ELIMINATION THD USING 9-LEVEL DC TO AC CASCADE H-BRIDGE MULTILEVEL INVERTER

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ABSTRACT

Nowaday, electronic devices are very sensitive with harmonics. The needs for a free harmonic and high rating power source is increased to meet the requirement from the industries. This project is to eliminate THD using 9 level cascaded H-bridge of multilevel DC–AC inverter. An Inverter can be broadly classified into single level inverter and multilevel inverter. The result of 9 Cascaded H-Bridge Multilevel Inverter level THD value are compared with 2 level inverter and 5 level Cascaded H-Bridge Multilevel Inverter. The compared multilevel inverter to a single level inverter has advantages like minimum harmonic distortion and higher power output. An implementation of cascaded H-Bridge topology and a sinusoidal pulse with modulation, synthesize a higher quality output power especially with multilevel configuration. Experimental results are included to demonstrate effectiveness of the proposed inverter. This project is to reduce THD contributed by the level of inverter.
CONTENTS

TITLE i
DECLARATION ii
DIDICATION iii
ACKNOWLEDGEMENT iv
ABSTRACT v
CONTENTS vi
LIST OF TABLES vii
LIST OF FIGURES ix

CHAPTER 1 INTRODUCTION 1
1.0 Project Background 1
1.1 Multilevel Converter 1
1.1 Multilevel inverter 4
1.3 Merit and Demerit of Multilevel Inverter 7
1.4. The Switching 8
1.5 Control Techniques 8
1.6. Problem Statements 9
1.7 Project Objective 10
1.8 Project Scopes 11

CHAPTER 2 LITERATURE REVIEW 12
2.1 Theories 12
2.1.1 Inverter 12
2.1.2 Cascaded H-bridge Multilevel Inverter 14
2.2 Diode-Clamped Multilevel Inverter 21
2.3 Flying Capacitor Multilevel Inverter 24
2.4 Pulse Modulation Scheme 28
2.4.1 Pulse Amplitude Modulation 28
2.4.2 Pulse Width Modulation
2.4.3 Pulse Position Modulation
2.4.4 Pulse Code Modulation
2.5. Performance parameters of inverters
2.6. Harmonic factor of nth harmonic.
   2.6.1 Total harmonic distortion (THD)
   2.6.2 Selective Harmonic elimination
   2.6.3 Distortion factor (DF)
   2.6.4 Lowest –order harmonics (LOH)
   2.6.5 Sinusoidal Pulse Width Modulation
2.7 Fault diagnosis in multilevel converters

CHAPTER 3
METHODOLOGY
3.0. Project Methodology
3.1 Simulation
3.2 Control Scheme and Algorithm Development
3.3 Inverter modelling
3.4 System Integration and Data Collection

CHAPTER 4
MODELLING AND SIMULATION
4.0 Simulink® SimPowerSystem
4.1 Simulink® S-Function
4.2 System Overview
   4.2.1 Control Block
   4.2.2 Inverter Circuit Block
   4.2.3 Measurement

CHAPTER 5
RESULT AND ANALYSIS
5.0 Voltage and current
5.1 Total Harmonic Distortion (THD)

CHAPTER 6
CONCLUSION AND SUGGESTION
6.0 Conclusion
6.1 Suggestion

REFERENCES
APPENDIX A
APPENDIX B
LIST OF TABLES

2.2  Diode-clamped six-level inverter voltage levels and corresponding switch states.  22
2.3  Flying-capacitor six-level inverter redundant voltage level and corresponding switch states  27
5.0  Voltage and Current for 9-Level CHB Multilevel Inverter  52
5.1  Voltage and Current for 5-Level CHB Multilevel Inverter  53
5.2  Voltage and Current for 2-Level Inverter  53
5.3  Comparism THD Value of 2-Level Inverter, 5-Level CHB MLI and 9-Level CHB MLI  55
## LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>Multilevel Inverter Output Waveform Using 5 Equal DC sources</td>
<td>2</td>
</tr>
<tr>
<td>1.1</td>
<td>Comparison of output phase voltage waveforms:</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>(a) two-level inverter, (b) three-level, (c) nine-level.</td>
<td></td>
</tr>
<tr>
<td>1.2</td>
<td>Multilevel inverter driven application overview</td>
<td>5</td>
</tr>
<tr>
<td>1.3</td>
<td>Multilevel inverter types:</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>(a) three-level DC-MLI, (b) three-level FC-MLI, (c) five-level CHB-MLI</td>
<td></td>
</tr>
<tr>
<td>1.4</td>
<td>Classification of multilevel inverter control scheme</td>
<td>9</td>
</tr>
<tr>
<td>2.1</td>
<td>Voltage source inverter(VCI) with variable DC link</td>
<td>13</td>
</tr>
<tr>
<td>2.2</td>
<td>M-Level Single Phase Cascaded H-Bridge Multilevel Inverter</td>
<td>15</td>
</tr>
<tr>
<td>2.3</td>
<td>Cascaded H-Bridge Multilevel Inverter Generalize Output Waveform</td>
<td>15</td>
</tr>
<tr>
<td>2.4</td>
<td>Three-phase wye-connection structure for electric vehicle motor drive and</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>battery charging.</td>
<td></td>
</tr>
<tr>
<td>2.5</td>
<td>Cascaded multilevel converter with transformers using standard</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>three-phase bi-level converters</td>
<td></td>
</tr>
<tr>
<td>2.6</td>
<td>Three-phase six-level structure of a diode-clamped inverter</td>
<td>22</td>
</tr>
<tr>
<td>2.7</td>
<td>Line voltage waveform for a six-level diode-clamped inverter</td>
<td>23</td>
</tr>
<tr>
<td>2.8</td>
<td>Three-phase six-level structure of a flying capacitor inverter</td>
<td>25</td>
</tr>
<tr>
<td>2.9</td>
<td>Basic Concept of Sinusoidal PWM generation</td>
<td>32</td>
</tr>
<tr>
<td>2.10</td>
<td>Switching Scheme of the PWM</td>
<td>33</td>
</tr>
<tr>
<td>2.11</td>
<td>Half-Bridge Inverter</td>
<td>33</td>
</tr>
<tr>
<td>2.12</td>
<td>Generated PWM Signal from the Mathematical Operation of Carrier and</td>
<td>34</td>
</tr>
<tr>
<td></td>
<td>Reference Signals</td>
<td></td>
</tr>
<tr>
<td>2.13</td>
<td>Structure of fault diagnosis system of a multilevel cascaded H-Bridges</td>
<td>36</td>
</tr>
<tr>
<td>3.0</td>
<td>Flowchart of Research Process</td>
<td>38</td>
</tr>
<tr>
<td>3.1</td>
<td>Example model circuit using Matlab Simulink</td>
<td>39</td>
</tr>
<tr>
<td>3.2</td>
<td>Flowchart of the SPWM switching scheme</td>
<td>40</td>
</tr>
<tr>
<td>4.0</td>
<td>Simulink® User Interface and Toolbox Library Browser</td>
<td>43</td>
</tr>
<tr>
<td>4.1</td>
<td>Interconnections between Simulink® and SimPowerSystem</td>
<td>43</td>
</tr>
</tbody>
</table>
4.2 Graphical View of Interaction between M-File S-Function with Simulink®
4.3 Block Diagram of Simulation Model
4.4 (a) 9-level CHB Multilevel Inverter Gate Driver,
     (b) 5-level CHB Multilevel Inverter Gate Driver and (c) 2-level
     Inverter Gate Driver
4.5 Sinusoidal Reference Signal and Triangular Carrier Signals for 9-
     Level Multilevel Inverter
4.6 Switching Signals for each Individual MOSFET
4.7 9-Level Cascaded H-Bridge Multilevel Inverter
4.8 Measurement Block to Capture (a)THD , (b) Voltage and Current
4.9 Modelling and Simulation Setup for 9 Level Cascaded H Bridge
     Multilevel Inverter.
5.0 Output Voltage and Current of 10-level MLI at (a) m = 0.1, (b)
     m=0.8, (c) m=0.6, (d) m= 0.4
CHAPTER 1

INTRODUCTION

1.0 Project Background

Ac loads require constant or adjustable voltages at their input terminals. When such loads are fed by inverters, it’s essential that output voltage of the inverters is so controlled as to fulfill the requirements of AC loads. This involves coping with the variation of DC input voltage, for voltage regulation of inverters and for the constant volts/frequency control requirement. There are various techniques to vary the inverter gain. The most efficient method of controlling the gain (and output voltage) is to incorporate pulse-width modulation (PWM) control within the inverters. The carrier based PWM schemes used for multilevel inverters is one of the most straightforward methods of describing voltage source modulation realized by the intersection of a modulating signal (Duty Cycle) with triangular carrier waveforms. Multilevel inverters are commonly used for DC to AC conversion in renewable energy conversion [1-3].
1.1 Multilevel Converter

Three main multilevel converter topologies which have been mostly applied in engineering application are known as the cascaded h-bridge converter with separated dc sources, the diode clamp and the flying capacitor and Here, it seems important ‘multilevel inverter’. The word ‘multilevel converter’ refers to the converter itself. The implication of the term reflects that the power can flow in one of two directions. Power which flow from the ac side to the dc side of the multilevel converter is operated in rectification mode. Vice-versa, the power also can flow from the dc side to the ac side of the converter. This mode is called as inverting mode of operation. The ‘multilevel inverter’ term basically is a ‘multilevel converter’ that uses the inverting mode of operation.

The multilevel inverter is meant to generate a preferred ac voltage waveform from dc voltages. Figure 1.0 shows an example of ac voltage waveform generated from several dc voltages.

![Figure 1.0: Multilevel Inverter Output Waveform Using 5 Equal DC sources](image-url)
In above figure, five 120 V dc source produce a pulse waveform with a peak-to-peak voltage of 1200V. Here, the multilevel inverter produces a fair approximation to a sinusoidal waveform. This approximation will get better and better once the amount of dc sources increase. Ideally, once the number of dc sources reach infinity, the pulse waveform will become a pure desired sinusoidal.

On sidding a switching scheme, there are many techniques has been develop to be implemented on a multilevel inverter. For example, Sinusoidal PWM, Space Vector PWM, and Selective Harmonic Elimination PWM.

One of the merits of using multilevel inverter is the better total harmonic distortion over the well-known conventional two level inverters. This can be proven by undergo a simulation and experimental exercise.

A multilevel converter has several advantages over a conventional two-level converter that uses high switching frequency pulse width modulation (PWM). The attractive features of a multilevel converter can be briefly summarized as follows.

- Staircase waveform quality: Multilevel converters not only can generate the output voltages with very low distortion, but also can reduce the dv/dt stresses; therefore electromagnetic compatibility (EMC) problems can be reduced.

- Common-mode (CM) voltage: Multilevel converters produce smaller CM voltage; therefore, the stress in the bearings of a motor connected to a multilevel motor drive can be reduced. Furthermore, CM voltage can be eliminated by using advanced modulation strategies such as that proposed in

- Input current: Multilevel converters can draw input current with low distortion.

- Switching frequency: Multilevel converters can operate at both fundamental switching frequency and high switching frequency PWM. It should be noted that lower switching frequency usually means lower switching loss and higher efficiency.
Unfortunately, multilevel converters do have some disadvantages. One particular disadvantage is the greater number of power semiconductor switches needed. Although lower voltage rated switches can be utilized in a multilevel converter, each switch requires a related gate drive circuit. This may cause the overall system to be more expensive and complex.

Plentiful multilevel converter topologies have been proposed during the last two decades. Contemporary research has engaged novel converter topologies and unique modulation schemes. Moreover, three different major multilevel converter structures have been reported in the literature: cascaded H-bridges converter with separate dc sources, diode clamped (neutral-clamped), and flying capacitors (capacitor clamped). Moreover, abundant modulation techniques and control paradigms have been developed for multilevel converters such as sinusoidal pulse width modulation (SPWM), selective harmonic elimination (SHE-PWM), space vector modulation (SVM), and others. In addition, many multilevel converter applications focus on industrial medium-voltage motor drives [11, 15, 16], utility interface for renewable energy systems [17], flexible AC transmission system (FACTS) [18], and traction drive systems [19].

1.2 Multilevel inverter

In today market, multilevel inverter comes with many function and advantages. These advantages are focused on improvement in the output signal quality and a nominal power increase in the inverters. This also true if a comparism done to well known two-level inverter[2]. The term multilevel inverter was first introduced back in 1981 by Nabae[3]. By increasing the numbers of levels inverter, the output voltages have more steps generating a staircase waveform, which has reduced harmonics distortion[4]. Figure 1 shows the comparison of the quality between a single-phase two-level inverter is compared to three and nine level voltage multilevel waveform.
Figure 1.1: Comparison of output phase voltage waveforms:

(a) two-level inverter, (b) three-level, (c) nine-level. (source:[4])

Multilevel inverters has gained much attention in the application areas of medium voltage and high power owing to their various advantages such as a lower common mode voltage, lower voltage stress on power switch, lower dv/dt ratio to supply lower harmonics content in output voltage and current [5]. Figure 2 shows the overview of the driven application of multilevel inverter.

Figure 1.2: Multilevel inverter driven application overview (source:[4])
Three major multilevel inverter structure which has been mostly applied in industrial application have been emphasized as the diode clamp, the flying capacitor and cascade H-bridge inverter with separated DC sources. Based on these three basic types, a hybrid and a asymmetric hybrid has been developed. Figure 3 shows common multilevel inverter types.

From this three types, Diode Clamp(DC) inverters and cascaded inverters are most popular. DC inverter used in high power area, mainly are three level inverter[7]. Comparing with two level inverter, DC three level inverters have economic advantages. A multilevel inverter type with less power devices requirement compared to previously mentioned types is known as cascaded H-bridge multilevel inverter (CHB-MLI) and the type is based on the series connection of H-bridge with separate DC source. Since the output terminals of the H-bridges are connected in series, the DC source must be isolated from each other. This topology is a good choice for more than five-level output waveform. Cascade inverter have structurally no problem of dc-link voltage unbalancing.
but require many separated dc sources in motor drive applications. CHB has a least component requires for a given number of levels[5].

1.3 Merit and Demerit of Multilevel Inverter

Obviously, in recent years multilevel inverter has gained an attention from many areas due to its advantages over the conventional inverters. The ability of the multilevel inverter to utilize a large number of dc sources is one of the merits that it holds. This makes multilevel inverters able to generate high voltages and thus high power ratings. Due to this, the use of bulky and expensive transformers to produces high voltages with conventional 12, 24 and 48-pulse inverter can be abandoned.

Another advantage of multilevel inverter is that it has a reduced Total Harmonic Distortion (THD) with low switching frequencies. Furthermore, due to its lower voltage steps, the value of EMI is lesser and because of its capability to utilize multiple levels on the dc bus, the multilevel inverters able to trim down the voltage stress on each power devices. Additionally, multilevel inverters have higher efficiency because the devices can be switched at low frequency.

Nevertheless, there is still a pitfalls on everything created in this world including multilevel inverter. One of the demerits of multilevel inverters is the isolated power supplies required for each one of the multiconverter. Furthermore, number of components is increased in multilevel inverter compared to traditional inverters. The idea of having larger number of components also means the probability of a device failure will increase.
1.4. The Switching

There are many ways and techniques have been developed to control multilevel inverter switching, from the very basic fundamental switching up to the most advance space vector pulse width modulation switching scheme. But, the most famous and applied by industries out there is the PWM switching control scheme. PWM switching control scheme comes with advantages over the traditional multilevel fundamental switching scheme.

One benefit of PWM methods employing much higher switching frequencies concerns harmonics. The harmonics filtering exercise is much easier and cheaper due to the fact that the undesirable harmonics occur at much higher switching frequencies. Also, the produced harmonics might be above the bandwidth of some actual system. This means that there is no power dissipation caused by the harmonics. On the contrary, multilevel fundamental switching scheme creates harmonics at lower switching frequencies and this increased the complexity of the filtering activity.

1.5 Control Techniques

Multilevel inverter parameter quality such as switching losses and harmonic reduction are basically depends on the modulation strategies applied to the inverter. Several modulation and control techniques have been developed for multilevel inverters. As shown in Figure 1.4, control technique for the multilevel inverter cab be classified into PWM, Selective Harmonic Elimination PWM (SHEPWM) and Optimized Harmonics Stepped Waveform (OHSW). PWM can be classified to open loop and closed loop. For this research, open loop modulation is proposed which will focus on Sinusoidal PWM (SPWM).
1.6. Problem Statements

One of the important components in the system is the inverter which converts the DC energy stored in the battery banks to AC energy which will then used by consumer or connected to power grid. As the current trend required cleaner power source, higher output power, less losses and almost free harmonics, people are looking forward for better inverter. Thus, a conventional single level inverter is no more relevant to cope with the current trend. Nowadays, industries, researches are focusing to come out with inverter that can overcome the above mentioned issues. As a result a multilevel inverter is created and first published by Nabae in 1980s.
The best performance on higher level of inverter and a promising result on Third Harmonic Injection PWM control technique over SPWM become a motivation for the proposed research. Based on the simulation and several experiment done by previous researches [6][3][7][10], as the level of inverter increases, the degree of complexity on NPC-MLI and FC-MLI hardware is also higher. Now, modern industrial devices are mostly based on electronic devices that are very sensitive to harmonics, even for the induction motor whereby extra heat will be generated with higher harmonic level [16]. Therefore, the proposed work is believed shall synthesize a better quality result with Third harmonic Injection PWM scheme but with better topology which required lesser components and hardware complexity in hardware development.

Ever since the industrial revolution in 1800, the demand for energy is increased dramatically, especially in developing countries in-line with the economy growth. Modern industrial machineries, electric vehicles, home appliances and public healthcare contribute to the high demand of energy. The recent policies situation in World Energy Outlook 2012 (WEO 12) revealed that “several fundamental trends persist: energy demand and CO2 emission rise even higher; energy market dynamics are increasingly determine by emerging economies; fossil fuels remain the dominant source; and providing universal energy access to the world's poor countries continues to be an elusive goal”.

1.7 Project Objective

There are three objective have been set for this work to be achieved at the end of the activities.

To simulate the modelled CHB-MLI performance with the implementation of Third harmonic Injection PWM control technique.

To analyse the multilevel inverter performance in term of THD, fundamental and harmonic rms of the voltage and current for different levels of harmonic injection.
1.8. Project Scopes

The scopes of this project are:
- This research will be focus on the way to development of 9 level multilevel inverter.
- Implementation of Cascade H-Bridge MLI type and Third harmonic Injection PWM control technique.
- Studies on improvement of total harmonic distortion among other level of harmonic injection levels.
CHAPTER 2

LITERATURE REVIEW

2.1 Theories

2.1.1 Inverter

A device that converts DC power into AC power at desired output voltage and frequency is called an Inverter. Phase controlled converters when operated in the inverter mode are called line commutated inverters. But line commutated inverters require an existing AC supply which is used for their commutation. This means that line commutated inverters can’t function as isolated AC voltage sources or as variable frequency and waveform on the AC side of the line commutated inverters can’t be changed. On the other hand, force commutated inverters provide an independent AC output adjustable voltage and frequency. Based on their operation the inverters can be broadly classified into

Voltage Source Inverters (VSI)
Current Source Inverters (CSI)
A **voltage source inverter** is one where the independently controlled ac output is a voltage waveform. A **current source inverter** is one where the independently controlled ac output is a current waveform. Some industrial applications of inverters are for adjustable-speed ac drives, induction heating, stand by air-craft power supplies, UPS uninterruptible power supplies) for computers, HVDC transmission lines etc. An inverter changes DC voltage from batteries or solar panels, into standard household AC voltage so that it can be used by common tools and appliances. Essentially, it does the opposite of what a battery charger or "converter" does. DC is usable for some small appliances, lights, and pumps, but not much else. Some DC appliances are available, but with the exception of lights, fans and pumps there is not a wide selection. Most other 12 volt items we have seen are expensive and/or poorly made compared to their AC cousins. The most common battery voltage inputs for inverters are 12, 24, and 48 volts DC - a few models also available in other voltages. There is also a special line of inverters called a **utility intertie** or grid tie, which does not usually use batteries - the solar panels or wind generator feeds directly into the inverter and the inverter output is tied to the grid power. The power produced is either sold back to the power company or (more commonly) offsets a portion of the power used. These inverters usually require a fairly high input voltage - 48 volts or more. Some, like the Sunny Boy, go up to 600 volts DC input.

Voltage source inverter (VSI) with variable DC link in Figure 2.1. DC link voltage is varied by a DC-to DC converter or controlled rectifier. Generate “square wave” output voltage. Output voltage amplitude is varied as DC link is varied. Frequency of output voltage is varied by changing the frequency of the square wave pulses.

![Figure 2.1 Voltage source inverter(VCI) with variable DC link.](image)
2.1.2 Cascaded H-bridge Multilevel Inverter

As the name suggests, a cascaded H-bridge inverter is constructed by a series of h-bridge inverter in cascade configuration. Basically, a three-phase inverter has a same structure as single H-bridge inverter which use unipolar PWM. This type of topology is relatively a new configuration after the NPC and FC structure [27]. The topology proposed a concept with a uses of separate dc source connected for each H-bridge to generate an ac voltage waveform. The final ac output waveform is produced by cascading the individual H-bridge output waveform.

Figure 2.2 illustrates an m-level cascaded H-bridge inverter. Three different output waveforms will be generated for each inverter level with an appropriate control scheme for the switches: +$V_{dc}$, 0 and -$V_{dc}$. With S1 and S2 turned on, +$V_{dc}$ will be produced, while –$V_{dc}$ can be realized by switching on S2 and S3. The 0 output voltage will be generated by switching on all S1, S2, S3 and S4 switches. The sum of different individual h-bridge inverter outputs connected in series synthesizes the final ac output voltage of the multilevel inverter. An equation of $m=2s+1$ determine the number of voltage levels $m$ in a cascaded H-bridge inverters where $s$ is the number of independent dc source connected to the individual H-bridge inverter. For instance, an 11 level cascaded h-bridge inverter with independent dc source is illustrated in Figure 2.3. The final output for a single phase van is a sum of $v_{a1}$, $v_{a2}$, $v_{a3}$, $v_{a4}$ and $v_{a5}$. 
Figure 2.2: M-Level Single Phase Cascaded H-Bridge Multilevel Inverter

Figure 2.3: Cascaded H-Bridge Multilevel Inverter Generalize Output Waveform
Multilevel cascaded inverters have been proposed for such applications as static
var generation, an interface with renewable energy sources, and for battery-based
applications. Three-phase cascaded inverters can be connected in wye, as shown in
Figure 2.4, or in delta. Peng has demonstrated a prototype multilevel cascaded static
var generator connected in parallel with the electrical system that could supply or draw
reactive current from an electrical system [20-23]. The inverter could be controlled to
either regulate the power factor of the current drawn from the source or the bus voltage
of the electrical system where the inverter was connected. Peng [20] and Joos [24] have
also shown that a cascade inverter can be directly connected in series with the electrical
system for static var compensation. Cascaded inverters are ideal for connecting
renewable energy sources with an ac grid, because of the need for separate dc sources,
which is the case in applications such as photovoltaics or fuel cells

Cascaded inverters have also been proposed for use as the main traction drive in
electric vehicles, where several batteries or ultracapacitors are well suited to serve as
SDCSs [19, 26]. The cascaded inverter could also serve as a rectifier/charger for the
batteries of an electric vehicle while the vehicle was connected to an ac supply as
shown in Figure 2.4. Additionally, the cascade inverter can act as a rectifier in a vehicle
that uses regenerative braking.

Figure 2.4 Three-phase wye-connection structure for electric vehicle motor drive and
battery charging.
Manjrekar has proposed a cascade topology that uses multiple dc levels, which instead of being identical in value are multiples of each other [27-28]. He also uses a combination of fundamental frequency switching for some of the levels and PWM switching for part of the levels to achieve the output voltage waveform. This approach enables a wider diversity of output voltage magnitudes; however, it also results in unequal voltage and current ratings for each of the levels and loses the advantage of being able to use identical, modular units for each level.

The advantages of cascaded H-bridge multilevel inverter are proven as it has been adopt in several application across an engineering field. The modularized circuit layout due to the same structure for each bridge allows the scalable structure of the inverter itself. This type of topology also required less number of components for its construction compare to NPC and FC as no extra clamping diode and voltage balancing capacitors are required. Furthermore, in-term of safety, potential to have an electric shock is lessen due the implementation of separate dc source. Nevertheless, there is still a drawback coming from this kind of inverter topology as it only restricted to certain applications wherever the independent dc source is applicable and available.

The main advantages and disadvantages of multilevel cascaded H-bridge converters are as follows [29, 30].

**Advantages:**

The number of possible output voltage levels is more than twice the number of dc sources \( m = 2s + 1 \).

The series of H-bridges makes for modularized layout and packaging. This will enable the manufacturing process to be done more quickly and cheaply.
Disadvantages:

Separate dc sources are required for each of the H-bridges. This will limit its application to products that already have multiple SDCSs readily available.

Another kind of cascaded multilevel converter with transformers using standard three-phase bi-level converters has been proposed [14]. The circuit is shown in Figure 2.5. The converter uses output transformers to add different voltages. In order for the converter output voltages to be added up, the outputs of the three converters need to be synchronized with a separation of 120° between each phase. For example, obtaining a three-level voltage between outputs a and b, the output voltage can be synthesized by

\[ V_{ab} = V_{a1-b1} + V_{b1-a2} + V_{a2-b2} \]

An isolated transformer is used to provide voltage boost. With three converters synchronized, the voltages \( V_{a1-b1} \), \( V_{b1-a2} \), \( V_{a2-b2} \), are all in phase; thus, the output level can be tripled [1].

Figure 2.5. Cascaded multilevel converter with transformers using standard three-phase bi-level converters
Cascaded multilevel inverter features a high modularity degree because each inverter can be seen as a module with similar circuit topology, control structure, and modulation [22]. Therefore in the case of a fault in one of these modules, it is possible to replace it quickly and easily. Furthermore, with an appropriated control strategy, it is possible to bypass the faulty module without stopping the load, bringing an almost continuous overall availability [23].

Due to its features and benefits, many research have been conducted using this topology as well as many analysis and synthesis have been carried out by researches to enhance the quality and performance of cascaded multilevel inverter. Recently in 2012, Suhitha.N and Ramani.K [15] had proposed a cascaded H-bridge multilevel inverter boost inverter with fundamental switching scheme for electric vehicle (EV) and hybrid EV(HEV) applications. In the research, proposed topology offers an intuitive method for minimizing the total harmonic distortion (THD) of the output voltage of the inverter.

Alireza Nami, Firuz Zare, Arindam Ghosh and Frede Blaabjerg had cascaded the diode-clamped multilevel H-bridge cell with the three-level conventional inverter in their work [24]. Idea of cascading multilevel H-bridge cells is used in [24] to propose different configurations using a seven-level symmetrical and asymmetrical diode-clamped H-bridge converter supplied with a multi-output boost (MOB) converter, cascaded with classical three-level inverters. The MOB converter can solve the capacitor voltage imbalance problem as well as boost the low output voltage of renewable energy system such as solar cells to desired value of the diode-clamp dc link voltage. From this, a nineteen output voltage levels performance was achieved, which has more voltage levels as well as lower voltage, and current THD rather than using a symmetrical diode-clamped inverter with the same configuration and equivalent number of power component.
Due to the fact that nowadays most of the modern industrial devices are based on electronic devices, they are very sensitive to disturbance and less tolerant to power quality problems. In 2011, N.Chellammal, K.N.V Prasad, S.S Dash, Y.S Anil Kumar and A.Murali Krishna had done a performance analysis of three phase cascaded H-bridge multilevel inverter for under voltage and over voltage conditions [25]. The work involved a design of closed loop control system using PI controller in order to maintain load voltage constant for under voltage and over voltage conditions. The triggering pulses to cascaded H-bridge multilevel inverter is given using multi carrier phase shift technique.

In the researches of multilevel inverters, its corresponding PWM control strategies are one of the research hot points. Therefore several works were carried out to compare and analyze on different type or technique to control the switching of the multilevel inverters. V.Kumar Chinnaiyan, Jovitha Jerome, J.Karpagam and T.Suresh had proposed a comparison between different switching strategies for cascaded multilevel inverters, based on sinusoidal pulse width modulation (SPWM) and space vector modulation (SVM) [8].

The work is based on simulation of 5-level cascaded multilevel inverter using Matlab and Simulink® software. The research reveal that the gain of the inverter is increased when using THIPWM, but a third order harmonic is present in the phase voltage, which causes serious problems when the neutral point is grounded. What have been done by a group of researchers from Greater India also carried out by Berrezzek Farid and Omeiri Amar. In [26], they are using new types of modulation in order to increase the output voltages of the inverter for the same continuous voltage supply. The so-called new modulation technique involves SPWM, THIPWM and SVPWM. The comparison studies show reveals that SVPWM and THIPWM technique give a better performance compared to conventional SPWM method. Based on above review a conclusion on the advantages of multilevel inverter are clear. Several researches reveal that the use of CHB-MLI has advantages over other multilevel inverter topologies and obviously better when the higher degree of levels
in introduced. With the implementation of cascaded H-bridge topology and SPWM method, it is believed that a better and efficient inverter shall be product.

2.2 Diode-Clamped Multilevel Inverter

The neutral point converter proposed by Nabae, Takahashi, and Akagi in 1981 was essentially a three-level diode-clamped inverter [5]. In the 1990s several researchers published articles that have reported experimental results for four-, five-, and six-level diode-clamped converters for such uses as static var compensation, variable speed motor drives, and high-voltage system interconnections [18-31]. A three-phase six-level diode-clamped inverter is shown in Figure 2.6. Each of the three phases of the inverter shares a common dc bus, which has been subdivided by five capacitors into six levels. The voltage across each capacitor is $V_{dc}$, and the voltage stress across each switching device is limited to $V_{dc}$ through the clamping diodes. Table 2.2.1 lists the output voltage levels possible for one phase of the inverter with the negative dc rail voltage $V_0$ as a reference. State condition 1 means the switch is on, and 0 means the switch is off. Each phase has five complementary switch pairs such that turning on one of the switches of the pair requires that the other complementary switch be turned off. The complementary switch pairs for phase leg a are $(S_{a1}, S'_{a1})$, $(S_{a2}, S'_{a2})$, $(S_{a3}, S'_{a3})$, $(S_{a4}, S'_{a4})$, and $(S_{a5}, S'_{a5})$. Table 2.1.3 also shows that in a diode-clamped inverter, the switches that are on for a particular phase leg are always adjacent and in series. For a six-level inverter, a set of five switches is on at any given time.
Figure 2.6. Three-phase six-level structure of a diode-clamped inverter.

Table 2.2. Diode-clamped six-level inverter voltage levels and corresponding switch states.

<table>
<thead>
<tr>
<th>Voltage $V_{dc}$</th>
<th>$S_{a5}$</th>
<th>$S_{a6}$</th>
<th>$S_{a3}$</th>
<th>$S_{a2}$</th>
<th>$S_{a1}$</th>
<th>$S_{a2}$</th>
<th>$S_{a3}$</th>
<th>$S_{a6}$</th>
<th>$S_{a7}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_5 = 5V_{dc}$</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$V_4 = 4V_{dc}$</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$V_3 = 3V_{dc}$</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$V_2 = 2V_{dc}$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$V_1 = V_{dc}$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>$V_0 = 0$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
The line voltage $V_{ab}$ consists of a phase-leg a voltage and a phase-leg b voltage. The resulting line voltage is an 11-level staircase waveform. This means that an m-level diode-clamped inverter has an m-level output phase voltage and a $(2m-1)$-level output line voltage.

Although each active switching device is required to block only a voltage level of $V_{dc}$, the clamping diodes require different ratings for reverse voltage blocking. Using phase a of Figure 2.7 as an example, when all the lower switches $S_{a'1}$ through $S_{a'5}$ are turned on, $D_4$ must block four voltage levels, or $4V_{dc}$. Similarly, $D_3$ must block $3V_{dc}$, $D_2$ must block $2V_{dc}$, and $D_1$ must block $V_{dc}$. If the inverter is designed such that each blocking diode has the same voltage rating as the active switches, $D_n$ will require $n$ diodes in series; consequently, the number of diodes required for each phase would be $(m-1) \times (m-2)$. Thus, the number of blocking diodes is quadratically related to the number of levels in a diode-clamped converter [30].

One application of the multilevel diode-clamped inverter is an interface between a high-voltage dc transmission line and an ac transmission line [30]. Another application would be as a variable speed drive for high-power medium-voltage (2.4 kV to 13.8 kV) motors as proposed in [3, 6, 25, 29-31]. Static var compensation is an additional function for which several authors have proposed for the diode-clamped converter. The main advantages and disadvantages of multilevel diode-clamped converters are as follows [1-3]:

![Figure 2.7. Line voltage waveform for a six-level diode-clamped inverter](image-url)
Advantages:

All of the phases share a common dc bus, which minimizes the capacitance requirements of the converter. For this reason, a back-to-back topology is not only possible but also practical for uses such as a high-voltage back-to-back interconnection or an adjustable speed drive.

The capacitors can be pre-charged as a group.

Efficiency is high for fundamental frequency switching.

Disadvantages:

Real power flow is difficult for a single inverter because the intermediate dc levels will tend to overcharge or discharge without precise monitoring and control.

The number of clamping diodes required is quadratically related to the number of levels, which can be cumbersome for units with a high number of levels.

2.3. Flying Capacitor Multilevel Inverter

Meynard and Foch introduced a flying-capacitor-based inverter in 1992 [32]. The structure of this inverter is similar to that of the diode-clamped inverter except that instead of using clamping diodes, the inverter uses capacitors in their place. The circuit topology of the flying capacitor multilevel inverter is shown in Figure 31.7. This topology has a ladder structure of dc side capacitors, where the voltage on each capacitor differs from that of the next capacitor. The voltage increment between two adjacent capacitor legs gives the size of the voltage steps in the output waveform.
REFERENCES


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