A SINGLE-PHASE D-STATCOM INVERTER FOR DISTRIBUTED ENERGY SOURCES

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Abstract

This thesis presents the design of a multilevel D-STATCOM inverter for small to mid-size (10–20 kW) permanent-magnet wind or solar installations. The proposed inverter can actively regulate the reactive power on individual feeder lines at a programmable output while providing the variable output power of the renewable energy source. The aim is to provide utilities with distributive control of VAR compensation and power factor correction on feeder lines. The designed inverter utilizes a 5-level hybrid-clamped multilevel voltage-source converter topology and uses the optimized harmonic stepped waveform technique for harmonic elimination. The topology allows for the separation of active and reactive power control and the ability to operate under any load conditions. Reactive power is controlled by the modulation index and active power is controlled by the phase angle. Simulations and validation of the proposed inverter were carried out using MATLAB/Simulink and SimPowerSystems toolboxes.
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Thank you!
## Glossary of Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>5L-HNPC</td>
<td>Five Level Hybrid Neutral Point Clamped</td>
</tr>
<tr>
<td>3L-ANPC</td>
<td>Three Level Active Neutral Point Clamped</td>
</tr>
<tr>
<td>5L-ANPC</td>
<td>Five Level Active Neutral Point Clamped</td>
</tr>
<tr>
<td>AWEA</td>
<td>American Wind Energy Association</td>
</tr>
<tr>
<td>BESS</td>
<td>Battery Energy Storage System</td>
</tr>
<tr>
<td>CHB</td>
<td>Cascaded H-Bridge</td>
</tr>
<tr>
<td>DBR</td>
<td>Dynamic Breaking Resistor</td>
</tr>
<tr>
<td>DOE</td>
<td>Department of Energy</td>
</tr>
<tr>
<td>DR</td>
<td>Distributed Renewable</td>
</tr>
<tr>
<td>D-STATCOM</td>
<td>Distribution Static Synchronous Compensator</td>
</tr>
<tr>
<td>DVR</td>
<td>Dynamic Voltage Restorer</td>
</tr>
<tr>
<td>FACTS</td>
<td>Flexible AC Transmission Systems</td>
</tr>
<tr>
<td>FC</td>
<td>Flying Capacitor</td>
</tr>
<tr>
<td>FFT</td>
<td>Fast Fourier Transform</td>
</tr>
<tr>
<td>HVDC</td>
<td>High Voltage DC</td>
</tr>
<tr>
<td>IGBT</td>
<td>Insulated Gate Bipolar Transistor</td>
</tr>
<tr>
<td>IGCT</td>
<td>Integrated Gate-Commutated Thyristor</td>
</tr>
<tr>
<td>IPFC</td>
<td>Interline Power Flow Controller</td>
</tr>
<tr>
<td>MMC</td>
<td>Modular Multilevel Converter</td>
</tr>
<tr>
<td>MPPT</td>
<td>Maximum Power Point Tracker</td>
</tr>
<tr>
<td>NPC</td>
<td>Neutral Point Clamped Inverter</td>
</tr>
<tr>
<td>NREL</td>
<td>National Renewable Energy Laboratory</td>
</tr>
<tr>
<td>OHSW</td>
<td>Optimized Harmonic Stepped Waveform</td>
</tr>
<tr>
<td>PCC</td>
<td>Point of Common Coupling</td>
</tr>
<tr>
<td>PSO</td>
<td>Particle Swarm Optimization</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaics</td>
</tr>
<tr>
<td>SDBR</td>
<td>Series Dynamic Breaking Resistor</td>
</tr>
<tr>
<td>SHEM</td>
<td>Selective Harmonic Elimination Modulation</td>
</tr>
<tr>
<td>SMC</td>
<td>Stacked Multicell</td>
</tr>
<tr>
<td>SPWM</td>
<td>Sinusoidal Pulse Width Modulation</td>
</tr>
<tr>
<td>SSSC</td>
<td>Static Series Synchronous Compensators</td>
</tr>
<tr>
<td>STATCOM</td>
<td>Static Synchronous Compensator</td>
</tr>
<tr>
<td>SVC</td>
<td>Static VAR Compensator</td>
</tr>
<tr>
<td>SVM</td>
<td>Space Vector Modulation</td>
</tr>
<tr>
<td>TCPAR</td>
<td>Thyristor Controlled Phase Angle Controller</td>
</tr>
<tr>
<td>TCSC</td>
<td>Thyristor Controlled Series Capacitor</td>
</tr>
<tr>
<td>THD</td>
<td>Total Harmonic Distortion</td>
</tr>
<tr>
<td>UPFC</td>
<td>Unified Power Flow Controller</td>
</tr>
<tr>
<td>VSC</td>
<td>Voltage Source Converter</td>
</tr>
</tbody>
</table>
Chapter 1 - Introduction

1.1 The Power Grid

The basic model of the United States electric grid is usually considered to have three distinct parts: generation, transmission, and distribution. The traditional view of generation in the United States has been large generator stations that are located outside of cities or in the country. These generators are usually massive and have the capability of supplying electricity to entire cities. For this reason they are usually directly connected into the transmission system so that the power they produce can be transported over large distances to meet the demands of multiple load centers. The rest of the grid is analogous to the transportation sector. Transmission can be thought of as the highway that interconnects all major cities and intermediate destinations. Transmission lines are big, carry large amounts of power, and form the backbone of the grid connecting large generation stations and major load centers. Just as a highway provides a car with the quickest route to travel a large distance, the transmission system provides the most efficient way to move bulk power over great distances. Distribution systems, on the other hand, contain smaller lines and transmit smaller amounts of power. They are generally placed in residential areas and carry power to individual homes and businesses. Distribution systems are analogous to back roads. Just as there are many more back roads than highways, there are millions of more miles of distribution lines than there are transmission lines. Consequently, distribution systems are cheaper to build and are not nearly as sophisticated as transmission networks. Distribution systems are generally radial structures that spread outwards from distribution substations in a tree-like manner. Distribution substations serve as the interconnection point between transmission and distribution systems. Transmission systems, unlike distribution systems, are not radial and have many loops and paths to the same destination. This makes them more reliable and controllable but also much more expensive to build. Figure 1.1 provides a graphic view of all three of these components and portrays how they fit together and make the electric grid.
1.2 Renewable Energy

During the last decade a major shift has begun in how generation is thought of and viewed all across the world. Renewable energies are now considered to be an important part of the energy mix and the future of electric generation. This has come about because of the increased awareness of the effects of $CO_2$ emissions as well as the urgency to gain independence from foreign sources of energy. Utilities in the United States are starting to shift away from the large centralized generating facilities like coal and nuclear power and are moving towards smaller, more distributed generation. Since 2003 natural gas and wind energy have dominated the percentage of newly installed electric generation in the United States (Figure 1.2). Utility-scale wind is currently the most economically viable form of renewable energy and has experienced unprecedented levels of growth since the turn of the century. At the end of 2011 the United

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Figure 1.1 Traditional view of the United States electric grid [1]
States had a total installed capacity of 41,181 MW of wind power, providing the equivalent generation of 10 nuclear facilities [2], [3]. The penetration of wind energy has grown to such high levels that the lack of adequate transmission is becoming very apparent. With the rapid development of wind research projects that occurred in the last decade many of the best locations for wind installations have been taken, and developers are having a hard time finding areas with both decent wind and capable transmission. Further, the wind curtailment that has occurred in places like Texas are showing wind developers that just because a project is constructed does not mean the transmission will be guaranteed [4]. This represents a big problem for developers, utilities, and politicians. Transmission is expensive and no one wants to pay for it or look at it. In order to continue developing large-scale wind projects further transmission systems will have to be built. This is especially true if the United States is going to meet either the 20% domestic wind energy scenario by 2030 that was produced by the DOE [5], or the 80% renewables by 2035 target that the U.S. President outlined in his 2011 State of the Union Address. Large-scale solar, unlike wind, is just starting to gain attention with many projects being added to queue but with few actually under construction. Solar, like wind, will face similar transmission constraints as most of the better locations for solar installations are away from large load centers. At the end of 2010 there was a total of 2,426 MW of installed solar capacity in the United States [6].

![Figure 1.2 Breakdown of new generation capacity since 2003 [2].](image)
One of the benefits of solar photovoltaics (PV) is that it is modular. A 200 kW or a 5 kW installation looks very similar, and while there are some reductions associated with the economies of scale, the difference is nowhere near that of the wind industry. Further, the larger planned solar installations are generally much smaller in comparison to large-scale wind, in the order of 10 to 50 MW. There are a few extremely large installations planned but they will use solar concentrator technologies such as solar towers and solar troughs, not PV. The breakdown of the wind industry is very different with large-scale turbines greater than 100 kW representing over 99% of the installed generation capacity. This does not mean that a small wind industry is nonexistent. Even though the capacity from larger generators greatly exceeds that of small wind, the numbers of small vs. large wind turbines installed in 2009 was 9,800 vs. 5,670. At the end of 2009 over 100 MW of small wind generation was installed over half of which was put in place since 2007 [7]. There are numerous benefits to small wind: it is easier to install in urban landscapes, requires little to no permitting, and is tremendously easier to finance. The major drawback is that small wind is often more expensive on a dollar/installed watt ratio than large wind even with the current economic incentives.

![Figure 1.3 Annual Installed grid-connected PV capacity by sector (2000-2009) [8].](image)

There are two major economic incentives for residential wind and solar installations. These are net metering, which is now available in 43 states [9], and the residential renewable energy tax
credit [10]. The net metering incentive varies greatly by state with most states only aiming to provide benefits to very small installations. The residential renewable energy tax credit provides residents with a tax credit equal to 30% of the total project costs and is currently set to expire on December 31, 2016.

For small businesses, farm owners, and other above-average electric users the economics of a renewable energy project can be even harder to justify, as net metering is not always favorable for medium-scale operations. In addition, for wind installations there are very few manufacturers who produce turbines in the 10 to 100 kW range; the small wind market is dominated by turbines ranging from 1-3 kW and 100 kW.

1.3 Distributed Static Synchronous Compensator (D-STATCOM)

Utilities are a major barrier to increasing the number of smaller distributed renewable installations. Small solar and wind installations are generally placed on the low-voltage portion of distribution systems which utilities do not monitor (Figure 1.1). Such installations can create problems for utilities if the amount of power they produce becomes a significant percentage of the total power provided on that line or system. Utilities whose revenues are set by regulatory bodies already have a hard time prioritizing where to spend their capital to make sure they can maintain reliability standards. This means that the necessary capital to modernize these distribution systems, making them available for large amounts of distributed generation, is not there. One of the ways that renewables can increase their penetration into these systems is by giving additional control to the utilities. This is problematic as additional control usually means additional dollars which neither industry has. If additional control is to be given, it is through the use of power electronic devices.

Power electronic devices, when incorporated into the transmission system, are generally referred to as flexible AC transmission systems (FACTS) devices. There exists a whole family of FACTS devices which have a wide range of uses. However, they all strive to do the same thing which is to provide more control and knowledge of the system. A more detailed explanation of FACTS is given in chapter 4. For now, the discussion of FACTS is limited to one type of device, the static synchronous compensator (STATCOM), which is one of the focuses of this thesis.
A STATCOM is the name given to a shunt-connected voltage-source controller that can provide reactive support to a transmission bus. A D-STATCOM is a STATCOM located on the distribution system. The general makeup of a STATCOM is a DC–AC converter that connects a small amount of energy storage such as a capacitor to the AC grid. Due to the low energy capacity on the DC side, steady-state operation dictates that the power transfer from the DC to the AC side must remain neutral. This gives the STATCOM device one degree of freedom which it uses to regulate the amount of reactive power it exchanges with the grid. The STATCOM is considered to be the modern static VAR compensator as it performs the same duties but has a faster response rate and wider operating range.

The main barrier to the deployment of FACTS devices is economics. FACTS devices are generally deployed in critical areas where the benefits of the device outweigh the high cost. As things move forward there will be an increased need for and deployment of these devices. The energy future and emergence of a smart grid are very much dependent on FACTS-type devices as they allow utilities to achieve the control necessary to run more efficiently and at lower margins. As more and more renewable energy sources are connected to the grid these kinds of devices will be required in order to control dynamic power. At this point FACTS devices are only being deployed on distribution systems, on the high-voltage side. These devices are usually implemented at substations that serve large load centers outside of big cities as they are the only places they make economic sense. Most distribution substations rely on capacitor banks for power factor correction if they have that capability at all. Further, it is not economical to install these types of devices on individual feeder lines as the cost is too great. This is the hole that the D-STATCOM Inverter fits into, as it can provide the benefits of a STATCOM device to individual feeder lines without the exorbitant costs.

The proposed D-STATCOM Inverter in this thesis is designed to replace the traditional inverter of a wind turbine or solar installation and to provide not only active power to the grid but also be able to absorb or generate reactive power as well. Having multiple D-STATCOM Inverters on the feeder lines would help utilities increase their knowledge of the distribution system leading to greater efficiency, reliability, and control. Further, it would allow renewables to increase their
presence on distribution systems without requiring utilities to spend massive amounts of money on upgrades.

1.4 Converter Outline

The proposed D-STATCOM Inverter described in the thesis is designed to be used with both wind and solar installations. While the D-STATCOM Inverter is the same for both solar and wind installations, the required backends of the overall converter structure are very different. This has to do with the way photovoltaics (PV) and wind turbines operate. PV arrays look like variable current sources while wind turbines look like a variable voltage sources. Both types of installations require a maximum power point tracker (MPPT) to operate efficiently. However, the operation of the MPPT is very different for a solar array than it is for a wind turbine and the outputs are very different as well. The output of a solar MPPT is a fairly stable and constant voltage. The job of the DC–DC Boost stage for a solar converter is to bring the voltage level up to the desired DC link voltage between the DC–DC boost and D-STATCOM Inverter, as shown in Figure 1.4. The output of the MPPT stage of a wind turbine is a variable DC voltage. This makes the job of the DC–DC boost stage much harder as it must boost a variable voltage to a constant DC link value. The D-STATCOM Inverter stage, which is the focus of the present research, would look the same for both solar and wind installations. Depending on the number of levels achieved by the D-STATCOM Inverter, the whole converter requires either a small low-pass filter, or none at all for a high-enough level inverter. The output of this stage is brought into a transformer to boost the final AC voltage up to the desired voltage level on the grid. The basic configuration for the entire converter is outlined in Figure 1.4.
1.5 Research Contribution

The unique work in this thesis is the bringing together and combination of several relatively new concepts. The design objectives of this project include: minimize the overall switching frequency of the inverter because higher switching frequencies mean higher losses; minimize the total harmonic distortion in order to maintain compliance with IEEE standards; and finally, keep the cost of the inverter as low as possible.

This thesis uses the multilevel hybrid-clamped inverter topology and the optimized harmonic stepped waveform modulation technique in the design of an inverter for a small- to medium-sized distributed renewable. The inverter contains the same functionality as a D-STATCOM device and is designed to be implemented in single-phase systems which have been an area of relatively little interest for D-STATCOMs due to traditional economics. Individually there has been research in these areas however, to this author’s knowledge, none have combined them together. Further, the prospect of using distributed renewables as VAR compensators is just beginning to get attention and be explored. This thesis provides the background necessary to
understand the framework of a D-STATCOM Inverter as well as the various choices and options that can be made. Additionally, the thesis covers the design of an inverter which brings together all of these concepts and provides a direction for future research.

The remaining chapters of the thesis are staged in a sequential manner covering the technical background information necessary to design the D-STATCOM Inverter portion of Figure 1.4. Chapter 2 covers different inverter topologies and provides a discussion of the performance criteria needed for a D-STATCOM Inverter. Chapter 3 provides an overview of various modulation techniques which are used to control the output waveform of the inverter and limit the total harmonic distortion. Chapter 4 discusses the operation of a D-STATCOM, introduces several other FACTS devices, and provides a review of similar work. Chapter 5 covers the complete design of the D-STATCOM Inverter. Chapter 6 discusses the results of the simulations, and Chapter 7 gives conclusion and recommendations for future work.
Chapter 2 - Multilevel Inverter Topologies

2.1 Multilevel Inverters

The concept of a multilevel inverter has been around since the 1970s with the first traceable patent appearing in 1975 [11], [12]. Due to the current and voltage limits of a single semiconductor device, multilevel topologies have opened the door for new uses of power electronics. Among the various types of multilevel topologies in existence today, there are three in particular that are considered to be the most fundamental. These are the neutral-point clamped, sometimes referred to as the diode-clamped, the flying-capacitor also known as the capacitor clamped, and the cascaded H-Bridge. The earliest of these topologies was the cascaded H-Bridge with its debut in 1975. The H-Bridge was then followed by the neutral-point clamped which was proposed by Takashi in 1981 [13], and lastly the flying-capacitor was introduced by Menard [14] in 1992.

The concept of a multilevel inverter is to use a series of connected semiconductor switches in order to reduce the voltage and consequently power that flows through each individual device. In recent years the amount of research and interest in multilevel converters has taken off. The advances in semiconductor science coupled with the advances in multilevel topologies have allowed the faster and newer power electronic switches: IGBTs, IGCTs and MOSFETs, to be utilized at higher voltages and power levels. The demand for these power electronic devices will continue to increase as they see a widening array of uses which already include large-scale utility applications, motor drives for electric vehicles, and inverters for renewable energy sources.

With all the attention in this field, research on new topologies has increased and, in the last decade, a variety of new multilevel topologies has been introduced. Choosing an inverter topology greatly depends on the intended application as each topology has its own advantages and disadvantages. The following three sections 2.2–2.4 provide a brief explanation of the three fundamental topologies, as most of the concepts used in all of the others stem from these original topologies. Section 2.5 introduces some of the more successful of these newer voltage source converter topologies representing what is currently considered to be state of the art. Section 2.6
introduces the final multilevel topology, the hybrid-clamped, which is the focus of this thesis. Section 2.7 provides a side-by-side comparison of all of the topologies.

2.2 The Neutral-Point Clamped Multilevel Topology

A single-phase, 3-level neutral-point clamped (NPC) multilevel inverter shown in Figure 2.1(a) splits the DC voltage across two capacitors in equal proportions. The operation of the inverter is simple and produces an output waveform like that in Figure 2.1(b). When switches (S₁, S₂) are on and (S₃, S₄) are off, the output $V_o$, is connected across the capacitor $C_1$ which outputs a voltage that is equal to half of $V_{dc}$. When switches (S₂, S₃) are on and (S₁, S₄) are off, the output of the inverter is connected to ground, and the resulting output voltage $V_o$ is 0. When switches (S₃, S₄) are on and (S₁, S₂) are off, the output $V_o$ of the inverter is across capacitor $C_2$ and produces a voltage equal to $-V_{dc}/2$.

![Figure 2.1 (a) Single-phase, 3-level NPC topology. (b) Output waveform.](image)

The NPC topology can be expanded to include additional levels. Figure 2.2 shows the topology and output waveform for a single-phase, 5-level NPC inverter. The operation of the 5-level inverter includes five different switching states that make up the varying levels of the output waveform. The $V_{dc}$ voltage is divided equally across four capacitors of the same rating. These are capacitors $C_1$, $C_2$, $C_3$, and $C_4$ in Figure 2.2(a). Including neutral, this provides five different
voltage output levels ranging from \(2V_{dc}/5\) to \(-2V_{dc}/5\). Table 2.1 summarizes the switching states for each level. Each diode in the circuit is sized to provide voltage blocking for the voltage across one capacitor. Thus, diode \(D_1\) is represented by three diodes in series of equal size to \(D_1\) as it must be able to block the voltage across capacitors \(C_2, C_3,\) and \(C_4\).

![Diagram of diode and capacitors](image)

Figure 2.2 (a) Single-phase 5-level NPC topology. (b) Output waveform.

Table 3.1 shows all of the switching states for the 5-level NPC inverter. The voltage output \(V_o\) can range from \(2V_{dc}/5\) to \(-2V_{dc}/5\) depending on the state of the switches. To provide an output voltage \(V_o\) of \(2V_{dc}/5\) switches \(S_1, S_2, S_3,\) and \(S_4\) must all be on, putting \(V_o\) in parallel with capacitors \(C_1\) and \(C_2\). To provide an output voltage \(V_o\) of \(V_{dc}/5\), switches \(S_2, S_3, S_4,\) and \(S_1\) must be on, putting \(V_o\) in parallel with capacitor \(C_2\). The rest of the output voltages can be reasoned out in a similar fashion.
Table 2.1 Switching table for the 5-level NPC inverter.

<table>
<thead>
<tr>
<th>Output Voltage $V_o$</th>
<th>Switches On</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2V_{dc}/5$</td>
<td>$S_1, S_2, S_3, S_4$</td>
</tr>
<tr>
<td>$V_{dc}/5$</td>
<td>$S_2, S_3, S_4, S_1'$</td>
</tr>
<tr>
<td>0</td>
<td>$S_3, S_4, S_1', S_2'$</td>
</tr>
<tr>
<td>$-V_{dc}/5$</td>
<td>$S_4, S_1', S_2', S_3'$</td>
</tr>
<tr>
<td>$-2V_{dc}/5$</td>
<td>$S_1', S_2', S_3', S_4'$</td>
</tr>
</tbody>
</table>

In general, a single-phase, $m$-level NPC inverter requires $(m - 1)$ DC link capacitors, $(m - 1)(m - 2)$ clamping diodes, and $2(m - 1)$ switches. This represents a quadratic relationship between the number of diodes and levels. The result is that for high levels the NPC topology can become bulky and problematic for high frequency switching schemes such as PWM due to the recovery time associated with the individual diodes. The biggest constraint of the NPC inverter is its inability to deliver real power from the DC to AC side for levels above three [15]. Without replacing the DC capacitors with independent DC sources, the control strategy necessary to keep the DC link capacitors balanced while delivering real power becomes extremely complex and impractical to implement at high levels. For these reasons, the NPC inverter is not a suitable topology at high levels for a D-STATCOM Inverter in which real power must be delivered from a connected wind turbine or solar array.

Another disadvantage of the NPC topology is that there is an unequal power flow between the outer and inner switches which causes uneven losses and heat distribution. This restricts the maximum frequency switching and power handling capability of the NPC as the outer switches will reach their limits before the rest of the device [16].

2.3 The Flying-Capacitor Inverter

The flying-capacitor (FC) topology is similar to NPC but uses capacitors instead of diodes to maintain voltage levels across the DC links. Figures 2.3 and 2.4 show the topology for a 3-level and 5-level flying-capacitor inverter. The operation of the flying-capacitor inverter involves using redundant switching combinations to balance the voltages across the DC link capacitors. For a 3-level flying-capacitor inverter, the switching scheme is the same as the NPC. When switches $(S_1, S_2)$ are on and $(S_1', S_2')$ are off, the voltage output $V_o$ is $V_{dc}/2$. Likewise when
switches \((S_1', S_2')\) are on and \((S_1, S_2)\) are off, the voltage output \(V_o\) is \(-V_{dc}/2\). The balancing operation of the 3-level flying-capacitor inverter is handled by cycling between two zero-voltage output combinations when either switches \((S_1, S_1')\) are on or when \((S_2, S_2')\) are on. When \((S_1, S_1')\) are on, the capacitor \(C_1\) is in a charging state and when \((S_2, S_2')\) are on the capacitor \(C_1\) is in a discharging state. Proper charge balance is maintained on \(C_1\) by switching between these two states of zero output voltage \(V_o\).

Figure 2.3 (a) Single-phase, 3-level flying-capacitor inverter topology. (b) Output waveform

For the 5-level flying-capacitor inverter there are 14 redundant switching states and thus maintaining the voltage balance across the capacitors becomes more complicated. Table 2.2 shows all of the different switching states for each of the five voltage output levels of the inverter. Depending on the switching state, capacitors can have different voltage values across them and thus be charging or discharging at different rates. The challenge of the 5-level flying-capacitor inverter is developing a control strategy that is able to maintain voltage balance on the capacitors. If the voltages across the \(C_4\) capacitors are allowed to deviate too much, the output levels of the inverter will collapse and the inverter will cease to operate in a usable manner.
Table 2.2 All switching combinations for the 5-level flying-capacitor inverter [12].

<table>
<thead>
<tr>
<th>Output Voltage</th>
<th>Switches On</th>
<th>Charging Capacitors</th>
<th>Discharging Capacitors</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_o = V_{dc}/2$</td>
<td>$S_2, S_3, S_4$</td>
<td>$V_{dc}/2 \rightarrow C_{41}, C_{42}$</td>
<td>$-V_{dc}/4 \rightarrow C_1$</td>
</tr>
<tr>
<td>$V_o = V_{dc}/4$</td>
<td>$S_2, S_3, S_4$</td>
<td>$V_{dc}/4 \rightarrow C_{31}, C_{42}$</td>
<td>$-V_{dc}/4 \rightarrow C_{31}, C_{44}$</td>
</tr>
<tr>
<td>$V_o = V_{dc}/4$</td>
<td>$S_2, S_3, S_4$</td>
<td>$3V_{dc}/4 \rightarrow C_{31}, C_{42}$</td>
<td>$-V_{dc}/2 \rightarrow C_{32}, C_{44}$</td>
</tr>
</tbody>
</table>

Figure 2.4 shows the topology and output waveform of the 5-level flying-capacitor inverter. In general a single-phase m-level flying-capacitor inverter requires $(m - 1)$ DC link capacitors, $(m - 1)(m - 2)/2$ auxiliary capacitors, and $2(m - 1)$ main switches. This means a 5-level inverter has 10 capacitors that must be balanced and a 7-level inverter has 21 capacitors. The number of capacitors increases on the order of $m^2$ as additional levels are added which means that the difficulty and complexity of the control scheme also increases on the order of $m^2$. For this reason practical implementation of the flying-capacitor inverter has been limited to 3–5 levels. The exact number of switching states for a single-phase flying-capacitor inverter is given by,

$$M_k = \frac{1}{(N-k)!} \prod_{n=0}^{N-k-1} (2N - n) \text{ for } 0 \leq k < N$$

where $N$ is the number of DC link capacitors and where $k$ defines the number of levels and is equal to 0 for the zero voltage level [17].
Figure 2.4 (a) Single-phase, 5-level flying-capacitor inverter topology. (b) Output waveform.

In addition to the already complicated control strategy, the flying-capacitor inverter has additional difficulties when trying to balance the DC link capacitors in purely reactive applications [18], and requires high-frequency switching for real power transfer which increases the losses. This makes the flying-capacitor inverter an impractical topology choice for a D-STATCOM Inverter which must be able to operate in a purely reactive mode as well as to deliver real power.

2.4 Cascaded H-Bridge Inverter
The last of the fundamental topologies, completely different from the neutral-point clamped or flying-capacitor, is the cascaded H-Bridge inverter. The cascaded H-Bridge offers the advantage of requiring the fewest number of components for a specified number of levels as compared to neutral point clamped and flying-capacitor inverters. The main drawback to the cascaded H-Bridge inverter is that it requires a separate DC source for each level. Figures 2.5 and 2.6 demonstrate 3 and 5-level cascaded H-Bridge topologies and their resulting output voltage waveforms.
The 3-level H-Bridge inverter works as follows. When switches (S₁, S₄) are on, the output voltage $V_o$ is $V_{dc}$. Similarly, when switches (S₂, S₃) are on, the output voltage $V_o$ is $-V_{dc}$. When either (S₁, S₂) or (S₃, S₄) are on, the output voltage $V_o$ is 0.

![Diagram of 3-level H-Bridge inverter](image)

**Figure 2.5** (a) Single-phase, 3-level H-Bridge inverter topology. (b) Output waveform.

Figure 2.6 shows the topology for a 5-level cascaded H-Bridge inverter. The voltage waveform for the 5-level inverter can be constructed in the same way as the 3-level with each individual bridge being able to produce voltage levels of $V_{dc}$, 0, and $-V_{dc}$. The result is that a 5-level cascaded H-Bridge has $3^2$ or 9 different switching states whose output voltage $V_o$ can be constructed by any combination of $V_1 + V_2$.

![Diagram of 5-level H-Bridge inverter](image)

**Figure 2.6** (a) Single-phase, 5-level H-Bridge inverter topology. (b) Output waveform.
In general a single-phase m-level cascaded H-Bridge inverter requires $2(m - 1)$ switches, $(m - 1)/2$ independent DC sources and has $2^{\frac{m-1}{2}}$ switching states. The main drawback of the cascaded H-Bridge inverter is its requirement of multiple independent DC sources. For this reason the topology is an infeasible solution for many applications including an inverter for a wind turbine in which only one DC source is available.

2.5 Other Multilevel Topologies

In the last decade many other multilevel topologies have been introduced and have gathered interest in both research communities and industry. Most of these topologies come from one of the three fundamentals and are either hybrids or use similar techniques. In order to limit the number of devices mentioned, the following discussion will be limited to single-phase voltage source converter topologies that focus on DC–AC conversion. This rules out topologies such as the multilevel matrix converters which are direct ac to ac converters. Among the various topologies that have been proposed, the ones with the most interest are the 5-level H-bridge neutral point clamped (5L-HNPC), the 3-level active neutral point clamped (3L-ANPC), the 5-level active neutral point clamped (5L-ANPC), the modular multilevel converter (MMC or M2C), the transistor-clamped converter (TCC), the cascaded H-Bridge (CHB) fed with unequal DC sources, and the stacked FC or stacked multicell [19], [20]. This section will provide a brief overview of each of these topologies as well as point to additional papers for more detailed explanations.

2.4.1 5L-HNPC Inverter

The 5-level hybrid neutral point clamped topology is a variation on the 3-level NPC where two NPC inverters are strung together. Figure 3.7 shows the 5L- HNPC topology.
Figure 2.7 Single-phase 5L-HNPC [20]

The construction of the voltage output levels is produced by combining the 3-levels of each NPC inverter. The result is that five different levels can be reached: \( V_{dc}, V_{dc}/2, 0, -V_{dc}/2, -V_{dc} \). Correct voltage balance across the capacitors \( C_1 \) and \( C_2 \) is maintained by using redundant switching states. By stacking additional cells in a cascaded manner additional levels can be achieved. Figure 3.8 shows a 9 level combination in which two cells are cascaded. The disadvantage to this approach is that for every additional module that is added, a separate DC source is required. Further, expanding the individual cells to a 5-level NPC topology will plague the HNPC with the same voltage balancing and active power flow difficulties that the diode clamped capacitor has. The 5L-HNPC has been commercialized by two manufacturers: ABB, and TMEIC-GE [19] for use with medium voltage drives. In addition, researchers have shown that this topology can be used with various modulation techniques including: selective harmonic elimination (SHE), sinusoidal pulse width modulation (SPWM), and space vector modulation (SVM) [21], [22].
2.4.2 3L-ANPC Inverter

The 3-level active neutral point clamped inverter is similar to the 3-level NPC inverter except that it replaces the two clamping diodes with additional switches to control the current paths of the neutral voltage levels. This rectifies the problem of unequal power dissipation between the outer and inner switches, and allows for a more even heat distribution, affecting the overall performance of the device and allowing for higher switching frequencies and power ratings[19]. Figure 2.9 shows the topology for the 3L-ANPC. This type of inverter is generally used for applications such as motor drives where a higher fundamental frequency is required.
2.4.3 5L-ANPC Inverter

A hybrid variation of the 3L-ANPC and flying capacitor inverter is the 5-level active neutral point clamped inverter shown in Figure 2.10. The 5L-ANPC, like the flying-capacitor inverter, relies on redundant switching states to maintain proper balance of the floating (FC) capacitor. The 5-levels of the output waveform are realized by combining the first stage of the inverter which can produce 3 different levels with two more stages that can produce two additional levels. The advantage is that this topology is able to realize five different voltage levels with only one floating capacitor as compared to the traditional 5-level NPC which has four floating capacitors. This inverter can also be expanded to m-levels. However, limitations of the storage capacity of the floating capacitor have restricted its practical application [23]. A commercial version of the 5L-ANCP is available, produced by ABB [17]. In addition, it has been shown [24] that with the correct control strategy it is possible to gain enough degrees of freedom to separate active and reactive power control. This is possible by making use of the added redundant switching states and by combining it with the virtual-flux direct power control technique [25]. It was also shown in [26] that this topology is suitable for use with selective harmonic elimination and can be used in STATCOM devices. The major drawback is that its operation becomes more complicated and limited when it is expanded above five levels as this adds additional floating capacitors that need to be balanced.
Figure 2.10 Single-phase 5L-ANPC

A variation of the 5L-ANCP is the 5L-ANCP with a common cross converter state (CCC) which increases the output of the inverter to nine levels. The 5L-ANCP + CCC shown in Figure 2.11 creates additional connections to intermediate voltage levels effectively increasing the inverter output from five levels to nine. With this added benefit come additional complexities associated with balancing capacitors C₃ and C₄ which can limit the maximum modulation index range of the inverter when delivering real power [27]. The last benefit of this topology is the possibility of expanding it to a greater number of levels by adding additional CCC stages. The drawback is that reverse voltage blocking required by the cross connected diodes and switches is not split up as additional stages are added, and the redundant switching states needed to maintain balance of the floating capacitors are not always guaranteed.

Figure 2.11 5L-ANCP with CCC stage increasing the output to 9-Levels
2.4.4 MMC or $M^2$LC Inverter

The modular multilevel converter is arguably the most advanced topology to see large scale commercial deployment, being the topology of choice for SIEMENS HVDC Plus technology [28], [29]. The topology itself was developed in the early 2000s and has received a large amount of attention [19]. The MMC topology is composed of multiple half bridges called power modules. The number of power modules depicted as PM1 in Figure 2.12 must be even to generate an equal number of positive and negative levels. To achieve a higher number of levels, the power modules are stacked. Each power module has two different states in normal operation. The first state is when the capacitor is on. In this state switch $S_1$ is on and $S_2$ is off. Depending on the charge of the capacitor, current either flows into the capacitor through $D_1$ or flows out of the capacitor through $S_1$. The second state is when the capacitor is in the off mode and the module is bypassed. For this mode $S_1$ is off and $S_2$ is on. Depending on the polarity at the terminals of the power module, current either flows through $D_2$ or through $S_2$. By proper switching between these two states proper voltage can be maintained for each power module. Usually capacitors with high energy storage are selected for each of the modules.

Figure 3.13 shows the three-phase topology of the MMC which is utilized in SIEMENS HVDC Plus technology. The advantage here is the elimination of the C link capacitors. Both of the figures depict 3-level topologies. It is necessary to point out that this topology allows for complete control of both the active and reactive power and thus is a very suitable topology for STATCOM devices and is also the topology used in what SIEMENS calls SVC Plus.
Figure 2.12 3-level, single-phase MMC

Figure 2.13 3-level, three-phase MMC
2.4.5 TCC or NPP Inverter
The transistor-clamped converter or neutral point piloted converter shown in Figure 2.14 is a variation of the NPC similar to the 3L-ANCP. The main advantage is that it can control the current paths to equalize the power losses and heat dissipation of the switches. This allows the device to be used in applications demanding higher power and faster switching. The topology has been made commercially available by Eaton [19].

![Figure 2.14 3-level, single-phase TCC or NPP](image)

2.4.6 Cascaded H-Bridge with Unequal DC Sources Inverter
The cascaded H-Bridge with Unequal DC sources has exactly the same structure as the regular cascaded H-Bridge except, as the name implies, it has unequal DC voltage sources. This structure has the advantage of being able to generate more levels with fewer sources [30]. The disadvantage is that the inverter will see unequal power losses and heat distribution. The inverter also still requires more than one DC source, giving it many of the same limitations as the original cascaded H-Bridge.

2.4.7 CHB with a Single DC Source
Another set of topologies that have been proposed recently are single source cascaded H-Bridge inverters. These topologies replace all but one of the DC sources with capacitors, incorporating sophisticated control techniques to keep the DC voltage levels intact [31], [32]. Variations of this scheme also include topologies that replace the traditional H-Bridge modules with NPC modules [33]. The drawback is that the control schemes used to balance the DC voltages especially
during active power conversion place restrictions and limits on the inverters’ operating range [34].

2.4.8 The Stacked Multicell (SMC)
The stacked multicell converter is a topology where multiple flying-capacitor inverter stages are stacked on top of each other. The concept, originally proposed in 2000 [35], is starting to see an increased amount of interest. The stacked configuration reduces the voltage across each of the individual devices allowing a reduction in energy storage and the use of smaller capacitors while creating additional voltage levels that can increase the quality of the output waveform. In addition, the SMC reduces the overall number of capacitors compared to an equivalent flying-capacitor topology. However it requires an independent DC source for each flying-capacitor module that is stacked in series [36]. The topology for a single phase 5-level stacked multicell inverter is given in Figure 3.15.

![Figure 2.15 5-level SMC](image_url)

2.6 The Hybrid-Clamped Multilevel Inverter
The final topology is the hybrid-clamped multilevel inverter [37], [38], [39], [40] which represents a cross between the NPC and flying-capacitor topologies. Displayed in Figure 2.7, the hybrid-clamped inverter can maintain balance across the DC link capacitors regardless of the load characteristics or its mode of operation, making it an ideal topology for a D-STATCOM Inverter.
The hybrid-clamped inverter maintains balance of the DC link capacitors by making use of the auxiliary switches $S_{c1}$–$S_{c6}$, and auxiliary clamping capacitors $C_5$–$C_7$. The switching states of the inverter are governed by Table 2.3. The balancing operation works by making use of the complementary switching pairs $(S_1, S_{c1})$, $(S_{c1}, S_{c2})$, $(S_{c2}, S_{c3})$, $(S_{c3}, S_{c4})$, $(S_{c4}, S_{c5})$, $(S_{c5}, S_{c6})$, and $(S_{c6}, S_{1'})$ which are in parallel with capacitors $C_1$, $C_5$, $C_2$, $C_6$, $C_3$, $C_7$, and $C_4$, respectively [4]. For example, when switches $S_1$, $S_{c2}$, $S_{c4}$, and $S_{c6}$, are on, capacitors $(C_1, C_5)$, $(C_2, C_6)$, and $(C_3, C_7)$ are placed in parallel. Likewise, when $S_1$ is off and $(S_{c2}, S_{c4}, S_{c6})$ are on, capacitors $(C_2, C_5)$, $(C_3, C_6)$, and $(C_4, C_7)$ are placed in parallel. This operation ensures that the voltages and charge on the DC link capacitors will remain the same, for each time capacitors are placed in parallel the charge and voltage of the two capacitors will equalize. By placing $C_1$ in parallel with $C_5$ for one state and then $C_2$ in parallel with $C_5$ for another, the relationship of $C_1=C_5=C_2$ can be kept. Since all of the capacitors are chained together in this manner, equal DC voltage among the links is kept. It is important to note, however, that proper-size capacitors have to be selected, as either too large or too small of a time constant can lead to instability.
The DC link balancing scheme of the hybrid-clamped inverter differs from that of the flying-capacitor in that the balancing is not dependent on redundant switching states that control the charging and discharging of capacitors. As long as at least once during each cycle, the two sets of capacitors are placed in series with each other and the time constants of the capacitors allow for equalization, the voltages will remain balanced regardless of the load characteristics. This is the major benefit of the hybrid-clamped inverter and why it is an ideal choice to be used for D-STATCOM operation.

The drawback of the hybrid-clamped inverter topology is that it requires the most number of switches and components out of all the topologies. In general, a single-phase m-level hybrid-clamped inverter requires, \((m - 1)\) DC link capacitors, \(2(m - 1)\) main switches, \(2(m - 2)\) auxiliary switches, \((m - 1)(m - 2)\) diodes, and \((m - 2)\) auxiliary capacitors.

### 2.7 A Brief Comparison of the Topologies

The following tables provide a general comparison of all the multilevel topologies that were outlined in this chapter. The first two tables summarize the advantages and disadvantages of each topology and the last five tables provide a comparison of the number of components that each topology uses for 3, 5, 7, 9, and 11 levels.

**Table 2.3 Switching States for the 5-level hybrid-clamped inverter [16].**

<table>
<thead>
<tr>
<th>Output Voltage</th>
<th>(S_1)</th>
<th>(S_2)</th>
<th>(S_3)</th>
<th>(S_4)</th>
<th>(S_1')</th>
<th>(S_2')</th>
<th>(S_3')</th>
<th>(S_4')</th>
<th>(S_{c1})</th>
<th>(S_{c2})</th>
<th>(S_{c3})</th>
<th>(S_{c4})</th>
<th>(S_{c5})</th>
<th>(S_{c6})</th>
<th>Parallel Capacitors</th>
</tr>
</thead>
<tbody>
<tr>
<td>(2V_o/5)</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>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>((C_1, C_5), (C_2, C_6), (C_3, C_7))</td>
</tr>
<tr>
<td>(V_o/5)</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>((C_2, C_3), (C_4, C_6), (C_5, C_7))</td>
</tr>
<tr>
<td>(V_o/5)</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
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<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>((C_1, C_3), (C_4, C_6), (C_5, C_7))</td>
</tr>
<tr>
<td>(-V_o/5)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
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<td>0</td>
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<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>((C_1, C_3), (C_2, C_6), (C_5, C_7))</td>
</tr>
<tr>
<td>(-V_o/5)</td>
<td>1</td>
<td>0</td>
<td>0</td>
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<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>((C_2, C_3), (C_4, C_6), (C_5, C_7))</td>
</tr>
<tr>
<td>(-2V_o/5)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
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<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>((C_2, C_3), (C_4, C_6), (C_5, C_7))</td>
</tr>
<tr>
<td>Table 2.4 Comparison of multilevel VSC topologies 1.</td>
<td></td>
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</tr>
<tr>
<td><strong>Advantages</strong></td>
<td><strong>Disadvantages</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Neutral-Point Clamped (NPC)</td>
<td>Requires a single DC source</td>
<td>Unequal power distribution among switches</td>
<td></td>
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<tr>
<td></td>
<td>Does not require auxiliary capacitors</td>
<td>Balancing problems while delivering real power above 3-levels</td>
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<tr>
<td></td>
<td></td>
<td>Requires a large number of diodes which is a quadratic function of the number of levels. The diodes reverse recovery time can become problematic for high switching frequencies</td>
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<tr>
<td>Capacitor-Clamped</td>
<td>Requires only one DC source</td>
<td>Cannot balance the DC link capacitors under purely reactive operation</td>
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<tr>
<td></td>
<td>Significantly reduced number of components compared to the NPC inverter</td>
<td>Requires a large number of clamping capacitors.</td>
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<tr>
<td></td>
<td>Redundant switching states allow for both active and reactive power conversions although purely reactive is problematic</td>
<td>The number of redundant switching states increases quadratically with the number of levels, making the control schemes very complex</td>
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<tr>
<td>Cascaded H-Bridge (CHB)</td>
<td>Requires the fewest number of components out of the three fundamental topologies</td>
<td>Requires multiple isolated DC sources</td>
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<tr>
<td></td>
<td>Can deliver both reactive and active power</td>
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</tr>
<tr>
<td>5L-HNPC</td>
<td>Reduction in DC link capacitors over 5-level NPC Inverter</td>
<td>Requires isolated DC sources for every additional module</td>
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<tr>
<td></td>
<td>Reduction in overall number of components</td>
<td>Expansion above 5-levels eliminates its effectiveness in delivering real power and balancing DC links.</td>
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<tr>
<td></td>
<td>Can deliver both reactive and active power for levels</td>
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<tr>
<td>3L-ANPC</td>
<td>Spreads power losses equally among all switches allowing for higher power ratings and switching frequencies than the 3-level NPC</td>
<td>Experiences voltage balancing issues and active power flow issues when increased to above 3-levels</td>
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<tr>
<td></td>
<td>Can deliver both active and reactive power for 3-levels</td>
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<tr>
<td>5L-ANPC</td>
<td>Reduction in floating capacitors over NPC and flying-capacitor</td>
<td>Increasing the number of levels beyond five increases the number of floating capacitors and reduces the range of operation for the inverter</td>
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<td></td>
<td>Additional redundant switching states</td>
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<td></td>
<td>Can deliver both active and reactive power</td>
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<td></td>
<td>Can be scaled to additional levels</td>
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</tr>
<tr>
<td>5L-ANPC + CCC</td>
<td>Reduction in floating capacitors over NPC and flying-capacitor</td>
<td>The CCC stage components have large reverse voltage blocking requirements for high power applications</td>
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<tr>
<td></td>
<td>Additional redundant switching states</td>
<td>The redundant switching states needed to maintain balance of the floating capacitors is not always guaranteed</td>
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<td></td>
<td>Can deliver both active and reactive power</td>
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<td></td>
<td>Increasing the number of CCC stages exponentially increases the number of output levels</td>
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</tbody>
</table>
### Table 2.5 Comparison of multilevel VSC topologies 2.

<table>
<thead>
<tr>
<th>Topology</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>MMC or M2C</td>
<td>- Modular topology so it is scalable to any level</td>
<td>- Requires high energy storage capacitors</td>
</tr>
<tr>
<td></td>
<td>- Simple structure that requires few components</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Can deliver both active and reactive power</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Relatively easy to balance DC capacitors</td>
<td></td>
</tr>
<tr>
<td>TCC or NPP</td>
<td>- Allows the current paths to be controlled which spreads the power losses equally among all switches allowing for higher power ratings and switching frequencies</td>
<td>- Experiences similar voltage balancing issues and active power flow issues as the NPC when increased to above 3-levels</td>
</tr>
<tr>
<td></td>
<td>- Can deliver both active and reactive power for 3-levels</td>
<td></td>
</tr>
<tr>
<td>CHB Unequal Sources</td>
<td>- Has a fewer amount of components</td>
<td>- Requires independent DC sources</td>
</tr>
<tr>
<td></td>
<td>- Can generate a greater number of levels for a given amount of DC sources as compared to the standard CHB</td>
<td>- Causes unequal power losses and heat dissipation</td>
</tr>
<tr>
<td></td>
<td>- The control strategies to balance the DC link voltages can become complex and can limit the operating range of the inverter</td>
<td>- Increases the complexity of the control algorithm and reduces its control range</td>
</tr>
<tr>
<td>CHB Single Source</td>
<td>- Requires only one DC source</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Requires a reduced number of components</td>
<td></td>
</tr>
<tr>
<td>SMC</td>
<td>- Reduced voltages across capacitors as compared to traditional flying capacitor topology</td>
<td>- Requires a independent DC sources for each stacked module</td>
</tr>
<tr>
<td></td>
<td>- Requires less capacitors than the traditional flying capacitor topology</td>
<td></td>
</tr>
<tr>
<td>Hybrid-Clamped</td>
<td>- Requires only one DC source. Can balance DC link voltages without redundant switching states and regardless of the load profile</td>
<td>- Requires a large number of switches and components which adds to the overall cost and can increase the amount of losses</td>
</tr>
<tr>
<td></td>
<td>- Does not require a complicated control algorithm</td>
<td></td>
</tr>
<tr>
<td>Comparison of Components For Different Single-Phase Multilevel Topologies</td>
<td>3-Level</td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Switches</td>
<td>DC Link Capacitors</td>
<td>Clamping Diodes</td>
</tr>
<tr>
<td>Neutral-Point Clamped</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Flying-Capacitor</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Cascaded H-Bridge</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>SL-HNCP*</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>SL-ANCP</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>SL-ANCP*</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>SL-ANCP + CCC*</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>MMC or M2C</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>TCP or NPP</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>CHB Unequal Sources</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>CHB-Single Source</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>SMC</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Hybrid-Clamped*</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

*The topology does not apply to this level
Table 2.7 Number of components for 5-level inverters.

<table>
<thead>
<tr>
<th>Comparison of Components For Different Single-Phase Multilevel Topologies</th>
<th>5-Level</th>
<th></th>
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<tbody>
<tr>
<td></td>
<td>Switches</td>
<td>DC Link Capacitors</td>
<td>Clamping Diodes</td>
<td>Auxiliary Capacitors</td>
<td>Inductors</td>
<td>DC Sources</td>
</tr>
<tr>
<td>Neutral-Point Clamped</td>
<td>8</td>
<td>4</td>
<td>12</td>
<td>0</td>
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<td>1</td>
</tr>
<tr>
<td>Flying-Capacitor</td>
<td>8</td>
<td>4</td>
<td>0</td>
<td>6</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Cascaded H-Bridge</td>
<td>8</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>5L-HNCP</td>
<td>8</td>
<td>2</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>3L-ANCP*</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>5L-ANCP</td>
<td>8</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>5L-ANCP + CCC</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>MMC or M2C</td>
<td>8</td>
<td>4</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>TCP or NPP**</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>CHB Unequal Sources</td>
<td>8</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>CHB-Single Source</td>
<td>8</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>SMC</td>
<td>12</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Hybrid-Clamped</td>
<td>14</td>
<td>4</td>
<td>6</td>
<td>3</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

*The topology does not apply to this level

**There are various ways to increase the levels
### Table 2.8 Number of components for 7-level inverters.

<table>
<thead>
<tr>
<th>Comparison of Components For Different Single-Phase Multilevel Topologies</th>
<th>Switches</th>
<th>DC Link Capacitors</th>
<th>Clamping Diodes</th>
<th>Auxiliary Capacitors</th>
<th>Inductors</th>
<th>DC Sources</th>
<th>Total Number of Components</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutral-Point Clamped</td>
<td>12</td>
<td>6</td>
<td>30</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>49</td>
</tr>
<tr>
<td>Flying-Capacitor</td>
<td>12</td>
<td>6</td>
<td>0</td>
<td>15</td>
<td>0</td>
<td>1</td>
<td>34</td>
</tr>
<tr>
<td>Cascaded H-Bridge</td>
<td>12</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>15</td>
</tr>
<tr>
<td>5L-HNCP*</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>3L-ANCP*</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>5L-ANCP*</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>5L-ANCP + CCC*</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>MMC or M2C</td>
<td>12</td>
<td>6</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>23</td>
</tr>
<tr>
<td>TCP or NPP**</td>
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<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>CHB Unequal Sources***</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>Na</td>
<td>Na</td>
</tr>
<tr>
<td>CHB-Single Source</td>
<td>12</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>15</td>
</tr>
<tr>
<td>SMC</td>
<td>12</td>
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<td>0</td>
<td>4</td>
<td>0</td>
<td>2</td>
<td>18</td>
</tr>
<tr>
<td>Hybrid-Clamped</td>
<td>22</td>
<td>6</td>
<td>20</td>
<td>5</td>
<td>0</td>
<td>1</td>
<td>54</td>
</tr>
</tbody>
</table>

*The topology does not apply to this level

**There are various ways to increase the levels

***Depends on what voltage ratios are chosen
Table 2.9 Number of components for 9-level inverter.

<table>
<thead>
<tr>
<th>Comparison of Components For Different Single-Phase Multilevel Topologies</th>
<th>9-Level</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th>Total Number of Components</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Switches</td>
<td>DC Link Capacitors</td>
<td>Clamping Diodes</td>
<td>Auxiliary Capacitors</td>
<td>Inductors</td>
<td>DC Sources</td>
</tr>
<tr>
<td>Neutral-Point Clamped</td>
<td>16</td>
<td>8</td>
<td>56</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Flying-Capacitor</td>
<td>16</td>
<td>8</td>
<td>8</td>
<td>28</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Cascaded H-Bridge</td>
<td>16</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>5L-HNCP*</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>3L-ANC*</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>5L-ANC****</td>
<td>16</td>
<td>4</td>
<td>8</td>
<td>0</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>5L-ANC + CCC</td>
<td>14</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>MMC or M2C</td>
<td>16</td>
<td>8</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>TCP or NPP**</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>CHB Unequal Sources***</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>CHB-Single Source</td>
<td>16</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>SMC</td>
<td>16</td>
<td>0</td>
<td>0</td>
<td>6</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Hybrid-Clamped</td>
<td>30</td>
<td>8</td>
<td>32</td>
<td>7</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

*The topology does not apply to this level
**There are various ways to increase the levels
***Depends on what voltage ratios are chosen
****Two of them cascaded creates a 9L-HNCP
### Table 2.10 Number of components for 11-level inverter.

| Comparison of Components For Different Single-Phase Multilevel Topologies | 11-Level |
|---|---|---|---|---|---|---|---|
| | Switches | DC Link Capacitors | Clamping Diodes | Auxiliary Capacitors | Inductors | DC Sources | Total Number of Components |
| Neutral-Point Clamped | 20 | 10 | 90 | 0 | 0 | 1 | 121 |
| Flying-Capacitor | 20 | 10 | 0 | 45 | 0 | 1 | 76 |
| Cascaded H-Bridge | 20 | 0 | 0 | 0 | 0 | 5 | 25 |
| SL-HNCP* | NA | NA | NA | NA | NA | NA | NA |
| 3L-ANCP* | NA | NA | NA | NA | NA | NA | NA |
| 5L-ANCP* | NA | NA | NA | NA | NA | NA | NA |
| 5L-ANCP + CCC | NA | NA | NA | NA | NA | NA | NA |
| MMC or M2C | 20 | 10 | 0 | 2 | 2 | 1 | 35 |
| TCP or NPP** | NA | NA | NA | NA | NA | NA | NA |
| CHB Unequal Sources*** | NA | NA | NA | NA | NA | NA | 0 |
| CHB-Single Source | 20 | 4 | 0 | 0 | 0 | 1 | 25 |
| SMC | 20 | 0 | 8 | 0 | 2 | 30 | |
| Hybrid-Clamped | 38 | 10 | 72 | 9 | 0 | 1 | 130 |

*The topology does not apply to this level
**There are various ways to increase the levels
***Depends on what voltage ratios are chosen
As tables 2.4 through 2.10 suggest, the hybrid-clamped topology represents one of the more suitable topologies to be used for a D-STATCOM Inverter. It is advantageous in that it can control the active and reactive power flows regardless of the load conditions and has a relatively simple scheme to balance the DC link voltages. The drawback to the hybrid-clamped topology is the number of components it uses. Additional components raise the cost of the inverter, increase the complexity of the circuit, increase the losses, and decrease the chances of building a successful prototype.

Aside from the hybrid-clamped topology, there is one other topology which looks like it would make a good choice for a D-STATCOM Inverter. That topology is the modular multilevel converter (MMC). Investigation into the MMC topology as a D-STATCOM Inverter however, is left to future research.
Chapter 3 - Harmonic Elimination and Modulation Strategies

3.1 Harmonic Elimination

One of the main concerns and performance indicators of an inverter is the level of total harmonic distortion (THD) in its output waveform. Harmonics can greatly reduce the efficiency of an inverter as well as damage other devices that are connected to it. For this reason the IEEE has published the IEEE standards 519-1992 [41], describing the harmonic requirements all inverters should meet.

The topic of harmonic elimination has been widely studied and researchers have produced many different techniques. Selecting one of these techniques depends greatly on the topology of your inverter as well as its intended application. For multilevel inverter topologies there are four well-known techniques each having their own advantages and disadvantages. These techniques are:

1) Sinusoidal Pulse Width Modulation [39], [42], [43].
2) Space Vector Modulation and 1-D Modulation [44], [45], [46].
3) Selective Harmonic Elimination [31], [42], [47], [48], [49], [50].
4) Optimized Harmonic Stepped Waveform Technique [42], [51], [52], [53], [54].

Each of the first three techniques is briefly discussed in sections 3.2-3.5 to establish a basic understanding of the various modulation techniques as they pertain to inverters. For the D-STATCOM Inverter in this thesis the OHSW technique is the primary consideration as it can theoretically provide the lowest THD for high level multistep inverters without using a filter. Section 3.6 will discuss solving the OSHW problem and introduce the concept of particle swarm optimization which was used to solve for the firing angles. A detailed explanation of solving the firing angles for 5, 7, 9, and 11 levels is given, and the code and tables containing the solved firing angles are included in Appendix A.

3.2 Sinusoidal Pulse Width Modulation

Sinusoidal Pulse Width Modulation (SPWM) is the simplest of the three techniques. The basic operating principle of SPWM is to compare a reference wave, usually of fixed magnitude but variable frequency, to a sinusoid of desired frequency but controllable magnitude. For a grid connected inverter, the frequency of this sinusoid, often referred to as the control voltage, is set
to the frequency of the grid. Figure 3.1 shows the basic waveform of a 2-level SPWM with a triangular waveform as the reference.

![Diagram of SPWM waveform](chart.png)

**Figure 3.1 Example of sinusoidal pulse width modulation for a two level inverter.**

The voltage at the output is controlled by the peak amplitude of $V_{\text{tri}}$ to $V_{\text{control}}$ which is defined as the modulation index given by,

$$MI = \frac{V_{\text{control}}}{V_{\text{tri}}} \quad (3.1)$$

Under normal operation the switches of the inverter are controlled by the comparison of the triangular wave to the control wave. When the triangular wave is greater than the control wave the inverter outputs a negative voltage and when the triangular wave is less than the control wave the inverter outputs a positive voltage. Usually, the frequency of the triangular waveform is on the order of 7–10 times greater than the frequency of the control waveform. The effect of SPWM
on the harmonics is that their frequencies are multiplied by the frequency modulation ratio defined by (3.2).

\[
m_f = \frac{f_{tri}}{f_{control}}
\] (3.2)

The harmonics can then be easily filtered out using a low-pass filter containing much smaller components. The drawback to this approach is twofold. First, none of the harmonics are being eliminated, but instead moved to a higher frequency and thus the losses associated with the filter will add to the inefficiencies of the inverter. Second, for every doubling of the switching frequency the switching losses will be doubled as well. In medium to higher power applications these losses are what dominate the losses of the whole inverter and so it is advantageous to keep the switching frequency as low as possible.

In multilevel inverters the SPWM technique works similarly to the 2-level SPWM. The major difference is that instead of one reference waveform, there are multiple waveforms. Figure 4.2 shows a SPWM waveform for a 5-level inverter containing four reference waveforms.

![Figure 3.2 Example of SPWM waveforms for a 5-level inverter.](image)
The advantage of using SPWM with a multilevel topology is a reduction in switching losses due to series-connected switches. Figure 3.2 shows that most of the switching in multilevel SPWM only occurs across the top and bottom levels which have smaller switches than the 2-level inverter and thus lower losses due to the reduced voltage. By only turning off and on one level, the overall efficiency of the inverter is improved. However, even with multiple levels SPWM inverters are unable to improve the total harmonic distortion without the use of a filtering circuit.

The biggest advantage of SPWM is its ability to respond quickly, having the capability to make adjustments mid cycle as the technique does not depend on pre-defined switching angles like SHE and OHSW. This combined with its simplistic control scheme makes it a very attractive modulation technique and way to reduce the THD.

Multilevel SPWM can also be referred to as carrier phase disposition pulse width modulation (PDPWM). When PDPWM is applied to various multilevel topologies the switching states for the voltage levels have to be maintained. For NPC and flying-capacitor topologies these are the switching states outlined in Tables 2.1, and 2.2 respectively. When this modulation scheme is applied to the hybrid-clamped topology, the carrier waveforms must adhere to the switching states outlined in Table 2.3. The carrier waveforms which adhere to the switching states of a 5-level hybrid-clamped inverter are shown in Figure 3.3. The figure provides the carrier waveforms for the upper four switches (S₁–S₄) of the 5-level hybrid-clamped inverter. The waveforms for the bottom switches (S₁′–S₄′) and the auxiliary switches (Sₖ₁–Sₖ₆) do not need to be constructed as their switching states can be taken as compliments of one of the upper switches.
A variation of this switching scheme proposed in [39], aims to reduce the fundamental switching frequency of the switches by inverting the lower portions of the carrier waveform. This modulation technique is called the higher and lower carrier cells alternative phase opposition pulse width modulation (HLCCAPOPWM) method. Figure 3.4 shows the carrier waveforms of the upper switches ($S_1$-$S_4$) for HLCCAPOPWM.
Figure 3.4 Carrier waveforms for the upper four switches using the HLCCAPOPWM method [39].

By inverting the bottom portion of the waveforms, the fundamental inverter switching frequency is halved. The output voltage levels are maintained thanks to the symmetry of the triangular reference waves.

3.3 Space Vector Modulation and 1DM

Space vector modulation (SVM) is a technique that is usually used in three-phase multilevel inverters. SVM takes advantage of the added degrees of freedom multilevel topologies offer including redundant switching states and the addition of extra voltage levels. SVM uses these parameters to separately control different modes of operation of the inverter. SVM has been widely studied, but even so, remains mostly a topic of research as industry has been slow to adopt its use. Research on SVM has produced many different control strategies encompassing 2-D and 3-D algorithms for inverters that have any number of levels and any number of phases. The basic principle of SVM is to construct vectors out of the different operational states of the
inverter. The 2-D and 3-D refer to the dimensionality of the vector and the number of variables it is controlling. A 2-D SVM is flat and circular in nature whereas a 3-D SVM is spherical. The rest of this section will briefly cover the SVM technique and then transition into 1-DM which is similar to SVM but can be used in single-phase applications [44].

The general operating principle of a 2-D SVM is to use the two dimensions to control the voltage levels and the duty cycle of the individual switching states. Figure 3.3 shows the switching state vectors for a 2-D, three-phase, 3-level inverter. The controller is able to control the output by picking a vector which corresponds to the desired voltage level for the three phases. The values of each vector in Figure 3.3 correspond to the line-to-neutral voltage levels of each phase. The inner hexagon, outlined in orange, represents all the space vectors with a magnitude of 1Vdc, and the blue hexagon outlines all the vectors with a magnitude of 2Vdc. A vector corresponding to (220) in Figure 3.3 provides a corresponding voltage output of \( V_{ab} = 0 \), \( V_{bc} = 0 \), and \( V_{ca} = -2V_{dc} \), where \( V_{dc} \) is the voltage across one DC-link. The overall output waveform of the inverter is a function of both the output voltage levels and their corresponding duty cycles. The SVM controller works by picking one of the three vectors whose output is the closest to the reference voltage level. It maintains the reference value by controlling the duty cycle of each voltage level to stay within a hysteresis band of desired value. The complication of the SVM technique is the process by which the controller is able to select the correct vector.

Figure 3.5 2-D Space vector modulation for a 3-level, three-phase inverter [44], [45].
A 3-D space vector modulation scheme has an additional dimension which the controller can use to control a third variable. This third variable can be used to select between redundant switching states to control other outputs such as DC-link balancing, reduced switching frequency, and THD.

1-DM is a modulation technique that is used for single-phase applications. It is similar to SVM, but since there exists only one phase, the states are represented in a linear fashion as points in a line instead of vectors. Figure 3.4 demonstrates the state space for a 5-level single-phase NPC Inverter.

![1-D state space for a 5-level single-phase NPC](image)

Control of the output voltage is handled in the same way as SVM. The modulation method controls the duty cycle of the individual voltage levels, switching between the two points on the line that are closest to the value of the reference signal. This keeps the output voltage waveform within a desired tolerance of the reference signal. Further control capability can be added to make use of the redundant switching states and control the firing order of the switches. This can be used to reduce the fundamental switching frequency and balance the DC-link voltages. Reduction in THD is achieved in a similar fashion to SPWM. Due to the rapid switching associated with both SVM and 1-DM, the frequencies of the individual harmonics are shifted to higher frequencies and become easier to filter out. The shift in frequency corresponds to the ratio of the SVM switching frequency to the frequency of the fundamental component.
3.4 Selective Harmonic Elimination

Selective harmonic elimination (SHE) is a technique in which the switching angles of an inverter are calculated offline so as to cancel out different ordered harmonics. The principle is based on harmonic cancellation, whereby if the integral of any harmonic evaluated over one switching period adds to zero, the harmonic is effectively cancelled. Using this principle it is then possible to chop up the waveform to eliminate any ordered harmonic.

![Diagram](image)

**Figure 3.7 Illustration of selective harmonic elimination of the third and fifth harmonics for a 3-level inverter. Note: The amplitudes are not drawn to scale [47].**

Figure 3.3 provides a graphic demonstration of how the 3\textsuperscript{rd} and 5\textsuperscript{th} harmonics can be eliminated in a 3-level inverter using SHE. As shown in Figure 3.3(b) to eliminate the 3\textsuperscript{rd} harmonic the firing angle has to be chosen so that the areas above and below the horizontal axis of the third harmonic are equal. To eliminate the 3\textsuperscript{rd} and 5\textsuperscript{th} harmonics more firing angles have to be introduced so that both the areas of the 3\textsuperscript{rd} and 5\textsuperscript{th} harmonics are canceled while the switches are in their \textit{on} state. Figure 3.3(c) demonstrates how this can be accomplished by overlaying the fifth
harmonic on the left side and the third harmonic on the right. As is shown, with correctly chosen firing angles both harmonics are eliminated.

A detailed explanation of how to calculate the angles for selective harmonic elimination is given by Patel [48]. Mathematically, the waveforms are calculated by solving a set of nonlinear equations that govern the amplitude of each individual harmonic. The selective harmonic elimination technique is the most difficult out of the four to solve, and greatly increases as levels are added.

The major drawback to SHE is that the total harmonic distortion remains relatively constant as the number of firing angles is increased [42]. The benefit is that the lower order harmonics are negated which allows for a much smaller filter and the switching frequency is generally a lot lower than SPWM.

The complexity associated with solving the SHE problem for higher level inverters increases greatly. Researchers have just recently published papers demonstrating how to solve the SHE equations for five- and seven-level inverters [49], [50].

3.5 Optimized Harmonic Stepped Waveform Technique

The optimized harmonic stepped-waveform technique (OHSW) is very similar to selective harmonic elimination except that it is better suited for higher level multilevel inverters and can reduce the THD without filters. Similar to SHE, the switching angles of the inverter are calculated offline so as to minimize any undesired harmonics. In general, the number of harmonics that can be eliminated using the OSHA technique for a single-phase inverter is given by Equation (3.3), as an m-level inverter has exactly \( \frac{m-1}{2} \) controllable firing angles and the first angle must be used to maximize the amplitude of the fundamental frequency.

\[
\text{Harmonics Eliminated} = \frac{\text{Number of Levels} - 1}{2} - 1 = \text{number of switching angles} \quad (3.3)
\]

Figure 3.4 demonstrates this with the output waveform of an 11-level inverter.
Like SHE, the main operating principle of OHSW is to effectively cancel out the areas of the individual harmonics over one period. The area of any one harmonic is a function of both the firing angles and the height positions of each firing level. This leaves three distinct methods for solving the harmonic elimination equations. 1) The heights can be varied keeping the angles constant, 2) the heights and angles can be varied, and 3) the angles can be varied while keeping the heights constant. Due to the nature of the multilevel inverter topology chosen where the individual DC levels are set by capacitors in series, the restriction is set that all of the DC levels must be the same, making option three the only practical method.

With all levels having the same DC value, the expression for the amplitude of each harmonic is given by [42]:

$$H_n(\alpha) = \begin{cases} \frac{4V_d}{n \pi} \sum_{k=1}^{l-1} \cos(n \alpha_k) & \text{for all odd } n \\ 0 & \text{for all even } n \end{cases}$$

Where $l$ is the number of levels.
\( n \) is the harmonic
\( \alpha_k \) is the kth switching angle
\( V_a \) is the voltage across one DC link capacitor

The complexity of eliminating each harmonic increases as more levels are added. In general solving a set of switching angles for an \( m \)-level inverter requires solving
\[
\frac{m-1}{2} \text{ equations each with } \frac{m-1}{2} \text{ nonlinear terms.}
\]
For 3-level and even 5-level inverters, it is possible with reasonably educated starting guesses to use conventional techniques such as Gradient Descent and Newton Raphson to solve for the angles. As the levels increase these techniques become less effective due to the large number of local minima. By combining Newton-Raphson with brute force or guess and check, it is still possible to solve for a set of firing angles for a given modulation index, but it is not practical to solve for a large range of modulation indices.

### 3.6 Particle Swarm Optimization and OHSW

To find the firing angles one solution is to pick a technique that is capable of solving nonlinear optimization problems. Barkati [51], [52], has proposed using particle swarm optimization (PSO). PSO is an optimization technique first introduced by Kennedy and Eberhart [54] to model the social interaction of a flock of birds or school of fish.

The basic concept of PSO is to assume that an optimal solution can be reached by a swarm of \( n \) particles that can exchange information. In PSO, each particle has a position and velocity and the position of each particle represents a potential solution to the optimization problem. During each iteration the position of each particle is evaluated by an objective function and at the end updates are made to each particle’s velocity and position. A particle’s velocity is updated by a contribution of three things: the particle’s current velocity, the particle’s best position, and the best position found by any particle. Once the particle’s velocity is updated, it is used to update the particle’s position. This process is repeated until either a tolerance or a maximum number of iterations is reached. The final solution is taken to be the best position found by any particle.
3.6.1 PSO and OHSW

As discussed in section 3.3, the goal of OHSW is to calculate the switching angles that make the amplitude of the fundamental component equal to a desired modulation index and to eliminate any undesired harmonic content. The number of harmonics that can be eliminated is equal to the number of independent switching angles minus one, as the first angle must be used to control the fundamental component. In general an m-level inverter using the OHSW technique has \((m - 1)/2\) switching angles and can eliminate \((m - 3)/2\) harmonics. This means that a single-phase 5-level inverter can eliminate the 3\(^{rd}\) harmonic, a 7-level inverter can eliminate the 3\(^{rd}\) and 5\(^{th}\) harmonics, a 9-level inverter can eliminate the 3\(^{rd}\), 5\(^{th}\), and 7\(^{th}\) harmonics, and an 11-level inverter can eliminate the 3\(^{rd}\), 5\(^{th}\), 7\(^{th}\), and 9\(^{th}\) harmonics.

3.6.2 Defining the Optimization Problem

The optimization problem as defined by Barkati [51] is to solve, for a given modulation index, a series of equations defined by (3.4). Equation (3.4) represents the amplitudes of every harmonic.

\[
H_n(\alpha) = \frac{4V_{dc}}{n\pi} \sum_{k=1}^{l-1} \cos(n\alpha_k)
\]

For a single-phase inverter using quarter wave symmetry, containing m-levels, k switching angles, and j DC link capacitors, the system of equations to be solved contains k non-linear equations and is represented by the following:

\[
\cos(\alpha_1) + \cos(\alpha_2) + \ldots + \cos(\alpha_k) = \frac{jM\pi}{4}
\]
\[
\cos(3\alpha_1) + \cos(3\alpha_2) + \ldots + \cos(3\alpha_k) = h_3 = 0
\]
\[
\cos(5\alpha_1) + \cos(5\alpha_2) + \ldots + \cos(5\alpha_k) = h_5 = 0
\]
\[
\vdots
\]
\[
\cos(n\alpha_1) + \cos(n\alpha_2) + \ldots + \cos(n\alpha_k) = h_n = 0
\]

where M represents the modulation index that fundamental component should be solved for.
The Fourier series of this waveform is written as:

\[ V(wt) = V_{link} \sum_n H_n(a)\sin(nwt) \]  \hspace{1cm} (3.5)

where \( V_{link} \) represents the DC voltage across one DC link capacitor.

### 3.6.3 Solving the Optimization Problem with PSO

To solve the optimization problem with PSO the first step is to identify the constraints and define the objective function. The constraints demand that all of the switching angles must be in increasing order and maintain quarter-wave symmetry. To keep symmetry every angle must be greater than 0 degrees and less than 90 degrees

\[
\text{Constraints: } 0 \leq \alpha_1 \leq \alpha_2 \leq \cdots \leq \alpha_k \leq 90
\]  \hspace{1cm} (3.3)

The objective function, also called the fitness function or cost function, represents the overall equation that should be minimized.

\[
\text{Fitness Function: } w_1|JM - H_1| + w_2|H_3| + \cdots + w_k|H_n|
\]  \hspace{1cm} (3.4)

\( w_1 \) through \( w_k \) represent different weights allowing different amounts of importance to be assigned to different harmonics. The first component of the equation \( w_1|JM - H_1| \) guarantees that the p.u. amplitude of the fundamental will be equal to the modulation index. The rest of the components eliminate particular individual harmonics.

The pseudo code for solving the harmonic elimination problem using PSO is defined as follows being slightly modified from its original form in [51].

FOR: all modulation indexes from 0.6 to 1.0 in step sizes of 0.001

\[
\text{INITIALIZE the starting position of n particles } p_n(0) = [\alpha_1 \alpha_2 \cdots \alpha_k] \text{ for every angle subject the constraint of (3.3). If an acceptable solution was found for the}
\]
previous modulation index, initialize half of the particles to the previous solution. Otherwise initialize randomly and then sort.

INITIALIZE the velocities for each angle in every particle to zero.

UNTIL a tolerance or max number of iterations is reached

COMPUTE the fitness value for each particle using equation (3.4).
SET the vector pbest to the personal best fitness and position for each particle reached during any iteration

SET the variable gbest to the global best fitness and position reached by any particle during any iteration

UPDATE the particle velocities according to:
\[ v_{i}^{\text{New}} = w \ast v_i + p_{\text{incr}} \ast \text{rand} \ast (p_{\text{best}_i} - p_i) + g_{\text{incr}} \ast \text{rand} \ast (g_{\text{best}} - p_i) \]

UPDATE the particle positions according to:
\[ p_{i}^{\text{New}} = p_i + v_{i}^{\text{new}} \ast \Delta t \quad \text{where} \quad \Delta t \text{ is 1} \]

ENDUNTIL

ENDFOR

3.6.4 5-Level Two Angle OHSW

The two equations to be solved for a 5-level inverter are:

\[
\cos(\alpha_1) + \cos(\alpha_2) = \frac{2\pi}{4} M \tag{3.5}
\]

\[
\cos(3\alpha_1) + \cos(3\alpha_2) = 0 \tag{3.6}
\]

where M is the modulation index and ranges from 0.6 to 1.
The objective function or cost function is given by,

\[
\text{Cost Function} (\alpha_1, \alpha_2) = w_1 |2M - H_1| + w_2 |H_3|
\]  

(3.7)

Figure 3.4 (a) shows the switching angle solutions for the 5-level inverter. Figure 3.4 (b) shows the final cost of each solution according to equation (3.7).

Figure 3.8 (a) Switching angles $\alpha_1$ and $\alpha_2$ vs. modulation index for 5-level single-phase inverter using OHSW. (b) Final cost function vs. modulation index for the switching angle solutions from (a).
Figure 3.9 (a) Total harmonic distortion vs. modulation index for 5-level single-phase OHSW. (b) Calculated individual harmonic contribution for a modulation index of 0.85.

3.6.5 7-Level Three Angle OHSW

The three equations to be solved for a 7-level inverter are:

\[
\cos(\alpha_1) + \cos(\alpha_2) + \cos(\alpha_3) = \frac{3\pi}{4} M \tag{3.8}
\]

\[
\cos(3\alpha_1) + \cos(3\alpha_2) + \cos(3\alpha_3) = 0 \tag{3.9}
\]

\[
\cos(5\alpha_1) + \cos(5\alpha_2) + \cos(5\alpha_3) = 0 \tag{3.10}
\]

where M is the modulation index and ranges from 0.6 to 1

The objective function or cost function is given by,

\[
Cost \ Function \ (\alpha_1, \alpha_2, \alpha_3) = w_1|3M - H_1| + w_2|H_3| + w_3|H_5| \tag{3.11}
\]

Figure 3.6 (a) shows the switching angle solutions for the 7-level inverter. Figure 3.6 (b) shows the final cost of each solution according to equation (3.11).
Figure 3.10 (a) Switching angles $\alpha_1$, $\alpha_2$, and $\alpha_3$ vs. modulation index for a 7-level single-phase inverter using OHSW. (b) Final cost function vs. modulation index for the switching angle solutions from (a).

Figure 3.11 (a) Total harmonic distortion vs. modulation index for 7-level single-phase OHSW. (b) Calculated individual harmonic contribution for a modulation index of 0.85.

3.6.6 9-Level Four Angle OHSW

The four equations to be solved for a 9-level inverter are:

\begin{align*}
\cos(\alpha_1) + \cos(\alpha_2) + \cos(\alpha_3) + \cos(\alpha_4) &= \frac{4\pi}{4} M \\
\cos(3\alpha_1) + \cos(3\alpha_2) + \cos(3\alpha_3) + \cos(3\alpha_4) &= 0 \\
\cos(5\alpha_1) + \cos(5\alpha_2) + \cos(5\alpha_3) + \cos(5\alpha_4) &= 0 \\
\cos(7\alpha_1) + \cos(7\alpha_2) + \cos(7\alpha_3) + \cos(7\alpha_4) &= 0
\end{align*}
where \( M \) is the modulation index and ranges from 0.6 to 1.

The objective function or cost function is given by,

\[
\text{Cost Function} (\alpha_1, \alpha_2, \alpha_3, \alpha_4) = w_1 |4M - H_1| + w_2 |H_3| + w_3 |H_5| + w_4 |H_7|
\]  

(3.16)

Figure 3.8 (a) shows the switching angle solutions for the 9-level inverter. Figure 3.8 (b) shows the final cost of each solution according to equation (3.16).

Figure 3.12 (a) Switching angles \( \alpha_1, \alpha_2, \alpha_3, \) and \( \alpha_4 \) vs. modulation index for a 9-level single-phase inverter using OHSW. (b) Final cost function vs. modulation index for the switching angle solutions from (a).
Figure 3.13 (a) Total harmonic distortion vs. modulation index for 9-level single-phase OHSW. (b) Calculated individual harmonic contribution for a modulation index of 0.85.

3.6.7 11-Level Five Angle OHSW

The five equations to be solved for an 11-level inverter are:

\[
\begin{align*}
\cos(\alpha_1) + \cos(\alpha_2) + \cos(\alpha_3) + \cos(\alpha_4) + \cos(\alpha_5) &= \frac{5\pi}{4} M \\
\cos(3\alpha_1) + \cos(3\alpha_2) + \cos(3\alpha_3) + \cos(3\alpha_4) + \cos(3\alpha_5) &= 0 \\
\cos(5\alpha_1) + \cos(5\alpha_2) + \cos(5\alpha_3) + \cos(5\alpha_4) + \cos(5\alpha_5) &= 0 \\
\cos(7\alpha_1) + \cos(7\alpha_2) + \cos(7\alpha_3) + \cos(7\alpha_4) + \cos(7\alpha_5) &= 0 \\
\cos(9\alpha_1) + \cos(9\alpha_2) + \cos(9\alpha_3) + \cos(9\alpha_4) + \cos(9\alpha_5) &= 0
\end{align*}
\]  

(3.17) \hspace{1cm} (3.18) \hspace{1cm} (3.19) \hspace{1cm} (3.20) \hspace{1cm} (3.21)

where \( M \) is the modulation index and ranges from 0.6 to 1.

The objective function or cost function is given by,

\[
\text{Cost Function} (\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5) = w_1|5M - H_1| + w_2|H_3| + w_3|H_5| + w_4|H_7| + w_5|H_9|
\]

(3.22)

Figure 3.10 (a) shows the switching angle solutions for the 11-level inverter. Figure 3.10 (b) shows the final cost of each solution according to equation (3.22).
Figure 3.14 (a) Switching angles $\alpha_1$, $\alpha_2$, $\alpha_3$, $\alpha_4$, and $\alpha_5$ vs. modulation index for a 11-level single-phase inverter using OHSW. (b) Final cost function vs. modulation index for the switching angle solutions from (a).

Figure 3.15 (a) Total harmonic distortion vs. modulation index for 11-level single-phase OHSW. (b) Calculated individual harmonic contribution for a modulation index of 0.85.

The actual code for implementing the PSO algorithm for any level inverter, single-phase or three-phase is included in Appendix A, along with tables containing the actual switching angles and costs for single-phase 5, 7, 9, and 11 level solutions.
Chapter 4 - Distributed Static Synchronous Compensator

4.1 FACTS Devices

A STATCOM device is part of an entire family of devices called flexible AC transmission systems (FACTS). The IEEE P1409 [55] has defined the term FACTS as “Alternating Current Transmission Systems incorporating power electronics-based and other static controllers to enhance controllability and power transfer capability.” Among the FACTS family many different devices exist which are often categorized as shunt, series, or shunt and series. They can also be categorized by generation, the thyristor devices considered to be the old, and voltage source controllers the new. These FACTS devices include Static Synchronous Compensators (STATCOM), Static Series Synchronous Compensators (SSSC), Dynamic Voltage Restorers (DVR), Unified Power Flow Controllers (UPFC), Interline Power Flow Controllers (IPFC), High Voltage DC (HVDC), Thyristor Controlled Series Capacitors (TCSC), Dynamic Breaking Resistors (DBR), Series Dynamic Breaking Resistors (SDBR), Static VAR Compensators (SVC), and Thyristor Controlled Phase Angle Controllers (TCPAR) [56–59].

The following provides a brief overview of each of these devices and what they are used for in transmission systems. Figure 5.2 further explains the FACTS family providing a comparison of all different devices. The proposed D-STATCOM Inverter is included in this comparison to show the value it can bring to distribution systems.

- STATCOM Behaves like a synchronous voltage source that can absorb or provide reactive power.
- SSSC Series voltage source that can compensate for voltage drop due to line reactance.
- DVR Custom FACTS device used to mitigate voltage sag. Has the same structure as a SSSC but operates differently.
- UPFC AC/DC/AC device connected in shunt and series used to compensate line reactance and provide power flow control.
- HVDC High voltage DC transmission used to transmit large amounts of power over long distances.
- TCSC Series capacitance used for VAR support.
DBR ▶ Shunt switchable resistor used to control active power.
SDBR ▶ Series switchable resistor used to control active power.
SVC ▶ Shunt connected device used to provide VAR compensation. Usually composed of a thyristor with capacitors.
TCPAR ▶ Represents a variable phase angle in series with line. Used for power flow control and oscillation dampening.

Table 4.1 Overview of current FACTS devices [56], [57].

<table>
<thead>
<tr>
<th>FACTS</th>
<th>Voltage Source Converter</th>
<th>Thyristor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Voltage Source Converter</td>
<td>Thyristor</td>
</tr>
<tr>
<td>Degrees of Freedom</td>
<td>Voltage Source Converter</td>
<td>Thyristor</td>
</tr>
<tr>
<td>Shunt</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>Series</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>Shunt &amp; Series</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>Voltage Source Converter</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>Thyristor</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>Implemented</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>Active Power Control</td>
<td>NONE</td>
<td>HIGH</td>
</tr>
<tr>
<td>Reactive Power Control</td>
<td>HIGH</td>
<td>HIGH</td>
</tr>
<tr>
<td>Power Flow Control</td>
<td>LOW</td>
<td>LOW</td>
</tr>
<tr>
<td>Voltage Control</td>
<td>HIGH</td>
<td>HIGH</td>
</tr>
<tr>
<td>Transient Stability</td>
<td>MED</td>
<td>MED</td>
</tr>
<tr>
<td>Oscillation Damping</td>
<td>MED</td>
<td>MED</td>
</tr>
<tr>
<td>COST</td>
<td>MED</td>
<td>MED</td>
</tr>
</tbody>
</table>

4.2 Similar D-STATCOM Inverter Devices

The D-STATCOM Inverter falls under the category of devices known as custom power electronics. The IEEE has defined custom power as “the concept of employing power electronic (static) controllers in 1 kV through 38 kV distribution systems for supplying a compatible level of power quality necessary for adequate performance of selected facilities and processes” [55].

To this date, very little research has been conducted on implementing renewable energy sources
with custom power electronics. One of the main reasons is the IEEE 1547 Standard which states in Section 4.1.1 that “the distributed renewable (DR) shall not actively regulate the voltage at the point of common coupling (PCC)” [60]. This severely limits the application of these devices as their operation directly contradicts the IEEE standard. Utilities are free to ignore the IEEE standards so testing of the devices is possible, but commercialization will not occur until the IEEE standard is changed. Research on the devices is very important so the technology can be proven allowing new standards to be developed.

Most of the research on custom power electronics has stemmed from the research done on D-STATCOM devices that integrate battery energy storage (BESS). Under steady state operating conditions STATCOMs with BESS behave and act like normal STATCOM devices but, when required, have the freedom to deliver real power for short durations. This added degree of freedom makes their operation very similar to the D-STATCOM Inverter. The STATCOM with BESS is a topic of ongoing research. Researchers have proposed using various multilevel topologies including the NPC and cascaded H-Bridge [61–63] as well as a wide array of control strategies for the improvement of power quality [64–66]. The general applications of a STATCOM with BESS are the same as a regular STATCOM. They are designed to be placed on weaker busses or on critical paths of the system. Often they are incorporated into the designs of large wind farms to provide additional control and dampen any effects a large wind farm may have on a constrained system. In these applications the STATCOM is an auxiliary unit to the wind farm and is a separate entity residing on the same bus.

In addition to STATCOMs with BESS there have been a few studies which looked at the direct application the custom power interfaces for renewable energy sources. Out of the two studies found, one conducted in 2007 [66], looked at the application of a custom power interface in two modes of operation: 1), as an active power filter and 2), as a STATCOM for a renewable energy source. The second study conducted by NREL and published in 2009 [67], [68] looked at the use of a current source inverter to perform VAR and voltage regulation at the point of common coupling (PCC). In the first study, the series STATCOM, called STATCOM-RES, uses two STATCOM stages, one to simulate a renewable energy source and the other to model the STATCOM-RES. The STATCOM-RES is able to draw real power from the modeled distributed
renewable and thus provide active and reactive power. The STATCOM model is three-phase and operates with PWM at a switching frequency of 10 kHz. The topology of the inverter is not mentioned. The NREL study is the most similar to the D-STATCOM Inverter as it looks at VAR control and voltage regulation on single-phase distribution systems. The study uses a 2-level single H-Bridge inverter topology with a connected DC source to model the distributed renewable. The controller operates the inverter as a current-controlled voltage source using a PWM modulation strategy at 10 kHz. The study demonstrates that both VAR control and voltage regulation at the PCC is possible through the use of a custom inverter for distributed energy applications.

4.3 Operating Principles of a STATCOM

The power flow between a STATCOM and a line is governed by the same equations that describe the power flow between two active sources separated by an inductive reactance. For normal transmission lines this inductive reactance, modeled by $jX$ in Figure 4.1, is the inductance of a transmission line. For a STATCOM the modeled inductance is the inductance of the transformer that connects the STATCOM to the line. In Figure 4.1 the RMS voltage of the STATCOM is given as $E_s$ and is considered to be out of phase by a angle of $\delta$ to the RMS line voltage $E_L$. The active power transferred from the STATCOM to the line is given by Equation (4.1) and the reactive power transferred from the STATCOM to the line is given by Equation (4.2).

![Figure 4.1 Simple system diagram describing the power flow between two sources.](image)

\[ P_s = -\frac{E_s E_L}{X} \sin \delta \]  
\[ Q_s = \frac{E_s E_L \cos \delta - E_L^2}{X} \]
Control over the reactive power provided by the STATCOM is achieved by selecting both the voltage level of the STATCOM and the angle between the two voltages $\delta$. By using power electronics it is possible to control the amplitude of the STATCOM voltage by adjusting the modulation index and the angle $\delta$ by adding a delay to the firing signals. Adding the modulation index into Equations (4.1) and (4.2) gives Equations (4.3) and (4.4).

\[
P_s = -\frac{mE_sE_L}{X} \sin \delta \quad (4.3)
\]

\[
Q_s = \frac{mE_sE_L \cos \delta - E_L^2}{X} \quad (4.4)
\]

These two equations govern the operation of the STATCOM device, and designing the STATCOM is a matter of specifying the DC voltage level that will be required, given a transformer and its reactance $X$, to meet the amount of reactive compensation that is required. The steady state operation of the STATCOM is controlled by adjusting the modulation index and power angle $\delta$ so that it provides the desired amount of compensation.

STATCOMs, like SVCs are implemented to provide stability to power systems and are usually placed on weak buses or critical paths. As most voltage instability issues are related to a lack of adequate VARs, STATCOMs and SVCs are able to provide support by providing VARs as the load demands. There are a few major operational advantages of STATCOMs over SVCs. First, STATCOMs have faster response times and are better able to react to faults and transients. Second, one of the most critical times for VAR support occurs after or during a fault when the system may require an injection of VARs to raise the voltage back to stable limits. STATCOMs have an advantage in this regard as the amount of VAR compensation they can provide is a linear function of the grid voltage whereas the amount of compensation a SVC can provide is a quadratic function of the grid voltage. This means that when the grid voltage is dropping and is in the most need of VAR support the SVC can provide the least amount. The third advantage is that STATCOMs have a wider operating range than SVCs and can deliver more compensation under normal operating conditions.
Chapter 5 - D-STATCOM Inverter Design

5.1 Design Criteria and Design Objectives

The aim of the D-STATCOM Inverter is to replace the inverter of a wind turbine or solar installation with one that gives the utilities additional control. In designing the D-STATCOM Inverter several criteria must be defined. These are the size of turbine or solar installation the inverter will be used with, the amount of VAR compensation it will provide, and where it will connect on the grid. The three choices are the basic design criteria of the D-STATCOM Inverter and are defined as follows.

1) The inverter should be able to support turbines rated from 10–20 kW.
2) The inverter should be able to provide up to 20 kVARs of capacitive compensation regardless of the active power conversion.
3) The inverter must be connected to a single-phase feeder line.

The three choices were made by taking small businesses and farms into consideration. A 10–20 kW wind turbine or solar installation is a good amount of generation and is financially feasible for these types of consumers. Anything smaller than this would not warrant adding the extra control to the inverter, as the amount of controllable generation would be insignificant compared to the power on the whole feeder line. Similarly 20 kVARs was picked as it provides both a decent and realistic amount of reactive power compensation. It would not make sense to size the inverter for 100 kVA if the turbine itself could only produce 20 kW.

In addition to the design criteria there are a few design objectives. One is to minimize the overall switching frequency of the inverter because higher switching frequencies mean higher losses. The second is to minimize the total harmonic distortion in order to maintain compliance with IEEE standards and third is to keep the cost of the inverter as low as possible.

In meeting the design objectives, the OHSW modulation technique was chosen as it has the potential to provide the lowest amount of THD while maintaining the lowest switching frequency. The full benefits of the OHSW method cannot be realized, however, unless the
number of levels of the inverter is large. As discussed in Section 3.5.4, a 5-level single-phase inverter using the OHSW technique can only eliminate one harmonic. For this thesis a 5-level inverter was designed and a comparison between OHSW and HLCCAPOPWM control was made. In addition, the model was expanded to 11 levels and results of the simulations for 11 levels are discussed in Chapter 6. HLCCAPOPWM was chosen as a comparison because it is a SPWM technique which is the most common form of control used in commercial inverter designs.

The major difference in the architecture of the two models using the different modulation schemes is in the controller. This chapter proceeds by going through the complete architecture and design of the D-STATCOM Inverter using the OSHW technique in Sections 5.2–5.8. In Section 5.9 the HLCCAPOPWM method is revisited and the HLCCAPOPWM controller is presented.

### 5.2 Meeting the Design Criteria

The first step in the design is to determine how to meet the specifications. The first two design criteria specify the active and reactive power ranges that the D-STATCOM Inverter should be able to operate within. The active and reactive power flow of the D-STATCOM is governed by Equations (5.3) and (5.4) which are listed below.

\[
P_s = -\frac{mE_vE_L}{X} \sin \delta 
\]

\[
Q_s = \frac{mE_vE_L \cos \delta - E_L^2}{X}
\]

The two equations have four variables which govern the active and reactive power range. These variables are the inductance of the transformer X, the voltage of the STATCOM DC link \(E_v\), the voltage of the secondary side of the transformer \(E_L\), the range of the voltage angle \(\delta\), and the range of the modulation index \(m\). In defining these four variables a few assumptions are made. One is that the range of the modulation index is from 0.6 to 1. This has to do with solving for the firing angles in the OHSW technique and also keeping the levels of the inverter intact. The
second is the inductance of the transformer. For this design, the inductance of the transformer is 0.05 H and the X/R ratio of the transformer is assumed to be large so that Equations (4.3) and (4.4) will hold. The primary of the transformer is defined to be 7.2 kV and the secondary 1.0 kV. This represents a nonstandard transformer size as most distribution transformers have secondary voltage ratings of either 240 V or 480 V. Further, most standard distribution transformers do not have large X/R ratios [1]. This means that the D-STATCOM Inverter would require a more expensive custom-built transformer. This is not ideal, as one of the objectives is to keep the cost as low as possible. However, there is no way to achieve the desired design criteria with a standard off-the-shelf distribution transformer. Another solution could be to replace the transformer with an additional AC–AC power electronic stage that would boost the AC voltage up to grid level. The inductance could then be provided by an inductor connecting the D-STATCOM Inverter to the AC–AC stage. However, this is beyond the scope of the thesis. The final variable is the angle $\delta$ which is assumed to have an operating range from $-90$ degrees to $+90$ degrees in order to maintain quarter-wave symmetry. Figure 5.1 provides a graphic view of the designed operating range of the D-STATCOM Inverter in accordance with the chosen values and Equations (4.3) and (4.4).

---

**Figure 5.1** Designed operating range of the D-STATCOM Inverter. Individual lines represent different modulation indexes in steps of 0.05 ranging from 0.6 to 1.0.
5.3 Overview of the D-STATCOM Inverter

The design of the D-STATCOM Inverter was carried out in MATLAB/Simulink using the SimPowerSystems toolbox. Simulink allows different systems and subsystems to be built within any one model. Necessary for large designs, it allows for the separation and organization of different parts of a model. Figure 5.2 provides an overview of the various systems and subsystems of the D-STATCOM Inverter. Figure 5.3 shows the complementary screenshot taken from the highest level of the D-STATCOM Inverter in SimPowerSystems. The highest level of the model consists of five distinct parts. These are the Thevenin equivalent of the grid, the data acquisition block, the D-STATCOM controller, the power electronics circuit, and the wind turbine/solar model. Sections 5.4–5.8 describe the operation of each of these blocks.
Figure 5.2 Overview of the D-STATCOM Inverter design.
Figure 5.3 High level screenshot of the SimPowerSystems D-STATCOM Inverter design.
5.4 The Thevenin Equivalent Model of the Grid

To model the grid a simple Thevenin equivalent was created using an AC voltage source and a fixed parallel resistive and inductive load. The AC voltage source is set at a frequency of 60 Hz and a voltage level of 3600 V RMS. The load was created using SimPowerSystems parallel load branch block with a resistive load of 50 kW and inductive load of 34.835 kVARs, which gives a power factor of 0.82 lagging. These values were chosen to exaggerate the effect the D-STATCOM Inverter would have on the distribution system. In reality the active and reactive load of the distribution system would be much bigger and a single D-STATCOM Inverter of the proposed size would have a small effect on the overall system.

5.5 The Data Acquisition Block

The data acquisition block is responsible for acquiring and calculating the signals that the D-STATCOM controller uses. The four primary signals are the voltage and current of the grid and the voltage and current at the low side of the transformer. With these signals the data acquisition block calculates the active and reactive power of the grid, the active and reactive power provided by D-STATCOM, and the grid power factor. It should be noted that the practicality of acquiring these signals in a real system was not looked into with much detail. Acquiring real-time measurements of the voltage and current on the grid would require a current sensor and voltage measuring unit to be placed past the point of common coupling (PCC) in series with the grid. This could have negative effects on the cost of the inverter and would require additional engineering to meet high voltage isolation standards. For the data acquisition block in the SimPowerSystems model, acquiring and calculating the necessary signals are a straight forward process. All of the blocks, with exception to the power factor block, come standard with Simulink and SimPowerSystems. Figure 5.4 shows the inside of the data acquisition block. Figure 5.5 shows the inside of the power factor block.
Figure 5.4 Block diagram of the data acquisition block in SimPowerSystems.

Made by Colin Tarell
Date: November 2, 2010
Calculates the Power Factor
P.F. = $Q / (Q^2 + P^2)^{0.5}$

Figure 5.5 Block diagram of the power factor block in SimPowerSystems.
5.6 The D-STATCOM Controller

The controller of the D-STATCOM Inverter contains several subsystems which are shown in Figure 5.4. The controller’s main task is to take the inputs provided by the data acquisition block and compute the gate firing signals for the IGBTs in the power electronics block. A close-up view of the D-STATCOM controller is provided in Figure 5.6 along with a SimPowerSystems screen shot of the controller in Figure 5.7. The first three blocks of the controller are the phase-locked loop (PLL), the reactive power and modulation index controller, and the active power/DC link delta controller. The task of the PLL is to provide the controller with the grid frequency. The modulation index controller controls the reactive compensation provided by the D-STATCOM, and the delta controller regulates the active power flow and the DC link voltage of the inverter.
Figure 5.6 D-STATCOM controller.
Figure 5.7 Block Diagram of the D-STATCOM controller in SimPowerSystems.
5.6.1 The PLL for the Grid Frequency

The PLL is responsible for acquiring the frequency of the grid and providing that signal for the rest of the controller to use. The PLL provides three different outputs. The first is a numerical value of the grid frequency in Hz. The second is a ramping value with a constant slope and falling edge, and the third is a sinusoid with amplitude unity and the same frequency as the grid. Fortunately, the PLL is a standard Simulink block making the implementation a straightforward process. The Simulink 1-phase PLL block was used in this design.

5.6.2 Modulation Index Controller

The modulation index controller is responsible for determining the modulation index and selecting the correct firing angles from a lookup table containing all of the predefined OHSW switching angles. The modulation index of a STATCOM is the primary governor of the reactive power compensation that is provided, and its main task is to make the power factor of the grid equal to the desired power factor of the utility. If the inverter were to be built and commercialized, the desired utility power factor would be a control signal sent to the inverter by some form of communication protocol. For this thesis the desired utility power factor is assumed to be readily available to the controller. The modulation index controller calculates the desired change in Q on the feeder line, compares it to its operating limits, and then feeds the signal into a PI controller.

The operation of the modulation index controller depends on a few assumptions. The first is that the load on the feeder line can be considered fixed for a small window of time. This assumes the load will not vary within one cycle of the grid frequency. Second, the feeder line can be accurately modeled as a constant P, Q load. This means the power produced by a wind turbine will displace other power on the feeder line and not add to it. Third, a change in the modulation index will predominantly affect Q, while a change in delta will predominantly affect P. Any effect on Q from a small change (one cycle of the grid frequency) in delta is thus ignored. This assumes that P and Q are independently controlled.

The block diagram of the modulation index controller is shown in Figure 5.8 and performs the following calculations given the following four inputs $P_G$, $Q_G$, $Q_S$, and $P_{F.T}$, where:
\( P_G \) is the amount of active power on the grid.

\( Q_G \) is the amount of reactive power on the grid.

\( Q_S \) is the amount of reactive power provided by the D-STATCOM Inverter.

\( P.F._T \) is the target power factor desired by the utility.

The first step is to create an equation that relates the target \( Q \) to the target power factor. This relationship is show in Equation (5.1).

\[
P_G = \left( \sqrt{\frac{P_G^2}{P.F._T}} + Q_T^2 \right) \ast P.F._T
\]  

\( \text{(5.1)} \)

where:

\( Q_T \) is the target amount of reactive power, given \( S \) and \( P_T \).

Next, \( Q_T \) is solved for in Equation (5.2)

\[
Q_T = \sqrt{\left( \frac{P_G}{P.F._T} \right)^2 - P_G^2}
\]

\( \text{(5.2)} \)

To keep the modulation index controller within the operating VAR limits and modulation index range of the D-STATCOM Inverter, there are two controls put in place. One takes the smaller of the values in equation (5.3) as the input to the PI controller, guaranteeing that the D-STATCOM Inverter will not try to provide compensation beyond its capability.

\[
PI_{Input} = \min \left\{ \frac{|Q_{Lim} - Q_S|}{|\Delta Q|} \right\}
\]

\( \text{(5.3)} \)

The other puts upper and lower saturation limits within the PI controller limiting the output to stay within the modulation index ranges of 0.6 and 1.
Figure 5.8 Block diagram of the modulation index controller in SimPowerSystems.
The output of the PI controller is used to select the row in the modulation index lookup table. Each row of the modulation index table corresponds to a set of predefined switching angles for a given modulation index. The modulation index table contains different sets of switching angles for different modulation indices ranging from 0.6 to 1.0 in increments of 0.001. The firing signals that are output by the table correspond to the row whose modulation index was closest to the output of the PI controller. Depending on how many levels the inverter has, the number of firing angles (columns) contained in the modulation index table will vary.

The PI controller within the modulation index controller has a proportional constant of \(1/200000\) and an integral constant of \(1/350000\). These values were selected by manual tuning of the controller.

### 5.6.3 Delta Controller

The delta controller is tasked with maintaining the DC link voltage at 4000 V. By maintaining the DC links at a constant voltage, the amount of active power that is transferred between the D-STATCOM and the grid is also controlled. The DC link voltage is kept constant by maintaining proper charge on the DC link capacitors. With proper selection of the angle delta in Figure 5.1 and Equations (4.3) and (4.4) the correct amount of active power is transferred between the D-STATCOM and the grid which maintains the proper charge across the DC link capacitors. In addition to the varying VAR compensation, the controller has to be able to respond to fluctuations in power provided by the wind turbine or solar array. If the power output of either of these devices is increased and no change is made to the angle delta, the voltage across the capacitors will rise. Similarly, if the output power is decreased and delta is not changed, the voltage across the capacitors will decrease. Figure 5.9 shows the block diagram of the delta controller.
The delta controller keeps the DC link voltage constant by feeding a PI controller with the difference between the DC link voltage and the desired DC link voltage of 4000 V. The output of the PI controller is fed into an arcsine block. The arcsine block is implemented to allow the PI controller to effectively operate in different regions of the angle delta. As the active power flow is governed by Equation (4.3), small perturbations of the angle delta around 0 degrees will have significant effects on the active power, while a small perturbation of the angle delta around 10 or 20 degrees will have a little effect on the active power flow. The arcsine function linearizes the effect of delta and allows the PI controller to operate effectively when the renewable source is not providing power and the angle delta is around zero, and when the renewable source is dynamically changing its output and the angle delta is much greater than zero. The output of the PI controller is limited from \(-0.99\) to \(0.99\). The PI controller’s proportional constant is \(1/5000\); its integral constant is \(1/12000\). These values were selected by manual tuning of the controller.

### 5.6.4 The Firing Signal Generator

The firing signal generator takes the firing angles from the modulation index table and constructs the desired output voltage waveform of the inverter. This voltage waveform is fed into the delta delay implementer where the waveform is delayed by the angle delta before being fed into the lookup table. The block diagram of the firing signal generator is given in Figure 5.10.

The firing signal generator has two inputs, the ramping value from the PLL and the switching angles from the modulation index table. The firing signal generator uses the PLL signal along...
with the switching angles to construct a full quarter-wave symmetric waveform of the firing angles in real time. The code for the embedded MATLAB Function is given in Appendix B.
Figure 5.10 Block diagram for the firing signal generator in SimPowerSystems.
5.6.5 The Delta Delay Implementer

The delta delay implementing block takes the quarter-wave symmetric waveform produced by the firing signal generator and delays it by the angle delta determined by the delta controller. The block diagram for the delta delay implementer is shown in Figure 5.11.

![Block diagram of the delta delay implementer in SimPowerSystems.](image)

For a delay between 0 and 90 degrees the block directly implements the delay. All negative delays from –90 to 0 degrees are shifted by 360 degrees. A delay of –90 degrees corresponds to a delay of 270 degrees. The delay is implemented by making use of the grid frequency provided by the PLL.

5.6.6 The Firing Signal Lookup Table

The firing signal lookup table contains the switching signals of the hybrid-clamped inverter corresponding to the different output voltage levels. For a 5-level hybrid-clamped inverter there are 8 main switches and 6 auxiliary switches. The firing operation of these switches for a 5-level inverter is given in Table 2.3. The tables implemented in SimPowerSystems for 5 and 11 levels are given in Appendix C. The output signals from the firing signal lookup table are the final gating signals provided to the switches in the power electronics block.
5.7 The Power Electronics Circuit

The power electronics block contains the hybrid-clamped inverter topology. The DC link side is connected to the wind turbine/solar array model and the AC side is connected to the low side of the transformer. The block diagram of the SimPowerSystems 5-level hybrid-clamped inverter is shown in Figure 5.12. The resistors in parallel with diode 14 and the main switches are not part of the original circuit. They represent impedances of $1 \, \text{M} \Omega$ each and are put in place to allow the model to run. SimPowerSystems models diodes as current sources which create errors when they are put in series if nothing is placed in parallel with them. Each of the switches has an internal resistance of $0.001 \, \Omega$, forward voltage of $1 \, \text{V}$, current 10% fall time of $1 \, \mu\text{s}$, current tail time of $2 \, \mu\text{s}$, snubber resistance of $0.1 \, \text{M} \Omega$, and infinite snubber capacitance. Each of the diodes has an internal resistance of $0.001 \, \Omega$ and forward voltage of $0.8 \, \text{V}$. The DC link and auxiliary capacitors are all $1100 \, \mu\text{F}$.
Figure 5.12 Block diagram of the 5-level hybrid-clamped power electronics circuit in SimPowerSystems.
5.8 The Wind Turbine and Solar Array Model

To model the power produced by a wind turbine/solar array two controlled current sources are used. The controlled current sources allow the voltage to be fixed while producing a varying output power by varying the current. The output of the controlled current sources is sent through a standard SimPowerSystems universal bridge block which rectifies the 3-phase AC to DC. The output of the controlled current sources is varied by feeding the input with a timer function containing discrete intervals of varying current amplitudes. To limit the change in current from the turbine to the DC link capacitors, an inductance of 0.001 H is placed between the output of the universal bridge and the DC link capacitors of the hybrid-clamped inverter. Figure 5.13 shows the block diagram of the wind turbine/solar array model.

Figure 5.13 Block diagram of the wind turbine/solar array model in SimPowerSystems.

Modeling the wind turbine/solar array in this manner has a drawback. The power produced by the controlled current sources is a function of the DC link voltage and the amplitude of the current. As the DC link voltage has a small degree of variance, so too does the power produced by the turbine. This coupling means the current sources can amplify the instability of the DC link voltages. As long as the DC link voltage remains relatively constant at 4000 V DC this effect does not create any problems.
5.9 D-STATCOM Controller using HLCCAPOPWM

The block diagram of the D-STATCOM controller using the higher and lower carrier cells alternative phase opposition PWM is shown in Figure 5.14. The main difference from the OHSW controller is the disappearance of the lookup tables for the switching angles. In the PWM controller the output of the modulation index controller is the modulation index, not switching angles. The modulation index is fed into the PWM controller to control the magnitude of the reference sine wave generated by the PLL block. The PWM controller uses the reference sine wave and the modulation index to generate the output waveform in accordance with the HLCCAPOPWM method discussed in Section 3.2. Figure 5.15 shows the modified block diagram for the D-STATCOM controller in SimPowerSystems that uses HLCCAPOPWM.

![Block diagram of the D-STATCOM controller using HLCCAPOPWM.](image)

Figure 5.14 Block diagram of the D-STATCOM controller using HLCCAPOPWM.
Figure 5.15 Block diagram of the D-STATCOM controller using HLCCAPOPWM in SimPowerSystems.
The PWM controller block generates the switching signals for the hybrid-clamped inverter. The block diagram for the PWM controller is shown in Figure 5.16. The PWM controller generates the carrier waveforms shown in Section 3.2 and compares these waveforms to the reference sine wave generated by the PLL. The selection circuit and combination circuit in Figure 5.16 implement the hybrid-clamped switching scheme and provide the correct firing signals for the auxiliary switches. The code for the two functions is provided in Appendix D.
Figure 5.16 Block diagram of the PWM controller in SimPowerSystems.
The outputs of the PWM controller are the firing signals for the hybrid-clamped switches. The firing signals are sent through the delta delay controller where they are delayed by the angle delta before being sent to the power electronics block. Other differences from the HLCCAPOPWM and OHSW methods are the values for the KI and KP constants of the delta controller. For the delta controller the KI and KP constants are $1/5000$ and $1/15000$. 


Chapter 6 - Distribution Static Synchronous Compensator Inverter Simulations

6.1 Overview

To confirm the operation of the D-STATCOM Inverter simulations were carried out in SimPowerSystems using the model described in Chapter 5. Sections 6.2–6.4 cover the simulations of a 5-level D-STATCOM Inverter using both the HLCCAPOPWM and OHSW method. The final section looks at simulations of an 11-level inverter and discusses the problems that arise as the number of levels is increased. For the 5-level inverter, three different cases are explored. The first is a 20-second simulation that contains a severe ramping and de-ramping of the distributed renewable. In this instance the distributed renewable is modeled as a wind turbine because the output of a wind turbine is generally more variable than a solar array. The second case is a snapshot of the 20-second simulation that focuses on the operation of a few cycles of the D-STATCOM Inverter, and the third case is a comparison of the simulated THD of the 5-level inverter to the calculated performance discussed in Chapter 3.

6.2 A 20 Second Simulation

For the 20-second simulation the load on the grid is set to 50 kW and 34.835 kVARs giving a power factor of 0.82 lagging. The voltages for both the DC link and auxiliary capacitors in the hybrid-clamped topology are initialized to 1000 volts and the discrete intervals for the amplitudes of the current controlled current sources are given in Table 6.1. For the first 6 seconds of the simulation the output is 0 W to give the D-STATCOM Inverter time to adjust to the required compensation demanded by a target power factor of 0.9 lagging.

<table>
<thead>
<tr>
<th>Time (Seconds)</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
<th>17</th>
<th>18</th>
<th>19</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Amplitude (Amps)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1.5</td>
<td>2</td>
<td>2.5</td>
<td>2</td>
<td>1.5</td>
<td>1</td>
<td>0.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>

As the voltage level of the DC links is controlled to maintain 4000 volts, the output power provided by the controlled current sources is calculated by multiplying the amplitude of the
current by the DC link voltage. Starting at the 7th second of the simulation the power provided by the current sources is ramped up to 10 kW in three seconds, and then ramped down to 2 kW four seconds later. This represents an extreme case as the inertia constants of a normal wind turbine would not allow for such drastic changes in output power.

### 6.2.1 The 5-Level OHSW

Figures 6.1–6.4 provide the results of the 20-second simulation of the five-level D-STATCOM Inverter using the OHSW technique. Figures 6.1 and 6.2 depict the voltage of the DC link along with the individual voltages across each of the link and auxiliary capacitors. Figures 6.3 and 6.4 depict the power factor of the feeder line, the P and Q on the feeder line, the output power factor of the inverter, the output P and Q of the inverter, the modulation index, the angle delta, and the power produced by the wind turbine/solar array.

**Figure 6.1 Variation of capacitor voltages using OHSW.**
The top graph in Figure 6.1 shows the DC link voltage and the voltages of the four DC link capacitors \( C_1 - C_4 \). Prior to the wind turbine providing power, starting at the 7\(^{th} \) second, the D-STATCOM delta controller stabilizes the DC link voltages. The DC link voltage settles to within 15 volts of the target of 4000 volts, and the individual DC link capacitor voltages settle to within 15 volts of their target of 1000 volts (Figure 6.2). It should be noted that Figures 6.1 and 6.2 represent the same simulations.

![Graph of DC Link Voltage](image1)

![Graph of DC Link Capacitor Voltages](image2)

![Graph of Auxiliary Capacitor Voltages](image3)

**Figure 6.2** The DC link voltage and capacitor voltages are stabilized prior to the wind turbine starting up.

As the power from the wind turbine is ramped up, the DC link voltage rises as the angle delta slowly starts to adjust to push more active power out onto the grid. The maximum height of the DC link voltage occurs during the 9\(^{th} \) second and reaches 4361 volts representing a 9.0\% increase over the 4000 volt target.
Figure 6.3 Feeder line power factor, feeder line P and Q, D-STATCOM power factor, and delivered P and Q of the D-STATCOM.

The top graph of Figure 6.3 shows the power factor of the feeder line during the course of the 20-second simulation. Starting at the 0\textsuperscript{th} second, the power factor of the line is 0.82 lagging as it is defined entirely by the load. As soon as the simulation starts, the D-STATCOM Inverter begins to provide compensation and the power factor is adjusted. The noise in the beginning of simulation is due to charging of capacitors and inductors within the power electronics circuit.

The second graph of Figure 6.3 shows the P and Q provided by the feeder line to the load. Initially, the feeder line is supplying the entire load of 50 kW and 34.8 kVAR. When the D-STATCOM provides capacitive VAR compensation, the amount of VARs provided by the feeder line to the load is decreased to around 20 kVARs. Additionally, as the output of the wind
turbine is increased, the amount of active power provided by the feeder line to the load is decreased by the same amount.

The third and fourth graphs of Figure 6.3 show the output power factor provided by the D-STATCOM Inverter and the amount of reactive and active power provided to the feeder line.

![Graphs of Figure 6.3](image)

**Figure 6.3** Variation of modulation index, angle delta, and distributed renewable output power.

The top two graphs of Figure 6.4 show the corresponding modulation index and delta angle of the D-STATCOM Inverter over the course of the 20-second simulation. The bottom graph shows the amount of power that is exchanged between the distributed renewable and the D-STATCOM Inverter. The noise in the beginning is due to the transfer of energy between capacitors and inductors within the power electronics circuit and the model of the distributed renewable.

One cause for concern in the 5-level D-STATCOM Inverter is the existence of a small variability, from cycle-to-cycle, in the output current. This variability creates an oscillation in the output power (Figure 6.3, Figure 6.5, and Figure 6.6). The variability of the current stems from
the switching of the 5-level hybrid-clamped inverter. To mitigate this, a snubber circuit should be designed and implemented and, if necessary, a control loop added to control the current flow. Figure 6.5 shows a few cycles of the inverter's output current, voltage, and power. Both the current and the power of the inverter vary from cycle-to-cycle but, the voltage waveform remains relatively constant.

Figure 6.5 Cycle-to-Cycle variations in current and power.

As Figure 6.6 shows the current varies in both its magnitude and phase. The varying phase angle predominately affects the active power and the varying magnitude predominately affects the reactive power. This relationship while demonstrated in Figure 6.6, also agrees with the calculations for active and reactive power. Active power is calculated as the product of the magnitudes of the fundamental voltage and current times the cosine of the difference between their angles. Reactive power is calculated as the product of the magnitudes of the fundamental voltage and current times the sine of the difference between their angles. For cosine, a slight shift
around 90° is a substantial change: \( \cos(-96°) \) is -.10 and \( \cos(-85°) \) is .087. Therefore, the variation in phase dominates the variation in the current magnitude and is the cause for the variation in active power. For the reactive power a slight shift around 90 degrees has little effect as it is governed by the sine function. As a result, the variation of the reactive power is caused mainly by the varying current magnitude. To stabilize both the active and reactive power it is necessary to stabilize the magnitude and phase angle of the current.

Figure 6.6 Variation in magnitude and phase angle of the D-STATCOM Inverters output current and active and reactive power delivered by the D-STATCOM Inverter.

6.2.2 The 5-Level HLCCAPOPWM

The 20-second simulation for the 5-level HLCCAPOPWM is shown in Figure 6.7. The HLCCAPOPWM control method is able to maintain a slightly closer balance between the individual DC link capacitors. The result is due to the higher switching frequency of the PWM method and its ability to equalize the voltages across the capacitors multiple times in one cycle.
The negative effect is that the increased switching frequency also increases the variability of the current, affecting the delta control, and consequently creating a slight oscillation in the DC link voltage.

![DC Link Capacitor Voltages](image1)

![Auxiliary Capacitor Voltages](image2)

**Figure 6.7 Variation of capacitor voltages using HLCCAPOPWM.**

The response of the delta controller for the HLCCAPOPWM method to the rise in output power of the distributed renewable is slower than that of the OHSW method due to the lower KI constant of the delta controller. The result is the peak voltage of the DC link is 4572 volts representing a 14.3% increase over the target of 4000 volts. Figure 6.8 shows that HLCCAPOPWM is able to maintain a closer relationship between the individual capacitor voltages than OHSW. However, due to the increased variability in the inverter current waveform, the DC link voltage of the inverter oscillates around 4000 volts (Figure 6.7).
Figure 6.8 Variation of capacitor voltages right before the wind turbine starts providing power.
Figure 6.9 Feeder line power factor, feeder line P and Q, D-STATCOM power factor, and delivered P and Q of the D-STATCOM.
Figure 6.10 Variation of the modulation index, angle delta, and distributed renewable output power.

Figures 6.9 and 6.10 show the equivalent graphs of Figures 6.3 and 6.4 using the HLCCAPOPWM method. The result is an increased variability in the amount of P and Q provided by the D-STATCOM. As discussed above, this variation stems from the variation in the current waveform. Likewise, Figures 6.11 and 6.12 show the equivalent graphs of Figures 6.6 and 6.7 for the HLCCAPOPWM method. As expected, the current oscillations are increased in both magnitude and phase for HLCCAPOPWM.
Figure 6.11 Variation of current and power from cycle-to-cycle.
Figure 6.12 Variation in magnitude and phase angle of the D-STATCOM Inverters output current and its effect on the amount of delivered active and reactive power.

For the HLCCAPOPWM method the phase oscillation of the current ranges from $-110^\circ$ to $-80^\circ$ (approximately 30 degrees) and the magnitude ranges from 10 to 14 amps. The result is the variation in phase is roughly double that of the OHSW method while the variation in magnitude is equal to the OHSW method.

6.3 Capacitor Balancing and the Output Waveform
This section examines a few cycles of the voltage balancing of the DC link capacitors showing the inner workings of the D-STATCOM Inverter. The examined signals are the output voltage of the D-STATCOM Inverter, the DC link voltages and the auxiliary capacitor voltages.
6.3.1 The 5-Level OHSW

Figure 6.13 contains three different graphs. The top graph shows three cycles of the voltages across the DC link capacitors. The time corresponds to seconds 9.37–9.43 of the 20-second simulation. The middle graph shows the voltages of the three auxiliary capacitors, and the bottom graph shows the voltage output of the inverter and low-side transformer voltage.

The top graph of Figure 6.13 represents the voltage across the DC link capacitors $C_1$–$C_4$ of Figure 2.16. The behavior of all the capacitors can be understood by comparing the topology with the switching states for each of the inverter output voltage levels. The switching states of the inverter’s operation are given in Table 6.2, the topology is shown in Figure 2.16(a), and the output voltage levels correspond to the bottom graph in Figure 6.13. The main signal of concern is the voltage of capacitor $C_4$ in the top graph of Figure 6.13. The voltage across capacitor $C_4$ is the one that tends to separate itself from the rest of the group. This happens because of the switching states. In all of the voltage levels, except for the fourth, switch Sa’ is on and Sa1 is off, which means that capacitors ($C_2$ & $C_5$), ($C_3$ & $C_6$), and ($C_4$ & $C_7$) are in parallel. It is only during the fourth voltage level that switch Sa1 is on and capacitors ($C_1$ & $C_5$), ($C_2$ & $C_6$), and ($C_3$ & $C_7$) are placed in parallel. This gives a very small portion of every cycle in which the capacitors can equalize and is why such a large change in the capacitor voltages occurs in this segment. The waveforms in Figure 6.13 represent one of the more critical cases as the time period for this snapshot is in the middle of an extreme power ramping of the wind turbine, not its typical steady state operation. Even with the extreme ramping and the slight separation of the capacitor $C_4$ voltage, the voltage levels among the capacitors do not go unstable and the voltage output waveform remains intact.

Table 6.2 One Set of Possible Switching States for the 5-level Hybrid-Clamped Inverter.

<table>
<thead>
<tr>
<th>Voltage Level</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S4'</th>
<th>S3'</th>
<th>S2'</th>
<th>S1'</th>
<th>Sc1</th>
<th>Sc2</th>
<th>Sc3</th>
<th>Sc4</th>
<th>Sc5</th>
<th>Sc6</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</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>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
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<td>0</td>
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<td>0</td>
<td>1</td>
<td>0</td>
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</tr>
<tr>
<td>2</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
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<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The bottom graph in Figure 6.13 depicts the voltage at the inverter output and the voltage on the transformer secondary. As can be seen from the graph, the two voltage waveforms are not in
phase. The phase shift corresponds to the angle delta which governs the active power flow. In this model the inductance associated with the transformer is placed on the low voltage line so that this signal can be viewed.

6.3.2 The 5-Level HLCCAPOPWM

Figure 6.13 Capacitor voltages and inverter output waveform.

Figure 6.14 provides the same three graphs as Figure 6.13, but for the 5-level HLCCAPOPWM method. The major difference is observed in the bottom graph which depicts the output voltage waveform of the inverter. The graph shows that each voltage level of the output waveform contains many more on and off cycles as compared to the OHSW method. This faster switching allows the capacitor voltages to remain closer to one another as the number of times the capacitors are alternated in series is increased for each cycle. The switching table used for this method is the same as that provided in Table 6.2. The other difference is that the voltage of the
DC link is higher than that of the OHSW method, due to the use of different KI and KP constants in the delta controller between the two methods.

![DC Link Capacitor Voltages](image1)

![Auxiliary Capacitor Voltages](image2)

![Auxiliary Capacitor Voltages](image3)

Figure 6.14 Capacitor voltage balancing and output waveform.

### 6.4 Simulated Harmonic Content

This section provides a comparison between the expected harmonic content in the inverter’s output predicted in Chapter 3, and the harmonic content provided in the simulations. In addition, the harmonic performances of the 5-level OHSW and HLCCAPOPWM methods are compared.

#### 6.4.1 The 5-Level OHSW

As stated in Chapter 3, the output waveform of the 5-level OHSW should contain no even harmonics, because of quarter-wave symmetry, and the 3rd order harmonic should be eliminated due to the OHSW technique. Figures 6.15 and 6.16 provide a fast Fourier transform (FFT)
analysis of the harmonic content for two different simulation times of the 20-second simulation. Figure 6.15 provides the harmonic content for the first cycle beginning during the 4th second of the simulation and Figure 6.16 provides the harmonic content for the first cycle beginning at a simulation time of 9.37 seconds.

Figure 6.15 FFT analysis at t = 4 seconds for OHSW.

Figure 6.16 FFT analysis at t = 9.37 seconds for OHSW.
Table 6.3 Simulated vs. Predicted Results for THD for the OHSW Method up to the 100th harmonic.

<table>
<thead>
<tr>
<th>Time 1 = 4s</th>
<th>Simulated</th>
<th>Predicted</th>
</tr>
</thead>
<tbody>
<tr>
<td>THD</td>
<td>29.10%</td>
<td>29.39%</td>
</tr>
<tr>
<td>3rd Harmonic Percentage of Fundamental</td>
<td>0.30%</td>
<td>0.00%</td>
</tr>
<tr>
<td>Modulation Index</td>
<td>0.878</td>
<td>0.878</td>
</tr>
<tr>
<td>Time 2 = 9.37s</td>
<td>Simulated</td>
<td>Predicted</td>
</tr>
<tr>
<td>THD</td>
<td>29.13%</td>
<td>29.39%</td>
</tr>
<tr>
<td>3rd Harmonic Percentage of Fundamental</td>
<td>0.86%</td>
<td>0.00%</td>
</tr>
<tr>
<td>Modulation Index</td>
<td>0.867</td>
<td>0.867</td>
</tr>
</tbody>
</table>

Results show that while the 3rd and even harmonics have not been eliminated they have been suppressed to a low level. Table 6.3 summarizes the differences between the simulated and predicted values. The presence of even harmonics is the result of non-optimal switching times in the simulation, inductances and capacitances in the inverter, and variations in the current and voltage waveforms. The contribution to the THD by the even harmonics is of little concern as all of the even harmonics are relatively the same size (Figures 6.15 and 6.16) and the higher order ones can be further suppressed with the use of a small filter. A surprising result is that the simulated THD is actually lower than the predicted THD. This is due to some of the harmonics being suppressed by the inductances and capacitances in the circuit.

6.4.2 The 5-Level HLCCAPOPWM

The HLCCAPOPWM is a PWM method which suggests that the harmonic distortion in the output should not decrease but rather the individual harmonics should be shifted to a higher frequency. The amount of shift depends on the ratio of the carrier frequency to frequency of the fundamental component. This is the same as saying the frequencies of the harmonics are increased by the frequency of the carrier waveform. In this case, the frequency of the carrier is 1 kHz which means all of the harmonics should be shifted by 1 kHz. Figures 6.17 and 6.18 show the FFT analysis of the output waveform for the HLCCAPOPWM method at t = 4 and t = 9.37 seconds respectively.
The results of the FFT show that the larger harmonics have been shifted to higher frequencies but, that there still exist a number of significant lower order harmonics. This result is due to both
the side bands of the harmonics resulting from the carrier frequency, and distortions in the current and voltage waveforms of the inverter’s output. The distortions, as discussed above, are greater for the HLCCAPOPWM method and will have a bigger impact on the harmonics. In comparison to the OHSW method, the THD distortion is higher; 35.35% vs. 29.13% for t = 9.37s. This is in agreement with the expected results as the OHSW method reduces the THD while PWM methods do not.

6.4.3 Comparing the Two Modulation Methods
Table 6.4 provides an overview of the comparison between the two modulation methods. The results indicate that the OHSW method has better THD performance and operates with a reduced switching frequency. In fact, due to topology of the inverter, the number of switches turned on and off in one cycle of the inverters operation is 20 for OHSW and 124 for HLCCAPOPWM. This means the switching losses for the OHSW inverter are 16% of the switching losses of the HLCCAPOPWM inverter. Further, the use of a higher carrier switching frequency is desired as not all of the harmonics are shifted high enough.

Table 6.4 Comparison of the OHSW and HLCCAPOPWM results.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>OHSW</th>
<th>HLCCAPOPWM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time 1=4s: THD</td>
<td>29.10%</td>
<td>34.87%</td>
</tr>
<tr>
<td>Time 2=9.37s: THD</td>
<td>29.13%</td>
<td>35.35%</td>
</tr>
<tr>
<td>Requires a Large Filter</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Switching Frequency</td>
<td>240 Hz</td>
<td>1kHz</td>
</tr>
<tr>
<td>Switches Switched in 1 Cycle using Table 6.2</td>
<td>20</td>
<td>124</td>
</tr>
<tr>
<td>DC Link Capacitor Deviation</td>
<td>80 Volts</td>
<td>15 Volts</td>
</tr>
</tbody>
</table>

The major drawback to the 5-level OHSW is that it requires a large filter to suppress the 5th harmonic. This is a non-ideal solution as large filters affect the overall energy loss of the inverter and also change the impedance of the inverter seen by the grid, affecting the power flow. For this reason a single-phase D-STATCOM Inverter that uses the OHSW method has to contain more levels, but a three-phase solution could be implemented, as a 5-level three-phase inverter looks
like an 11-level inverter single-phase inverter and can suppress all of the harmonics up to the 17th.

### 6.5 The 11-Level D-STATCOM Inverter using OHSW

Expanding the number of levels from 5 to 11 can allow for a significant reduction in THD and reduce the voltages across the DC link and auxiliary capacitors. With an 11-level hybrid-clamped inverter, the DC link voltage is split across 10 capacitors with each capacitor having 400 volts across it. This reduced voltage allows for the use of smaller capacitors, but greatly increases the number of components within the inverter adding to the difficulty of maintaining stable current waveforms and voltage levels. The result is that the inverter is unable to maintain proper balance of the DC link and capacitor voltages while the distributed renewable is generating power.

Figure 6.19 shows the DC link and capacitor voltages of the 11-level inverter for the 20-second simulation. The graph shows that the inverter is able to maintain the DC link voltage up to the 7th second of the simulation at which point the distributed renewable starts producing power and the individual capacitor voltages begin to separate and become unstable.
Figure 6.19 Capacitor voltage waveforms for the 11-level OHSW D-STATCOM Inverter.

Figure 6.20 shows several cycles of the DC link and capacitor voltages just prior to the distributed renewable providing power. The graphs show that although there is an oscillation in the DC link voltage around the target of 4000 volts, the voltages of the DC link and auxiliary capacitors remain stable from cycle-to-cycle. The downside is that the some of the capacitors swing 25 volts in both the positive and negative direction of the 400 volt target for each cycle. This represents a $\mp 6.25\%$ tolerance of the 400 volts which is too high, especially for steady-state operation. To remedy this, larger capacitors can be used and or redundant switching states implemented. When the oscillation of the DC link voltage is eliminated, the swing will also be greatly reduced.
Figure 6.20 DC link voltage and capacitor voltages stabilize prior to the wind turbine starting up.

Even though the 11-level inverter is unable to maintain the DC link voltage while the distributed renewable source is varying, the reduction in THD that can be achieved is significantly greater than the 5-level OHSW and warrants future research. Figure 6.21 and Table 6.5 show the FFT analysis of the inverter’s output waveform at the 4th second of the simulation and provide an overview of the THD performance of the inverter.
Figure 6.21 FFT analysis of 11-level OHSW Inverter for t=4 seconds.

Table 6.5 Simulated vs. Predicted THD for the 11-level OHSW at t=4s

<table>
<thead>
<tr>
<th>Time 1 = 4s</th>
<th>Simulated</th>
<th>Predicted</th>
</tr>
</thead>
<tbody>
<tr>
<td>THD</td>
<td>12.16%</td>
<td>12.67%</td>
</tr>
<tr>
<td>3rd Harmonic % of fundamental</td>
<td>1.39%</td>
<td>0.00%</td>
</tr>
<tr>
<td>5th Harmonic % of fundamental</td>
<td>0.10%</td>
<td>0.00%</td>
</tr>
<tr>
<td>7th Harmonic % of fundamental</td>
<td>1.51%</td>
<td>1.50%</td>
</tr>
<tr>
<td>9th Harmonic % of fundamental</td>
<td>1.74%</td>
<td>1.65%</td>
</tr>
<tr>
<td>Modulation Index</td>
<td>0.898</td>
<td>0.898</td>
</tr>
</tbody>
</table>

As the FFT shows, the 3\textsuperscript{rd}, 5\textsuperscript{th}, 7\textsuperscript{th}, and 9\textsuperscript{th}, and even harmonics have all been suppressed and the overall THD is reduced to 12.16%. Table 6.5 summarizes the data and gives the amplitudes of the 3\textsuperscript{rd}, 5\textsuperscript{th}, 7\textsuperscript{th}, and 9\textsuperscript{th} harmonics as a percentage of the fundamental component. As the table shows, the suppression of the 3\textsuperscript{rd} and 5\textsuperscript{th} harmonics would be even better if the variation in the current and voltage waveforms of the inverter were reduced. The deviations from the desired steady state operation are the primary cause for the difference between the simulated and predicted individual harmonic amplitudes.
Chapter 7 - Conclusions and Future Work

7.1 Conclusions
The concept of a D-STATCOM Inverter is presented and shows a new way in which distributed renewable sources can be used to provide control and support in distribution systems. The D-STATCOM Inverter is able to provide utilities with capacitive VAR compensation and demonstrates how distributed renewable sources can strengthen the existing grid, not weaken it.

In this thesis, a variety of multilevel topologies and modulation schemes are discussed. The design of a 5-level D-STATCOM Inverter using the hybrid-clamped topology and OHSW modulation scheme is presented and simulations are carried out in MATLAB/Simulink and SimPowerSystems toolboxes. The results show that the OHSW technique is a feasible modulation scheme for the D-STATCOM Inverter and that the hybrid-clamped topology is able to operate under the dynamic conditions presented to it by a wind turbine or solar array.

The design objectives of the inverter were to minimize: the overall switching frequency, the total harmonic distortion, and the overall cost of the inverter. In selecting the OHSW method, the switching frequency is minimized to the lowest possible result. As shown in Table 6.4, the number of switches turned on in one cycle of the inverters operation is 20 using the OHSW method as compared to 124 for the HLCCAPOPWM method. Likewise, the overall total harmonic distortion at the output of the inverter is reduced. However, the current 5-level inverter would be unable to meet grid requirements without implementation of a large and bulky filter thus more levels would be required for practical implementation of the OHSW scheme. Finally, the cost of the inverter if built would be rather high due to both the number of components used in the hybrid-clamped topology as well as the need for a customized transformer to boost the output voltage to grid level.

7.2 Future Work
The current oscillation of the D-STATCOM Inverter stems from the switching of hybrid-clamped topology. To improve the performance a snubber circuit should be designed and implemented specifically for the hybrid-clamped topology. Further options for additional current
control need to be researched and explored to reduce the instability in the current waveform. In exploring the options for additional control, the small-signal equations should be derived to find the transfer function of the inverter. Once the oscillations are minimized, a prototype of the D-STATCOM Inverter should be built and tested.

Other modulation schemes should be investigated for the 5-level D-STATCOM Inverter, specifically SHEM. SHEM can retain a reduced switching frequency while eliminating any number of lower-order harmonics. In addition, control strategies making use of the redundant switching states for each voltage level could be explored. The redundant switching states could lead to the ability to maintain an even closer relationship between the DC link voltages.

A three-phase design of the D-STATCOM Inverter can also be investigated. A three-phase design increases the number of harmonics that can be eliminated using the OHSW technique. A 5-level three-phase inverter looks like an 11-level single-phase inverter. Additionally, the single-phase solutions for the OHSW technique provide regions of non-optimal solutions for modulation indexes ranging from 0.6 to 1 in 7, 9, and 11 levels. The three-phase solutions do not contain any of these regions.

The last area but perhaps most important is to take another look at the available multilevel topologies, specifically the MMC topology. The MMC topology may be able to provide a simpler solution using fewer components than the hybrid-clamped topology. This would allow for higher levels to be achieved more easily and would eliminate the need for a snubber circuit. In addition, the associated cost of building the inverter would be greatly decreased as the number of required components is less than half.
References


[58] D. Retzmann, K. Uecker, “Benefits of HVDC & FACTS for sustainability and security of power supply,” Siemens, Germany


Appendix A - PSO Code and Firing Angles

A.1 PSO Code

Main Program

```
clear all
TRUE=1;
ON=1;
FALSE=0;

%% BASED ON PAPERS

%% DESCRIPTION AND ABOUT THE PROGRAM
This program is set to find the optimal switching angles for a single phase inverter meaning it will try to eliminate the triplin harmonics. The control panel below is the only area that should be adjusted to run this for different level inverters. Along with the PSO solutions there is a second part to this script that will further increase the accuracy of the solutions by running the newton method using the PSO solutions as starting guesses. To turn this functionality off just set it to off in the control panel. Further, there are a bunch of different graphing options that can either be turned on or off from the control panel. Turn these on or off as you like.

After the PSO solution has been solved the results will be stored in a variable called RESULTS.
```

RESULTS=[ALPHA MI' GLOBAL_COST']
Column 1: # of Angles will be the switching angles
Column 2nd to last will be the corresponding modulation index
The last column will be the final solution cost according to the objective function.

If the Newton method is turned on, the results of the Newton method will be stored in a variable called RESULTS2 and will be in the same format as the PSO results.

The final sections contain all of the graphing functionality. all of the graphs can be turned on or off from the control panel. There are five graphs in total.

Figure2: Switching angles vs. modulation index for PSO
Figure3: Cost function vs. Modulation Index for PSO
Figure4: Cost function vs. Modulation Index for PSO Newton Hybrid
Figure5: Total Harmonic Distortion vs. Modulation Index
Figure6: Individual Harmonic Contributions

THE CONTROL PANNEL FOR PSO

DEFINE THE NUMBER OF LEVELS
NUMBER_OF_LEVELS=11;

IF THREE PHASE 3rd ORDER HARMONICS ARE CANCELED
THREE_PHASE=FALSE;

IF SINGLE PHASE WE MUST ELIMINATE 3rd ORDER HARMONICS
SINGLE_PHASE=TRUE;

MINIMUM ACCEPTABLE VALUE OF COST FUNCTION TO NOT REPEAT THE ITERATION
FIT_TOL=5;

ACCEPTABLE VALUE OF THE COST FUNCTION FOR LOOP TO BREAK
GOL_TOL=.001;

INITIALIZES THE MODULATION INDEX VALUES WE WANT TO PLOT GRAPHS OF THE INDIVIDUAL HARMONIC AMPLITUDES FOR
HARMONIC_MI=0.9;

TURN ON OR OFF GRAPHING OF THE AMPLITUDES
GRAPH_AMPLITUDES=ON;

TURN ON OR OFF GRAPHING OF TOTAL HARMONIC DISTORTION
GRAPH_THD=ON;

TURN ON OR OFF THE NEWTON METHOD HYBRID FOR MORE ACCURACY
NEWTON_METHOD=ON;

TURN ON OR OFF THE GRAPHING OF THE NEWTON METHOD
GRAPH_NEWTON=ON;

END OF THE CONTROL PANNEL

INITIALIZING PSO PARAMETERS

NOTE: THE NUMBER OF FIRING ANGLES = (NUMBER OF LEVELS -1)/2
NUMBER_OF_FIRING_ANGLES=(NUMBER_OF_LEVELS-1)/2;

HARM_ELIM=NUMBER_OF_FIRING_ANGLES; % NUMBER OF HARMONICS WE ARE ELIMINATING
PARTICLALS=20; % DEFINE THE NUMBER OF PARTICALS IN THE SWARM
WEIGHTS=[10 ones(1,(HARM_ELIM-1))]; % INITIALIZE THE WEIGHTS OF EACH HARMONIC
HARMONICS=[1:2:HARM_ELIM*2]; % THE HARMONICS, ONE FOR EACH LEVEL.
P_INCR=1.8; % WEIGHT FACTOR FOR PARTICAL VELOCITY
G_INCR=1.8; % WEIGHT FACTOR FOR GLOBAL VELOCITY
NUM=1; % CURRENT MODULATION INDEX NUMBER WE ARE ON
GLOBAL_FITNESS=10; % INITIALIZE THE GLOBAL FITNESS
MINDEX=0.5999; % STARTING MI FOR(MINDEX=.6:.001:1.1)
TRY_NUM_MAX=2; % NUMBER OF TIMES IT TRIES TO SOLVE FOR A SPECIFIC
GLOBAL_FITNESS=10; % MODULATION INDEX BEFORE MOVING ON
TRY_NUM=0; % CURRENT TRY
TRUE=1; % CONTINUE SOLVING FOR WHILE
SOLVED=FALSE; % IF THE LAST MODULATION INDEX SOLVED SUCCESSFULLY

while(TRUE==1)
    if(GLOBAL_FITNESS>0.001 && TRY_NUM<TRY_NUM_MAX)
        MINDEX=MINDEX;
        TRY_NUM=TRY_NUM+1;
    else
        MINDEX=MINDEX+0.0001;
        TRY_NUM=1;
        GLOBAL_FITNESS=10;
    end
    if(MINDEX>=1)
        TRUE=0;
    end

    A=rand(PARTICLALS,HARM_ELIM).*pi()/2;
    B=sort(A');
    PARTICAL_ANGLES=B';

    if(TRY_NUM==1)
        if(SOLVED==TRUE)
            PARTICAL_ANGLES(1:10,:)=repmat(GLOBAL_BEST_ANGLES,10,1);
        end
    end

    VELOCITY=zeros(PARTICLALS,HARM_ELIM);
%INITIALIZE THE BEST POSITIONS OF EACH PARTICAL AS WELL AS THE BEST
%% GLOBAL BEST POSITIONS. INITIALIZE THE GLOBAL BEST FITNESS TO SOME
%% ARBITRARILY LARGE VALUE
PARTICAL_BEST_ANGLES=zeros(PARTICALS,HARM_ELIM);
GLOBAL_BEST_ANGLES_OLD=zeros(1,HARM_ELIM);
GLOBAL_FITNESS=1000000;

%% INITIALIZE THE FITNESS VALUE FOR EACH OF THE PARTICALS IN THE SWARM
PARTICAL_FITNESS = ones(1, PARTICALS)*100;

ITERATION=1;  %% CURRENT ITERATION OF A PARTICULAR MODULATION INDEX
MAX_ITERATION=50000;  %% MAXIMUM NUMBER OF ITERATIONS BEFORE FAILURE
TOL=1;  %% DETERMINES IF THE ANGLES ARE STILL CHANGING EACH ITERATION

while((GLOBAL_FITNESS>=GOL_TOL | TOL >=0.001) & (ITERATION ...
   <= MAX_ITERATION))
   %% INITIALIZE THE FITNESS FUNCTION TO BE SOLVED OR OPTIMIZED
   %% INPUTS: (PARTICAL_ANGLES, WEIGHTS, HARMONICS, MINDEX)
   %% OUTPUT: COST
   %$$ COST FUNCTION (p1, p2, p3...)=w1|#M-H1|+w2|H5|+w3|H7|...
   [FITNESS]=fitness(PARTICAL_ANGLES, WEIGHTS, HARMONICS, MINDEX);

   %% ITERATE THROUGH THE NEW FITNESS OF EACH PARTICAL
   for(j=1:length(FITNESS))
      %% IF THE FITNESS IS LESS THAN THE GLOBAL_FITNESS THEN THERE
      %% IS A NEW BEST FITNESS AND THE GLOBAL FITNESS IS UPDATED
      if(FITNESS(j) < GLOBAL_FITNESS)
         GLOBAL_BEST_ANGLES=PARTICAL_ANGLES(j,:);
         GLOBAL_FITNESS=FITNESS(j);
         TOL=abs(sum(GLOBAL_BEST_ANGLES-GLOBAL_BEST_ANGLES_OLD));
         GLOBAL_BEST_ANGLES_OLD=GLOBAL_BEST_ANGLES;
      end

      %% IF THE FITNESS OF PARTICAL J IS LESS THAN THE PREVIOUS
      %% FITNESS OF PARTICAL J THEN UPDATE THE FITNESS OF THAT
      %% PARTICAL AND STORE THE CORRESPONDING ANGLES
      if(FITNESS(j) <= PARTICAL_FITNESS(j))
         PARTICAL_FITNESS(j)=FITNESS(j);
         PARTICAL_BEST_ANGLES(j,:)=PARTICAL_ANGLES(j,:);
      end
   end

   %% UPDATE THE VELOCITIES OF ALL OF THE PARTICALS. THIS WILL
   %% CONTAIN TWO PARTS. ONE PART ASSOCIATED WITH THE GLOBAL BEST
   %% AND THE OTHER WITH EACH PARTICALS INDIVIDUAL BEST

   %% A WEIGHT FOR UPDATING THE VELOCITIES
   VELOCITY_WEIGHT=0.75;

   for(n=1:1:PARTICALS)
      VELOCITY(n,:)=VELOCITY_WEIGHT.*VELOCITY(n,:)+ ...
         P_INCR*rand(1).*(PARTICAL_BEST_ANGLES(n,:)- ...)
PARTICAL_ANGLES(n,:) + G_INCR*rand(1).*...
(GLOBAL_BEST_ANGLES - PARTICAL_ANGLES(n,:));

end

% UPDATE THE POSITION OF THE PARTICAL WHICH ARE THE ANGLES
NP_ANGLES = PARTICAL_ANGLES + VELOCITY*1;

%%% FOR EACH PARTICAL UPDATE THE POSITION AS LONG AS THE
%%% CONSTRAINT THAT ALPHA 1 < ALPHA 2 < ALPHA 3... HOLDS
for (bb=1:PARTICALS)
    if (NP_ANGLES(bb,1)>=0 & NP_ANGLES(bb,end)<=pi/2 & ...
        NP_ANGLES(bb,:) - sort(NP_ANGLES(bb,:)) == ...
        zeros(1,HARM_ELIM))

        TOL = abs(sum(abs(PARTICAL_ANGLES)) - sum(abs(NP_ANGLES)));
        PARTICAL_ANGLES(bb,:) = NP_ANGLES(bb,:);
end
end

ITERATION = ITERATION + 1;
end

%%% END THE WHILE LOOP FOR A PARTICULAR MODULATION INDEX
ITERATION

%%% CHECK TO SEE IF THE GLOBAL FITNESS TOLERANCE HAS BEEN REACHED
%%% WE WANT SOLUTIONS WITH A FITNESS BELOW .001. IF IT HAS WE STORE
%%% THE ANGLES AS THE SOLUTION TO THAT PARTICULAR MODULATION INDEX AS
%%% WELL AS THE FITNESS VALUE OF THE SOLUTION
if (GLOBAL_FITNESS < FIT_TOL)
    ALPHA(NUM,:) = GLOBAL_BEST_ANGLES*180/pi;
    MI(NUM) = MINDEX;
    GLOBAL_COST(NUM) = GLOBAL_FITNESS;
    SOLVED = TRUE;
else
    if (SOLVED == FALSE)
        if (FIT_TOL < BEST)
            ALPHA(NUM,:) = GLOBAL_BEST_ANGLES*180/pi;
            BEST = FIT_TOL;
        end
    else
        ALPHA(NUM,:) = GLOBAL_BEST_ANGLES*180/pi;
        BEST = FIT_TOL;
    end
    MI(NUM) = MINDEX;
    GLOBAL_COST(NUM) = 100;
    SOLVED = FALSE;
end

[ALPHA(end,:) MI(end)' GLOBAL_COST(end)']

NUM = NUM + 1;
end

RESULTS=[ALPHA MI' GLOBAL_COST'];
%save RESULTS

figure(2)
plot(MI, ALPHA, '.');
xlabel('Modulation index, MI')
ylabel('Switching angle (Degrees)')
title('PSO Algorithm')
legend('Alpha1', 'Alpha2', 'Alpha3', 'Alpha4', 'Alpha5', 'Alpha6')

figure(3)
plot(MI, GLOBAL_COST, '.');
xlabel('Modulation index, MI')
ylabel('Cost Function')
title('PSO Algorithm')

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%                       BEGIN NEWTON METHOD                           %%%
%%% FOR AN m-LEVEL SINGLE PHASE INVERTER                  %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

if (NEWTON_METHOD==1)

    for (NUM=1:length(MI))

        %% CONVERT FROM DEGREES TO RADIANS
        ALPHA1=ALPHA*pi/180;

        %% DEFINE THE ODD MATRIX TO BE USED IN FUNCTION
        ODD=(1:2:2*(length(ALPHA1(1,:))-1));

        %% DEFINE THE EQUATIONS
        %%
        %% EXAMPLE FUNCTION FOR 2 ANGLES
        %% FUNCTION=[ cos(ALPHA(NUM,1)) cos(ALPHA(NUM,2));
        %%             cos(3*ALPHA(NUM,1)) cos(3*ALPHA(NUM,2))];
        FUNCTION=cos(repmat(ODD',1,length(ODD)).*repmat(ALPHA1(NUM,:)',1,length(ODD)));

        %% DEFINE THE DERIVATIVES OR JACOBIAN MATRIX
        %%
        %% EXAMPLE JOCOBIAN FOR 2 ANGLES
        %% JACOBIAN=[ -sin(ALPHA(NUM,1)) -sin(ALPHA(NUM,2));
        %%            -3*sin(3*ALPHA(NUM,1)) -3*sin(3*ALPHA(NUM,2))];
        JACOBIAN=repmat(ODD',1,length(ODD)).*-sin(repmat(ODD',1,...
                      length(ODD)).*repmat(ALPHA1(NUM,:)',1,length(ODD)));

        %% WHAT THE EQUATIONS SHOULD EQUAL
        T=zeros(NUMBER_OF_FIRING_ANGLES,1);
        T(1)=RESULTS(NUM,end-1)*NUMBER_OF_FIRING_ANGLES*pi/4;
%% CALCULATE THE CHANGE IN ALPHA
D_ALPHA=pinv(JACOBIAN)*(T-FUNCTION(1,:))';

%% UPDATE ALPHA
ALPHA1(NUM,:)=ALPHA1(NUM,:)+D_ALPHA';

%% CACULATE THE FITNESS ACCODRING TO THE COST EQUATION
FITNESS_NEWTON=fitness(1, WEIGHTS, HARMONICS, MI);[FITNESS_NEWTON]=fitness(1, WEIGHTS, HARMONICS, MINDEX);

%% SAVE THE COST AS THE FITNESS VALUE
COST_NEWTON(NUM)=FITNESS_NEWTON;
end

%% STORE THE RESULTS OF THE NEWTON METHOD
RESULTS2=[ALPHA1*180/pi MI' COST_NEWTON'];
end

%%% END NEWTON METHOD

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%                GRAPH THE NEWTON METHOD RESULTS                    %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

if(GRAPH_NEWTON==TRUE)

%% DISPLAY THE COST OF THE NEWTON METHOD
figure(4)
plot(MI, COST_NEWTON, '.');
xlabel('Modulation index, M')
ylabel('Cost Function')
title('Cost after PSO-Newton-Hybrid')
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%                CALCULATING THD AND MAKING GRAPHS                   %%%
%%%             INCLUDE HARMONICS UP TO THE 101st ORDER                %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
ALPHA=ALPHA*pi/180;
if(GRAPH_THD==1)

%% CALCULATE THE THD UP TO THE 101st HARMONIC FOR EACH MI
if(THREE_PHASE==0 & SINGLE_PHASE==1)
N=3:2:101;
elseif(THREE_PHASE==1 & SINGLE_PHASE==0)
   N=3:2:101;
   %%% REMOVES ALL MULTIPLES OF THREE
   N=NN(find(mod(NN,3)));
else
   warning('Please select either Single Phase or Three Phase')
end

%% DEFINE THE FUNCTIONS I WILL USE
NOM=@(N,ALPHA)sqrt(sum(((4./(pi*N)).*(sum((cos(repmat...
(N',1,length(ALPHA)).*repmat(ALPHA,length(N),1)).^2));
DEN=@(ALPHA)(4/pi)*sum(cos(ALPHA));
%%% CALCULATE THE TOTAL THD
for(k=1:length(MI))
    TOTAL_THD(k)=100*NOM(N,ALPHA(k,:))/DEN(ALPHA(k,:));
end
%%% GRAPH THE THD vs MODULATION INDEX
figure(5)
plot(MI, TOTAL_THD, '.');
xlabel('Modulation Index, M')
ylabel('Line Voltage THD (%)')
title('THD up to the 101st Harmonic vs Modulation Index')
end
%%% END GRAPH THD
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%     FOR A SPECIFIC MODULATION INDEX GRAPH THE HARMONIC FACTORS     %%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%
if(GRAPH_AMPLITUDES==1)
    %%% DEFINE ALL OF THE HARMONICS TO CALCULATE
    if(THREE_PHASE==0 & SINGLE_PHASE==1)
        N=1:2:101;
    elseif(THREE_PHASE==1 & SINGLE_PHASE==0)
        NN=1:2:101;
        N=NN(find(mod(NN,3)));
    else
        warning('Please select either Single Phase or Three Phase')
    end
    %%% EQUATION FOR THE HARMONIC AMPLITUDE WHERE N IS THE ORDER
    HN=@(N,ALPHA)(4/(N*pi))*sum(cos(N*ALPHA));
    %%% CALCULATE THE INDIVIDUAL HARMONIC AMPLITUDES
    p=find(MI > (HARMONIC_MI -.00001) & MI < (HARMONIC_MI + .00001));
    %%% VALUE OF FUNDAMENTAL
    FUNDAMENTAL=(4/pi)*sum(cos(ALPHA(p,:)));
    %%% COUNTER FOR THE HAR_AMP VECTOR
    COUNT=2;
    %%% PUT THE FUNDAMENTAL IN THE HAR_AMP
    HAR_AMP(1)=1;
    for(m=2:length(N))
        HAR_AMP(COUNT)=abs(HN(N(m),ALPHA(p,:)))/FUNDAMENTAL;
        COUNT=COUNT+1;
    end
    %%% INSERT HISTOGRAM PLOT
    figure(6)
    bar(N,HAR_AMP*100, 'g','EdgeColor',[0 0 0])
    %hist(HAR_AMP*100,N)
end
The Fitness Function

function [COST] = fitness(p, WEIGHTS, h, MINDEX)

%% DETERMINES THE FITNESS FUNCTION AND COMPUTES THE COST FOR A PARTICULAR
%% MODULATION INDEX
for(x=1:1:size(p,1))

H=cosm(cos(repmat(h(size(p,2),1)',*repmat(p(x,:),length(h,1),1)'));

H(1)=MINDEX*pi/4*length(h)-H(1);

COST(x)=WEIGHTS*abs(h)';
end
end

A.2 Switching angles for Single-Phase 5, 7, 9, and 11 Level Inverters
| 0.990 | 3.843 | 56.349 | 0.0000002 | 21.162 | 21.857 | 63.502 | 0.340 | 1.563 | 1.631 | 37.804 | 37.903 | 63.779 | 0.279 | 10.988 | 10.988 | 30.517 | 46.295 | 67.922 | 0.310 |
| 0.992 | 3.993 | 56.007 | 0.21447 | 21.194 | 21.884 | 63.387 | 0.330 | 0.984 | 0.984 | 37.773 | 37.773 | 63.640 | 0.302 | 10.935 | 10.935 | 30.313 | 45.899 | 68.120 | 0.191 |
| 0.993 | 4.113 | 50.889 | 0.21123 | 21.273 | 21.629 | 61.273 | 0.330 | 0.287 | 0.287 | 37.777 | 37.683 | 63.607 | 0.256 | 10.935 | 10.935 | 30.313 | 45.899 | 68.120 | 0.225 |
| 0.995 | 4.311 | 50.700 | 0.21082 | 21.296 | 21.555 | 61.102 | 0.320 | 1.908 | 1.908 | 37.932 | 37.932 | 63.420 | 0.244 | 11.816 | 11.816 | 30.440 | 45.847 | 67.550 | 0.335 |
| 0.995 | 4.350 | 50.556 | 2.225-15 | 21.359 | 21.995 | 61.060 | 0.324 | 0.000 | 0.000 | 37.987 | 37.987 | 63.474 | 0.352 | 11.090 | 11.090 | 31.026 | 45.940 | 67.189 | 0.310 |
| 0.995 | 4.479 | 50.529 | 0.21035 | 21.305 | 21.305 | 60.993 | 0.199 | 0.335 | 0.335 | 37.997 | 37.997 | 63.249 | 0.229 | 10.976 | 11.296 | 30.781 | 45.413 | 67.182 | 0.129 |
| 0.995 | 4.560 | 50.418 | 2.785-13 | 21.378 | 21.539 | 60.823 | 0.315 | 0.733 | 0.733 | 37.958 | 37.958 | 63.138 | 0.271 | 10.920 | 11.258 | 30.977 | 45.620 | 67.307 | 0.321 |
| 0.995 | 4.712 | 50.287 | 0.21198 | 21.218 | 21.218 | 60.707 | 0.131 | 1.764 | 1.764 | 37.095 | 37.448 | 63.085 | 0.213 | 10.902 | 11.238 | 30.611 | 45.132 | 67.025 | 0.115 |
| 0.995 | 4.850 | 50.164 | 0.21157 | 21.157 | 21.157 | 60.583 | 0.186 | 1.797 | 1.797 | 36.875 | 37.365 | 62.955 | 0.205 | 10.880 | 11.249 | 30.700 | 44.998 | 66.809 | 0.213 |
| 1.000 | 4.957 | 50.034 | 0.21192 | 21.192 | 21.195 | 60.582 | 0.136 | 14.099 | 17.850 | 42.302 | 61.048 | 62.955 | 0.296 | 1.952 | 17.382 | 28.506 | 45.544 | 66.579 | 0.114 |

Table 7.1 Switching Angles for 5, 7, 9, and 11 level single-phase OHSW
Appendix B - Embedded Matlab Function

The Firing Signal Generation Code

function Signal = fcn(Angles)
    if (isequal(Angles', [1 1 1 1 1 1 1 1])==1)
        Signal = 2;
    elseif (isequal(Angles', [0 0 0 1 1 1 1 1])==1)
        Signal = 2;
    elseif (isequal(Angles', [0 1 1 1 1 1 1 1])==1)
        Signal = 3;
    elseif (isequal(Angles', [0 0 0 1 1 1 1 1])==1)
        Signal = 3;
    elseif (isequal(Angles', [0 0 0 0 0 1 1 1])==1)
        Signal = 4;
    elseif (isequal(Angles', [0 0 0 0 0 0 0 1])==1)
        Signal = 1;
    elseif (isequal(Angles', [0 0 0 0 0 0 0 0])==1)
        Signal = 0;
    else
        Signal = 0;
    end
end
Appendix C - Hybrid-Clamped Switching States

The following tables contain all of the switching states for each voltage level of 5, 7, 9 and 11 level hybrid-clamped inverters. The odd and evens columns refer to the switching states of the auxiliary switches.

<table>
<thead>
<tr>
<th>5-Level Hybrid-Clamped Inverter Switching States</th>
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</thead>
<tbody>
<tr>
<td>Voltage Level</td>
</tr>
<tr>
<td>---------------</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>3</td>
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<td>2</td>
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<tr>
<td>1</td>
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<tr>
<td>0</td>
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</tbody>
</table>

Table 7.2 Switching states for the 5-level hybrid-clamped inverter.

<table>
<thead>
<tr>
<th>7-Level Hybrid-Clamped Inverter Switching States</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage Level</td>
</tr>
<tr>
<td>---------------</td>
</tr>
<tr>
<td>6</td>
</tr>
<tr>
<td>5</td>
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<tr>
<td>4</td>
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<tr>
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<td>1</td>
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<td>0</td>
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Table 7.3 Switching states for the 7-level hybrid-clamped inverter.

<table>
<thead>
<tr>
<th>9-Level Hybrid-Clamped Inverter Switching States</th>
</tr>
</thead>
<tbody>
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<td>Voltage Level</td>
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<tr>
<td>---------------</td>
</tr>
<tr>
<td>8</td>
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<tr>
<td>7</td>
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<tr>
<td>6</td>
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<tr>
<td>5</td>
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Table 7.4 Switching states for the 9-level hybrid-clamped inverter.
<table>
<thead>
<tr>
<th>Voltage Level</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
<th>S6</th>
<th>S7</th>
<th>S8</th>
<th>S9</th>
<th>S10</th>
<th>S10'</th>
<th>S9'</th>
<th>S8'</th>
<th>S7'</th>
<th>S6'</th>
<th>S5'</th>
<th>S4'</th>
<th>S3'</th>
<th>S2'</th>
<th>S1'</th>
<th>Odds</th>
<th>Evens</th>
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Table 7.5 Switching states for the 11-level hybrid-clamped inverter.
Appendix D - Selection and Combination Block Code for PWM

D.1 Selection Circuit Code

```matlab
function [OUT, S] = fcn(L)

%%% CONDITIONAL LOGIC FOR SWITCHES

%%% SWITCH S1
if (L(1)==1)
    S1=1;
    S1p=0;
else
    S1=0;
    S1p=1;
end

%%% SWITCH S2
if (L(2)==1)
    S2=1;
    S4p=0;
else
    S2=0;
    S4p=1;
end

%%% SWITCH S3
if (L(3)==1)
    S3=1;
    S3p=0;
else
    S3=0;
    S3p=1;
end

%%% SWITCH S4
if (L(4)==1)
    S4=1;
    S2p=0;
else
    S4=0;
    S2p=1;
end

S=[S1 S2 S3 S4 S4p S3p S2p S1p];

OUT=[S1+3, S2+2, S3+1, S4];
```

D.2 Combination Circuit Code

```matlab
function Switches = fcn(S)

if (S(1)==1)
```
Sc1=0;
Sc2=1;
Sc3=0;
Sc4=1;
Sc5=0;
Sc6=1;
else
Sc1=1;
Sc2=0;
Sc3=1;
Sc4=0;
Sc5=1;
Sc6=0;
end

Aux_S=[Sc1 Sc2 Sc3 Sc4 Sc5 Sc6];

Switches=[S Aux_S];