control schemes or filter designs. The lower the THD value, the better its power quality.

## III. MULTILEVEL INVERTER TOPOLOGIES

Generally, there are three well established and classical topologies of multilevel inverter. These are as follows:

1. Neutral point clamped (NPC) or diode clamped
2. Flying capacitor (FC) or capacitor clamped
3. Cascaded H-bridge (CHB)

In recent times, researchers have overcome the multilevel inverter circuit's complexity by switches arrangement which helped in production of a completely new variety of topologies: active NPC (ANPC) multilevel inverter, hybridized cascaded H-bridge (HCHB) multilevel inverter, modular multilevel converter (MMC), switched series/parallel sources (SSPS)-based multilevel inverter and H-bridge and two-level power modules (HBTPM)-based multilevel inverter. These topologies are discussed in this paper.

### *A. Neutral Point Clamped Multilevel Inverter*

Neutral point clamped (NPC) inverter was initially introduced in 1981 by Nabae et al. [3]. It was considered as the first type of multilevel inverters, known as the 3-level NPC.

Figure 2 shows a single phase 5-level NPC power circuit. It has been constructed by utilizing two traditional inverters of 2-level. One has been fixed over the other for the purpose of stacking. Moreover, two diodes of series-connected have been joined between lower and upper inverter between the neutral mid-points, *N*. Capacitors assist in splitting the DC bus voltage in two identical phases. Thus, the requirement for having an extra source of DC is invalid in this case.

Over the past thirty years, these inverters have commonly been used in industrial applications requiring approximately 6kV. For supporting a higher operating and power voltage, NPC inverter could be stretched and extended to higher levels of voltage. It is fairly easy to extend the scheme to a common *n*-level conformation and arrangement. Conversely, the use of NPC topology in industrial application is limited to 3-level only because of the series connected capacitors require voltage balancing control.

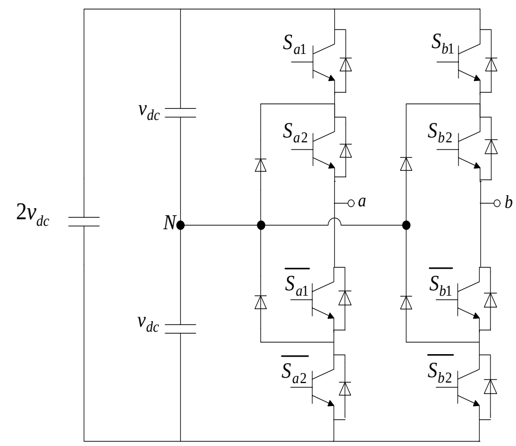


Figure 2: Neutral point clamped multilevel inverter

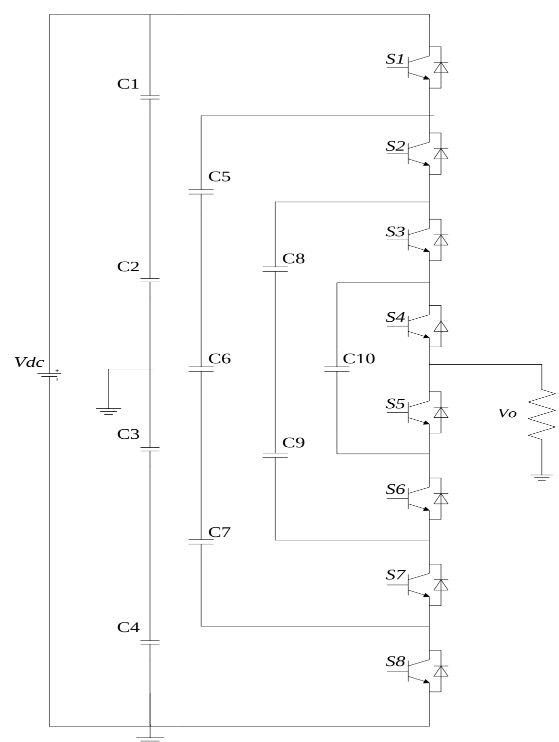


Figure 3: Flying capacitor multilevel inverter

### *B. Flying Capacitor Multilevel Inverter*

In mid-1990s, Meynard and Foch [4] and Lavieville et al. [5] introduced flying capacitor (FC) inverter which is considered as another modification of multilevel inverter topology. The basis of this inverter was the usage of capacitors. It is built up by connecting a series of capacitors clamped switching cell. Limited voltages are transferred to electrical devices through capacitors.

The switching states in FC inverter are similar to the NPC inverter. However, clamping diodes are not needed for this topology of multilevel inverter. The advantages of these inverters are have redundancy of switching within the phase for balancing the FC. It has the ability to control both reactive and active flows of power. An excellent illustration of half-

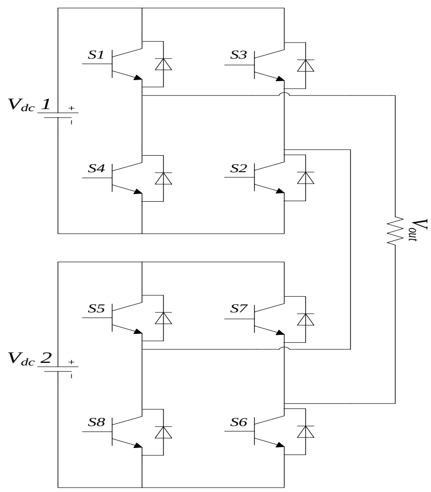


Figure 4: Cascaded H-bridge (CHB) multilevel inverter

bridge topology of FC multilevel inverter is shown in Figure 3. The main drawback of the half-bridge of FC inverter is that its output voltages are almost half of the input DC voltage.

### *C. Cascaded H-Bridge Multilevel Inverter*

In the mid of 1970s, Baker and Bannister [6] described the first patent of converter topology which had the ability to produce multilevel voltages through the source of various DC voltage. In this topology, a series of single phase inverters were linked and connected together. The circuit of CHB multilevel inverters have been designed with eight switches consisting of five levels of inverter. Each source of DC is linked with the corresponding H-bridge generating five unique voltage outputs. These outputs vary from -2$V_{dc}$, -$V_{dc}$, 0, +$V_{dc}$, and +2$V_{dc}$ by utilization of switching combinations of four switches [7]. The series of H-bridge connections synthesise the multilevel inverter output. In cascaded inverter, the number of voltage levels for output phase are calculated through $n = 2s + 1$, where, $s$ is the number of DC sources and $n$ is the inverter output levels. Figure 4 shows the single phase 5-level CHB multilevel inverter.

### *D. Active NPC Multilevel Inverter*

A new multilevel inverter names as active clamped (ANPC) multilevel inverter has presented by Bruckner et al. [8],[9]. It was introduced with the intention of overcoming the inadequate and uneven losses share between outer and inner switched through the placement of power switches instead of normal diodes [10]. The 3-level ANPC inverter is shown in Figure 5.

Figure 6 shows the 9-level ANPC multilevel converter which combination of NPC and FC inverter topologies [10]. The number of two-level inverter in this arrangement is obtained by ($n$-1) / 2, where $n$ is the inverter output levels. Therefore, there are four two-level inverters were cascaded to obtain a 9-level inverter in each part of this topology. There are three main parts in this type of ANPC multilevel converter. The switches $S_9$ to $S_{16}$ and capacitors $C_4$, $C_5$, $C_6$ are comprised in the first part while, the switches $S_{17}$ to $S_{24}$ and capacitors $C_7$, $C_8$, $C_9$ are comprised in the second part of this inverter. In the third part of this inverter, switches $S_1$ to $S_8$ and capacitors $C_1$,

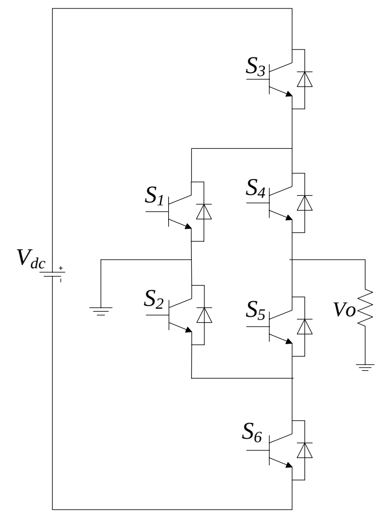


Figure 5: Active NPC multilevel inverter

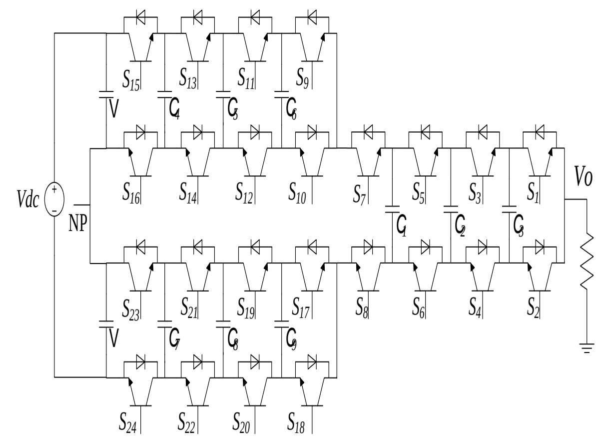


Figure 6: Active NPC multilevel inverter (combination of NPC and FC inverter topologies

$C_2$, $C_3$ are comprised and it is used to connect the inverter to the load.

### *E. Hybridised Cascaded H-Bridge Multilevel Inverter*

A new classification of multilevel inverter was presented by Odeh and Nnadi [11] namely hybridised cascaded H-bridge (HCHB) multilevel inverter. Figure 7 shows a 9-level HCHB multilevel inverter with two DC input voltages. In this kind of inverter topology, nine levels of voltages per cycle are provided by interconnecting of two 5-level hybrid inverter. This type of topology is similar to the CHB topology.

The only difference is that in each H-bridge cell, an auxiliary/clamping switch has been added for enhancement of the harmonic profile of waveforms which are attained in the output. In comparison to the traditional CHB inverter, the number of components used in this topology is highly reduced for the similar output voltage level [12].

Keeping into view the switching and operational functions, the benefits of HCHB multilevel inverter are doubled RMS output voltage value, voltage steps quantity and reduction of DC source. The main limitation of this topology is that it cannot be used in the applications where high voltages are required.

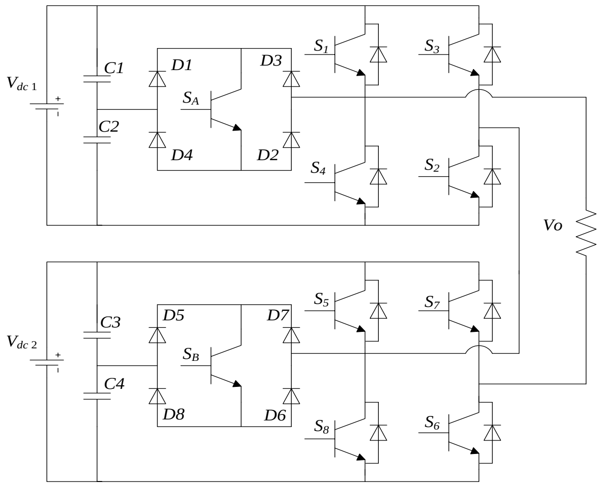


Figure 7: Hybridised cascaded H-bridge (HCHB) multilevel inverter

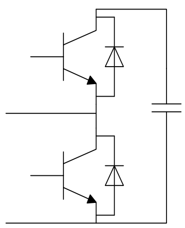

Figure 8: Single modular multilevel converter (MMC) cell

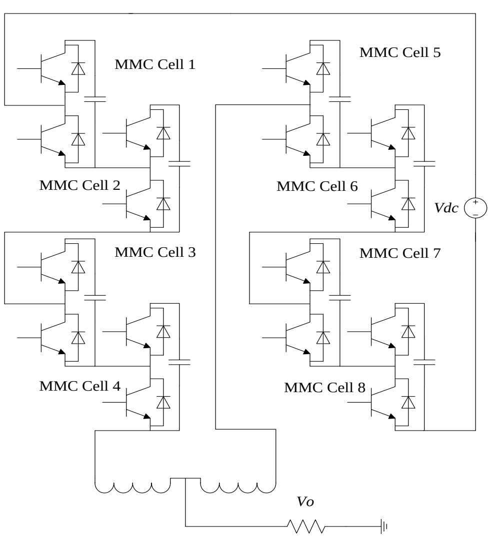


Figure 9: Modular multilevel converter

## F. Modular Multilevel Converter

There is another new classification of the multilevel inverter, named as modular multilevel converter (MMC) were presented by Lesnicar and Marquardt in [13]. In comparison to CHB inverter, MMC has a simplified construction and there are various advantages of it. These advantages include redundancy and modular extension to any output level.

A single cell of MMC is shown in Figure 8. A single cell of MMC constitutes of two switches with one balancing capacitor. The 9-level MMC topology is illustrated in Figure 9. The connection of 9-level MMC consists of 8 cells which

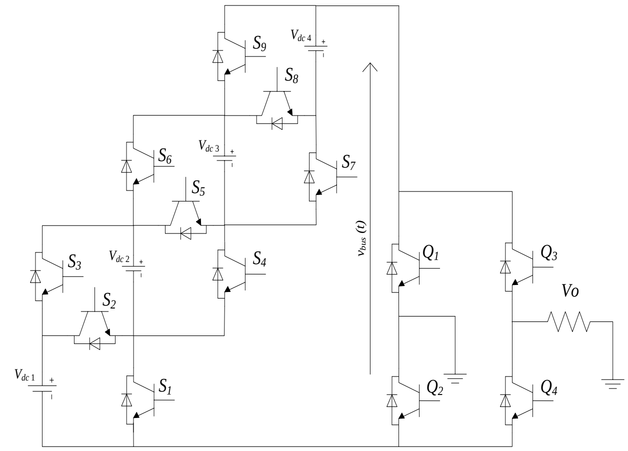


Figure 10: Switched series/ parallel sources (SSPS)-based multilevel inverter

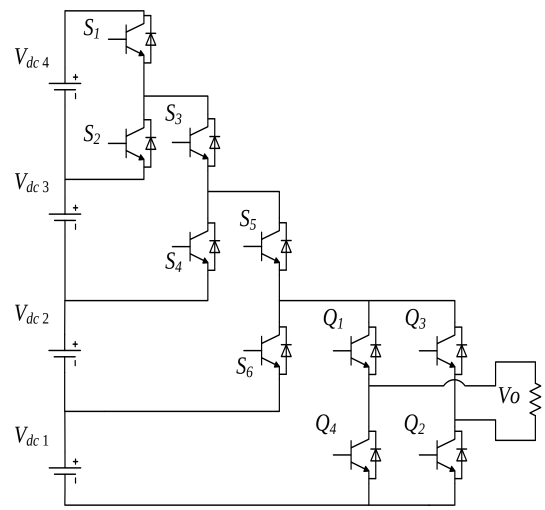


Figure 11: H-Bridge and two-level power modules (HBTPM)-based multilevel inverter

connected by 2 sets of cells in parallel. Each set of cell consists of 4 cells that have a series of connection. In cascaded inverter, the quantity of voltage levels in output phase is similar to cascaded H-bridge inverter which is $n = 2c + 1$, where $n$ is the inverter output levels and $c$ represents the number of cells connected in this cascaded MMC.

## G. Switched Series /Parallel Sources-based Multilevel Inverter

Hinago and Koizumi [14] proposed multilevel inverter which consists of DC sources that could be switches in parallel and in series along with the H-bridge. This topology is referred as switched series/parallel sources (SSPS)-based multilevel inverter. For producing the similar levels of output as CHB, the similar number of sources is required by SSPS inverter but will the lesser quantity of switches.

Figure 10 shows the aforesaid topology of 9-level SSPS multilevel inverter with four input DC sources, based on two sections. First sections comprise of switched sources and produces bus voltage $v_{bus}(t)$ and the second section synthesizes negative and positive cycles of voltage $v_{bus}(t)$ for feeding AC load. The four sources which are $V_{dc1}$ to $V_{dc4}$ and power

Table 1
Comparison of power electronics components and applications for various multilevel inverter topologies

| Multilevel Inverter Topology | Number of level | Power Switches | Power Diodes | DC bus Capacitors | Balancing Capacitors | Isolated DC Supply | Applications |
|---|---|---|---|---|---|---|---|
| NPC | 9 | 16 | 12 | 4 | - | 1 | Renewable energy<br>Motor drives [16] |
| FC | 9 | 16 | - | 4 | 6 | 1 | Renewable energy<br>Motor drives |
| CHB | 9 | 16 | - | 4 | - | 4 | Renewable energy<br>FACTS [17] |
| ANPC | 9 | 28 | - | 4 | - | 1 | Renewable energy |
| ANPC (NPC + FC) | 9 | 24 | - | 2 | 9 | 1 | Renewable energy |
| HCHB | 9 | 10 | 8 | 4 | - | 2 | Renewable energy [18]<br>Motor drive [19] |
| MMC | 9 | 16 | - | - | 8 | 1 | High Voltage DC (HVDC) transmission [20]<br>STATCOM [21] |
| SSPS | 9 | 13 | - | - | - | 4 | Renewable energy<br>Electric vehicle [14] |
| HBTPM | 9 | 10 | - | 4 | - | 1 | Renewable energy |

switches $S_1$ to $S_9$ consist in the first part while power switches $Q_1$ to $Q_4$ consist in the second part.

An important application suggested is for electric vehicular applications where a single battery composed of a number of series-connected battery cells is available. It can be rearranged using the SSPS topology, hence reducing the requirement of switching devices. More importantly, possibility of combining two or more sources in series and parallel gives enough flexibility for meeting voltage/power requirements in the vehicle drive system.

### H. H-Bridge and Two-level Modules-based Multilevel Inverter

Suroso and Noguchi [15] introduced a topology of multilevel inverter known as H-bridge and two-level power modules (HBTPM) multilevel inverter. Figure 11 shows the 9-level topology inverter with four input DC sources $V_{dc1}$ to $V_{dc4}$. The terminals with low potentials of sources are interconnected with the help of power switches. Along with this, they are also connected to the high potential terminal of proceeding source through power switches. There are two parts of this topology; one is polarity generation ($Q_1$ to $Q_4$) and the other is level generation ($S_1$ to $S_6$).

Although the structure is simple but it could be seen that there are very limited possibilities of various levels synthesis at bus end. In fact, all the individual level accessible by sources could not be obtained as $v_{bus}(t)$, except $V_{dc1}$. This is the reason, why no possibilities of asymmetric source configuration are offered by this topology for further reduction of switch count.

### I. Summary of the Multilevel Inverter Topologies and Its Applications

Finally, the general comparisons for various type of multilevel inverters and their industrial applications are presented in Table 1. The comparisons are made for single phase inverter system with the same 9-level voltage outputs. Some applications of multilevel inverter such as, motor drives, renewable energy, flexible AC transmission system (FACTS), high voltage DC (HVDC) transmission and static synchronous compensator (STATCOM) systems were visualized the applications that can be suited with multilevel inverters.

## IV. Conclusion

With the advancement and development of various industries and sectors at international as well as domestic levels, demands for high energy converters are continuously increasing. It can be said that the multilevel inverters are continued to gain popularity and importance for the applications of low as well as high power. This paper has presented and discussed eight categories of multilevel inverter topologies. Based on the review, conclusion can be done in the process of reducing the power switch count of multilevel inverters, is either by reducing or re-arranging the DC input voltages. Other than that, particular topological explanations and resolutions have been provided by various researchers considering the intended use of application.

## Acknowledgment

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