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

by

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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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Glossary of Acronyms

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

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.

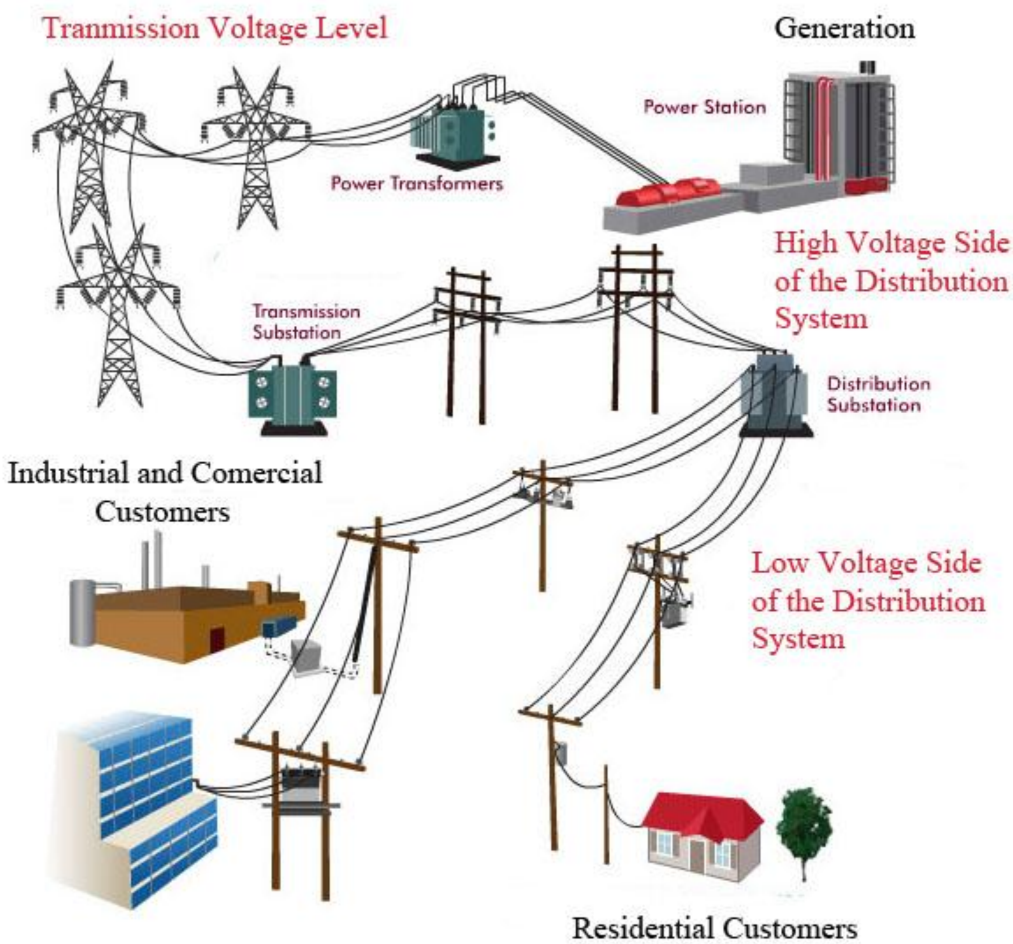


Figure 1.1 Traditional view of the United States electric grid [1]

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

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].

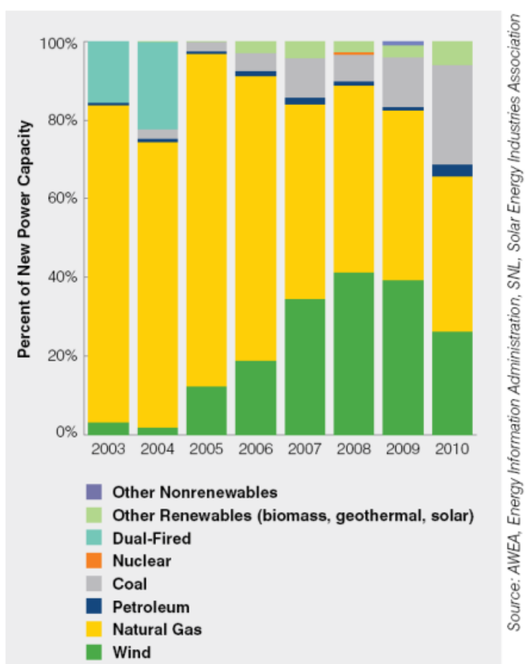


Figure 1.2 Breakdown of new generation capacity since 2003 [2].

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.

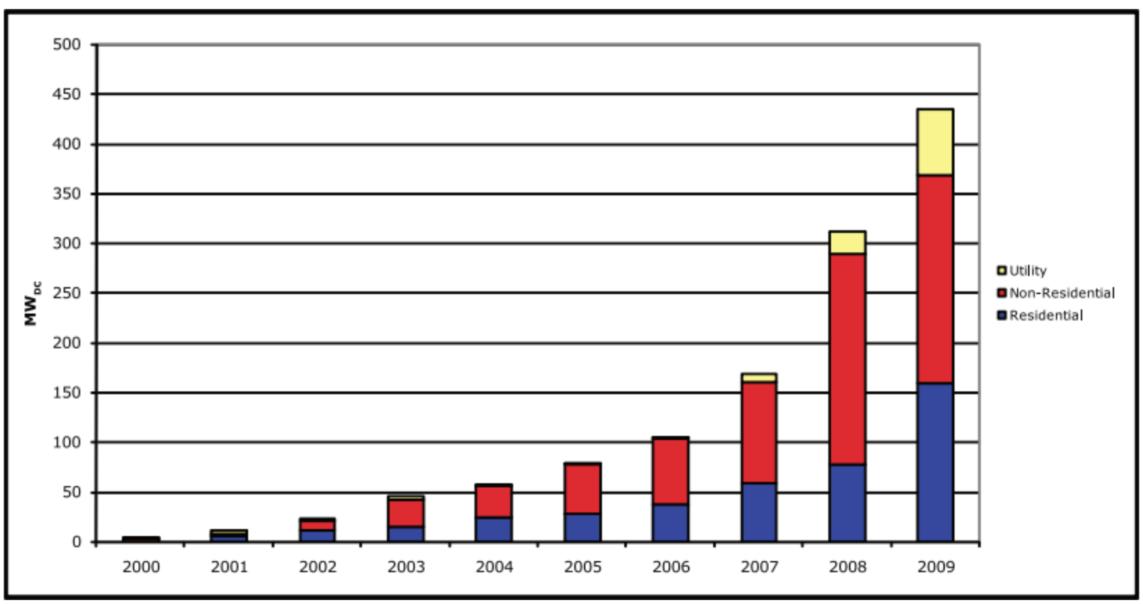


Figure 1.3 Annual Installed grid-connected PV capacity by sector (2000-2009) [8].

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.

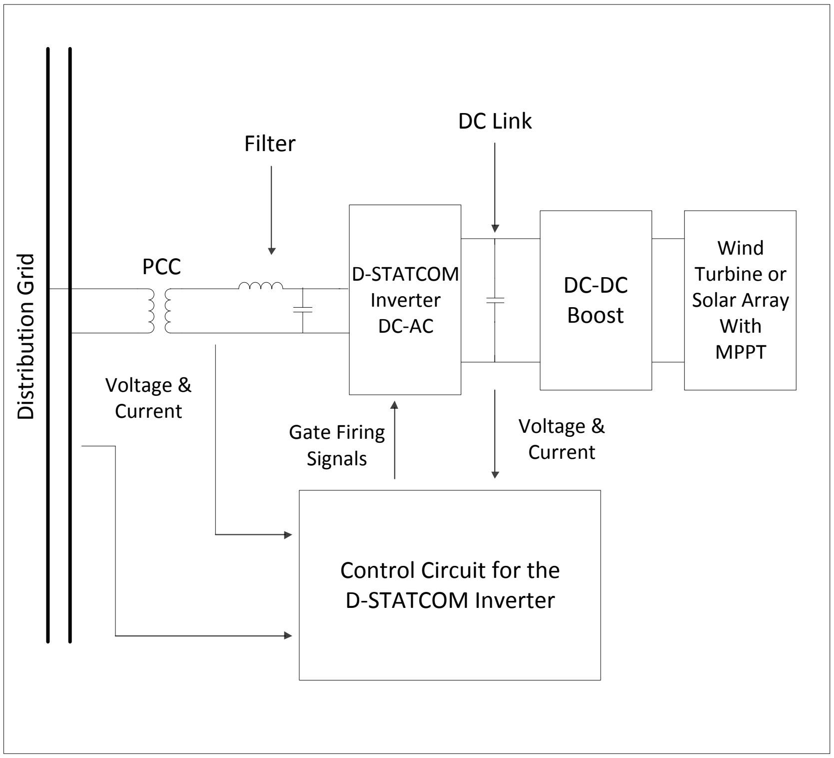


Figure 1.4 Basic outline of a D-STATCOM Inverter

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 (S_1, S_2) are *on* and (S_3, S_4) 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 (S_2, S_3) are *on* and (S_1, S_4) are *off*, the output of the inverter is connected to ground, and the resulting output voltage V_o is 0. When switches (S_3, S_4) are *on* and (S_1, S_2) are *off*, the output V_o of the inverter is across capacitor C_2 and produces a voltage equal to $–V_{dc}/2$.

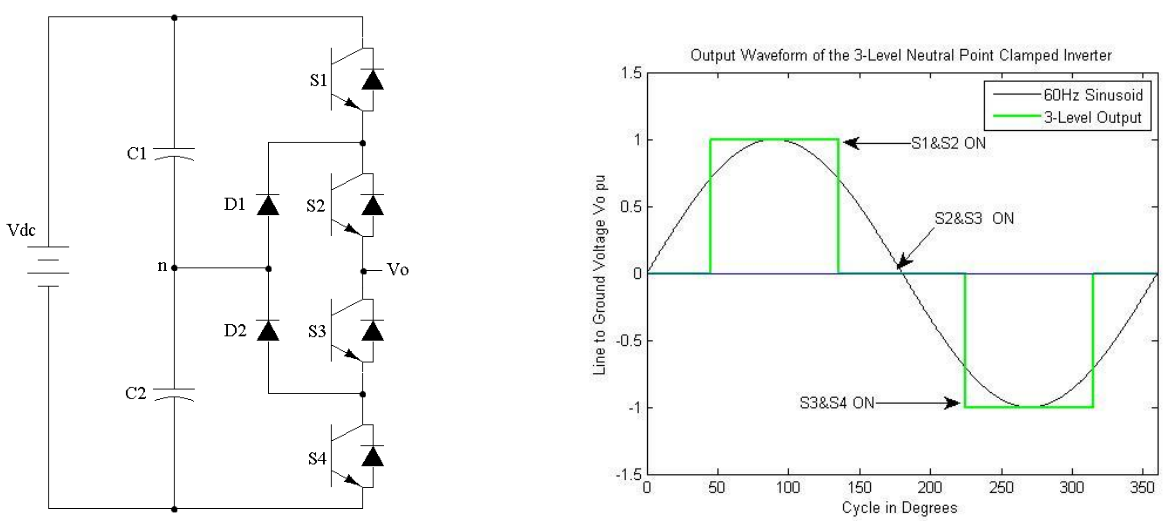


Figure 2.1 (a) Single-phase, 3-level NPC topology. (b) Output waveform.

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 $-2V_{dc}/$. 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.

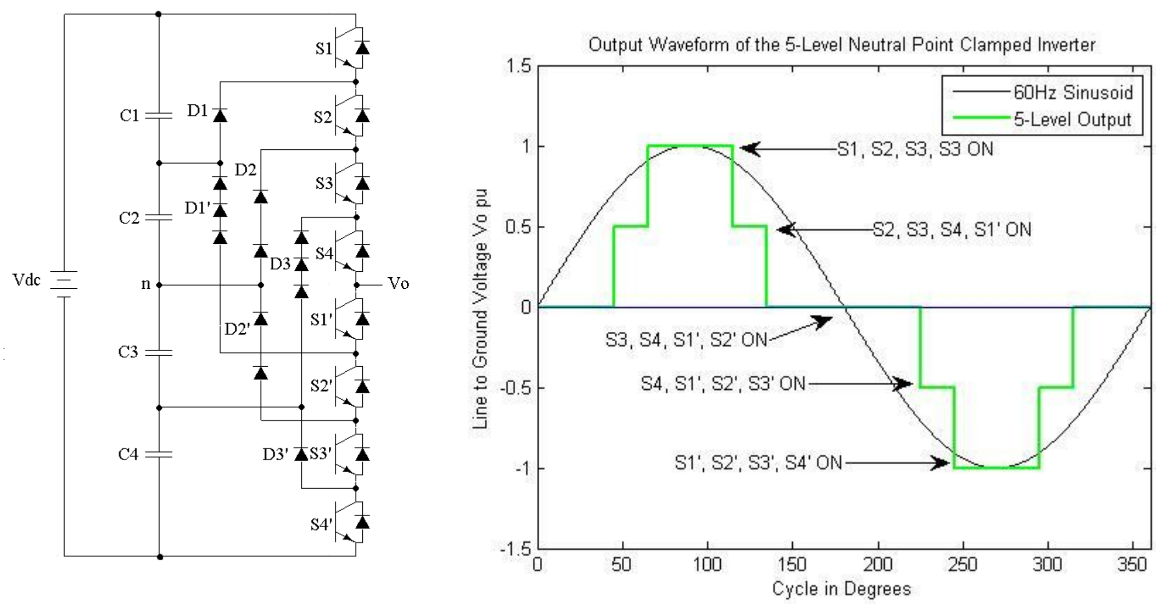


Figure 2.2 (a) Single-phase 5-level NPC topology. (b) Output waveform.

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, S4, 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.

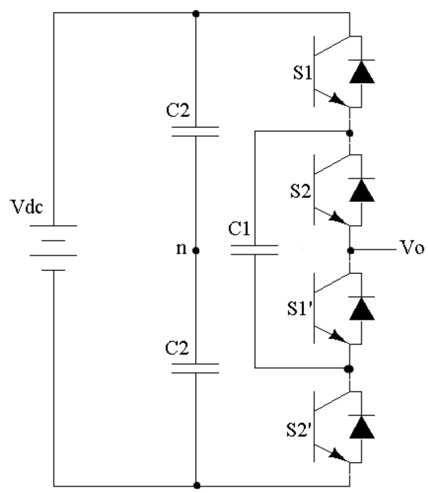
Output Voltage V_o	Switches *On*
$2V_{dc}/5$	S_1, S_2, S_3, S_4
$V_{dc}/5$	S_2, S_3, S_4, S_1'
0	S_3, S_4, S_1', S_2'
$-V_{dc}/5$	S_4, S_1', S_2', S_3'
$-2V_{dc}/5$	S_1', S_2', S_3', S_4'

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.



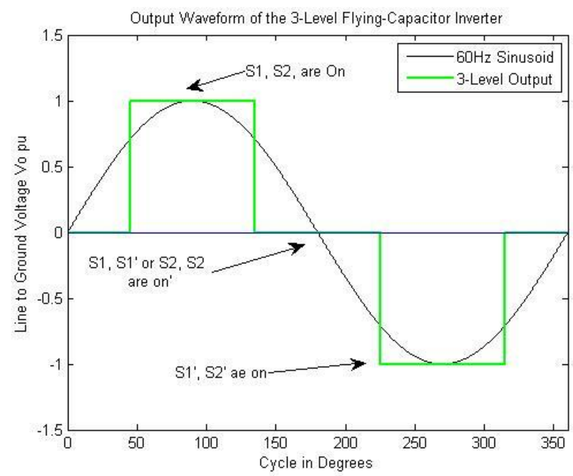


Figure 2.3 (a) Single-phase, 3-level flying-capacitor inverter topology. (b) Output waveform

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].

Output Voltage	Switches On	Charging Capacitors	Discharging Capacitors
$V_o = V_{dc}/2$	S_1, S_2, S_3, S_4		
$V_o = V_{dc}/4$	S_1, S_2, S_3, S_1'	$V_{dc}/2$ -- C_{41}, C_{42}	$-V_{dc}/4$ -- C_1
$V_o = V_{dc}/4$	S_2, S_3, S_4, S_4'	$3V_{dc}/4$ -- C_{31}, C_{32}, C_{33}	$-V_{dc}/2$ -- C_{43}, C_{44}
$V_o = V_{dc}/4$	S_1, S_3, S_4, S_3'	$V_{dc}/2$ -- C_{41}, C_{42} |$2V_{dc}/2$ -- C_{21}, C_{22}	$-3V_{dc}/4$ -- C_{31}, C_{32}, C_{33}
$V_o = 0$	S_1, S_2, S_1', S_2'	$V_{dc}/2$ -- C_{41}, C_{42},	$-V_{dc}/2$ -- C_{21}, C_{22}
$V_o = 0$	S_3, S_4, S_3', S_4'	$V_{dc}/2$ -- C_{21}, C_{22}	$-V_{dc}/2$ -- C_{43}, C_{44}
$V_o = 0$	S_1, S_3, S_1', S_3'	$V_{dc}/2$ -- C_{41}, C_{42} | $V_{dc}/2$ -- C_{21}, C_{22}	$-3V_{dc}/4$ -- C_{31}, C_{32}, C_{33} |$-V_{dc}/4$ -- C_1
$V_o = 0$	S_1, S_4, S_2', S_3'	$V_{dc}/2$ -- C_{41}, C_{42} | $V_{dc}/4$ -- C_1	--$3V_{dc}/4$ -- C_{31}, C_{32}, C_{33}
$V_o = 0$	S_2, S_4, S_2', S_4'	$3V_{dc}/4$ -- C_{31}, C_{32}, C_{33} | $V_{dc}/4$ -- C_1	$-V_{dc}/2$ -- C_{21}, C_{22} | $-V_{dc}/2$ -- C_{43}, C_{44}
$V_o = 0$	S_2, S_3, S_1', S_4'	$3V_{dc}/4$ -- C_{31}, C_{32}, C_{33}	$-V_{dc}/4$ -- C_1 | $-V_{dc}/2$ -- C_{43}, C_{44}
$V_o = -V_{dc}/4$	S_1, S_1', S_2', S_3'	$V_{dc}/2$ -- C_{41}, C_{42}	$-3V_{dc}/4$ -- C_{31}, C_{32}, C_{33}
$V_o = -V_{dc}/4$	S_4, S_2', S_3', S_4'	$V_{dc}/4$ -- C_1	$-V_{dc}/2$ -- C_{43}, C_{44}
$V_o = -V_{dc}/4$	S_3, S_1', S_3', S_4'	$V_{dc}/2$ -- C_{21}, C_{22}	$-V_{dc}/4$ -- C_1 | $-V_{dc}/2$ -- C_{43}, C_{44}
$V_o = -V_{dc}/2$	S_1', S_2', S_3', S_4'		

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,

$$M_k = \frac{1}{(N-k)!} * \prod_{n=0}^{N-k-1}(2N-n) \; for \; 0 \le k < N \qquad (2.1)$$

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].

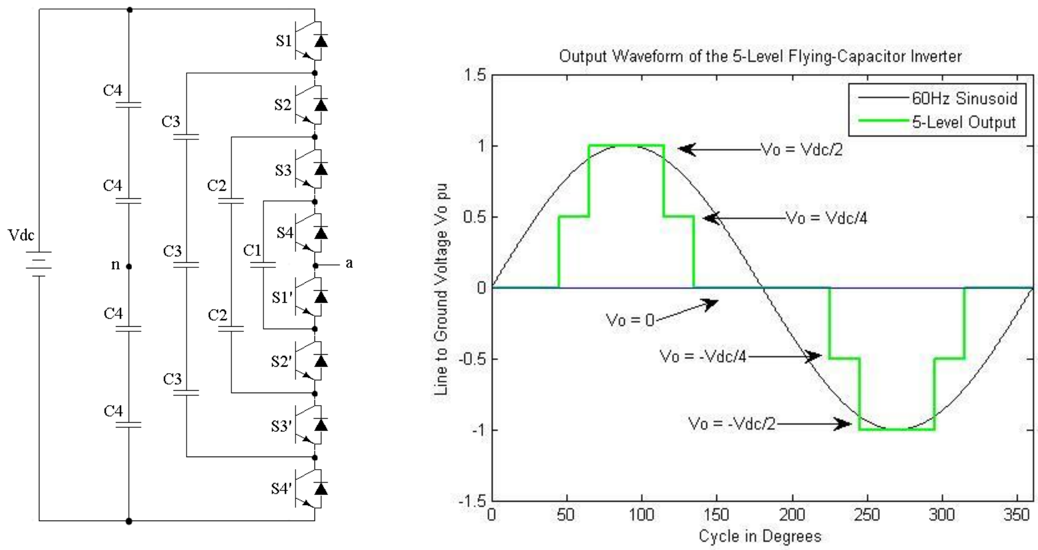


Figure 2.4 (a) Single-phase, 5-level flying-capacitor inverter topology. (b) Output waveform.

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 (S_1, S_4) are *on*, the output voltage V_o is V_{dc}. Similarly when switches (S_2, S_3) are *on*, the output voltage V_o is $–V_{dc}$. When either (S_1, S_2) or (S_3, S_4) are on, the output voltage V_o is 0.

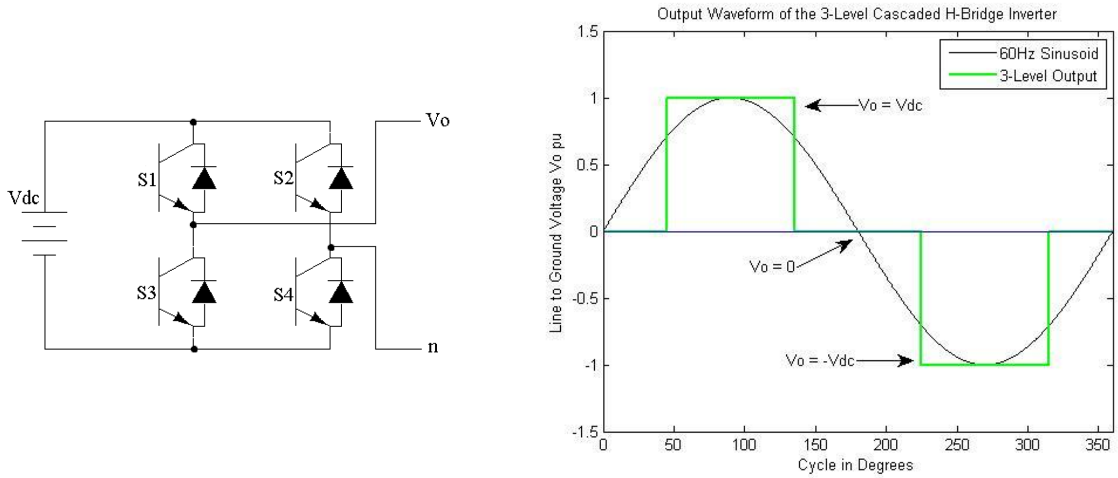


Figure 2.5 (a) Single-phase, 3-level H-Bridge inverter topology. (b) Output waveform.

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 $V_1 + V_2$.

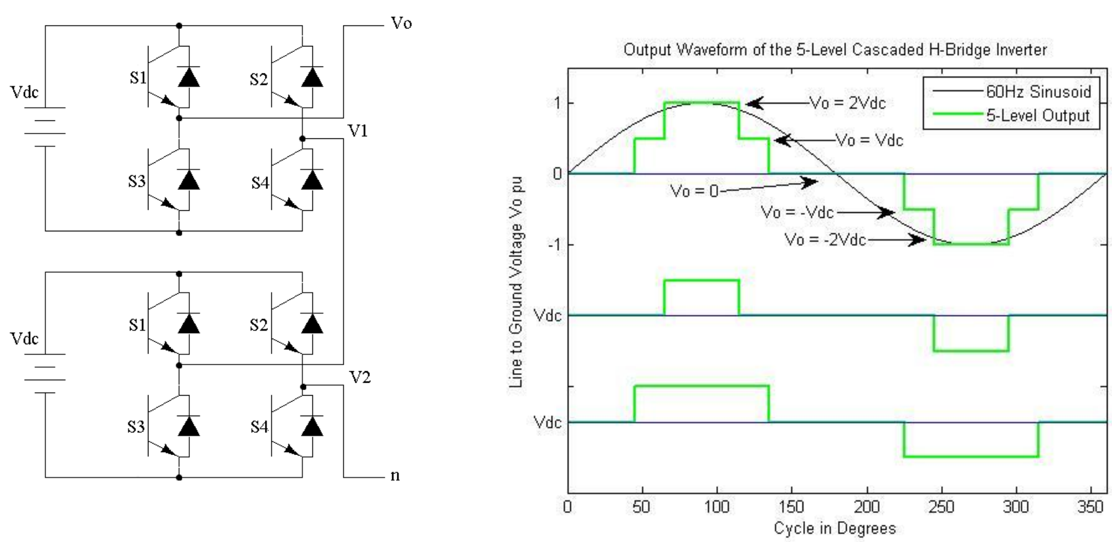


Figure 2.6 (a) Single-phase, 5-level H-Bridge inverter topology. (b) Output waveform.

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.

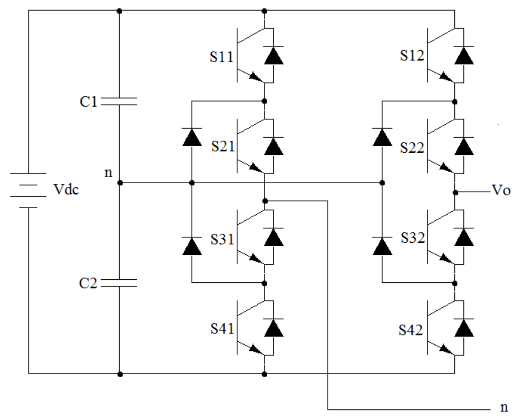


Figure 2.7 Single-phase 5L-HNPC [20]

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].

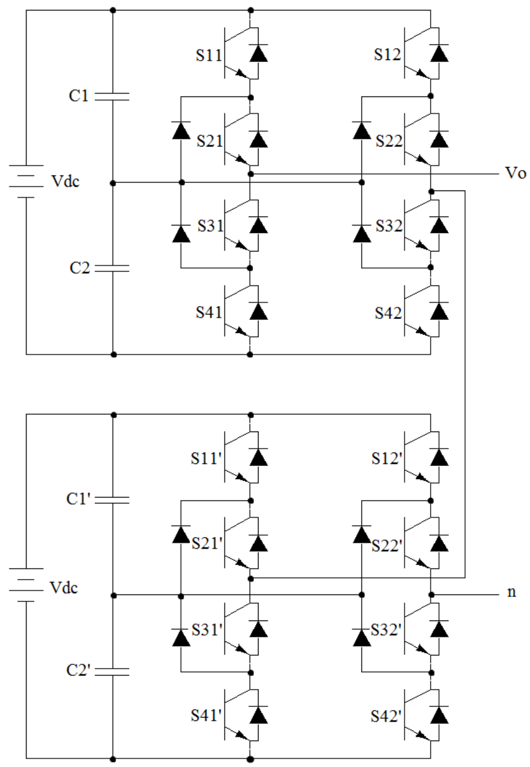


Figure 2.8 Single-phase 9L-HNPC

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.

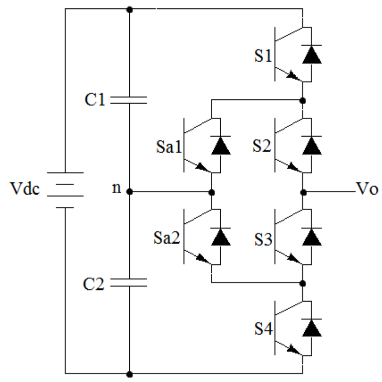


Figure 2.9 Single-phase 3L-ANPC

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.

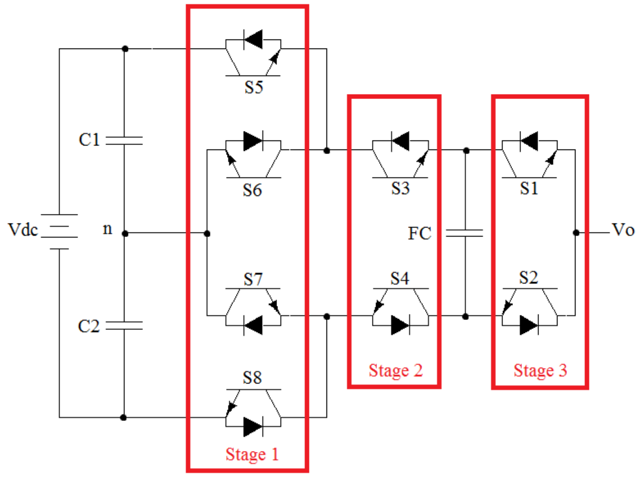


Figure 2.10 Single-phase 5L-ANPC

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 C_3 and C_4 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 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.

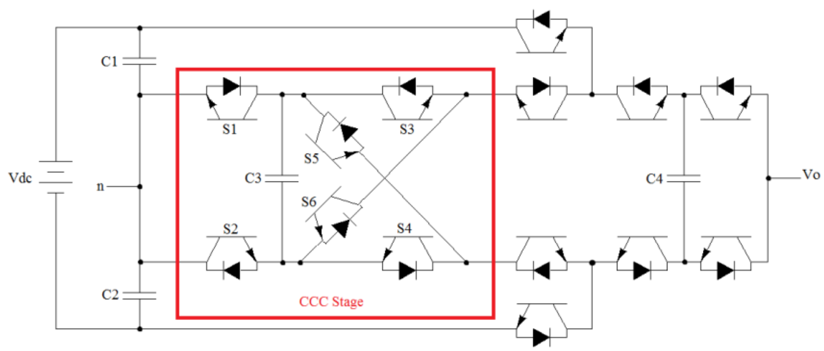


Figure 2.11 5L-ANCP with CCC stage increasing the output to 9-Levels

2.4.4 MMC or M^2LC 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.

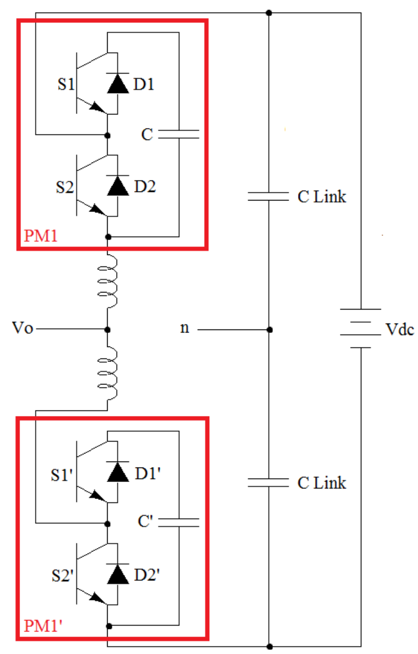


Figure 2.12 3-level, single-phase MMC

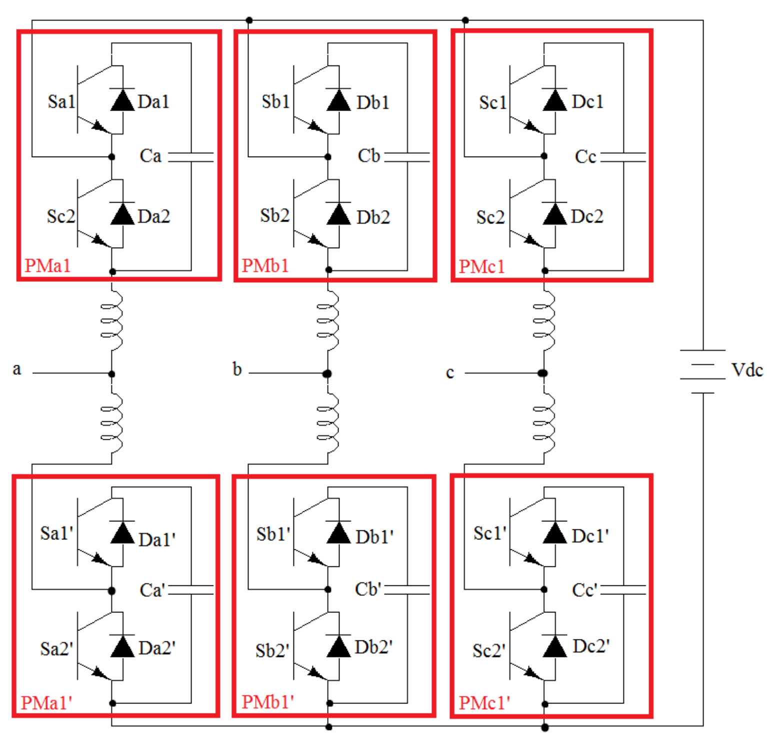


Figure 2.13 3-level, three-phase MMC

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].

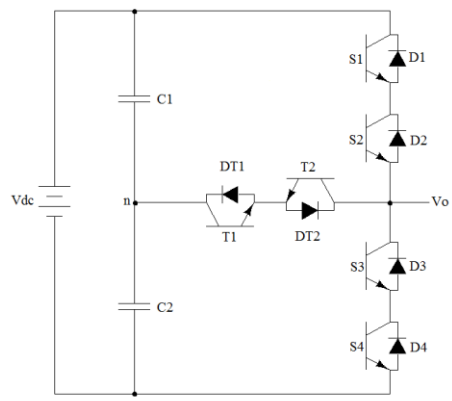


Figure 2.14 3-level, single-phase TCC or NPP

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.

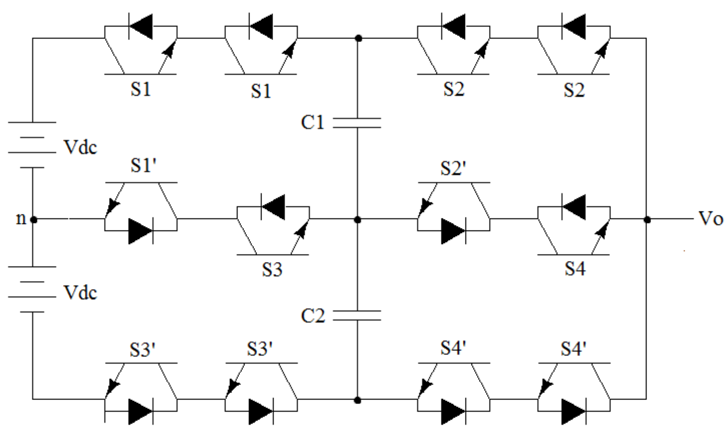


Figure 2.15 5-level SMC

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.

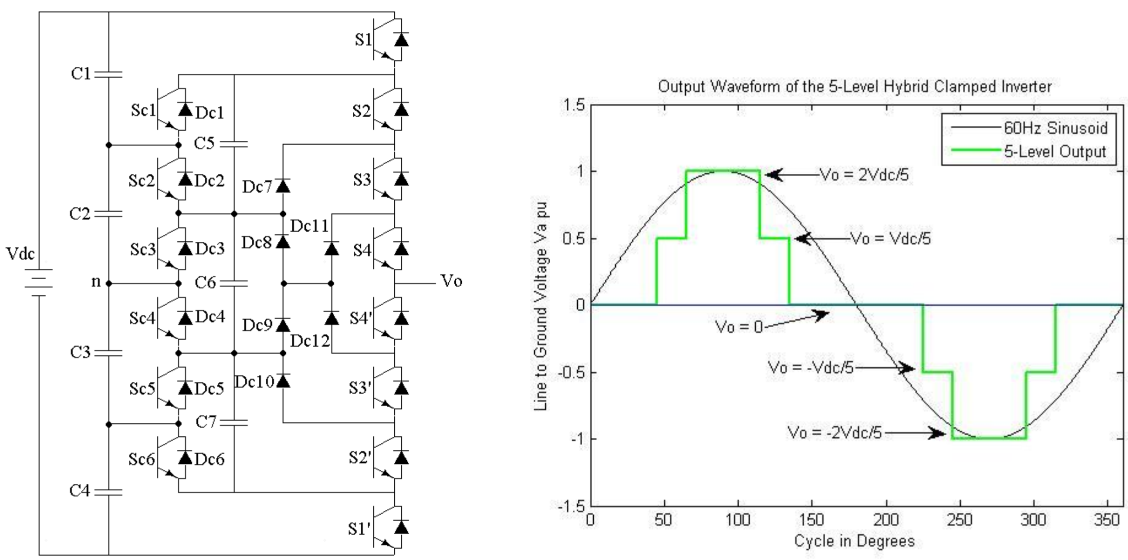


Figure 2.16 5-level hybrid-clamped inverter topology and output voltage waveform

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.

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

Output Voltage	S_1	S_2	S_3	S_4	S_4'	S_3'	S_2'	S_1'	S_{c1}	S_{c2}	S_{c3}	S_{c4}	S_{c5}	S_{c6}	Parallel Capacitors
$2V_o/5$	1	1	1	1	0	0	0	0	0	1	0	1	0	1	(C_1, C_5), (C_2, C_6), (C_3, C_7)
$V_o/5$	0	1	1	1	0	0	0	1	1	0	1	0	1	0	(C_2, C_5), (C_3, C_6), (C_4, C_7)
$V_o/5$	1	0	1	1	1	0	0	0	0	1	0	1	0	1	(C_1, C_5), (C_2, C_6), (C_3, C_7)
0	0	0	1	1	1	0	0	1	1	0	1	0	1	0	(C_2, C_5), (C_3, C_6), (C_4, C_7)
0	1	0	0	1	1	1	0	0	0	1	0	1	0	1	(C_1, C_5), (C_2, C_6), (C_3, C_7)
$-V_o/5$	0	0	0	1	1	1	0	1	1	0	1	0	1	0	(C_2, C_5), (C_3, C_6), (C_4, C_7)
$-V_o/5$	1	0	0	0	1	1	1	0	0	1	0	1	0	1	(C_1, C_5), (C_2, C_6), (C_3, C_7)
$-2V_o/5$	0	0	0	0	1	1	1	1	1	0	1	0	1	0	(C_2, C_5), (C_3, C_6), (C_4, C_7)

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 2.4 Comparison of multilevel VSC topologies 1.

	Advantages	Disadvantages
Neutral-Point Clamped (NPC)	▶Requires a single DC source ▶Does not require auxiliary capacitors	▶Unequal power distribution among switches ▶Balancing problems while delivering real power above 3-levels ▶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
Capacitor-Clamped	▶Requires only one DC source ▶Significantly reduced number of components compared to the NPC inverter ▶Redundant switching states allow for both active and reactive power conversions although purely reactive is problematic	▶Cannot balance the DC link capacitors under purely reactive operation ▶Requires a large number of clamping capacitors. ▶The number of redudant switching states increases quadratically with the number of levels, making the control shemes very complex
Cascaded H-Bridge (CHB)	▶Requires the fewest number of components out of the three fundamental topologies ▶Can deliver both reactive and active power	▶Requires multiple isolated DC sources
5L-HNPC	▶Reduction in DC link capacitors over 5-level NPC Inverter ▶Reduction in overal number of components ▶Can deliver both reactive and active power for 5-levels	▶Requires isolated DC sources for every additional module ▶Expansion above 5-levels eliminates its effetiveness in delivering real power and balancing DC links.
3L-ANPC	▶Spreads power losses equally among all switches allowing for higher power ratings and switching frequencies than the 3-level NPC ▶Can deliver both active and reactive power for 3-levels	▶Experiences voltage balancing issues and active power flow issues when increased to above 3-levels
5L-ANPC	▶Reduction in floating capacitors over NPC and flying-capacitor ▶Additional redundent switching states ▶Can deliver both active and reactive power ▶Can be scalled to addtional levels	▶Increasing the number of levels beyond five increases the number of floating capacitors and reduces the range of operation for the inverter
5L-ANPC + CCC	▶Reduction in floating capacitors over NPC and flying-capacitor ▶Additional redundent switching states ▶Can deliver both active and reactive power ▶Increasing the number of CCC stages exponentially increases the number of output levels	▶The CCC stage components have large reverse voltage blocking requirements for high power applications ▶The redundant switching states needed to maintain balance of the floating capacitors is not always guaranteed

Table 2.5 Comparison of multilevel VSC topologies 2.

	Advantages	Disadvantages
MMC or M2C	▸Modular topology so it is scalable to any level ▸Simple structure that requires few components ▸Can deliver both active and reactive power ▸Relatively easy to balance DC capacitors	▸Requires high energy storage capacitors
TCC or NPP	▸Allows the current paths to be controlled which spreads the power losses equally among all switches allowing for higher power ratings and switching frequencies ▸Can deliver both active and reactive power for 3-levels	▸Experiences similar voltage balancing issues and active power flow issues as the NPC when increased to above 3-levels
CHB Uneqal Sources	▸Has a fewer amount of components ▸Can generate a greater number of levels for a given amount of DC sources as compared to the standard CHB	▸Requires independent DC sources ▸Causes unequal power losses and heat dissipation ▸Increases the complexity of the control algorithm and reduces its control range
CHB Single Source	▸Requires only one DC source ▸Requires a reduced number of components	▸The control strategies to balance the DC link voltages can become complex and can limit the operating range of the inverter
SMC	▸Reduced voltages across capacitors as compared to traditional flying capacitor topology ▸Requires less capacitors than the traditional flying capacitor topology	▸Requires a independent DC sources for each stacked module
Hybrid-Clamped	▸Requires only one DC source. ▸Can balance DC link voltages without redundant switching states and regardless of the load profile ▸Does not require a complicated control algorithm	▸Requires a large number of switches and components which adds to the overall cost and can increase the amount of losses

Table 2.6 Number of components for 3-level inverters.

3-Level							
Comparison of Components For Different Single-Phase Multilevel Topologies	Switches	DC Link Capacitors	Clamping Diodes	Auxiliary Capacitors	Inductors	Additional DC Sources	Total Number of Components
Neutral-Point Clamped	4	1	2	0	0	0	7
Flying-Capacitor	4	1	0	1	0	0	6
Cascaded H-Bridge	4	0	0	0	0	0	4
5L-HNCP*	NA	NA	NA	NA	NA	NA	NA
3L-ANCP	6	2	0	0	0	0	8
5L-ANCP*	NA	NA	NA	NA	NA	NA	NA
5L-ANCP + CCC*	NA	NA	NA	NA	NA	NA	NA
MMC or M2C	4	2	0	2	2	0	10
TCP or NPP	6	2	0	0	0	0	8
CHB Unequal Sources	4	0	0	0	0	0	4
CHB-Single Source	4	1	0	0	0	0	5
SMC	3	2	0	2	0	0	7
Hybrid-Clamped*	NA	NA	NA	NA	NA	NA	NA
*The topology does not apply to this level							

Table 2.7 Number of components for 5-level inverters.

5-Level							
Comparison of Components For Different Single-Phase Multilevel Topologies	Switches	DC Link Capacitors	Clamping Diodes	Auxiliary Capacitors	Inductors	DC Sources	Total Number of Components
Neutral-Point Clamped	8	4	12	0	0	1	25
Flying-Capacitor	8	4	0	6	0	1	19
Cascaded H-Bridge	8	0	0	0	0	2	10
5L-HNCP	8	2	4	0	0	1	15
3L-ANCP*	NA	NA	NA	NA	NA	NA	NA
5L-ANCP	8	2	0	1	0	1	12
5L-ANCP + CCC	NA	NA	NA	NA	NA	NA	NA
MMC or M2C	8	4	0	2	2	1	17
TCP or NPP**	NA	NA	NA	NA	NA	NA	NA
CHB Unequal Sources	8	0	0	0	0	2	10
CHB-Single Source	8	1	0	0	0	1	10
SMC	12	0	0	2	0	2	16
Hybrid-Clamped	14	4	6	3	0	1	28
*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.

7-Level							
Comparison of Components For Different Single-Phase Multilevel Topologies	Switches	DC Link Capacitors	Clamping Diodes	Auxiliary Capacitors	Inductors	DC Sources	Total Number of Components
Neutral-Point Clamped	12	6	30	0	0	1	49
Flying-Capacitor	12	6	0	15	0	1	34
Cascaded H-Bridge	12	0	0	0	0	3	15
5L-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	12	6	0	2	2	1	23
TCP or NPP**	NA	NA	NA	NA	NA	NA	NA
CHB Unequal Sources***	NA	NA	NA	NA	NA	NA	Na
CHB-Single Source	12	2	0	0	0	1	15
SMC	12	0	0	4	0	2	18
Hybrid-Clamped	22	6	20	5	0	1	54
*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.

9-Level							
Comparison of Components For Different Single-Phase Multilevel Topologies	Switches	DC Link Capacitors	Clamping Diodes	Auxiliary Capacitors	Inductors	DC Sources	Total Number of Components
Neutral-Point Clamped	16	8	56	0	0	1	81
Flying-Capacitor	16	8	0	28	0	1	53
Cascaded H-Bridge	16	0	0	0	0	4	20
5L-HNCP*	NA	NA	NA	NA	NA	NA	NA
3L-ANCP*	NA	NA	NA	NA	NA	NA	NA
5L-ANCP****	16	4	8	0	0	2	30
5L-ANCP + CCC	14	2	0	2	0	1	19
MMC or M2C	16	8	0	2	2	1	29
TCP or NPP**	NA	NA	NA	NA	NA	NA	NA
CHB Unequal Sources***	NA	NA	NA	NA	NA	NA	NA
CHB-Single Source	16	3	0	0	0	1	20
SMC	16	0	0	6	0	2	24
Hybrid-Clamped	30	8	32	7	0	1	78
*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.

11-Level							
Comparison of Components For Different Single-Phase Multilevel Topologies	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
5L-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	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.

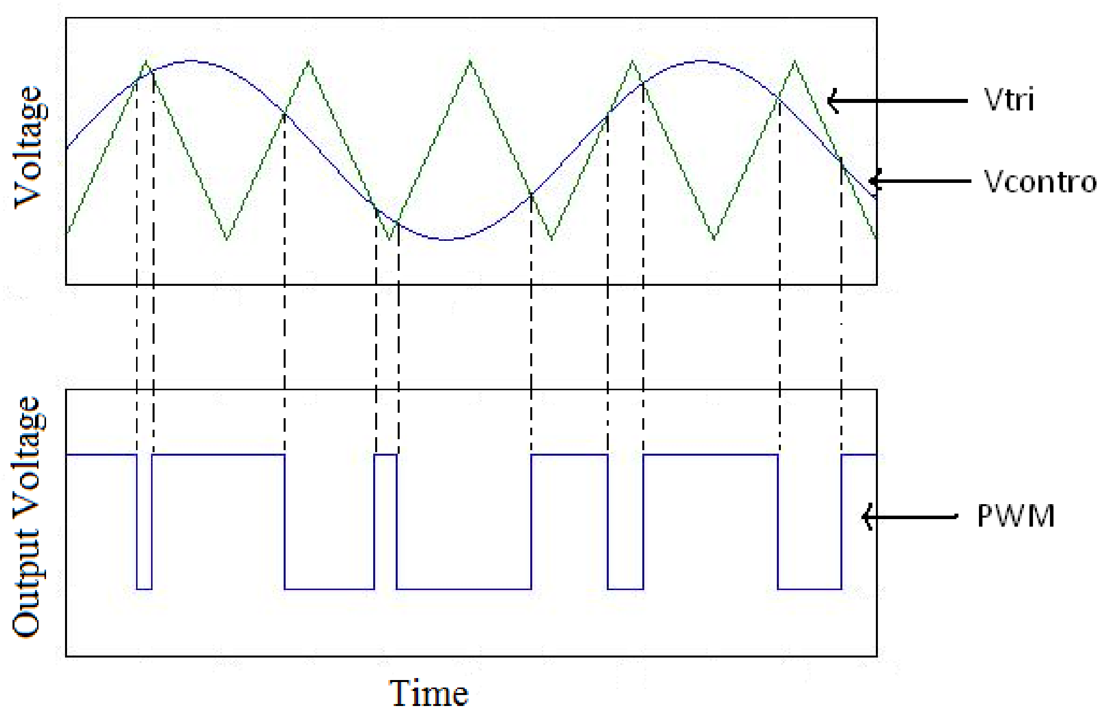


Figure 3.1 Example of sinusoidal pulse width modulation for a two level inverter.

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

$$MI = \frac{V_{control}}{V_{tri}} \tag{3.1}$$

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).

$$m_f = \frac{f_{tri}}{f_{control}} \tag{3.2}$$

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.

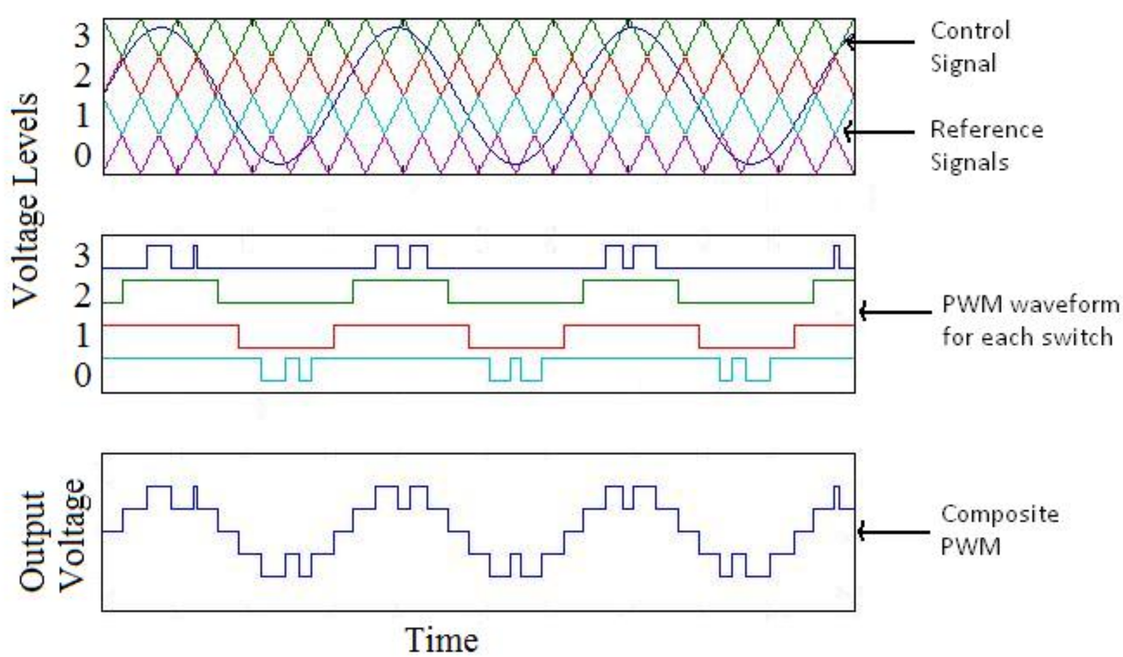


Figure 3.2 Example of SPWM waveforms for a 5-level inverter.

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 (S_1–S_4) of the 5-level hybrid-clamped inverter. The waveforms for the bottom switches (S_1'-S_4') and the auxiliary switches (S_{c1}-S_{c6}) do not need to be constructed as their switching states can be taken as compliments of one of the upper switches.

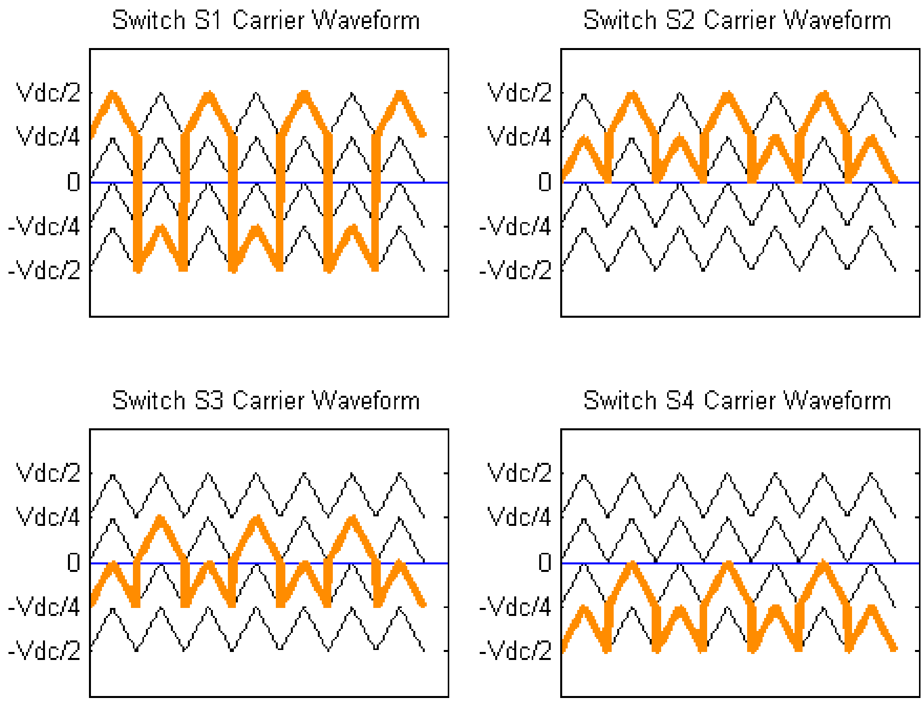


Figure 3.3 Carrier waveforms for the upper four switches of a 5-level hybrid-clamped inverter [43].

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.

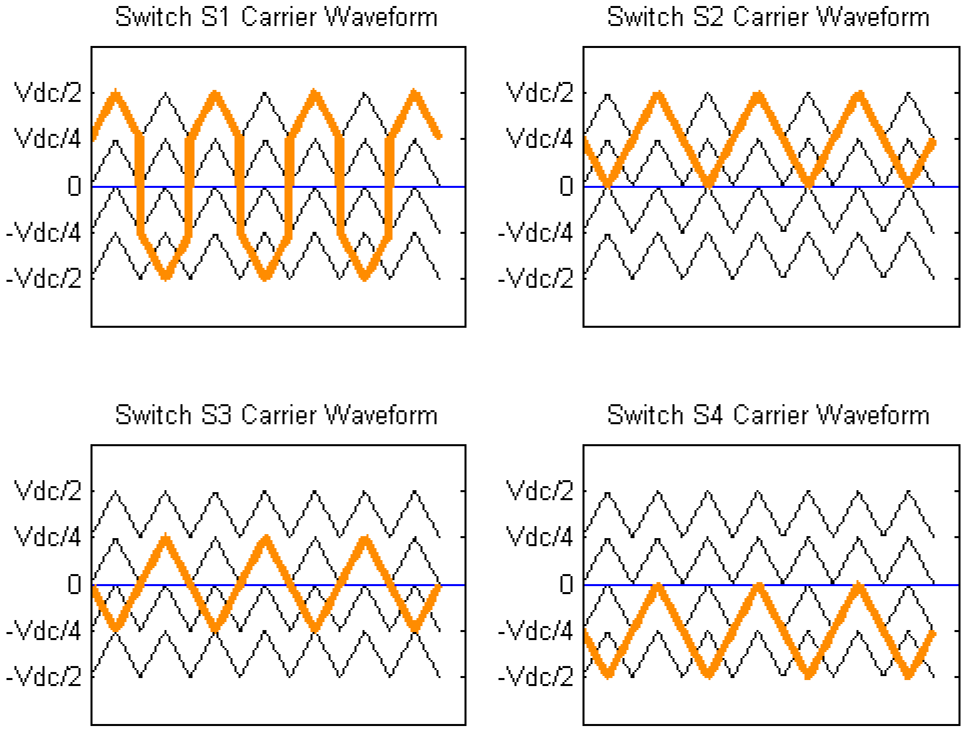


Figure 3.4 Carrier waveforms for the upper four switches using the HLCCAPOPWM method [39].

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 $2V_{dc}$. 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.

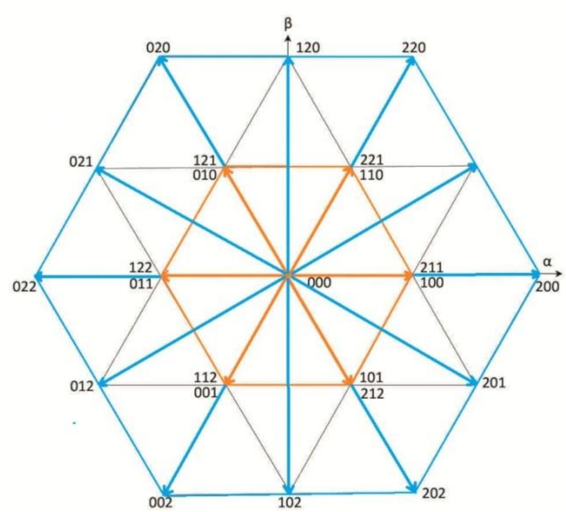


Figure 3.5 2-D Space vector modulation for a 3-level, three-phase inverter [44], [45].

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.

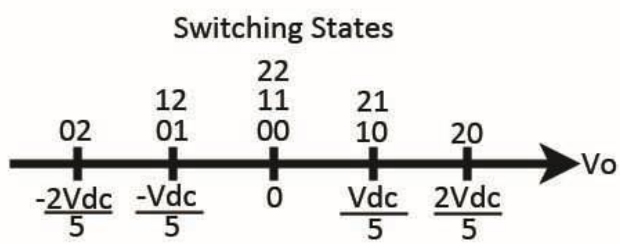


Figure 3.6 1-D state space for a 5-level single-phase NPC [46].

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.

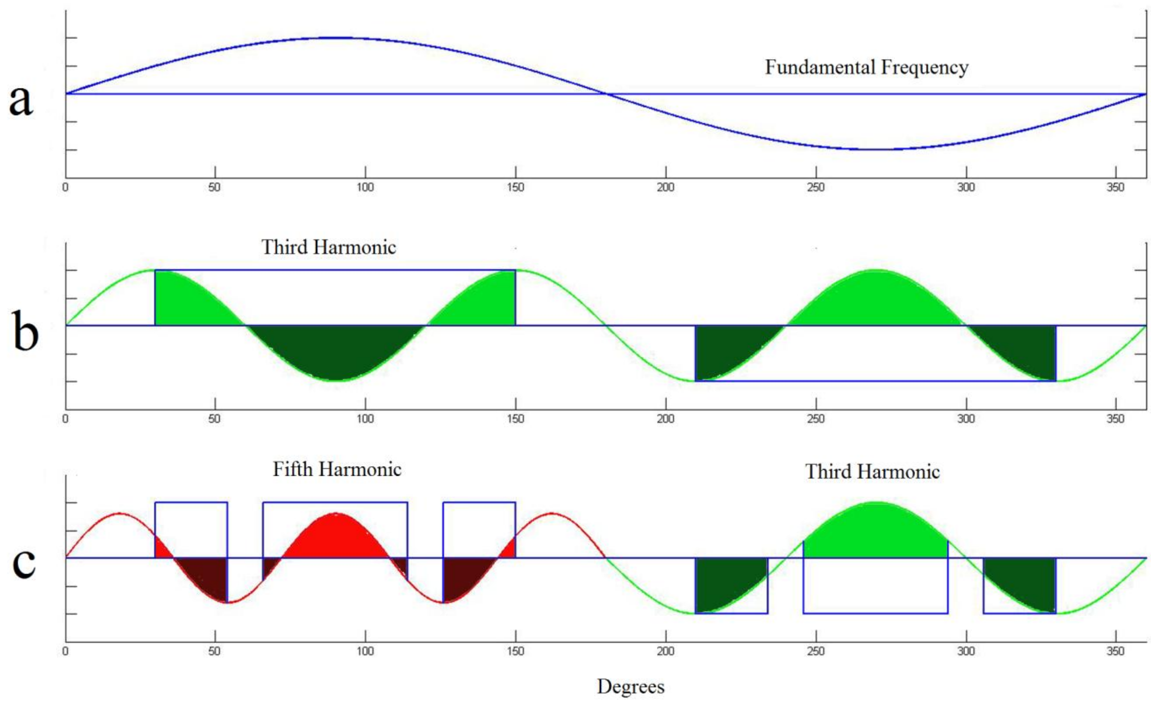


Figure 3.7 Illustration of selective harmonic elimination of the third and fifth harmonics for a 3-level inverter. Note: The amplitudes are not drawn to scale [47].

Figure 3.3 provides a graphic demonstration of how the 3rd and 5th harmonics can be eliminated in a 3-level inverter using SHE. As shown in Figure 3.3(b) to eliminate the 3rd 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 3rd and 5th harmonics more firing angles have to be introduced so that both the areas of the 3rd and 5th harmonics are canceled while the switches are in their *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.

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

Figure 3.4 demonstrates this with the output waveform of an 11-level inverter.

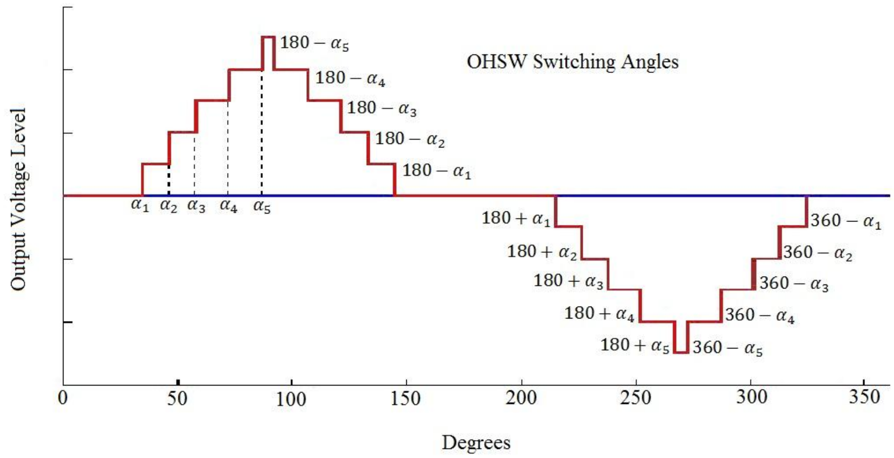


Figure 3.4. OHSW waveform for a single-phase, 11-level inverter. There are five controllable firing angles.

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]:

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

Where l is the number of levels

n is the harmonic

α_k is the kth switching angle

V_d 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 $\frac{m-1}{2}$ *equations each with* $\frac{m-1}{2}$ *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 nparticles 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 particles 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 3rd harmonic, a 7-level inverter can eliminate the 3rd and 5th harmonics, a 9-level inverter can eliminate the 3rd, 5th, and 7th harmonics, and an 11-level inverter can eliminate the 3rd, 5th, 7th, and 9th 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.

$$H_n(\alpha) = \frac{4V_{dc}}{n\pi}\sum_{k=1}^{l-1}\cos(n\alpha_k) \tag{3.4}$$

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:

$$\begin{aligned}
\cos(\alpha_1) + \cos(\alpha_2) + \cdots + \cos(\alpha_k) &= \frac{jM\pi}{4} \\
\cos(3\alpha_1) + \cos(3\alpha_2) + \cdots + \cos(3\alpha_k) &= h_3 = 0 \\
\cos(5\alpha_1) + \cos(5\alpha_2) + \cdots + \cos(5\alpha_k) &= h_5 = 0 \\
&\vdots \\
\cos(n\alpha_1) + \cos(n\alpha_2) + \cdots + \cos(n\alpha_k) &= h_k = 0
\end{aligned}$$

where M represents the modulation index that fundamental component should be solved for.

The Fourier series of this waveform is written as:

$$V(wt) = V_{link} \sum_n H_n (\alpha) \sin(nwt) \tag{3.5}$$

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

$$\text{Constraints: } 0 \leq \alpha_1 \leq \alpha_2 \leq \cdots \leq \alpha_k \leq 90 \tag{3.3}$$

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

$$\text{Fitness Function: } w_1|jM - H_1| + w_2|H_3| + \ldots + w_k|H_n| \tag{3.4}$$

$w_1$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

> INITIALIZE the starting position of n particles $p_n(0) = [\alpha_1\ \alpha_2 \ldots\ \alpha_k]$ 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:
$v_i^{New} = w * v_i + p_{incr} * rand * (pbest_i - p_i) + g_{incr} * rand * (gbest - p_i)$

UPDATE the particle positions according to:
$p_i^{New} = p_i + v_i^{new} * \Delta t$ where Δt 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,

$$Cost\ Function\ (\alpha_1, \alpha_2) = w_1|2M - H_1| + w_2|H_3| \tag{3.7}$$

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).

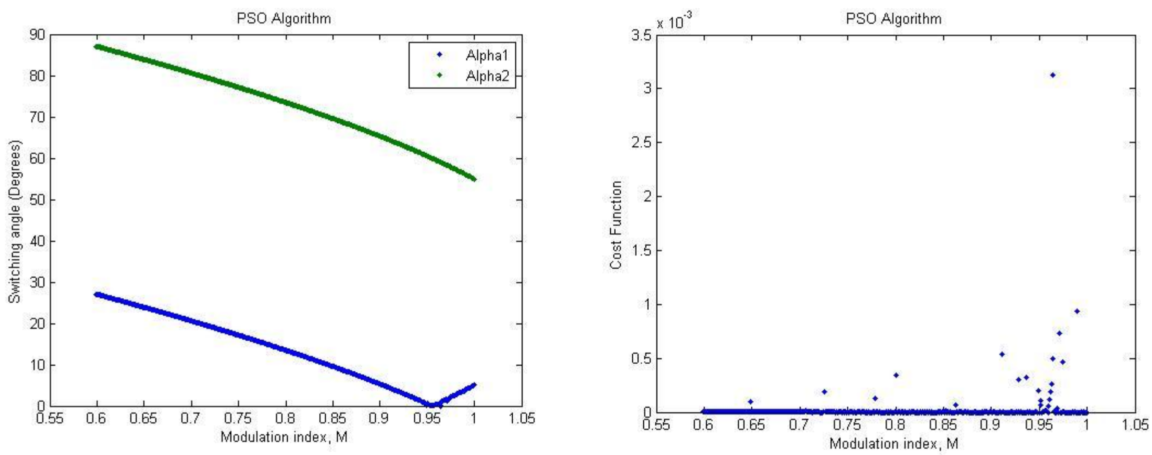


Figure 3.8 (a) Switching angles α_1 and α_2 vs. modulation index for 5-level single-phase inverter using OHSW. (b) Final cost function vs. modulation index for the switching angle solutions from (a).

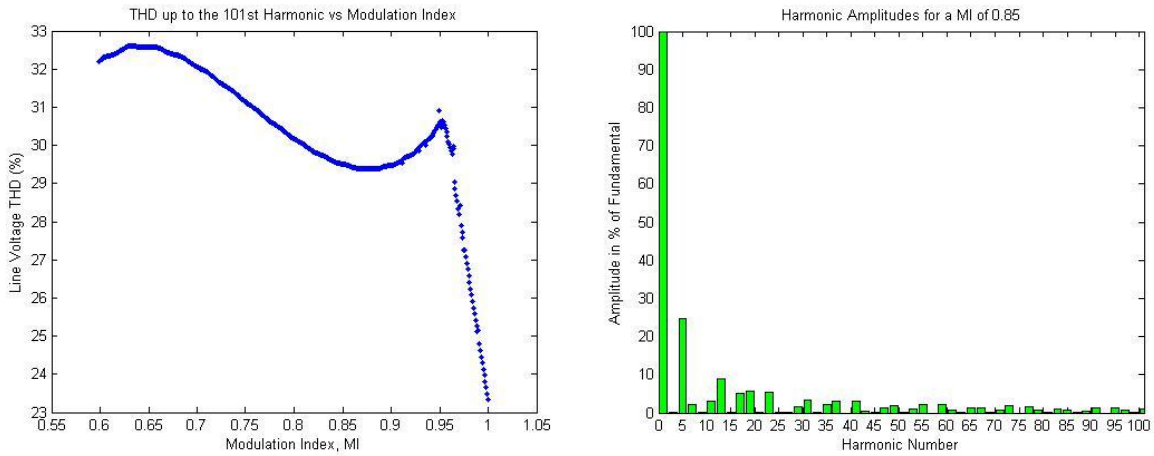


Figure 3.9 (a) Total harmonic distortion vs. modulation index for 5-level single-phase OHSW. (b) Calculated individual harmonic contribution for a modulation index of 0.85.

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).

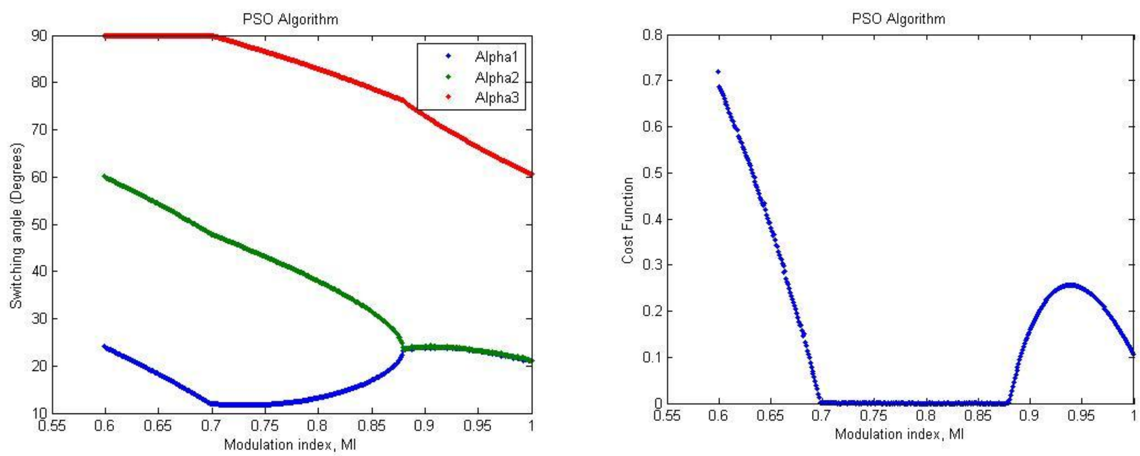


Figure 3.10 (a) Switching angles α_1, α_2, and α_3 vs. modulation index for a 7-level single-phase inverter using OHSW. (b) Final cost function vs. modulation index for the switching angle solutions from (a).

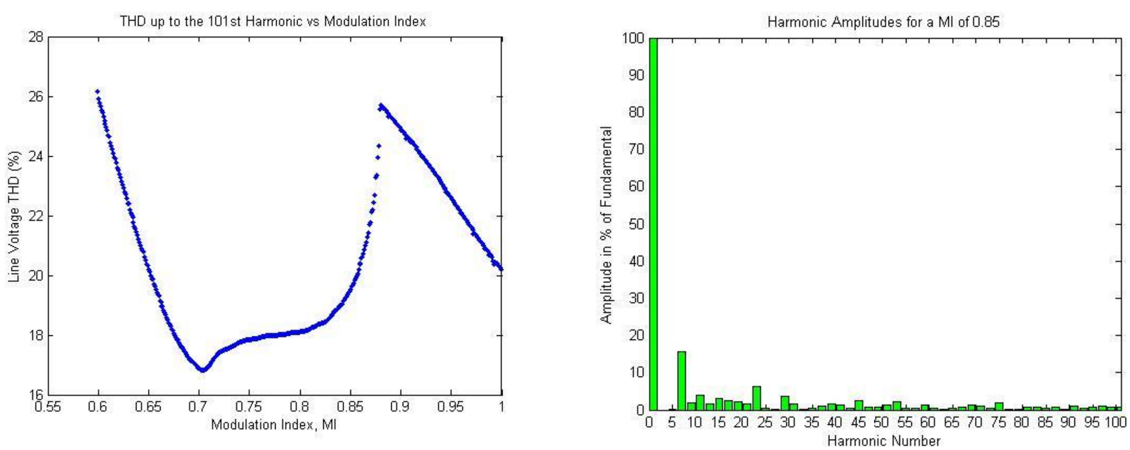


Figure 3.11 (a) Total harmonic distortion vs. modulation index for 7-level single-phase OHSW. (b) Calculated individual harmonic contribution for a modulation index of 0.85.

3.6.6 9-Level Four Angle OHSW

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

$$\cos(\alpha_1) + \cos(\alpha_2) + \cos(\alpha_3) + \cos(\alpha_4) = \frac{4\pi}{4}M \tag{3.12}$$

$$\cos(3\alpha_1) + \cos(3\alpha_2) + \cos(3\alpha_3) + \cos(3\alpha_4) = 0 \tag{3.13}$$

$$\cos(5\alpha_1) + \cos(5\alpha_2) + \cos(5\alpha_3) + \cos(5\alpha_4) = 0 \tag{3.14}$$

$$\cos(7\alpha_1) + \cos(7\alpha_2) + \cos(7\alpha_3) + \cos(7\alpha_4) = 0 \tag{3.15}$$

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

The objective function or cost function is given by,

$$Cost\ Function\ (\alpha_1, \alpha_2, \alpha_3, \alpha_4) = \ w_1|4M - H_1| + \ w_2|H_3| + w_3|H_5| + w_4|H_7| \qquad (3.16)$$

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).

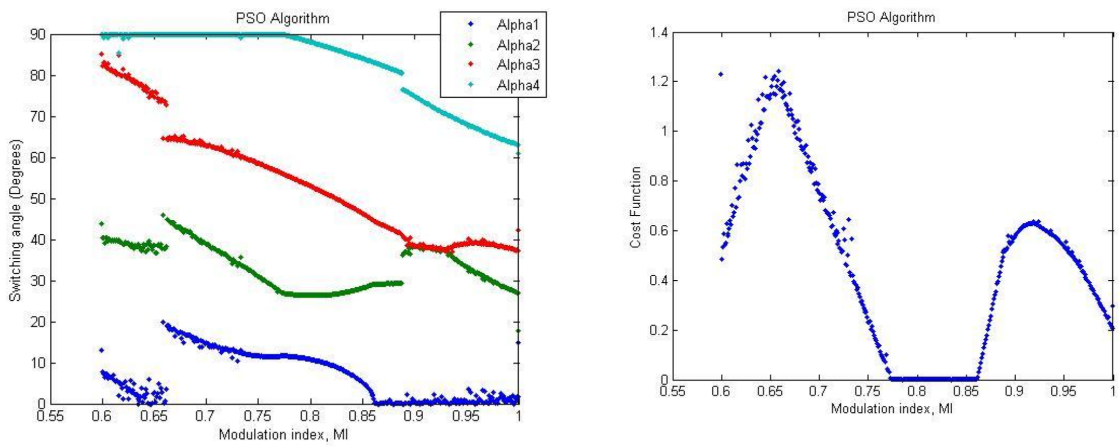


Figure 3.12 (a) Switching angles α_1, α_2, α_3, and $\alpha_4$vs. modulation index for a 9-level single-phase inverter using OHSW. (b) Final cost function vs. modulation index for the switching angle solutions from (a).

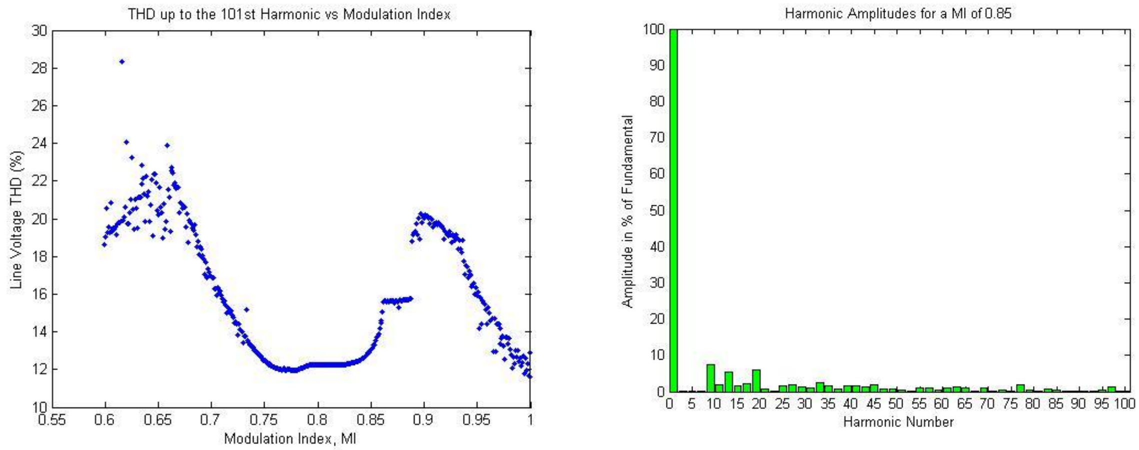


Figure 3.13 (a) Total harmonic distortion vs. modulation index for 9-level single-phase OHSW. (b) Calculated individual harmonic contribution for a modulation index of 0.85.

3.6.7 11-Level Five Angle OHSW

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

$$\cos(\alpha_1) + \cos(\alpha_2) + \cos(\alpha_3) + \cos(\alpha_4) + \cos(\alpha_5) = \frac{5\pi}{4}M \tag{3.17}$$

$$\cos(3\alpha_1) + \cos(3\alpha_2) + \cos(3\alpha_3) + \cos(3\alpha_4) + \cos(3\alpha_5) = 0 \tag{3.18}$$

$$\cos(5\alpha_1) + \cos(5\alpha_2) + \cos(5\alpha_3) + \cos(5\alpha_4) + \cos(5\alpha_5) = 0 \tag{3.19}$$

$$\cos(7\alpha_1) + \cos(7\alpha_2) + \cos(7\alpha_3) + \cos(7\alpha_4) + \cos(7\alpha_5) = 0 \tag{3.20}$$

$$\cos(9\alpha_1) + \cos(9\alpha_2) + \cos(9\alpha_3) + \cos(9\alpha_4) + \cos(9\alpha_5) = 0 \tag{3.21}$$

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

The objective function or cost function is given by,

$$Cost\ Function\ (\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5) = w_1|5M - H_1| + w_2|H_3| + w_3|H_5| + w_4|H_7| + w_5|H_9| \tag{3.22}$$

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).

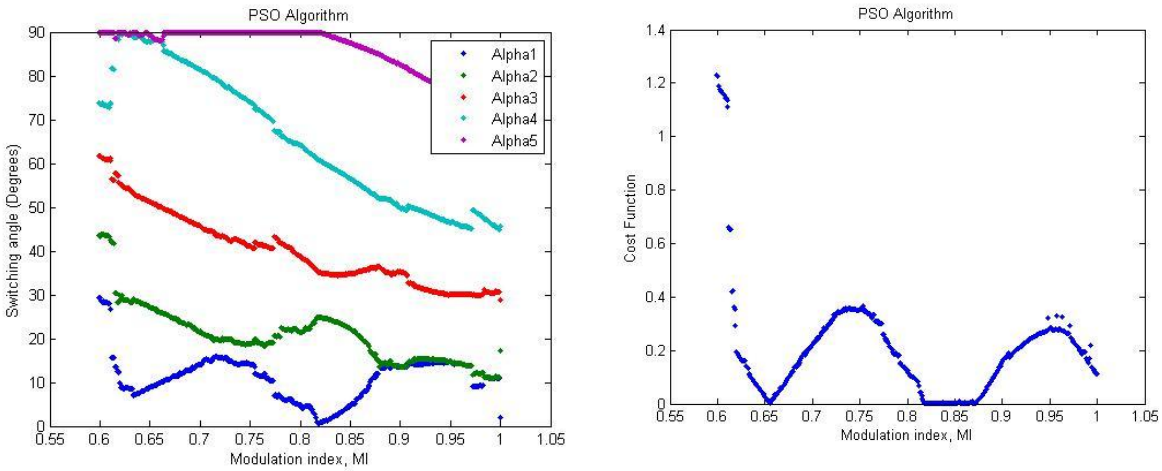


Figure 3.14 (a) Switching angles α_1, α_2, α_3, α_4, and $\alpha_5$vs. modulation index for a 11-level single-phase inverter using OHSW. (b) Final cost function vs. modulation index for the switching angle solutions from (a).

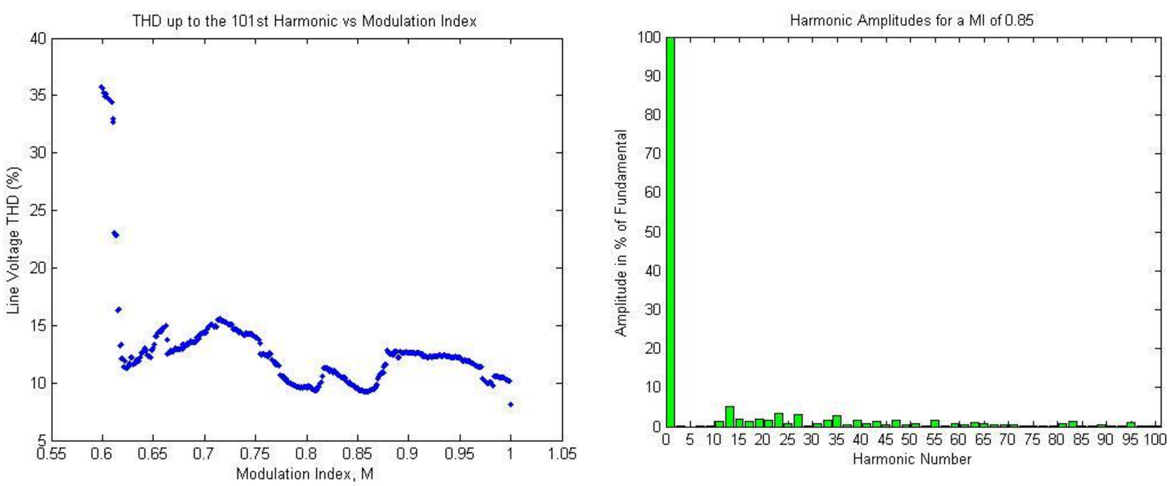


Figure 3.15 (a) Total harmonic distortion vs. modulation index for 11-level single-phase OHSW. (b) Calculated individual harmonic contribution for a modulation index of 0.85.

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].

FACTS	STATCOM	STATCOM with BESS	D-STATCOM Inverter	SSSC	SSSC with BESS	DVR	UPFC/IPFC	HVDC	TCSC	DBR	SDBR	SVC	TCPAR
	Voltage Source Converter								Thyristor				
Degrees of Freedom	1	2	2	1	2	1	3	3	1	1	1	1	
Shunt	YES	YES	YES	NO	NO	NO	YES	YES	NO	YES	NO	NO	NONE
Series	NO	NO	NO	YES	YES	YES	YES	YES	YES	NO	YES	YES	YES
Shunt & Series	NO	NO	NO	NO	NO	NO	YES	YES	NO	NO	NO	YES	NONE
Voltage Source Converter	YES	YES	YES	YES	YES	YES	YES	NEW	NO	NO	NO	NO	NONE
Thyristor	NO	NO	NO	NO	NO	NO	NO	OLD	YES	YES	YES	YES	YES
Implemented	YES	YES	NO	NO	NO	YES	YES	YES	YES	YES	YES	NO	YES
Active Power Control	NONE	HIGH	HIGH	NONE	HIGH	NONE	HIGH	HIGH	NONE	MED	MED	NONE	NONE
Reactive Power Control	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	MED	NONE	NONE	HIGH	NONE
Power Flow Control	LOW	LOW	LOW	HIGH	HIGH	HIGH	HIGH	HIGH	NONE	LOW	MED	MED	MED
Voltage Control	HIGH	HIGH	HIGH	MED	HIGH	HIGH	HIGH	HIGH	LOW	NONE	NONE	MED	LOW
Transient Stability	MED	MED	MED	HIGH	HIGH	HIGH	HIGH	HIGH	HIGH	NONE	NONE	LOW	MED
Oscillation Damping	MED	MED	MED	MED	MED	MED	HIGH	HIGH	MED	LOW	LOW	MED	MED
COST	MED	HIGH	LOW	MED	HIGH	MED	HIGH	HIGH	LOW	LOW	LOW	LOW	MED

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 δ 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).

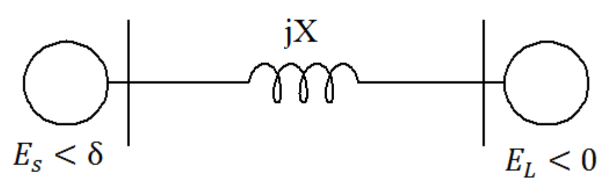


Figure 4.1 Simple system diagram describing the power flow between two sources.

$$P_S = -\frac{E_S E_L}{X} \sin\delta \quad (4.1)$$

$$Q_s = \frac{E_S E_L \cos\delta - E_L^2}{X} \quad (4.2)$$

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 δ. By using power electronics it is possible to control the amplitude of the STATCOM voltage by adjusting the modulation index and the angle δ 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).

$$P_S = -\frac{mE_S E_L}{X}\sin\delta \tag{4.3}$$

$$Q_s = \frac{mE_s E_L \cos\delta - E_L^2}{X} \tag{4.4}$$

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 δ 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.

$$P_S = -\frac{mE_S E_L}{X}\sin\delta \tag{5.3}$$

$$Q_s = \frac{mE_s E_L \cos\delta - E_L^2}{X} \tag{5.4}$$

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_s, the voltage of the secondary side of the transformer E_l, the range of the voltage angle δ, 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 δ 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).

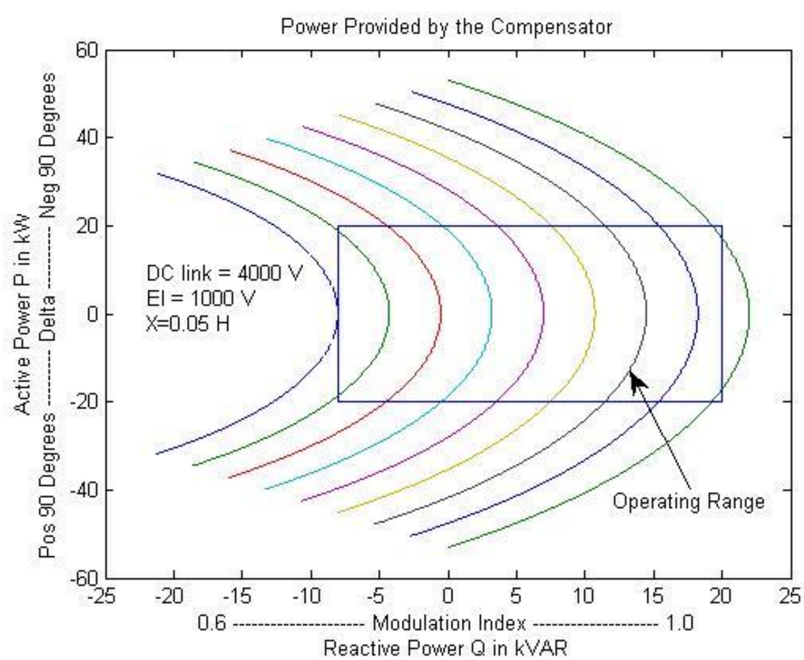


Figure 5.1 Designed operating range of the D-STATCOM Inverter. Individual lines represent different modulation indexes in steps of 0.05 ranging from 0.6 to 1.0.

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.

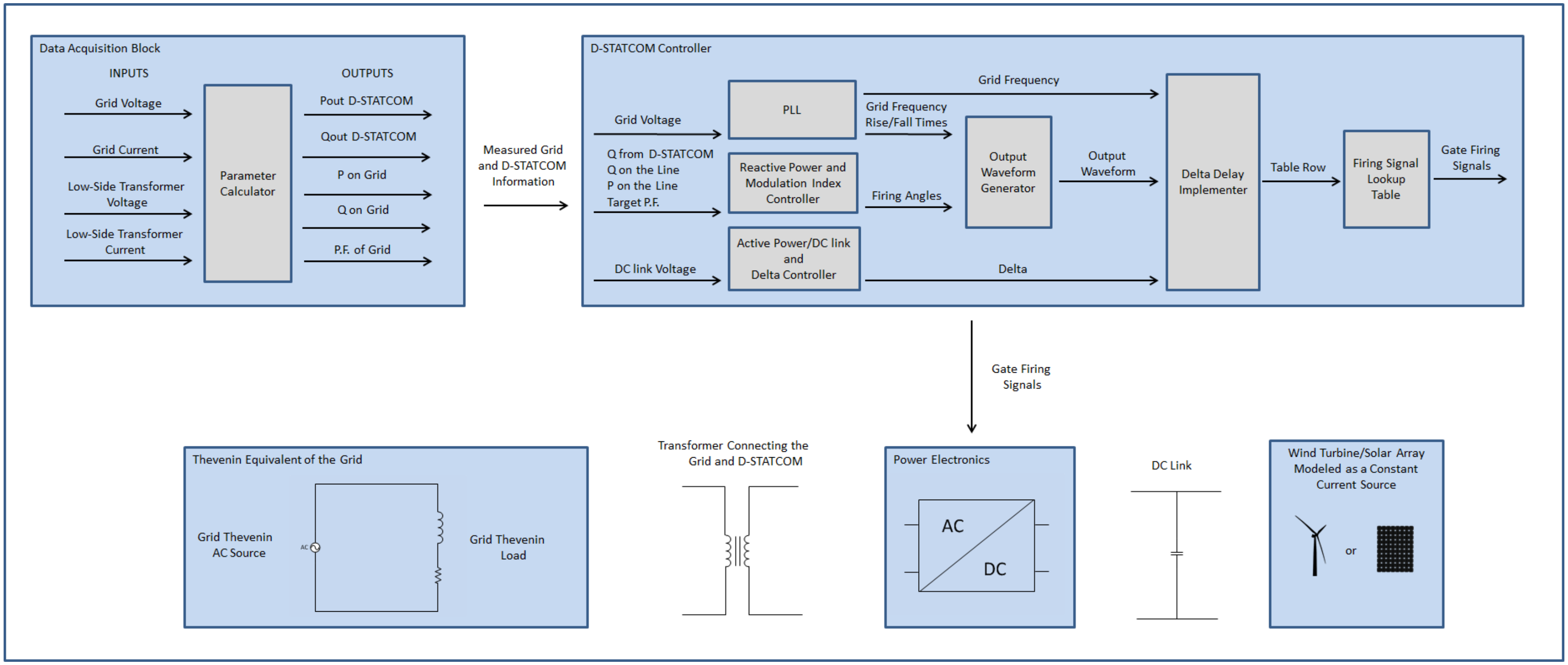


Figure 5.2 Overview of the D-STATCOM Inverter design.

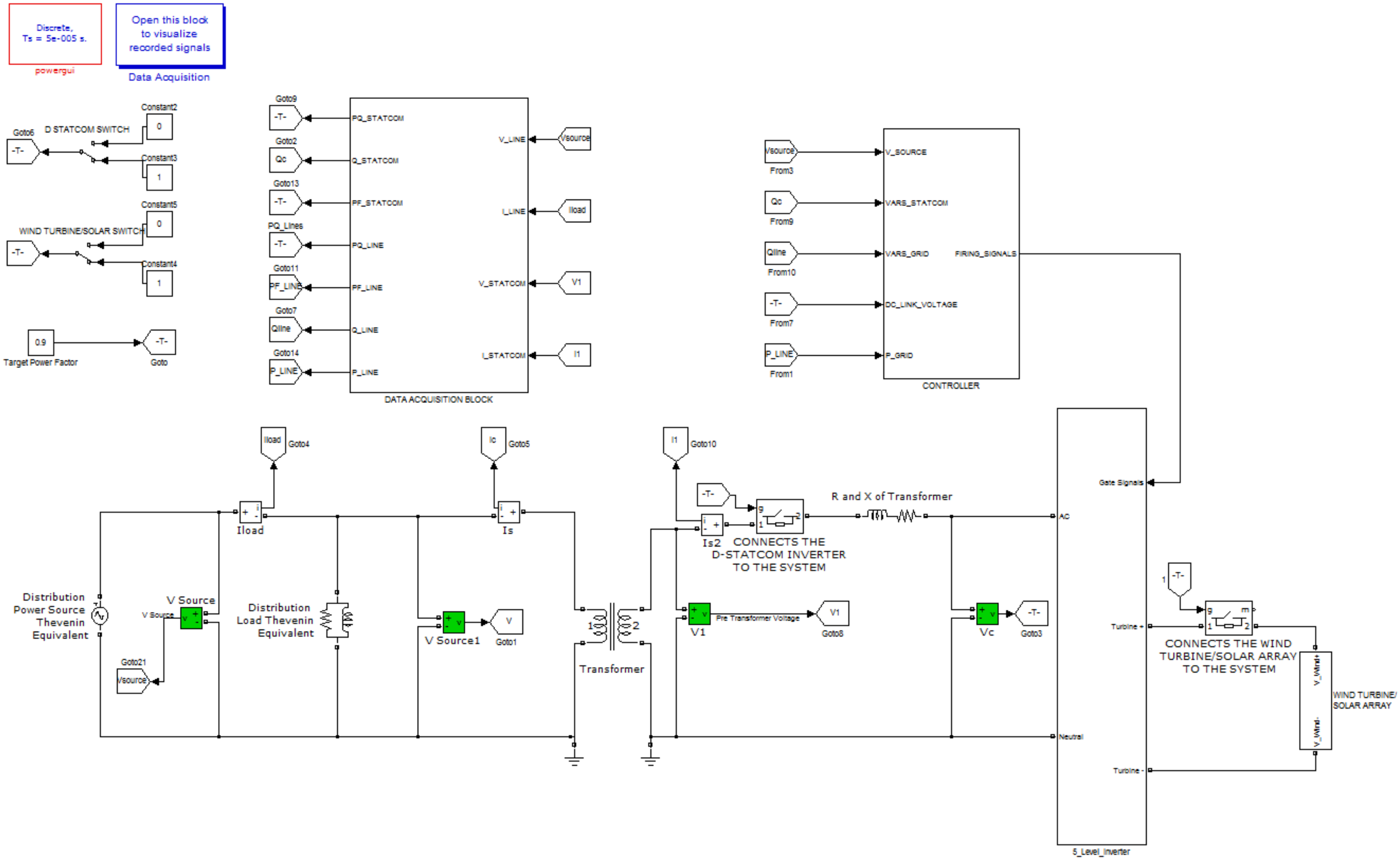


Figure 5.3 High level screenshot of the SimPowerSystems D-STATCOM Inverter design.

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.

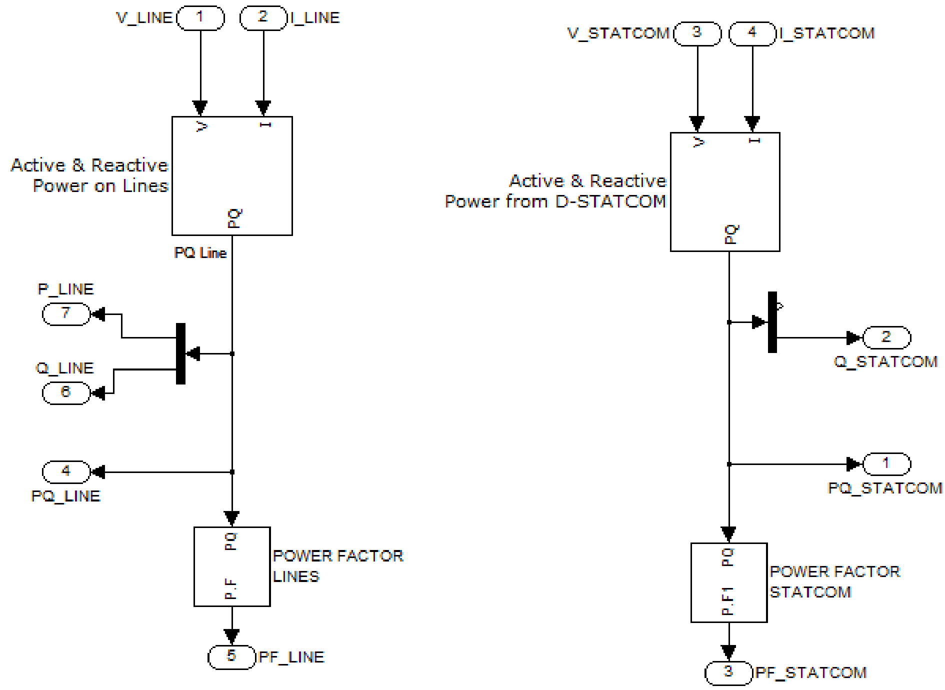


Figure 5.4 Block diagram of the data acquisition block in SimPowerSystems.

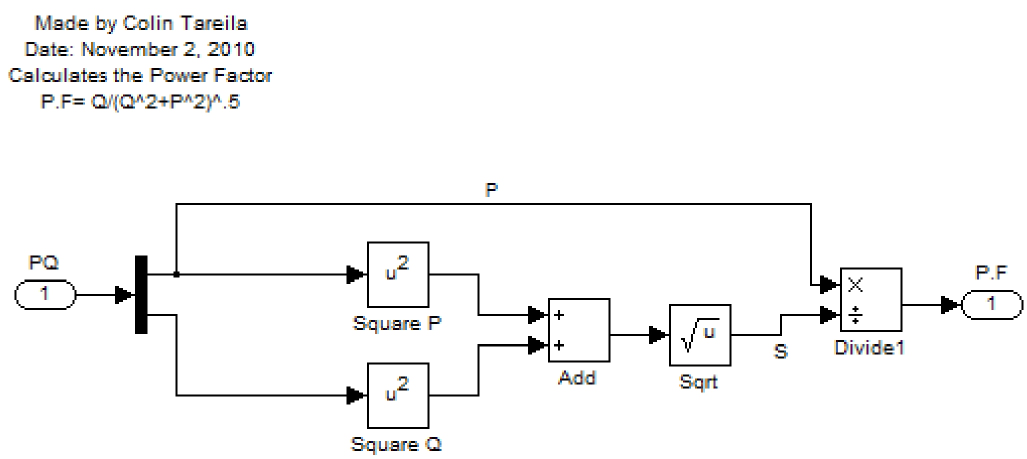


Figure 5.5 Block diagram of the power factor block in SimPowerSystems.

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.

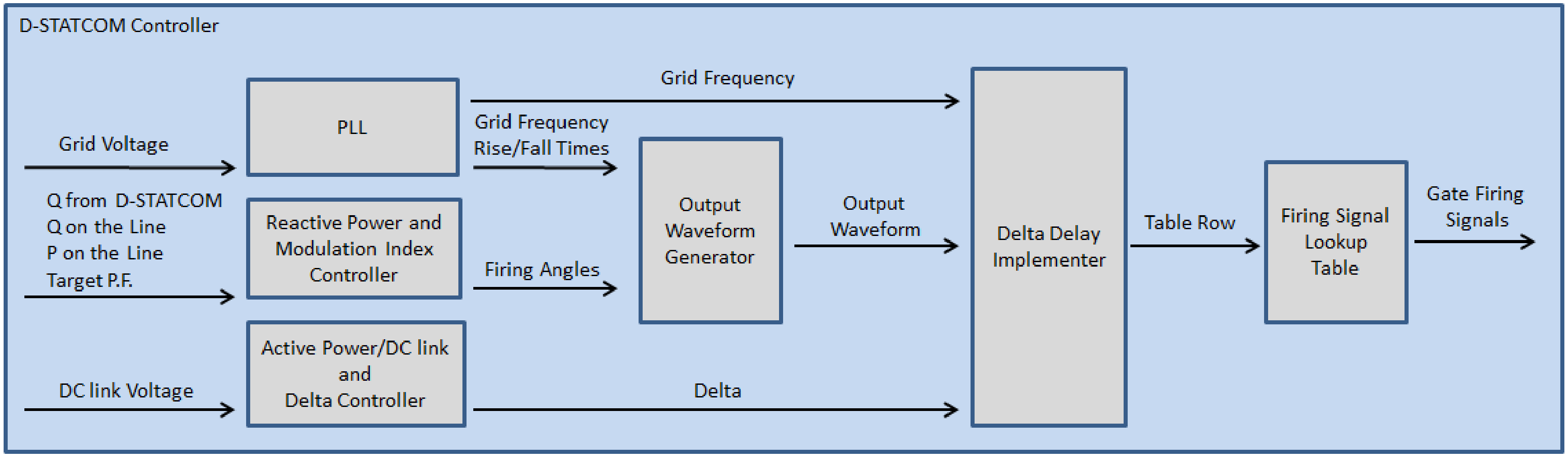


Figure 5.6 D-STATCOM controller.

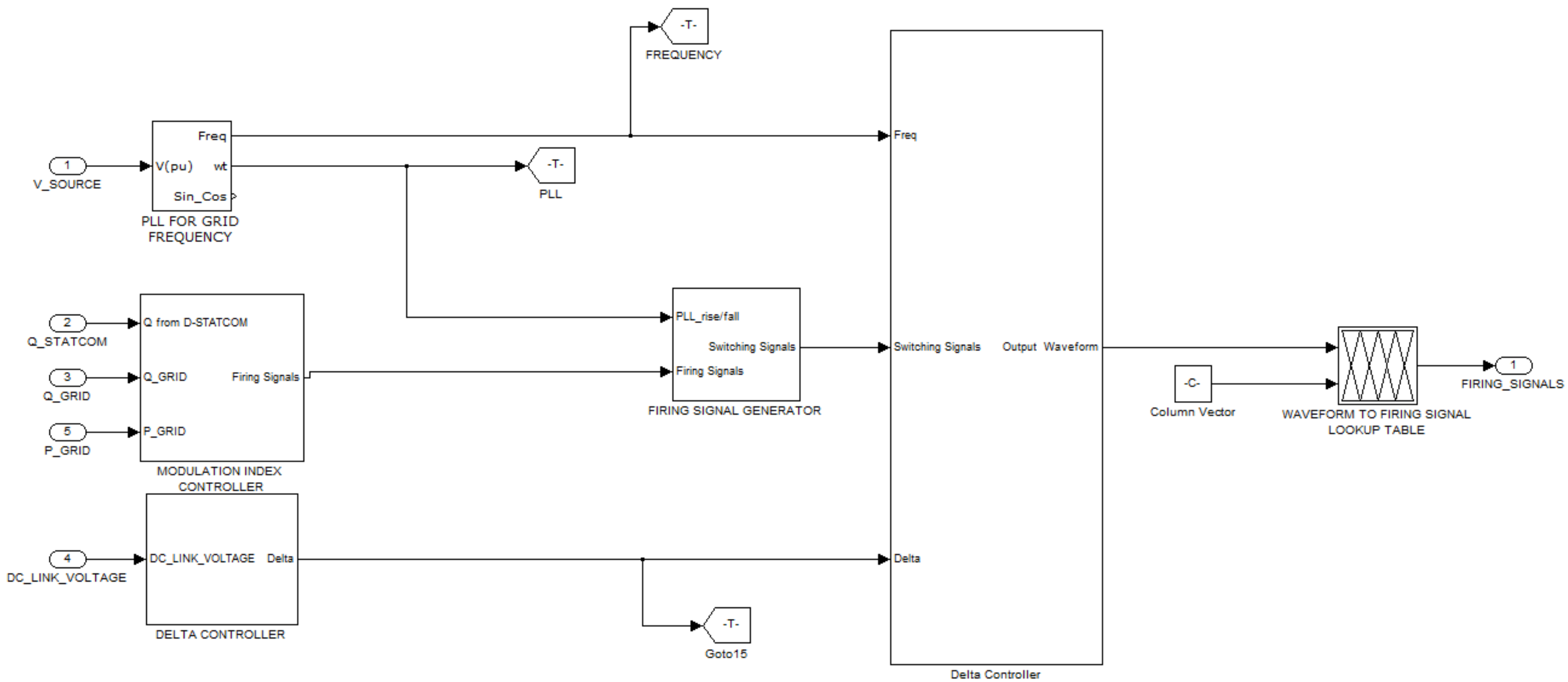


Figure 5.7 Block Diagram of the D-STATCOM controller in SimPowerSystems.

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).

$$P_G = \left(\sqrt{P_G^2 + Q_T^2}\right) * P.F._T \tag{5.1}$$

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)

$$Q_T = \sqrt{\left(\frac{P_G}{P.F._T}\right)^2 - P_G^2} \tag{5.2}$$

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.

$$PI_{Input} = min \begin{cases} |Q_{Lim} - Q_S| \\ |\Delta Q| \end{cases} \tag{5.3}$$

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.

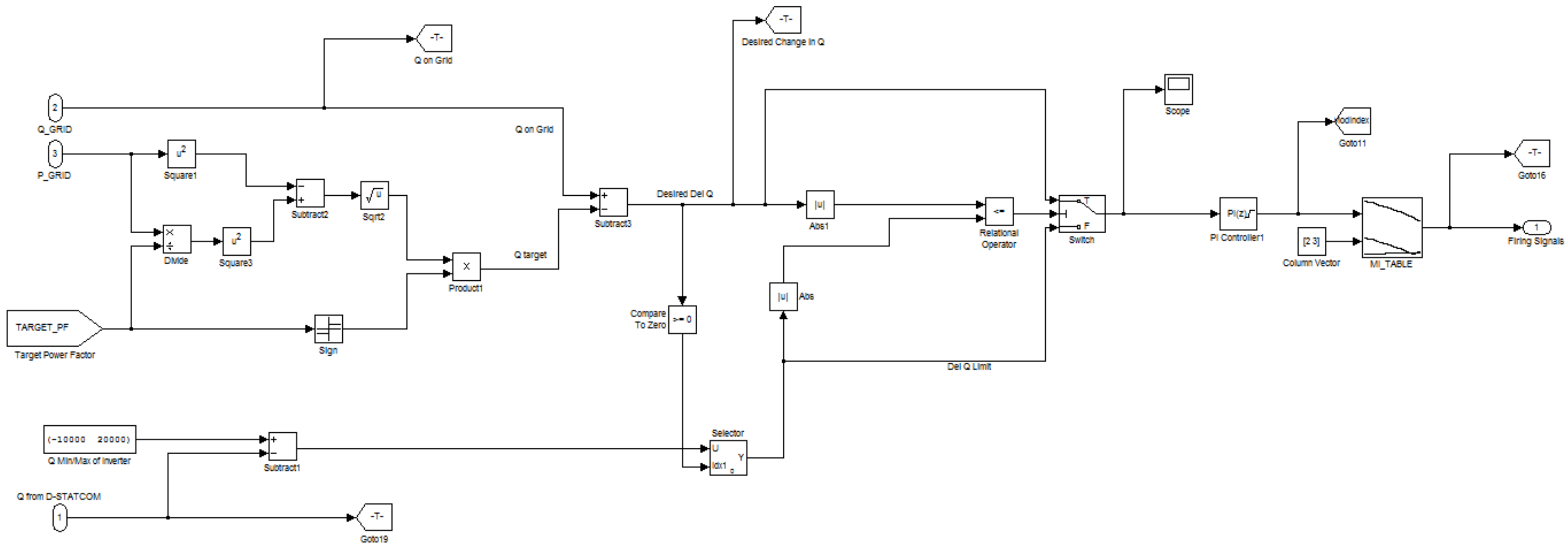


Figure 5.8 Block diagram of the modulation index controller in SimPowerSystems.

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.

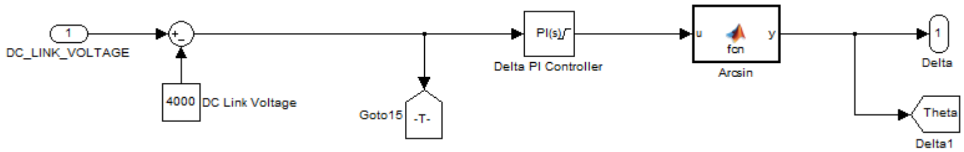


Figure 5.9 Block diagram of the delta controller in SimPowerSystems.

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 –.99 to .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.

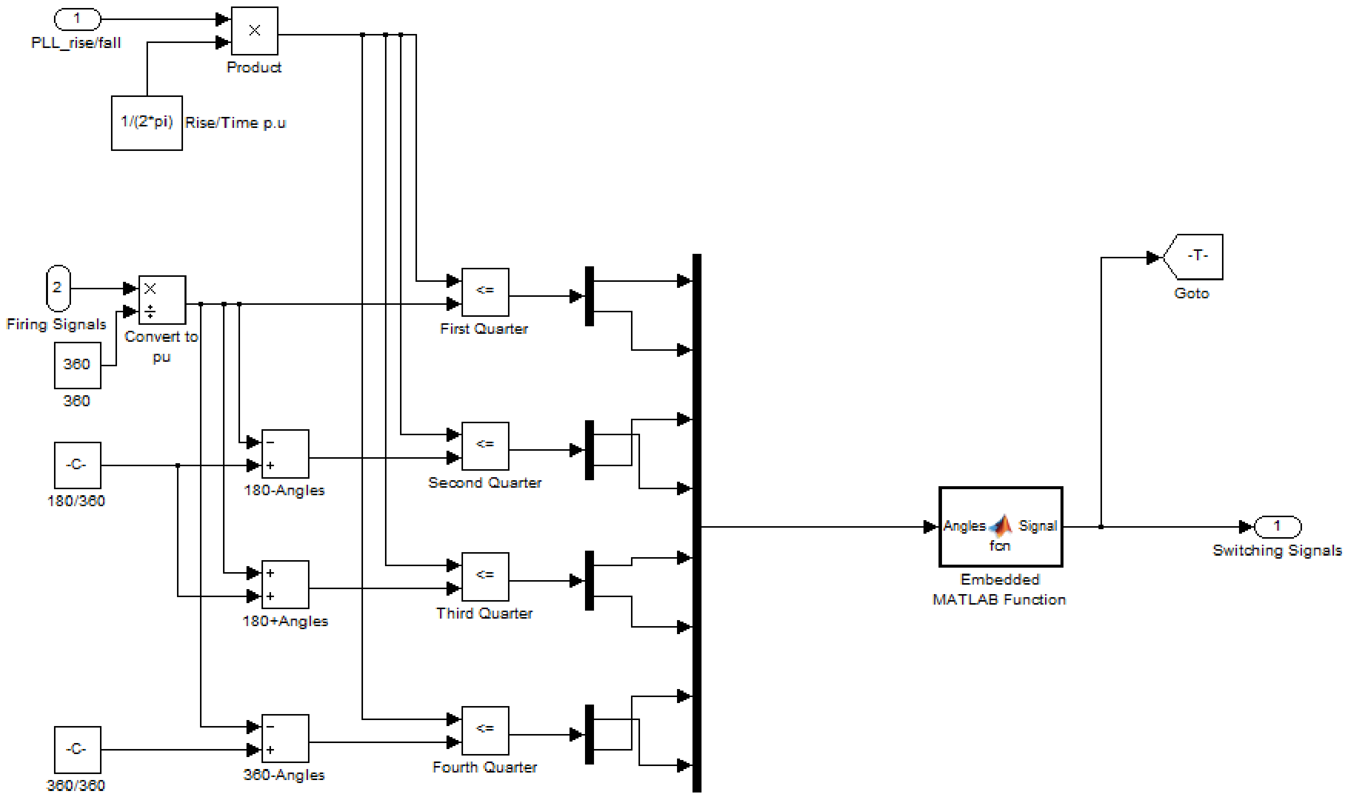


Figure 5.10 Block diagram for the firing signal generator in SimPowerSystems.

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.

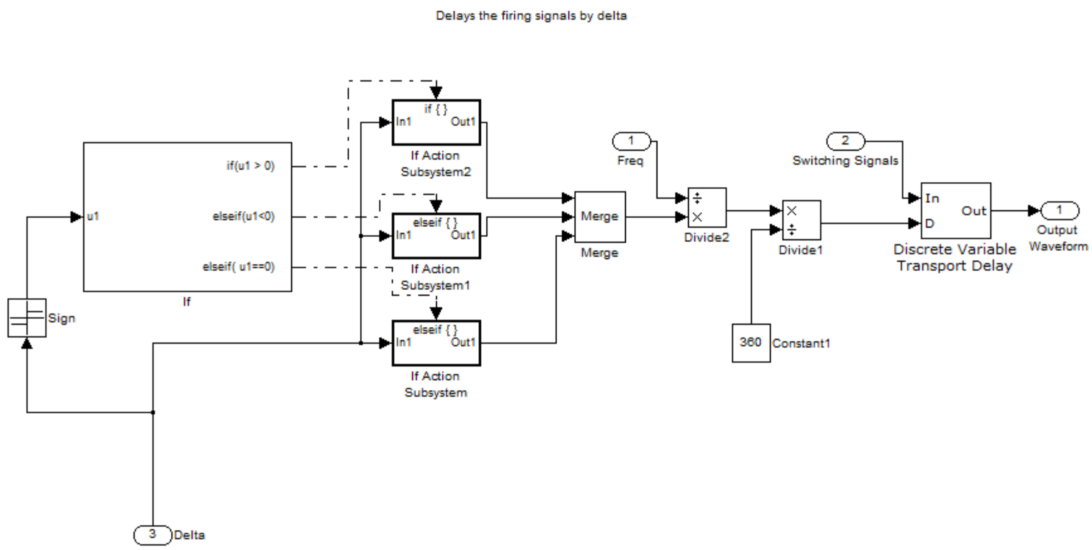


Figure 5.11 Block diagram of the delta delay implementer in SimPowerSystems.

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 MΩ 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 Ω, forward voltage of 1 V, current 10% fall time of 1 μs, current tail time of 2 μs, snubber resistance of .1 MΩ, and inf (infinite) snubber capacitance. Each of the diodes has a internal resistance of 0.001 Ω and forward voltage of 0.8 V. The DC link and auxiliary capacitors are all 1100 μF.

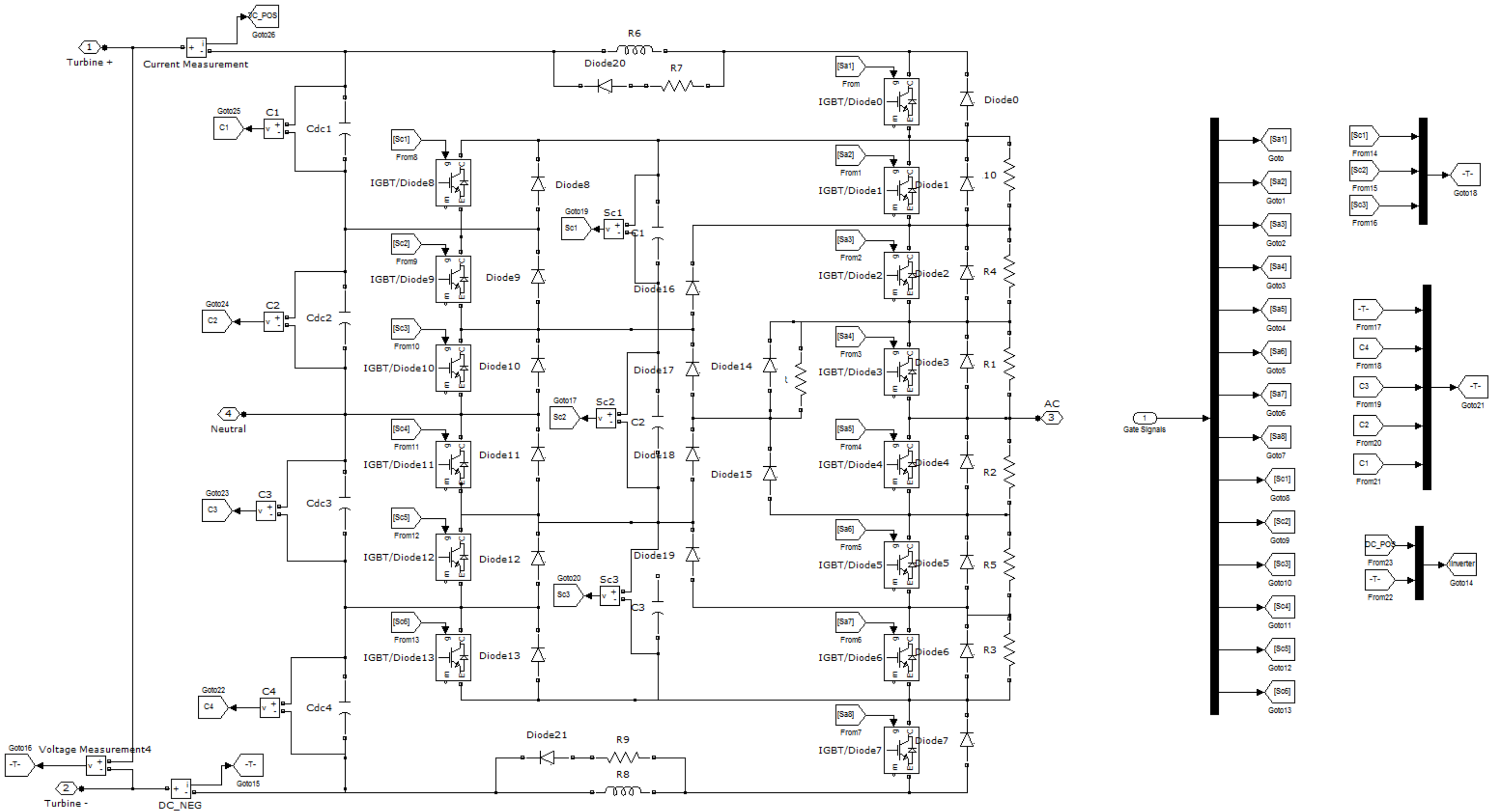


Figure 5.12 Block diagram of the 5-level hybrid-clamped power electronics circuit in SimPowerSystems.

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.

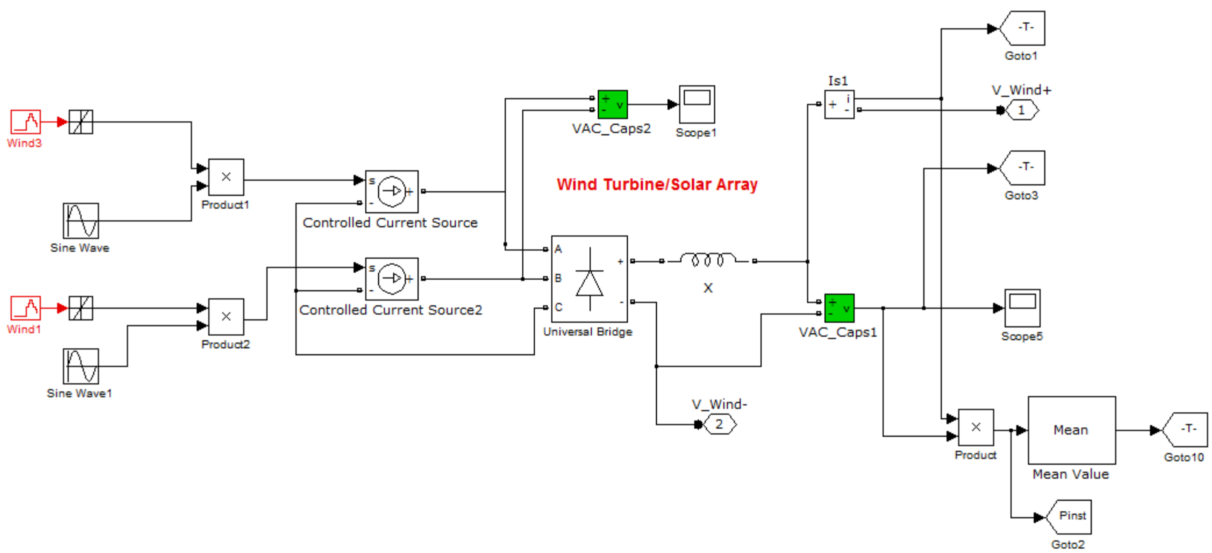


Figure 5.13 Block diagram of the wind turbine/solar array model in SimPowerSystems.

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.

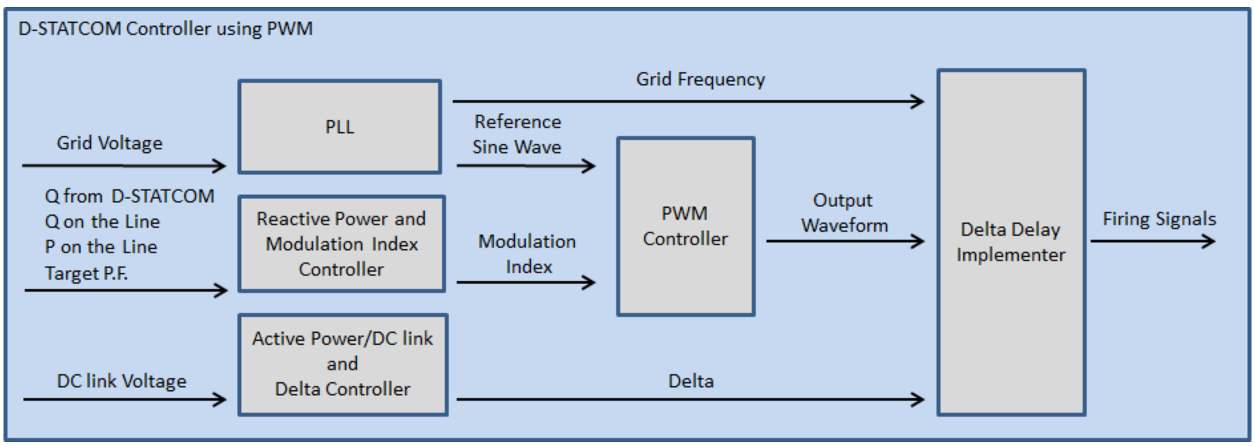


Figure 5.14 Block diagram of the D-STATCOM controller using HLCCAPOPWM.

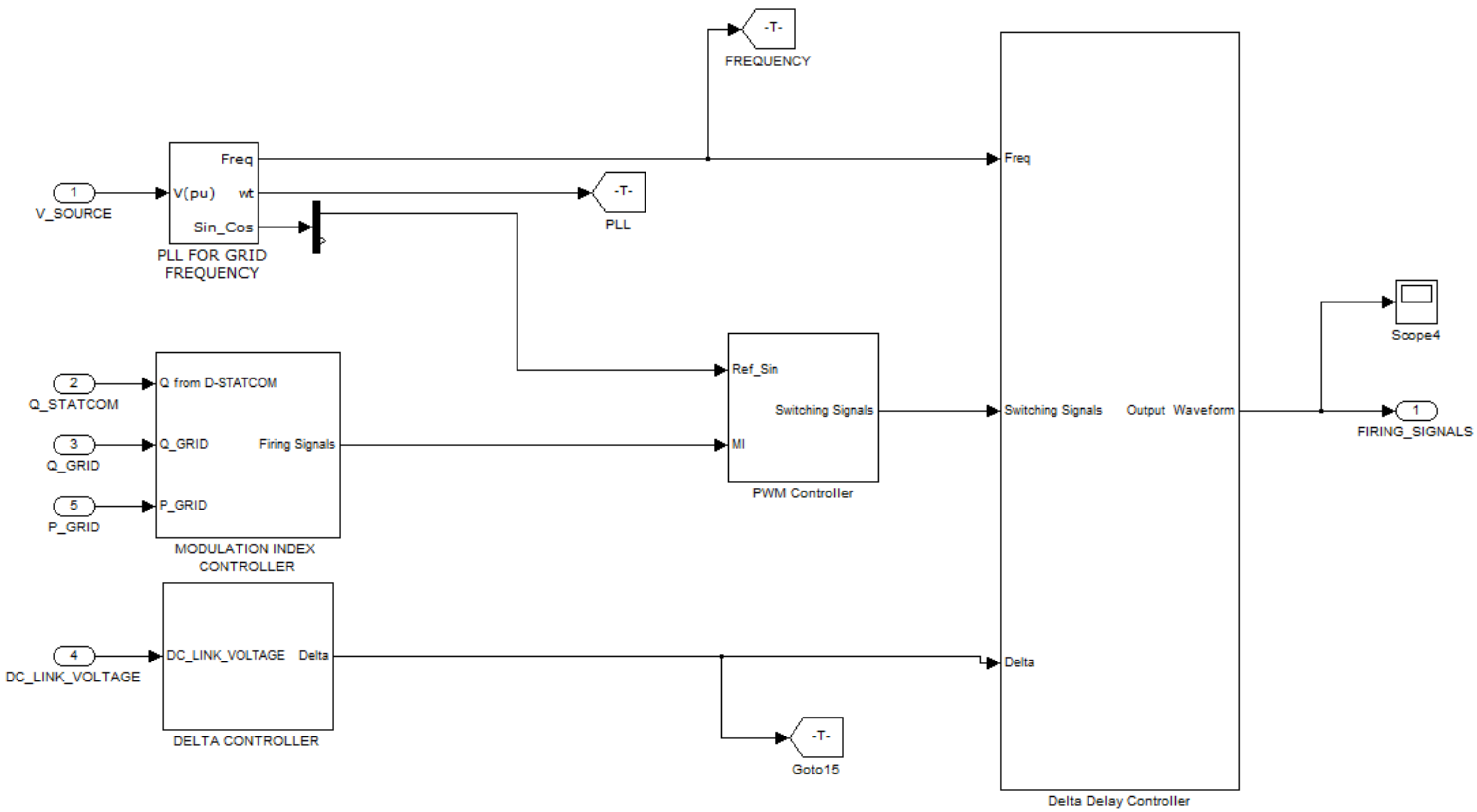


Figure 5.15 Block diagram of the D-STATCOM controller using HLCCAPOPWM in SimPowerSystems.

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.

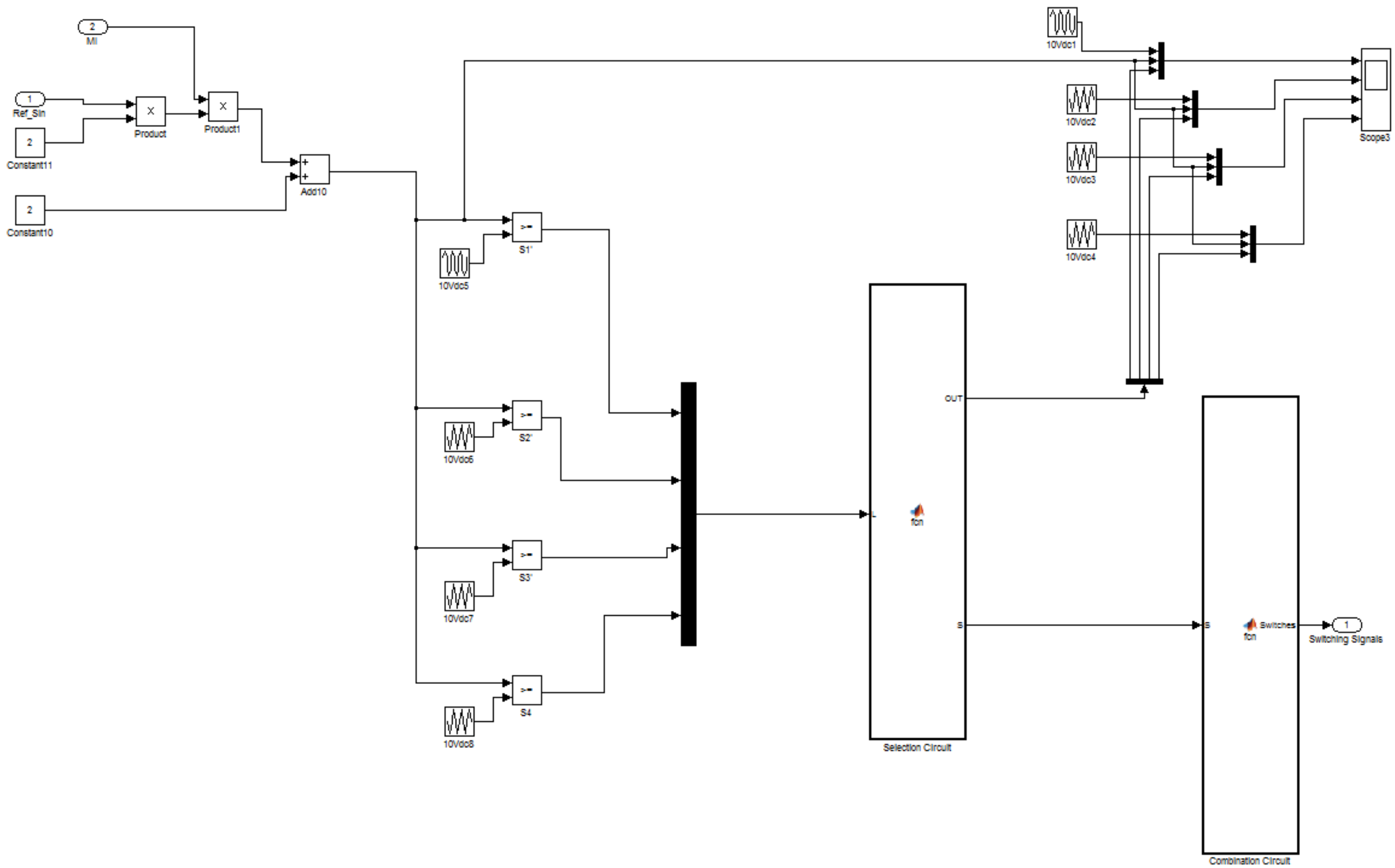


Figure 5.16 Block diagram of the PWM controller in SimPowerSystems.

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 6.1 Discrete Intervals for the Amplitudes of the Current Controlled Current Sources.

Controlled Current Source Amplitudes																					
Time (Seconds)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Current Amplitude (Amps)	0	0	0	0	0	0	0	1.5	2	2.5	2	1.5	1	0.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5

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.

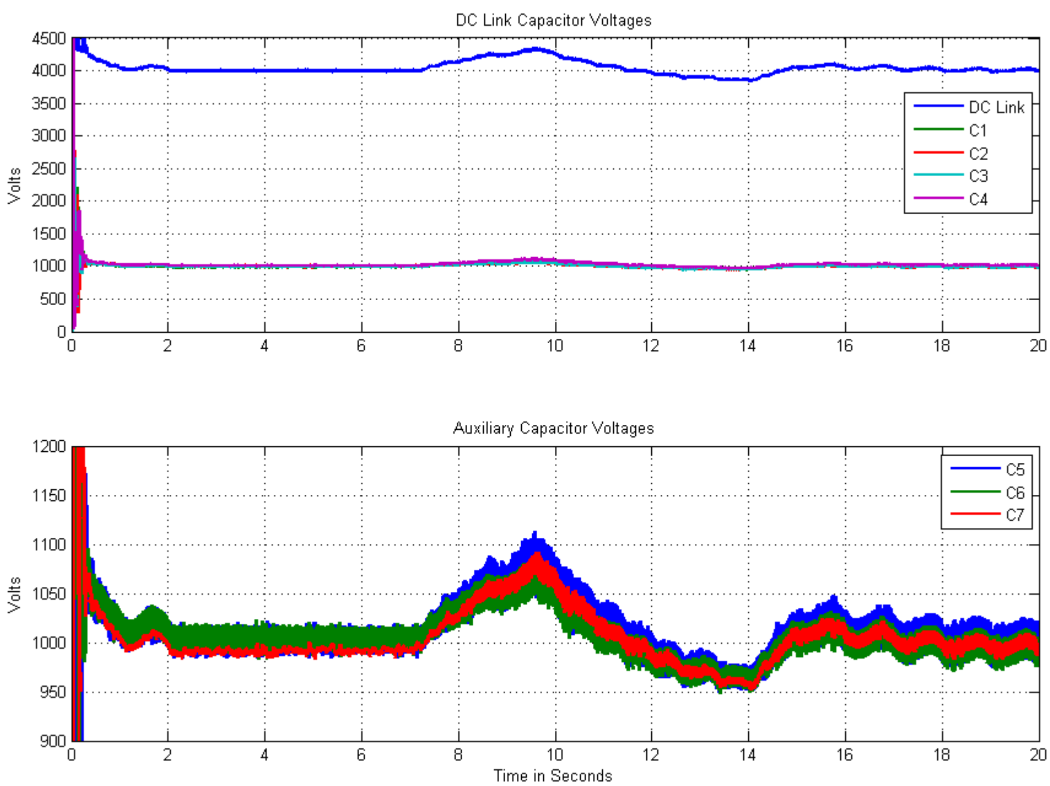


Figure 6.1 Variation of capacitor voltages using OHSW.

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 7th 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.

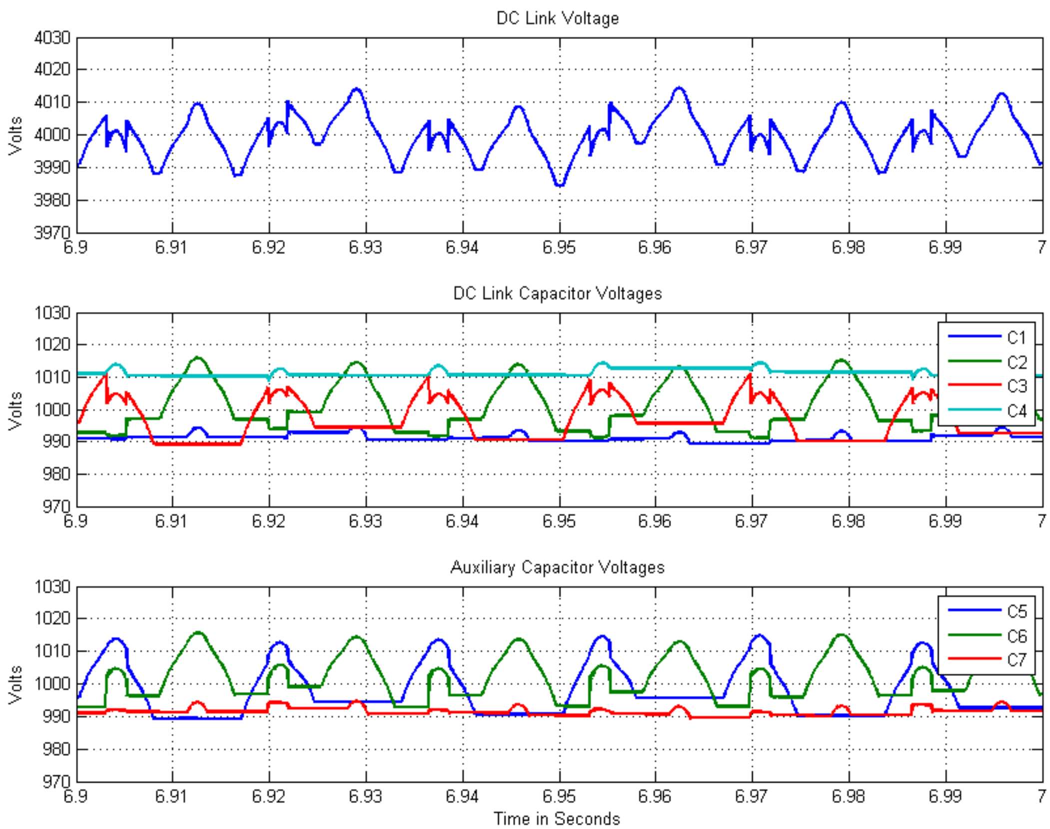


Figure 6.2 The DC link voltage and capacitor voltages are stabilized prior to the wind turbine starting up.

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 9th second and reaches 4361 volts representing a 9.0% increase over the 4000 volt target.

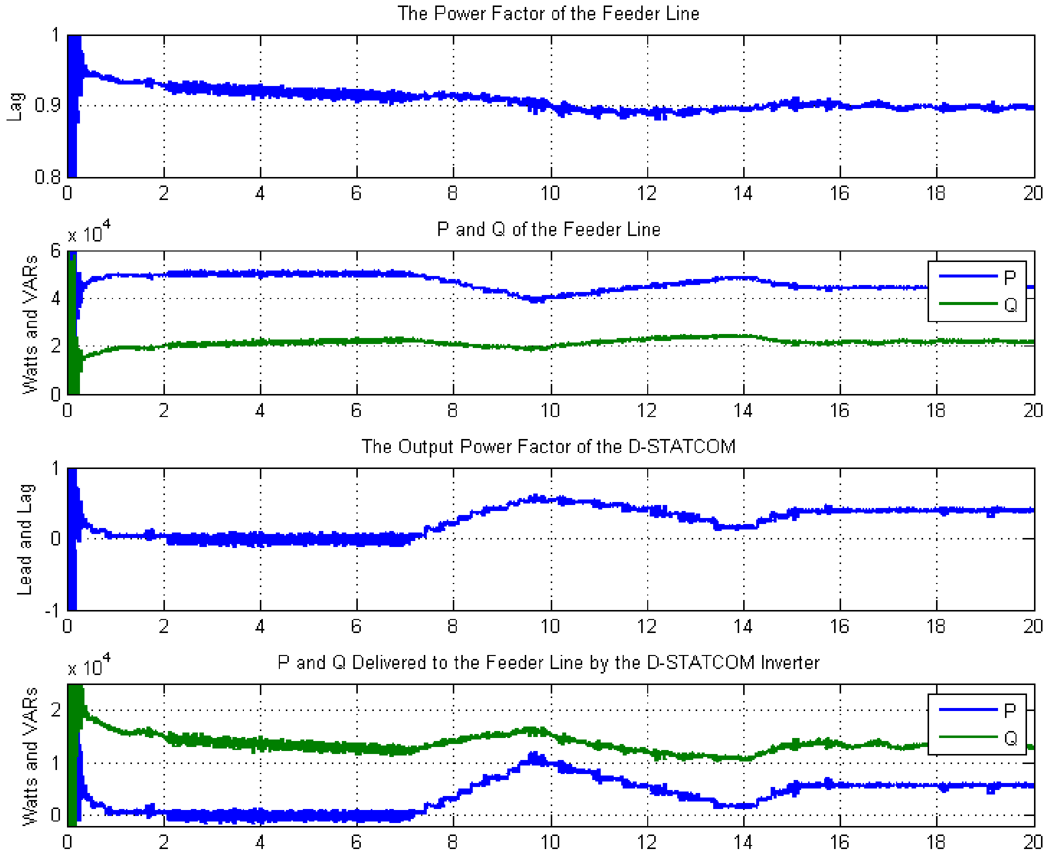


Figure 6.3 Feeder line power factor, feeder line P and Q, D-STATCOM power factor, and delivered P and Q of the D-STATCOM.

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^{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.

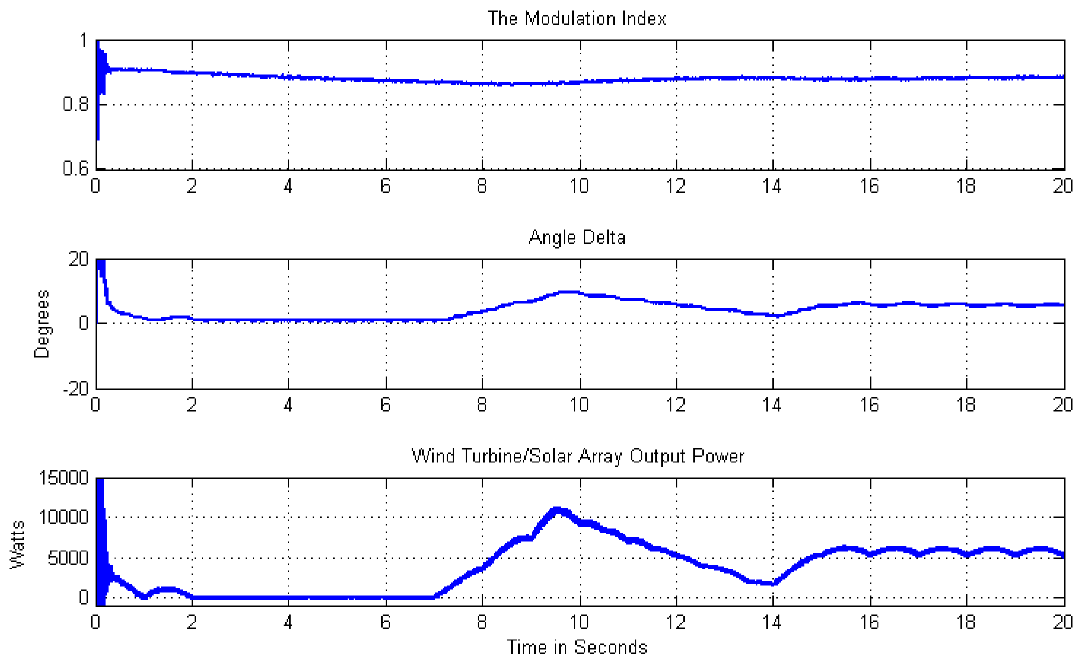


Figure 6.4 Variation of modulation index, angle delta, and distributed renewable output power.

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 inverters 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.

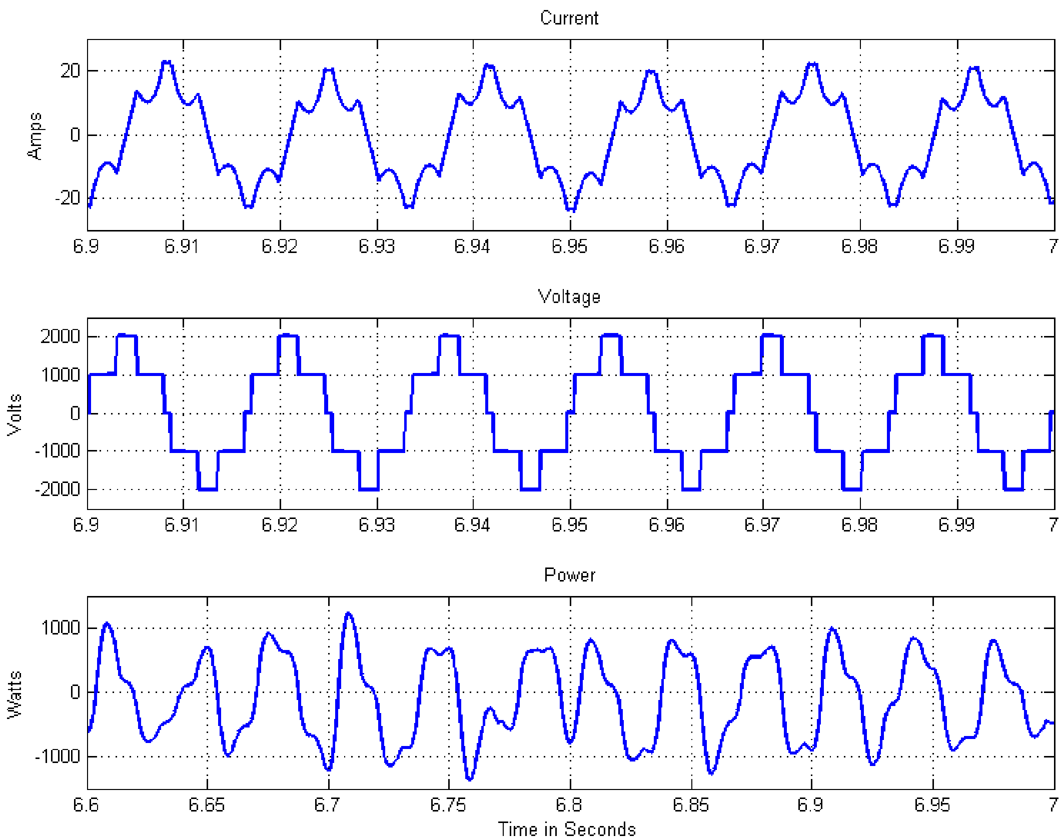


Figure 6.5 Cycle-to-Cycle variations in current and power.

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.

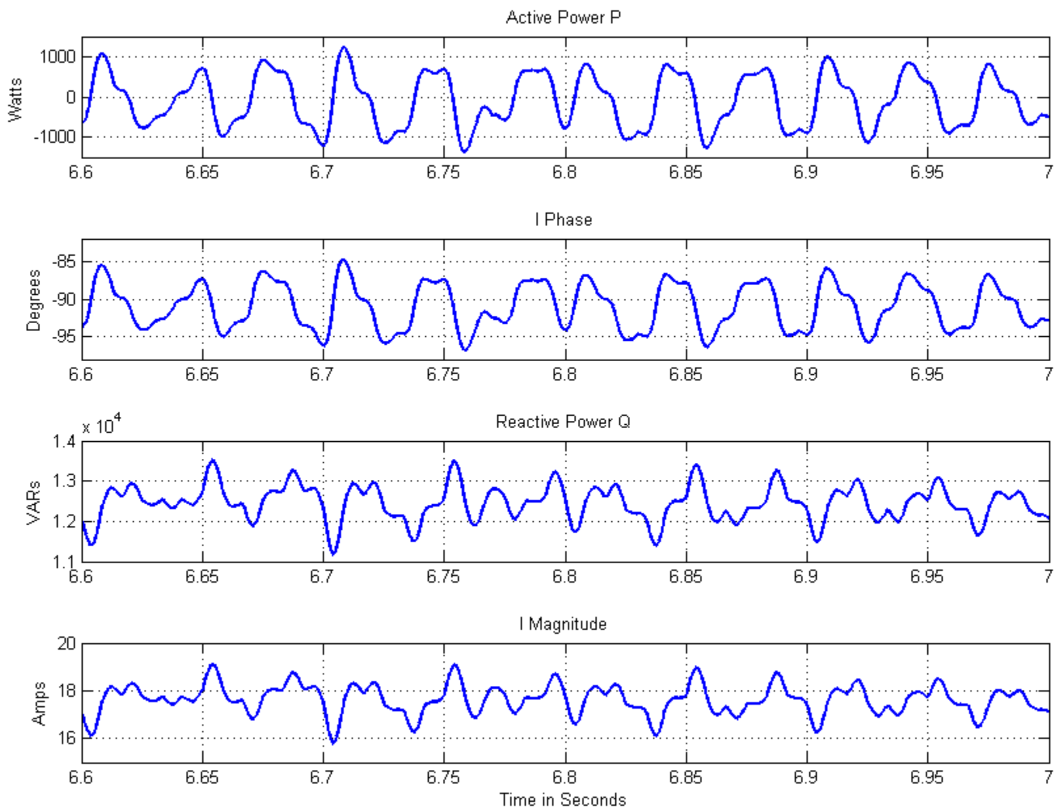


Figure 6.6 Variation in magnitude and phase angle of the D-STATCOM Inverters output current and active and reactive power delivered by the D-STATCOM Inverter.

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.

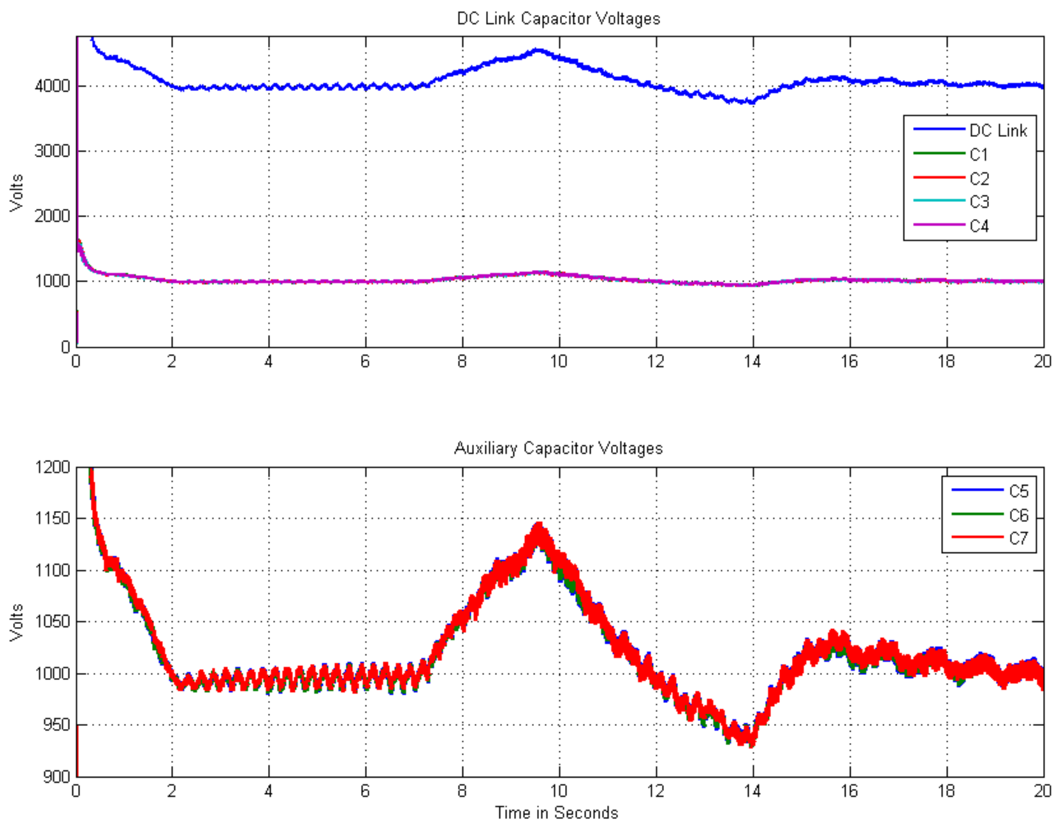


Figure 6.7 Variation of capacitor voltages using HLCCAPOPWM.

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).

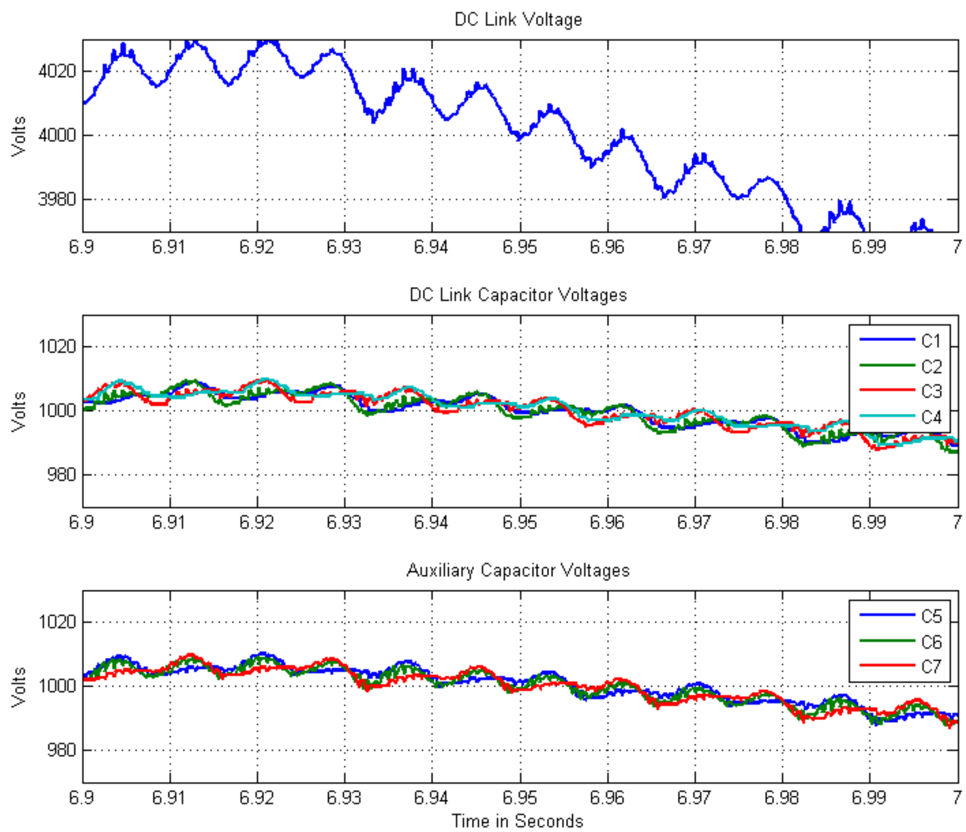


Figure 6.8 Variation of capacitor voltages right before the wind turbine starts providing power.

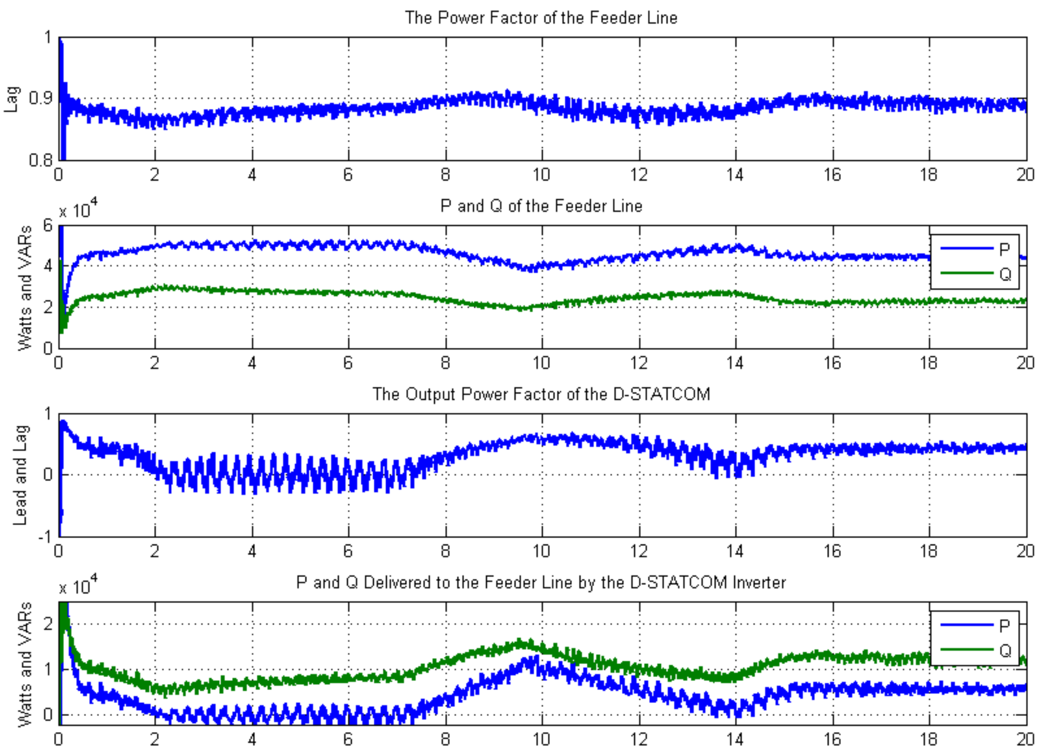


Figure 6.9 Feeder line power factor, feeder line P and Q, D-STATCOM power factor, and delivered P and Q of the D-STATCOM.

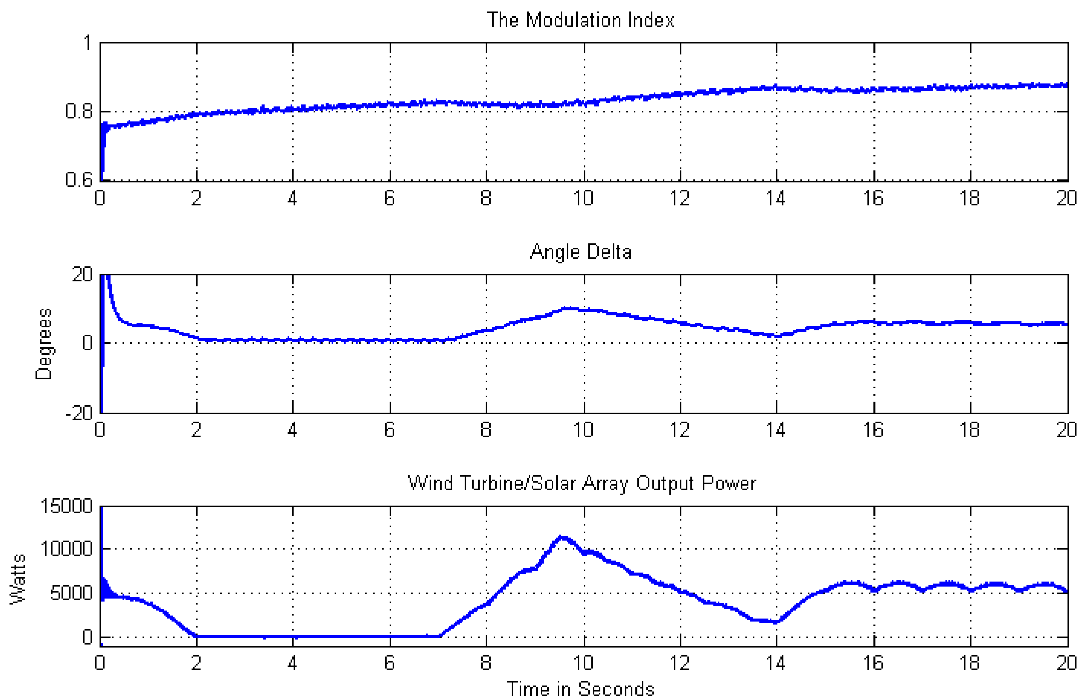


Figure 6.10 Variation of the modulation index, angle delta, and distributed renewable output power.

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.

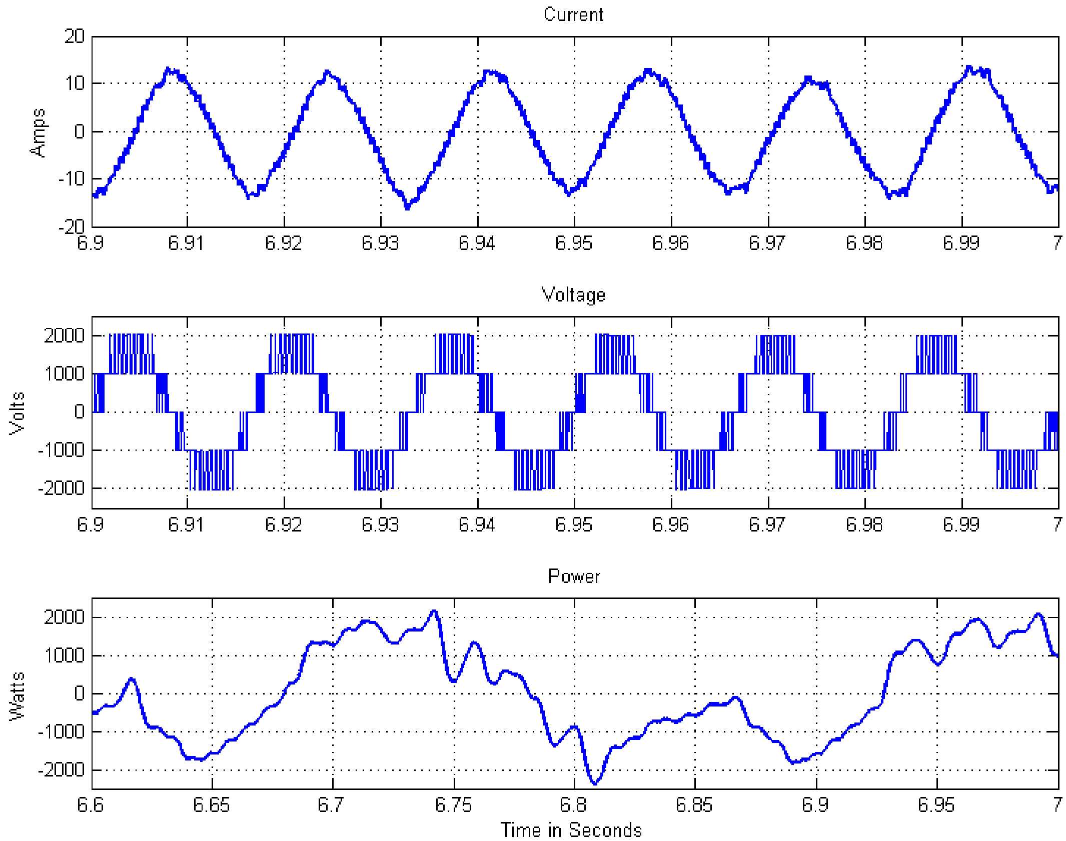


Figure 6.11 Variation of current and power from cycle-to-cycle.

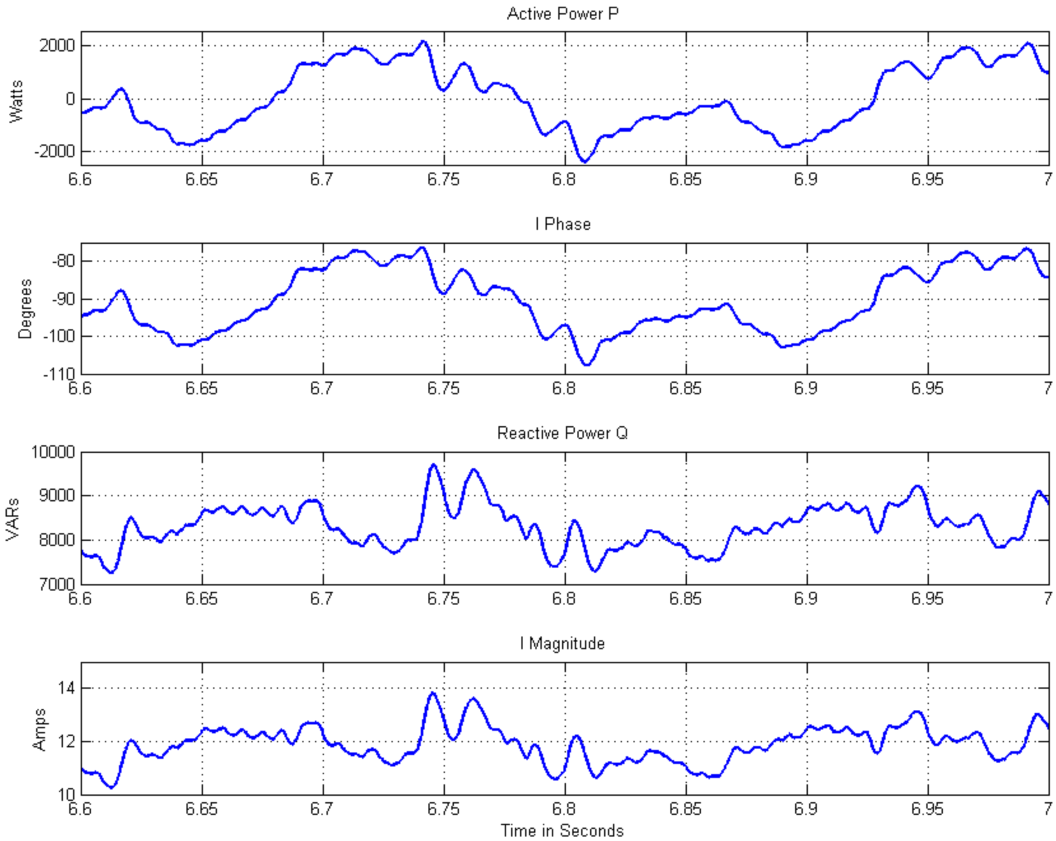


Figure 6.12 Variation in magnitude and phase angle of the D-STATCOM Inverters output current and its effect on the amount of delivered active and reactive power.

For the HLCCAPOPWM method the phase oscillation of the current ranges from $-110°$ to $-80°$ (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 Sa1′ 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.

Voltage Level	Switching States													
	S1	S2	S3	S4	S4'	S3'	S2'	S1'	Sc1	Sc2	Sc3	Sc4	Sc5	Sc6
4	1	1	1	1	0	0	0	0	0	1	0	1	0	1
3	0	1	1	1	0	0	0	1	1	0	1	0	1	0
2	0	0	1	1	1	0	0	1	1	0	1	0	1	0
1	0	0	0	1	1	1	0	1	1	0	1	0	1	0
0	0	0	0	0	1	1	1	1	1	0	1	0	1	0

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.

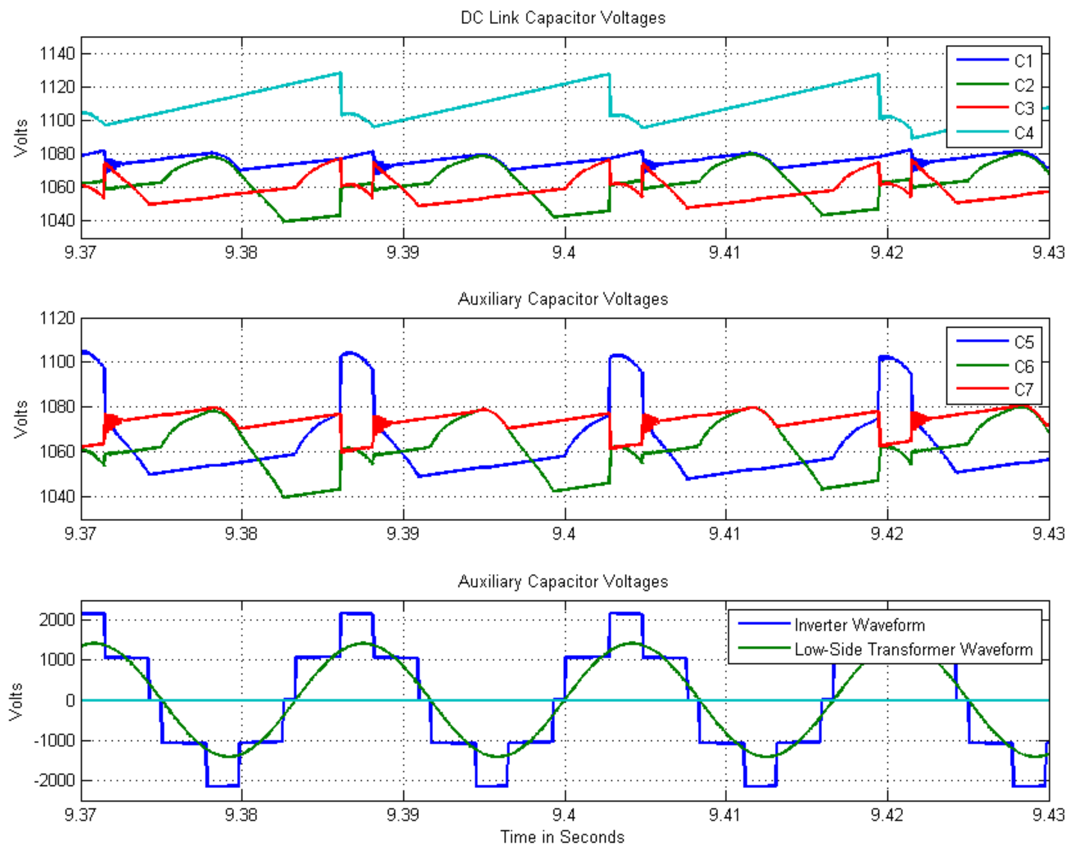


Figure 6.13 Capacitor voltages and inverter output waveform.

6.3.2 The 5-Level HLCCAPOPWM

Figure 6.14 provides the same three graphs as Figure 6.13, butfor 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.

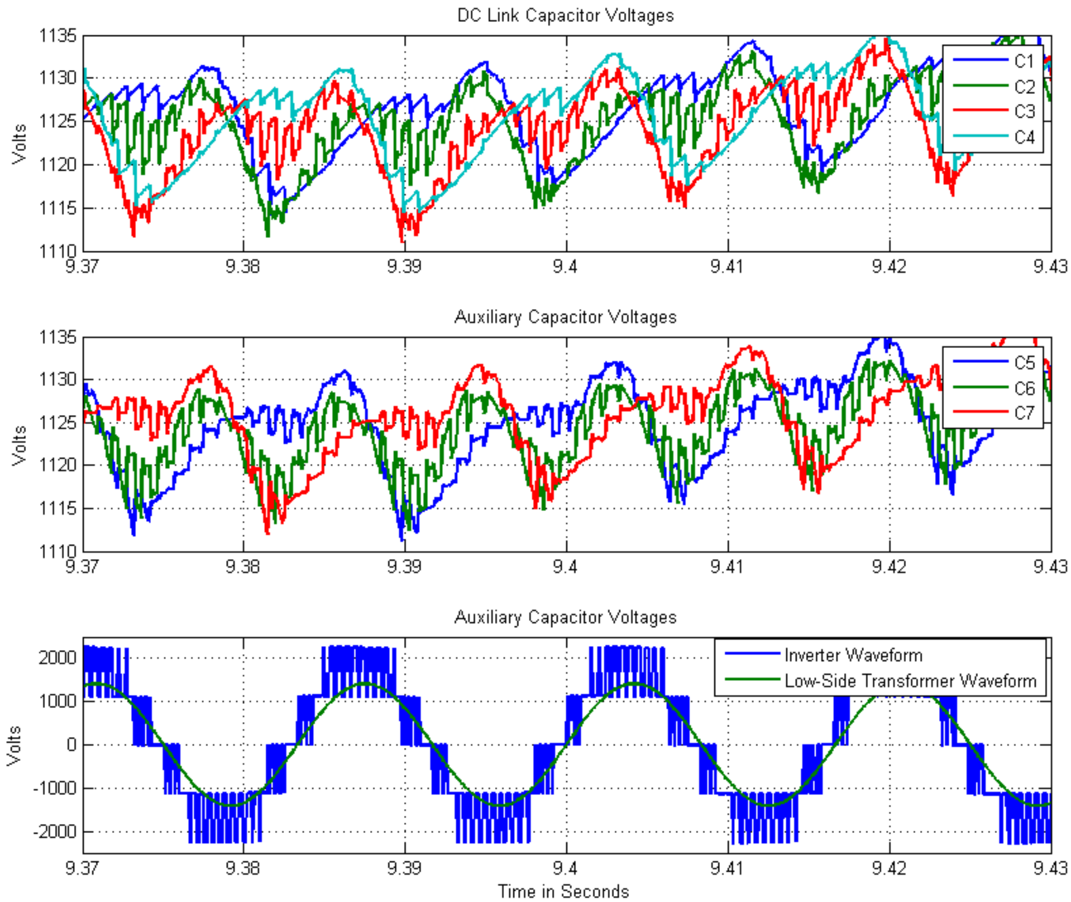


Figure 6.14 Capacitor voltage balancing and output waveform.

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 4^{th} 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.

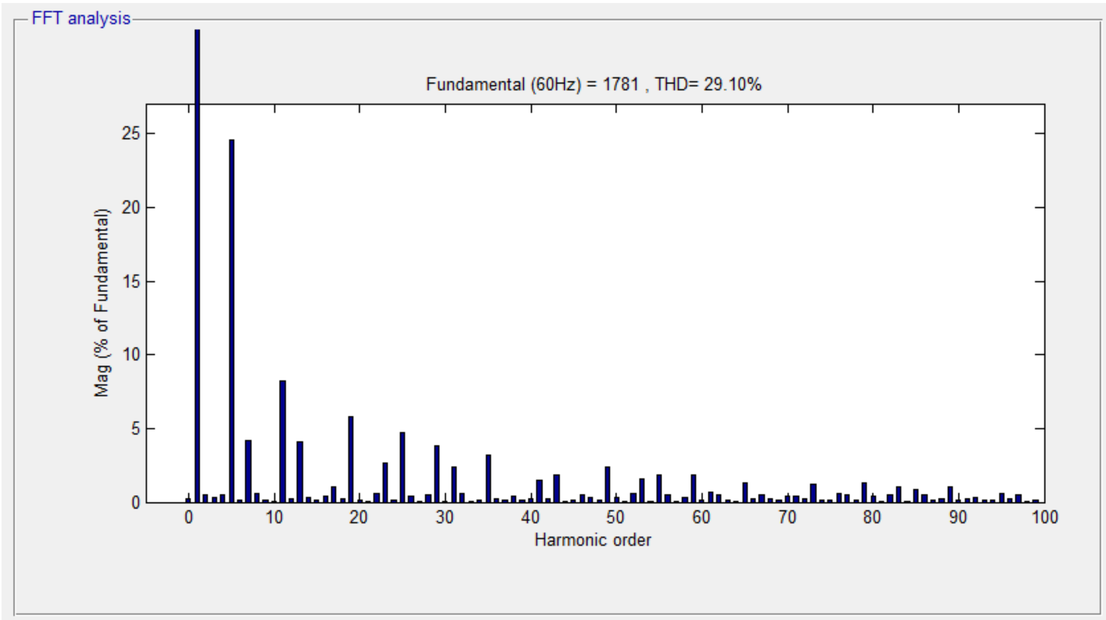


Figure 6.15 FFT analysis at t = 4 seconds for OHSW.

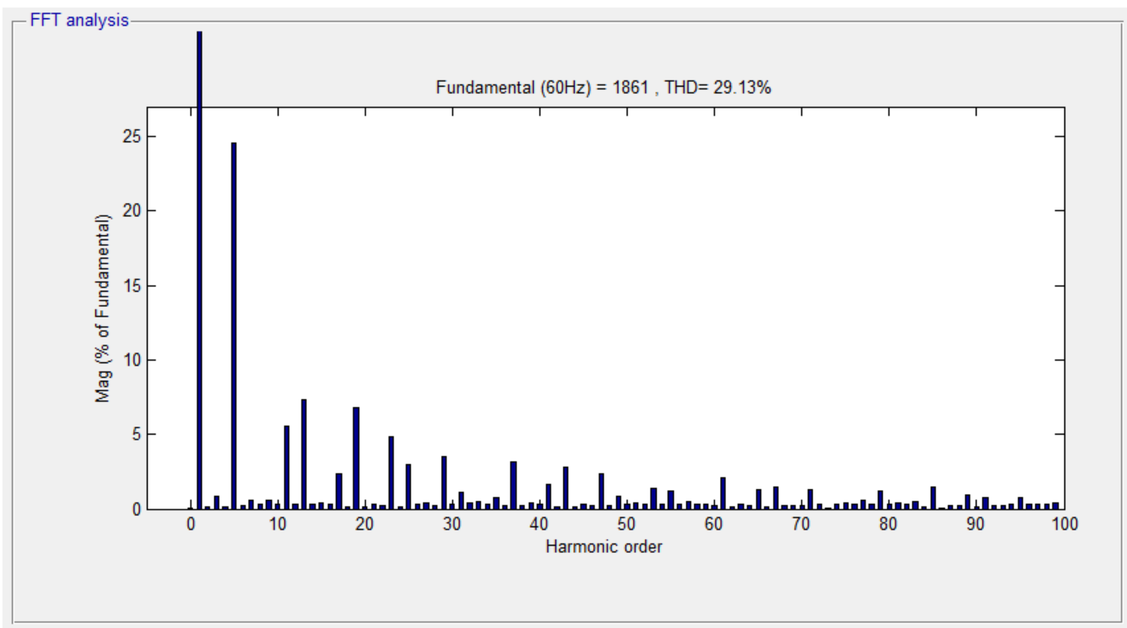


Figure 6.16 FFT analysis at t = 9.37 seconds for OHSW.

Table 6.3 Simulated vs. Predicted Results for THD for the OHSW Method up to the 100^{th} harmonic.

Time 1 = 4s	Simulated	Predicted
THD	29.10%	29.39%
3rd Harmonic Percentage of Fundamental	0.30%	0.00%
Modulation Index	0.878	0.878
Time 2 = 9.37s	Simulated	Predicted
THD	29.13%	29.39%
3rd Harmonic Percentage of Fundamental	0.86%	0.00%
Modulation Index	0.867	0.867

Results show that while the 3^{rd} 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.

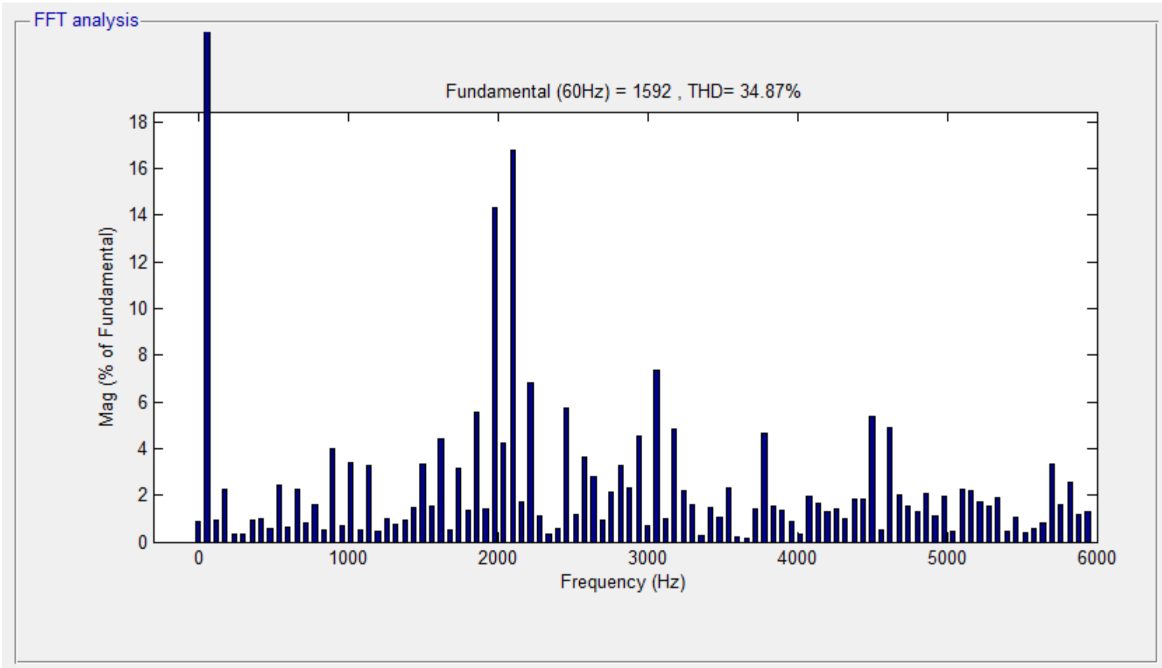


Figure 6.17 FFT analysis of HLCCAPOPWM for t = 4 seconds.

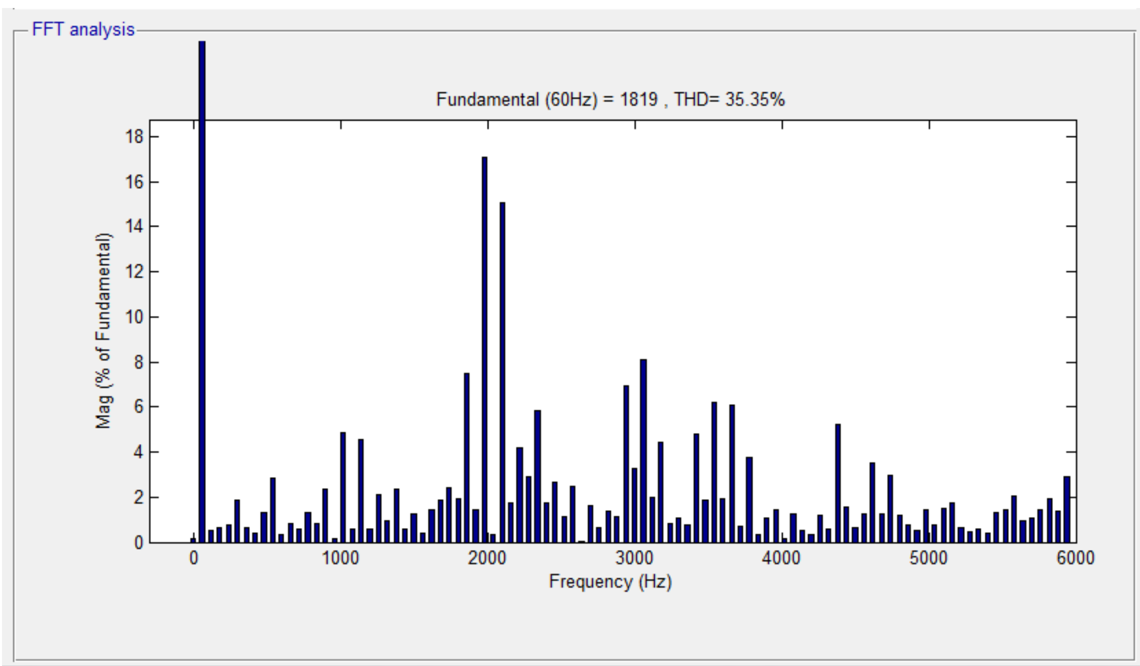


Figure 6.18 FFT analysis of HLCCAPOPWM for t = 9.37 seconds.

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.

Comparison of OHSW and HLCCAPOPWM		
Criteria	OHSW	HLCCAPOPWM
Time 1=4s: THD	29.10%	34.87%
Time 2=9.37s: THD	29.13%	35.35%
Requires a Large Filter	Yes	Yes
Switching Frequency	240 Hz	1kHz
Switches Switched in 1 Cycle using Table 6.2	20	124
DC Link Capacitor Deviation	80 Volts	15 Volts

The major drawback to the 5-level OHSW is that it requires a large filter to suppress the 5^{th} 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 17^{th}.

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 7^{th} second of the simulation at which point the distributed renewable starts producing power and the individual capacitor voltages begin to separate and become unstable.

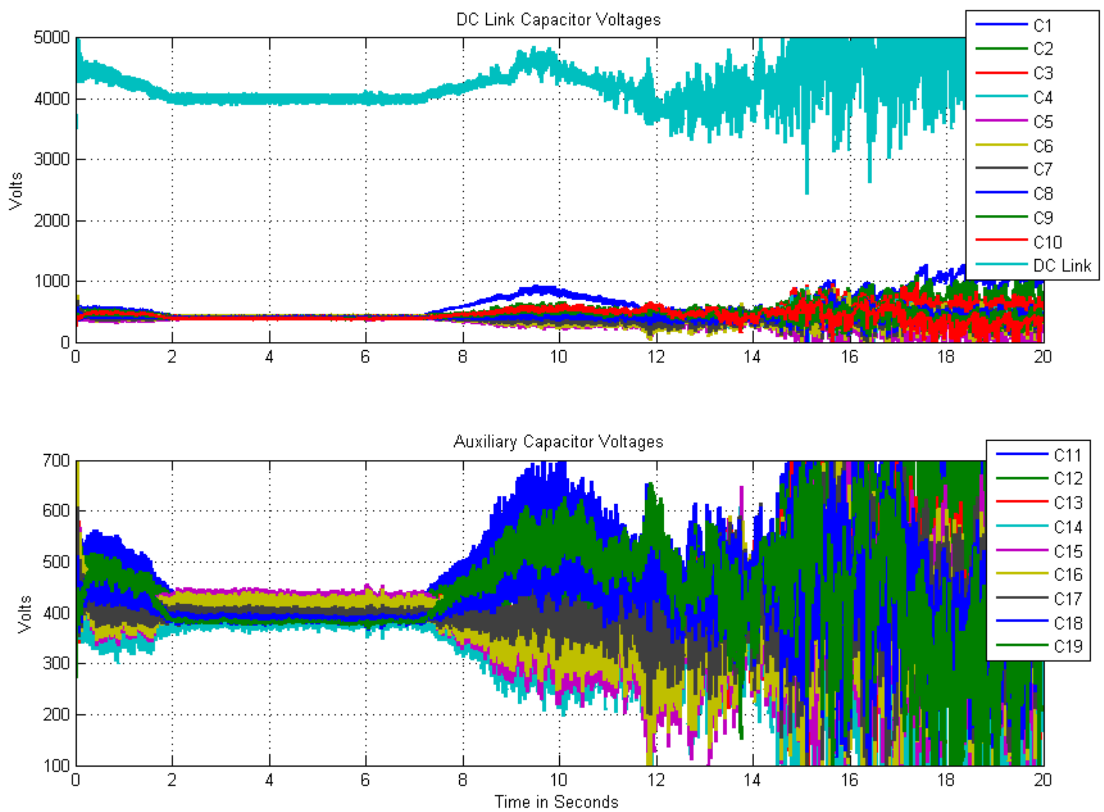


Figure 6.19 Capacitor voltage waveforms for the 11-level OHSW D-STATCOM Inverter.

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 ∓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.

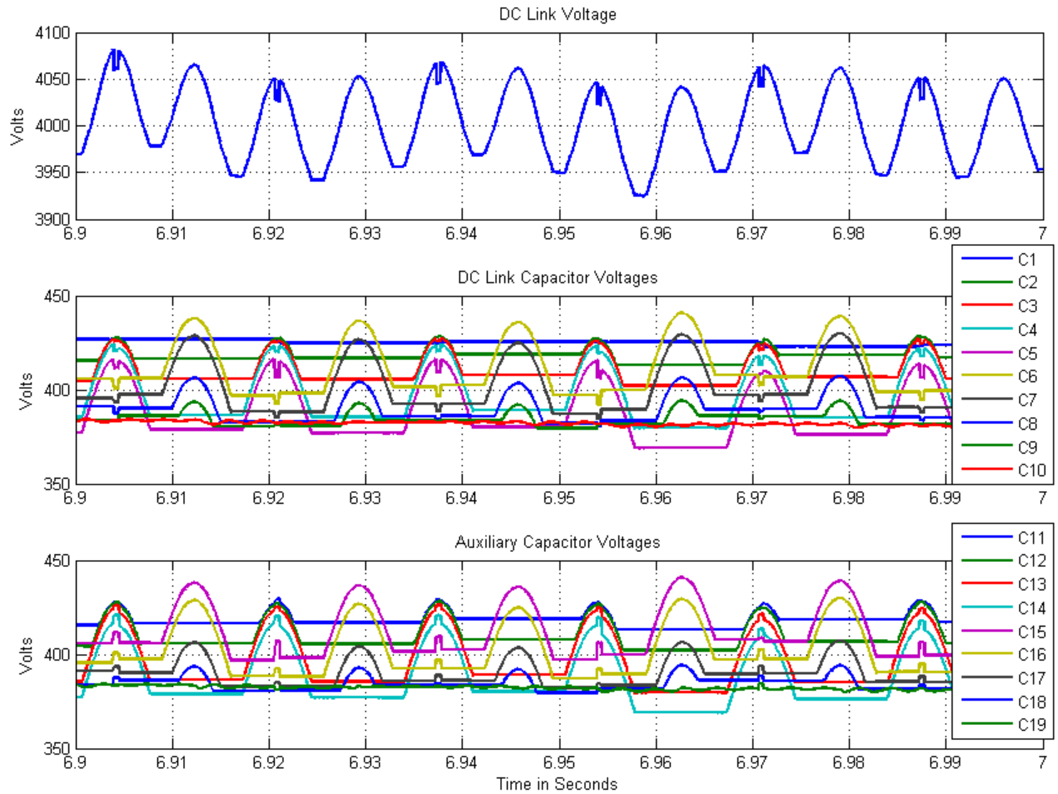


Figure 6.20 DC link voltage and capacitor voltages stabilize prior to the wind turbine starting up.

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.

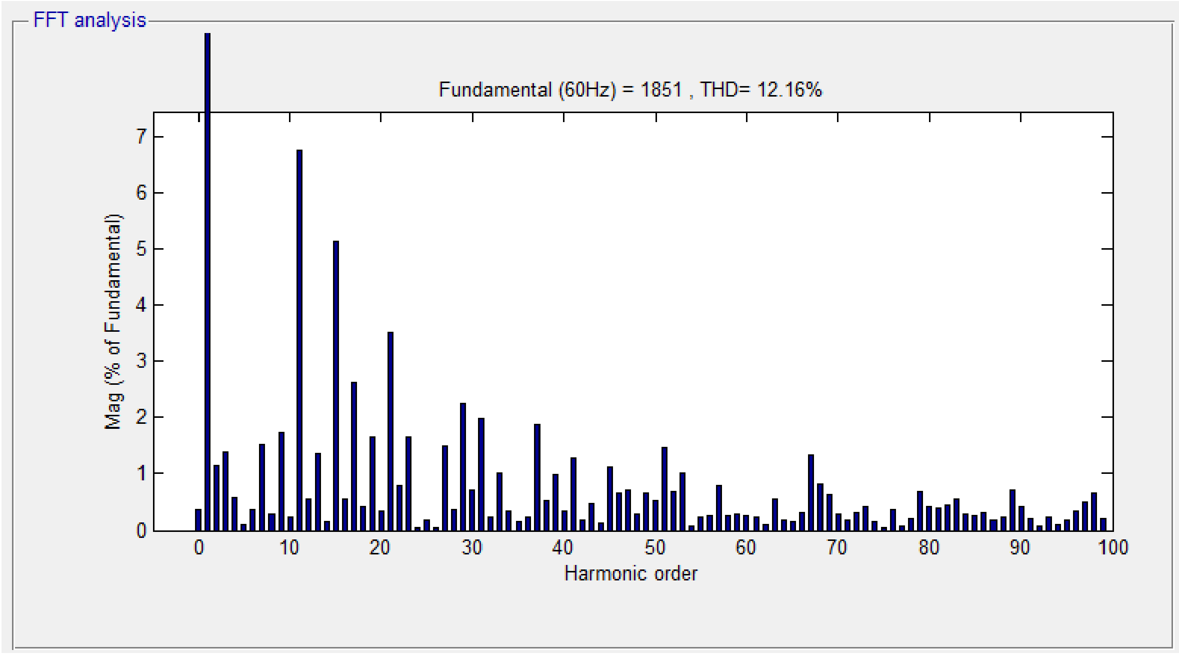


Figure 6.21 FFT analysis of 11-level OHSW Inverter for t=4 seconds.

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

Time 1 = 4s	Simulated	Predicted
THD	12.16%	12.67%
3rd Harmonic % of fundamental	1.39%	0.00%
5th Harmonic % of fundamental	0.10%	0.00%
7h Harmonic % of fundamental	1.51%	1.50%
9th Harmonic % of fundamental	1.74%	1.65%
Modulation Index	0.898	0.898

As the FFT shows, the 3^{rd}, 5^{th}, 7^{th}, 9^{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^{rd}, 5^{th}, 7^{th}, and 9^{th} harmonics as a percentage of the fundamental component. As the table shows, the suppression of the 3^{rd} and 5^{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.

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Appendix A - PSO Code and Firing Angles

A.1 PSO Code

Main Program

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%                                                                   %%%
%%%             TITLE: PSO FOR M-LEVEL OHSW WITH NEWTON HYBRID        %%%
%%%             AUTHOR: COLIN TAREILA                                 %%%
%%%             DATE CREATED: FEBRUARY 19, 2011                       %%%
%%%             LAST MODIFIED: MAY 19, 2011                           %%%
%%%                                                                   %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%                          BASED ON PAPERS                          %%%
%%%  [1] S. Barkati, L. Baghli, El. M. Berkouk, M. S. Boucherit,      %%%
%%%  "Harmonic elimination in diode-clamped multilevel inverter using %%%
%%%  evolutionary algorithms," Elsevier, Electric Power Systems       %%%
%%%  Research 78, pp. 1736-1746, 2008.                                %%%
%%%                                                                   %%%
%%%  [2]S. Barkati, E.M. Berkouk, M.S. Boucherit, “Partical swarm     %%%
%%%  optimization for harmonic elimination in multi-level inverters,” %%%
%%%  Springer, Electr Eng 91, pp. 221-228, 2009.                      %%%
%%%                                                                   %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

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

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%                 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 AMPLIDTUDES
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
PARTICALS=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
                           %%% 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

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%       STARTS THE WHILE LOOP FOR MODULATION INDEX PARAMETERS        %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

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

    %%% INITIALIZES THE ANGLE FOR EACH PARTICAL. THESE ANGLES ARE RANDOM
    %%% BUT THEN SORTED TO MEET THE CONSTRAINT THAT THE FIRING ANGLE OF
    %%% EACH LEVEL SHOULD BE INCREASING. THAT IS ALPHA 1 < ALPHA 2 <
    %%% ALPHA 3 < pi()/2
    A=rand(PARTICALS,HARM_ELIM).*pi()/2;
    B=sort(A');
    PARTICAL_ANGLES=B';

    %%% INITIALIZE HALF OF THE ANGLES TO BE THE SOLUTION FROM THE LAST
    %%% ITERATION BUT ONLY IF ON THE FIRST TRY
    if(TRY_NUM==1)
        if(SOLVED==TRUE)
            PARTICAL_ANGLES(1:10,:)=repmat(GLOBAL_BEST_ANGLES,10,1);
        end
    end

    %%% CREATE A VECTOR FOR THE VELOCIEITES OF EACH PARTICAL AND INITIALIZE
    %%% THEM TO ZERO
    VELOCITY=zeros(PARTICALS,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 UPDAING 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))

           %%% UPDATE THE TOLERANCE SUM(OLD ANGLES - NEW ANGLES)
           TOL=abs(sum(abs(PARTICAL_ANGLES))-sum(abs(NP_ANGLES)));
           %%% UPDATES THE ANGLES
           PARTICAL_ANGLES(bb,:) = NP_ANGLES(bb,:);
        end
    end

ITERATION=ITERATION+1;
end %%% END THE WHILE LOOP FOR A PARTICULAR MODULATION INDEX
ITERATION %%% PRINTS OUT THE CURRENT 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 %%% END OF FOR LOOP FOR MODULATION INDEX
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';

        %%% CACLULATE THE FITNESS ACCODRING TO THE COST EQUATION
        [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)

    %%% CACLULATE 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)
        NN=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;
        %%% REMOVES ALL MULTIPLES OF THREE
        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)
```

```
    xlabel('Harmonic Number')
    ylabel('Amplitude in % of Fundamental')
    title('Harmonic Amplitudes for a MI of 0.85')
    set(gca,'XLim',[0 101])
    set(gca,'XTick',[0:5:100])
    set(gca,'XTickLabel',[0:5:100])

end %%% END GRAPH HARMONIC FACTORS
```

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=sum(cos(repmat(h,size(p,2),1)'.*repmat(p(x,:),length(h),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

Modulation	5- Levels (2-Angles)			7-Level (3-Angles)				9-Level (4-Angles)					11-Level (5-Angles)					
Index	Alpha 1	Alpha 2	Cost	Alpha 1	Alpha 2	Alpha 3	Cost	Alpha 1	Alpha 2	Alpha 3	Alpha 4	Cost	Alpha 1	Alpha 2	Alpha 3	Alpha 4	Alpha 5	Cost
0.599	27.096	87.096	4.71E-17	24.121	60.082	90.000	0.720	13.136	43.795	85.113	90.000	1.228	29.400	43.427	61.683	73.715	90.000	1.231
0.600	27.034	87.034	4.71E-17	23.889	59.884	90.000	0.686	7.788	40.463	82.240	90.000	0.485	29.331	43.356	61.596	73.644	90.000	1.228
0.601	26.972	86.972	3.53E-17	23.763	59.788	90.000	0.681	7.277	40.493	82.910	89.172	0.533	28.510	43.914	61.333	73.636	90.000	1.188
0.602	26.910	86.910	4.71E-17	23.682	59.701	90.000	0.677	6.454	38.974	83.008	90.000	0.588	28.343	43.749	61.270	73.688	90.000	1.176
0.603	26.848	86.848	4.71E-17	23.557	59.557	90.000	0.673	7.148	40.282	82.132	89.755	0.541	28.464	43.815	61.176	73.432	90.000	1.172
0.604	26.786	86.786	3.53E-17	23.499	59.534	90.000	0.669	7.232	40.352	81.726	90.000	0.550	28.322	43.753	61.157	73.333	90.000	1.168
0.605	26.724	86.724	3.53E-17	23.362	59.357	90.000	0.660	6.081	39.689	82.806	89.159	0.627	28.292	43.650	61.036	73.268	90.000	1.166
0.606	26.662	86.662	1.38E-09	23.249	59.257	90.000	0.654	6.829	40.100	81.460	90.000	0.579	28.234	43.546	61.024	73.183	90.000	1.159
0.607	26.599	86.599	4.71E-17	23.161	59.155	90.000	0.649	6.682	40.051	81.364	90.000	0.586	28.169	43.466	60.937	73.105	90.000	1.155
0.608	26.537	86.537	2.24E-16	23.038	59.102	90.000	0.648	6.392	39.992	81.171	90.000	0.610	27.987	43.518	60.825	73.026	90.000	1.142
0.609	26.475	86.475	4.71E-17	22.951	58.970	90.000	0.639	6.333	39.625	81.335	90.000	0.639	27.973	43.339	60.877	72.879	90.000	1.144
0.610	26.413	86.413	2.56E-08	22.811	58.811	90.000	0.631	6.145	39.882	80.999	90.000	0.625	26.728	42.534	61.075	73.634	90.000	1.134
0.611	26.350	86.350	5.59E-13	22.774	58.770	89.996	0.629	6.935	39.502	80.919	90.000	0.703	26.662	42.521	60.578	73.892	90.000	1.111
0.612	26.288	86.288	4.71E-17	22.617	58.601	89.986	0.621	5.760	39.738	80.806	90.000	0.659	15.695	42.066	56.377	81.696	90.000	0.660
0.613	26.225	86.225	1.46E-11	22.493	58.499	90.000	0.615	5.450	39.511	80.833	89.993	0.673	15.680	41.899	56.267	81.673	90.000	0.654
0.614	26.163	86.163	2.36E-16	22.418	58.404	90.000	0.611	5.578	39.747	80.187	90.000	0.773	15.666	41.826	56.209	81.548	90.000	0.655
0.615	26.100	86.100	2.24E-16	22.286	58.288	90.000	0.603	5.413	39.588	80.397	90.000	0.694	13.654	30.418	57.722	88.654	88.654	0.420
0.616	26.037	86.037	4.71E-17	22.150	58.152	90.000	0.597	1.912	39.780	84.784	85.476	0.865	13.603	30.340	57.669	88.590	88.590	0.423
0.617	25.975	85.975	1.30E-16	22.138	58.135	89.997	0.595	5.098	39.370	80.128	90.000	0.730	12.535	28.259	57.319	88.562	89.999	0.363
0.618	25.912	85.912	3.01E-11	21.986	58.038	90.000	0.592	4.699	39.358	79.969	90.000	0.735	12.511	28.183	57.230	88.401	90.000	0.355
0.619	25.849	85.849	3.53E-17	21.824	57.825	90.000	0.578	3.773	39.207	79.945	90.000	0.802	12.293	28.178	55.560	89.764	89.764	0.294
0.620	25.787	85.787	1.30E-16	21.744	57.746	90.000	0.575	1.176	38.782	81.556	88.707	0.867	9.849	29.920	55.484	89.332	89.744	0.194
0.621	25.724	85.724	1.30E-16	21.617	57.615	89.998	0.567	5.129	38.846	79.802	90.000	0.822	8.904	28.984	55.211	89.690	90.000	0.191
0.622	25.661	85.661	4.71E-17	21.531	57.528	90.000	0.564	5.357	39.229	79.956	90.000	0.871	9.140	29.861	55.013	89.368	89.793	0.181
0.623	25.598	85.598	3.06E-16	21.390	57.387	90.000	0.556	4.046	38.975	79.358	90.000	0.812	8.681	28.780	54.721	89.887	89.887	0.176
0.624	25.535	85.535	3.53E-17	21.285	57.291	90.000	0.550	3.051	38.972	79.401	89.852	0.810	8.676	28.723	54.585	89.812	89.876	0.171
0.625	25.472	85.472	1.30E-16	21.180	57.171	89.991	0.544	1.179	39.016	80.052	89.127	0.868	8.689	28.713	54.464	89.782	89.782	0.166
0.626	25.409	85.409	4.71E-17	21.062	57.065	90.000	0.537	3.539	38.707	79.038	90.000	0.848	8.779	28.840	54.375	89.643	89.695	0.162
0.627	25.346	85.346	1.41E-16	20.988	56.986	90.000	0.533	5.541	38.354	79.182	90.000	0.963	8.798	28.838	54.328	89.575	89.575	0.160
0.628	25.282	85.282	3.53E-17	20.862	56.863	90.000	0.526	2.719	38.902	78.524	90.000	0.871	8.747	28.880	54.402	89.426	89.426	0.163
0.629	25.219	85.219	1.81E-08	20.673	56.709	90.000	0.520	3.266	38.472	78.755	90.000	0.897	8.637	28.681	54.275	89.420	89.420	0.160
0.630	25.156	85.156	1.41E-16	20.684	56.682	89.997	0.516	4.967	37.755	78.765	90.000	1.025	8.572	28.313	53.780	89.417	89.786	0.142

0.631	25.092	85.092	3.06E-16	20.485	56.473	90.000	0.506	2.304	38.676	77.964	90.000	0.970	8.613	28.315	53.667	89.333	89.729	0.137
0.632	25.029	85.029	1.18E-16	20.361	56.361	90.000	0.498	2.236	38.289	78.168	90.000	0.937	8.557	28.215	53.518	89.212	89.801	0.132
0.633	24.966	84.966	2.27E-15	20.267	56.271	90.000	0.493	2.236	38.289	78.168	90.000	0.933	7.158	29.096	53.065	89.115	89.804	0.111
0.634	24.902	84.902	3.43E-09	20.209	56.197	90.000	0.491	1.165	38.411	77.931	90.000	0.932	7.086	28.944	52.935	88.881	90.000	0.107
0.635	24.839	84.839	1.41E-16	20.009	56.007	90.000	0.481	0.000	38.865	77.683	89.740	1.002	7.193	28.809	52.809	88.859	89.949	0.100
0.636	24.775	84.775	4.71E-17	19.889	55.890	90.000	0.474	0.656	38.211	77.627	90.000	0.965	7.356	28.673	52.718	88.741	89.959	0.096
0.637	24.711	84.711	1.41E-16	19.811	55.813	90.000	0.468	1.659	37.868	77.724	90.000	0.990	7.424	28.610	52.605	88.817	89.770	0.091
0.638	24.648	84.648	4.71E-17	19.688	55.695	90.000	0.461	3.866	37.107	77.871	90.000	1.127	7.513	28.491	52.494	89.200	89.295	0.086
0.639	24.584	84.584	4.71E-17	19.572	55.579	90.000	0.455	0.300	37.873	77.273	90.000	1.014	7.623	28.387	52.390	88.960	89.427	0.081
0.640	24.520	84.520	2.27E-15	19.438	55.437	90.000	0.447	1.901	38.769	76.551	90.000	1.035	7.740	28.286	52.288	88.866	89.410	0.077
0.641	24.456	84.456	4.71E-17	19.322	55.311	90.000	0.442	1.445	38.640	76.508	90.000	1.035	7.894	28.140	52.191	88.785	89.390	0.073
0.642	24.392	84.392	2.27E-15	19.207	55.207	90.000	0.434	3.619	36.960	77.116	90.000	1.149	7.956	28.073	52.076	88.818	89.246	0.067
0.643	24.329	84.329	2.12E-16	19.070	55.078	90.000	0.430	2.506	38.870	75.881	90.000	1.088	8.049	27.959	51.965	88.555	89.412	0.062
0.644	24.265	84.265	1.41E-16	18.947	55.088	90.000	0.433	0.080	37.411	76.695	90.000	1.085	8.151	27.855	51.859	88.155	89.705	0.058
0.645	24.201	84.201	4.71E-17	18.948	54.952	90.000	0.420	5.950	39.671	74.700	90.000	1.217	8.261	27.751	51.754	87.996	89.754	0.053
0.646	24.136	84.136	1.41E-16	18.750	54.750	90.000	0.408	0.000	38.677	75.622	89.756	1.141	8.436	27.675	51.671	87.829	89.771	0.049
0.647	24.072	84.072	1.56E-13	18.634	54.634	90.000	0.400	0.000	38.677	75.622	89.756	1.138	8.509	27.511	51.547	87.721	89.816	0.044
0.648	24.008	84.008	4.71E-17	18.498	54.495	89.997	0.392	0.135	37.379	75.862	90.000	1.135	8.606	27.411	51.434	87.943	89.490	0.038
0.649	23.946	83.943	9.65E-05	18.456	54.453	90.000	0.391	2.624	38.668	74.905	90.000	1.132	8.723	27.300	51.327	87.906	89.418	0.033
0.650	23.880	83.880	4.71E-17	18.278	54.275	90.000	0.380	2.868	38.648	74.603	90.000	1.148	8.815	27.200	51.215	87.850	89.368	0.028
0.651	23.815	83.815	9.51E-09	18.156	54.163	90.000	0.374	0.402	36.644	75.891	89.999	1.182	8.953	27.105	51.116	87.847	89.246	0.023
0.652	23.751	83.751	1.41E-16	18.007	54.007	90.000	0.365	1.650	36.582	75.609	90.000	1.211	9.053	26.972	50.998	88.208	88.796	0.017
0.653	23.686	83.686	4.71E-17	17.847	53.879	90.000	0.366	2.586	38.494	74.321	90.000	1.150	9.168	26.862	50.889	88.112	88.783	0.012
0.654	23.622	83.622	4.71E-17	17.853	53.851	90.000	0.356	4.887	38.719	73.683	90.000	1.223	9.289	26.750	50.781	88.393	88.393	0.007
0.655	23.557	83.557	4.71E-17	17.649	53.649	90.000	0.343	1.535	38.167	74.131	90.000	1.148	9.372	26.624	50.677	88.343	88.343	0.004
0.656	23.493	83.493	2.12E-16	17.541	53.576	90.000	0.340	3.885	38.687	73.546	90.000	1.182	9.302	26.598	50.577	88.279	88.279	0.010
0.657	23.428	83.428	4.71E-17	17.428	53.429	90.000	0.330	2.809	37.757	73.983	90.000	1.207	9.494	26.301	50.393	88.225	88.351	0.011
0.658	23.363	83.363	4.71E-17	17.285	53.285	90.000	0.322	19.868	45.971	64.490	90.000	1.241	9.537	26.125	50.236	88.200	88.344	0.017
0.659	23.298	83.298	4.71E-17	17.170	53.172	90.000	0.315	0.000	37.845	73.608	90.000	1.169	9.872	26.175	50.230	88.108	88.137	0.020
0.660	23.234	83.234	2.27E-15	17.114	53.130	90.000	0.313	0.677	37.644	73.471	90.000	1.170	9.912	25.865	50.067	88.137	88.137	0.033
0.661	23.169	83.169	4.71E-17	16.921	52.923	90.000	0.302	3.672	38.279	72.867	90.000	1.187	10.108	25.938	50.005	87.883	88.147	0.030
0.662	23.104	83.104	2.24E-15	16.864	52.878	90.000	0.298	18.755	44.892	64.573	90.000	1.161	10.232	25.826	49.896	87.721	88.194	0.036
0.663	23.039	83.039	4.71E-17	16.665	52.662	90.000	0.285	18.971	44.968	64.463	89.973	1.134	10.202	25.637	49.724	86.876	89.032	0.042
0.664	22.974	82.974	4.71E-17	16.589	52.641	90.000	0.286	18.978	44.485	64.471	90.000	1.197	10.333	25.655	49.675	85.688	90.000	0.042
0.665	22.909	82.909	4.71E-17	16.425	52.425	90.000	0.270	18.028	44.297	64.790	90.000	1.143	10.442	25.561	49.565	85.612	89.955	0.046
0.666	22.843	82.843	3.06E-16	16.312	52.312	90.000	0.263	18.384	44.188	64.422	90.000	1.110	10.537	25.589	49.429	85.415	90.000	0.060
0.667	22.778	82.778	4.71E-17	16.216	52.210	90.000	0.258	17.932	44.135	64.664	90.000	1.105	10.682	25.314	49.334	85.543	89.811	0.057
0.668	22.713	82.713	1.18E-16	16.046	52.030	90.000	0.248	18.110	44.078	64.510	90.000	1.087	10.705	25.271	49.218	85.232	90.000	0.062
0.669	22.648	82.648	2.27E-15	15.890	51.913	90.000	0.240	18.198	43.993	64.348	90.000	1.066	10.787	25.112	49.080	85.162	90.000	0.068
0.670	22.582	82.582	4.71E-17	15.786	51.777	90.000	0.232	16.339	43.262	65.189	90.000	1.154	10.979	24.995	48.988	85.095	89.924	0.072
0.671	22.517	82.517	2.24E-15	15.678	51.677	90.000	0.225	17.641	43.134	64.624	90.000	1.087	11.071	24.828	48.949	85.056	89.820	0.079
0.672	22.451	82.451	4.71E-17	15.576	51.574	90.000	0.219	17.513	43.136	64.207	90.000	1.068	11.241	24.765	48.774	84.845	89.931	0.081
0.673	22.386	82.386	1.41E-16	15.410	51.384	90.000	0.211	17.133	43.052	64.428	90.000	1.049	11.349	24.654	48.659	84.702	89.959	0.086
0.674	22.320	82.320	8.39E-12	15.325	51.313	90.000	0.205	17.307	43.023	64.293	90.000	1.019	11.335	24.495	48.652	84.511	90.000	0.094
0.675	22.254	82.254	1.09E-14	15.169	51.149	89.981	0.195	17.449	42.970	64.120	90.000	0.995	11.376	24.513	48.458	84.415	90.000	0.100
0.676	22.189	82.189	4.71E-17	15.043	51.045	90.000	0.187	15.967	42.313	64.867	90.000	1.036	11.404	24.479	48.311	84.307	90.000	0.106
0.677	22.123	82.123	4.71E-17	14.864	50.879	90.000	0.177	17.198	42.619	64.030	90.000	0.970	11.416	24.351	48.268	84.203	89.962	0.114
0.678	22.057	82.057	2.27E-15	14.754	50.754	90.000	0.169	14.931	41.623	65.236	90.000	1.042	11.437	24.354	48.072	84.078	90.000	0.121
0.679	21.991	81.991	4.71E-17	14.704	50.740	90.000	0.170	17.101	42.113	64.030	90.000	1.010	12.048	23.944	47.962	84.055	89.925	0.117
0.680	21.925	81.925	2.24E-15	14.539	50.517	90.000	0.157	16.705	42.179	64.015	90.000	0.966	12.143	23.845	47.850	83.857	90.000	0.121
0.681	21.859	81.859	4.71E-17	14.357	50.345	90.000	0.145	16.799	42.030	63.905	90.000	0.939	12.027	23.894	47.849	83.639	90.000	0.137
0.682	21.793	81.793	1.18E-16	14.317	50.183	90.000	0.150	16.643	41.864	63.773	90.000	0.927	11.929	23.679	47.828	83.533	90.000	0.141
0.683	21.727	81.727	4.71E-17	14.151	50.150	89.999	0.132	16.639	41.680	63.673	90.000	0.926	12.340	23.578	47.520	83.490	90.000	0.139
0.684	21.661	81.661	4.71E-17	14.006	50.007	90.000	0.125	16.740	41.913	63.601	89.806	0.937	12.292	23.548	47.433	83.350	90.000	0.148
0.685	21.594	81.594	2.36E-17	13.814	49.819	90.000	0.113	16.435	41.411	63.581	90.000	0.910	12.680	23.309	47.254	83.280	89.987	0.147
0.686	21.528	81.528	4.71E-17	13.710	49.722	90.000	0.106	15.869	40.737	63.480	90.000	0.942	12.874	23.120	47.155	83.219	89.926	0.152
0.687	21.462	81.462	2.27E-15	13.590	49.589	90.000	0.099	16.136	41.029	63.503	90.000	0.873	12.835	23.033	47.161	82.957	90.000	0.161
0.688	21.395	81.395	2.36E-17	13.417	49.417	90.000	0.088	15.156	40.557	63.984	90.000	0.897	12.651	23.210	46.918	82.881	90.000	0.169
0.689	21.329	81.329	2.24E-15	13.275	49.275	90.000	0.079	15.875	40.734	63.407	90.000	0.853	12.831	23.178	46.685	82.798	90.000	0.177
0.690	21.262	81.262	2.36E-17	13.135	49.135	90.000	0.070	15.923	40.493	63.439	90.000	0.874	12.784	23.078	46.657	82.647	90.000	0.182
0.691	21.195	81.195	8.91E-15	13.027	49.017	89.991	0.063	15.309	40.245	63.537	90.000	0.842	12.774	22.945	46.664	82.465	90.000	0.189
0.692	21.129	81.129	1.18E-16	12.916	48.912	90.000	0.057	15.526	40.245	63.269	90.000	0.838	13.468	22.413	46.525	82.387	90.000	0.182
0.693	21.062	81.062	1.54E-08	12.789	48.790	90.000	0.049	15.526	39.894	63.447	90.000	0.854	13.414	22.338	46.456	82.327	89.926	0.191
0.694	20.995	80.995	4.71E-17	12.591	48.612	90.000	0.039	13.852	39.358	64.081	90.000	0.867	13.398	22.538	46.113	82.202	90.000	0.196
0.695	20.928	80.928	1.18E-16	12.477	48.477	90.000	0.033	15.321	39.817	63.096	90.000	0.786	13.341	22.444	46.092	82.047	89.994	0.203
0.696	20.861	80.861	2.27E-15	12.305	48.312	90.000	0.020	13.904	39.088	63.872	90.000	0.851	13.921	21.893	46.080	81.894	90.000	0.201
0.697	20.794	80.794	4.71E-17	12.179	48.180	90.000	0.012	15.042	39.373	63.122	90.000	0.794	13.870	21.787	46.014	81.767	90.000	0.209
0.698	20.727	80.727	2.27E-15	12.009	48.018	90.000	0.002	14.821	39.256	63.010	90.000	0.764	14.094	21.625	45.904	81.625	90.000	0.211
0.699	20.660	80.660	4.71E-17	11.987	47.930	89.951	0.000	14.725	38.977	63.125	90.000	0.788	14.072	21.552	45.816	81.493	90.000	0.218
0.700	20.593	80.593	4.71E-17	11.978	47.884	89.919	0.000	14.812	38.910	62.666	90.000	0.753	14.108	21.660	45.557	81.405	90.000	0.223
0.701	20.525	80.525	2.36E-17	11.967	47.820	89.874	0.000	14.732	38.816	62.670	90.000	0.722	14.092	21.558	45.464	81.284	90.000	0.231
0.702	20.458	80.458	4.71E-17	11.950	47.729	89.810	0.000	14.735	38.797	62.638	90.000	0.727	14.379	21.213	45.495	81.091	90.000	0.232
0.703	20.391	80.391	4.71E-17	11.930	47.610	89.726	0.000	13.818	38.256	63.011	90.000	0.742	14.704	21.162	45.159	81.049	90.000	0.235
0.704	20.323	80.323	1.88E-16	11.906	47.464	89.623	0.000	14.044	38.149	62.635	90.000	0.721	15.044	20.952	44.947	80.952	90.000	0.235
0.705	20.256	80.256	2.27E-15	11.904	47.455	89.617	0.000	13.695	37.756	62.624	90.000	0.735	15.223	20.871	44.743	80.850	90.000	0.247
0.706	20.188	80.188	1.27E-05	11.886	47.335	89.533	0.000	14.319	38.128	62.417	90.000	0.682	15.292	20.651	44.747	80.684	90.000	0.245
0.707	20.120	80.120	2.24E-15	11.870	47.234	89.462	0.000	13.947	37.853	62.468	90.000	0.679	15.191	20.568	44.725	80.528	90.000	0.251
0.708	20.053	80.053	4.71E-17	11.855	47.124	89.384	0.000	14.234	37.862	62.199	90.000	0.669	15.126	20.570	44.638	80.377	90.000	0.257
0.709	19.985	79.985	4.71E-17	11.847	47.069	89.345	0.000	14.035	37.563	62.199	90.000	0.669	14.958	20.515	44.666	80.193	90.000	0.264
0.710	19.917	79.917	4.71E-17	11.837	46.995	89.293	0.000	13.859	37.317	62.192	90.000	0.663	14.901	20.454	44.581	80.062	90.000	0.270
0.711	19.849	79.849	4.71E-17	11.822	46.875	89.208	0.000	13.546	37.186	62.120	90.000	0.650	14.938	20.290	44.573	79.887	90.000	0.274
0.712	19.781	79.781	4.71E-17	11.807	46.755	89.123	0.000	13.804	37.201	61.917	90.000	0.617	14.881	20.326	44.623	79.626	90.000	0.284
0.713	19.713	79.713	0	11.800	46.691	89.077	0.000	13.544	36.897	61.866	90.000	0.620	15.729	19.651	44.277	79.650	90.000	0.276
0.714	19.645	79.645	2.27E-15	11.787	46.579	88.999	0.000	12.548	36.370	62.403	90.000	0.672	15.662	19.563	44.215	79.513	90.000	0.282
0.715	19.576	79.576	4.71E-17	11.777	46.477	88.926	0.000	13.542	36.694	61.665	90.000	0.587	16.037	19.976	43.607	79.467	90.000	0.287
0.716	19.508	79.508	2.22E-15	11.771	46.412	88.880	0.000	13.415	36.436	61.622	90.000	0.577	15.977	19.988	43.574	79.275	90.000	0.294
0.717	19.440	79.440	4.71E-17	11.759	46.292	88.794	0.000	13.267	36.483	61.568	90.000	0.601	15.845	19.825	43.620	79.107	90.000	0.297
0.718	19.371	79.371	6.45E-10	11.750	46.180	88.715	0.000	13.467	36.418	61.387	90.000	0.593	15.750	19.755	43.493	79.017	90.000	0.299
0.719	19.303	79.303	4.71E-17	11.745	46.115	88.669	0.000	13.264	36.098	61.377	90.000	0.546	15.713	19.592	43.478	78.864	90.000	0.303
0.720	19.234	79.234	9.42E-17	11.740	46.059	88.629	0.000	13.209	36.043	61.275	90.000	0.557	15.656	19.666	43.405	78.665	90.000	0.312

0.721	19.166	79.166	0	11.732	45.937	88.542	0.000	13.168	35.848	61.216	89.986	0.529	15.634	19.631	43.386	78.478	90.000	0.315
0.722	19.097	79.097	0	11.728	45.872	88.496	0.000	12.792	35.436	61.206	90.000	0.527	15.774	20.068	43.473	77.997	90.000	0.332
0.723	19.028	79.028	0	11.723	45.787	88.436	0.000	13.008	35.504	61.047	90.000	0.512	15.433	19.701	43.289	78.118	90.000	0.325
0.724	18.959	78.959	4.71E-17	11.716	45.656	88.342	0.000	12.924	35.262	60.936	90.000	0.517	15.632	19.904	43.265	77.779	90.000	0.335
0.725	18.890	78.890	4.93E-10	11.712	45.571	88.282	0.000	11.305	34.171	61.774	90.000	0.606	15.640	19.901	43.184	77.605	90.000	0.339
0.726	18.821	78.821	0.000193	11.708	45.458	88.201	0.000	13.257	35.164	60.457	90.000	0.561	15.634	19.933	43.128	77.404	90.000	0.343
0.727	18.752	78.752	2.22E-15	11.704	45.355	88.127	0.000	12.715	34.794	60.665	90.000	0.463	15.611	19.850	43.040	77.272	90.000	0.345
0.728	18.683	78.683	4.71E-17	11.702	45.279	88.073	0.000	12.681	34.692	60.631	89.996	0.460	14.982	19.978	42.544	77.519	90.000	0.343
0.729	18.614	78.614	2.83E-16	11.700	45.175	87.999	0.000	12.847	34.466	60.414	90.000	0.500	14.953	19.788	42.442	77.425	90.000	0.341
0.730	18.545	78.545	4.71E-17	11.699	45.071	87.925	0.000	10.403	33.486	61.352	90.000	0.643	14.945	19.777	42.365	77.256	90.000	0.344
0.731	18.475	78.475	4.71E-17	11.698	44.995	87.870	0.000	12.491	34.174	60.268	89.998	0.432	14.901	19.778	42.288	77.087	90.000	0.346
0.732	18.406	78.406	9.42E-17	11.698	44.929	87.823	0.000	12.459	34.113	60.291	90.000	0.420	14.872	19.656	42.402	76.825	90.000	0.350
0.733	18.336	78.336	4.71E-17	11.698	44.834	87.755	0.000	13.091	35.611	59.982	89.020	0.567	14.674	19.676	42.500	76.570	90.000	0.354
0.734	18.267	78.267	2.27E-15	11.700	44.681	87.646	0.000	12.325	33.614	60.042	90.000	0.420	14.257	19.198	42.736	76.448	90.000	0.350
0.735	18.197	78.197	4.71E-17	11.701	44.605	87.591	0.000	12.188	33.513	60.005	90.000	0.396	14.228	18.985	42.726	76.290	90.000	0.356
0.736	18.127	78.127	2.22E-15	11.703	44.519	87.530	0.000	12.171	33.212	59.807	90.000	0.388	14.215	18.986	42.701	76.091	90.000	0.352
0.737	18.057	78.057	0	11.708	44.375	87.427	0.000	12.171	33.212	59.807	90.000	0.385	14.176	19.029	42.619	75.912	90.000	0.354
0.738	17.988	77.988	2.36E-16	11.710	44.317	87.385	0.000	12.055	32.947	59.662	90.000	0.362	14.041	19.131	42.574	75.711	90.000	0.356
0.739	17.918	77.918	0	11.713	44.240	87.330	0.000	12.052	32.955	59.710	90.000	0.369	13.987	19.079	42.354	75.661	90.000	0.356
0.740	17.848	77.848	0	11.718	44.135	87.255	0.000	11.934	32.592	59.457	90.000	0.348	13.977	18.971	42.351	75.471	90.000	0.356
0.741	17.777	77.777	1.88E-16	11.726	44.000	87.158	0.000	11.978	32.610	59.412	90.000	0.334	14.284	18.806	42.125	75.373	90.000	0.354
0.742	17.707	77.707	1.41E-16	11.729	43.951	87.123	0.000	11.935	32.385	59.292	90.000	0.314	14.247	18.841	42.024	75.217	90.000	0.356
0.743	17.637	77.637	2.22E-15	11.739	43.796	87.012	0.000	11.709	32.106	59.311	90.000	0.319	14.286	18.722	42.002	75.024	90.000	0.354
0.744	17.567	77.567	0	11.742	43.767	86.992	0.000	11.750	31.963	59.157	90.000	0.302	14.271	18.694	41.887	74.879	90.000	0.353
0.745	17.496	77.496	2.22E-15	11.752	43.631	86.894	0.000	11.841	31.988	59.054	90.000	0.289	14.254	18.637	41.745	74.770	90.000	0.354
0.746	17.426	77.426	2.36E-16	11.763	43.514	86.810	0.000	11.797	31.821	58.956	90.000	0.280	14.476	18.719	41.435	74.664	90.000	0.351
0.747	17.355	77.355	0	11.772	43.417	86.740	0.000	11.700	31.495	58.864	90.000	0.274	14.387	18.788	41.299	74.524	90.000	0.352
0.748	17.284	77.284	4.71E-17	11.776	43.378	86.712	0.000	11.761	31.374	58.634	90.000	0.273	14.417	18.838	41.130	74.391	89.991	0.351
0.749	17.214	77.214	0	11.791	43.241	86.614	0.000	11.614	31.197	58.580	90.000	0.253	14.249	18.828	41.115	74.204	90.000	0.351
0.750	17.143	77.143	4.74E-10	11.803	43.133	86.537	0.000	11.659	31.011	58.490	90.000	0.233	14.156	18.875	41.093	73.994	90.000	0.354
0.751	17.072	77.072	0	11.814	43.044	86.474	0.000	11.618	30.967	58.446	90.000	0.233	14.152	18.876	40.906	73.905	89.984	0.355
0.752	17.001	77.001	2.27E-15	11.825	42.956	86.410	0.000	11.479	30.724	58.329	90.000	0.236	14.142	19.018	40.675	73.754	90.000	0.361
0.753	16.930	76.930	8.64E-08	11.840	42.837	86.325	0.000	11.586	30.550	58.196	90.000	0.204	14.091	19.106	40.667	73.519	90.000	0.365
0.754	16.859	76.859	2.22E-15	11.854	42.738	86.255	0.000	11.355	30.129	58.215	90.000	0.215	13.563	19.139	40.713	73.380	89.994	0.351
0.755	16.787	76.787	6.69E-08	11.866	42.659	86.198	0.000	11.510	30.247	58.077	90.000	0.194	12.032	19.771	41.948	72.420	90.000	0.347
0.756	16.716	76.716	0	11.878	42.580	86.141	0.000	11.543	30.020	57.842	90.000	0.179	12.063	19.802	41.891	72.214	90.000	0.350
0.757	16.645	76.644	5.07E-07	11.898	42.450	86.048	0.000	11.541	29.893	57.810	90.000	0.167	11.701	19.113	41.612	72.484	90.000	0.342
0.758	16.573	76.573	0	11.908	42.391	86.006	0.000	11.481	29.600	57.675	90.000	0.156	11.629	18.976	41.566	72.339	90.000	0.339
0.759	16.501	76.501	0	11.937	42.221	85.884	0.000	11.452	29.371	57.585	90.000	0.146	11.410	18.982	41.526	72.177	90.000	0.337
0.760	16.430	76.430	1.41E-16	11.941	42.201	85.870	0.000	11.499	29.305	57.469	90.000	0.133	11.411	18.920	41.423	72.019	90.000	0.338
0.761	16.358	76.358	2.22E-15	11.970	42.040	85.755	0.000	11.471	29.028	57.337	90.000	0.138	11.441	18.922	41.359	71.833	90.000	0.328
0.762	16.286	76.286	4.71E-17	11.990	41.940	85.683	0.000	11.503	29.001	57.273	90.000	0.114	11.568	18.862	41.336	71.604	90.000	0.322
0.763	16.214	76.214	2.22E-15	11.996	41.909	85.662	0.000	11.503	28.725	57.113	90.000	0.098	11.645	18.725	41.191	71.501	90.000	0.322
0.764	16.142	76.142	0	12.022	41.778	85.568	0.000	11.498	28.545	56.996	90.000	0.090	12.041	18.300	41.252	71.278	90.000	0.334
0.765	16.070	76.070	4.71E-17	12.037	41.707	85.517	0.000	11.492	28.344	56.915	90.000	0.083	11.896	18.413	41.109	71.134	90.000	0.332
0.766	15.998	75.998	4.71E-17	12.076	41.525	85.387	0.000	11.488	28.174	56.777	90.000	0.075	10.920	18.924	41.079	70.948	90.000	0.309
0.767	15.926	75.926	9.42E-17	12.083	41.494	85.365	0.000	11.568	28.091	56.768	90.000	0.071	10.891	18.913	40.981	70.788	90.000	0.309
0.768	15.853	75.853	0	12.106	41.392	85.293	0.000	11.413	27.299	56.837	90.000	0.098	10.797	18.976	40.910	70.594	90.000	0.308
0.769	15.781	75.781	0	12.147	41.219	85.169	0.000	11.550	27.656	56.457	90.000	0.042	10.722	19.009	40.756	70.468	90.000	0.309
0.770	15.708	75.708	2.22E-15	12.157	41.178	85.140	0.000	11.573	27.543	56.372	89.973	0.034	10.417	19.080	40.708	70.296	90.000	0.302
0.771	15.636	75.636	0	12.192	41.034	85.037	0.000	11.580	27.210	56.303	90.000	0.029	10.426	19.038	40.738	70.060	90.000	0.303
0.772	15.563	75.563	2.22E-15	12.224	40.910	84.949	0.000	11.653	27.015	56.117	90.000	0.007	10.409	18.990	40.652	69.889	90.000	0.302
0.773	15.490	75.490	0	12.229	40.889	84.935	0.000	11.658	26.908	55.973	89.948	0.000	10.413	19.016	40.561	69.703	90.000	0.302
0.774	15.417	75.417	0	12.262	40.765	84.846	0.000	11.649	26.886	55.907	89.907	0.000	7.102	20.729	43.281	67.424	90.000	0.260
0.775	15.344	75.344	0	12.288	40.672	84.780	0.000	11.636	26.863	55.829	89.858	0.000	7.122	20.695	43.131	67.314	90.000	0.259
0.776	15.271	75.271	1.61E-07	12.337	40.495	84.655	0.000	11.615	26.820	55.696	89.776	0.000	6.664	20.491	42.916	67.355	90.000	0.244
0.777	15.198	75.198	4.71E-17	12.346	40.464	84.633	0.000	11.598	26.789	55.597	89.713	0.000	6.818	20.533	42.715	67.224	90.000	0.237
0.778	15.125	75.125	0	12.379	40.349	84.551	0.000	11.581	26.763	55.508	89.658	0.000	6.998	20.734	42.690	66.898	90.000	0.245
0.779	15.049	75.052	0.000125	12.426	40.191	84.440	0.000	11.555	26.728	55.374	89.573	0.000	7.131	20.568	42.048	67.169	90.000	0.235
0.780	14.978	74.978	4.71E-17	12.449	40.118	84.388	0.000	11.535	26.698	55.273	89.511	0.000	7.006	20.367	41.901	67.124	90.000	0.227
0.781	14.904	74.904	2.22E-15	12.492	39.980	84.291	0.000	11.507	26.663	55.139	89.427	0.000	6.389	22.433	41.827	66.185	90.000	0.215
0.782	14.830	74.830	0	12.512	39.917	84.246	0.000	11.482	26.635	55.026	89.357	0.000	6.233	22.252	41.684	66.142	90.000	0.210
0.783	14.757	74.757	4.71E-17	12.556	39.779	84.149	0.000	11.450	26.603	54.891	89.272	0.000	6.172	22.139	41.515	66.073	90.000	0.206
0.784	14.683	74.683	0	12.570	39.736	84.119	0.000	11.416	26.573	54.756	89.187	0.000	5.902	21.985	41.362	66.032	90.000	0.203
0.785	14.609	74.609	0	12.631	39.555	83.991	0.000	11.398	26.558	54.688	89.144	0.000	5.899	21.924	41.264	65.881	90.000	0.195
0.786	14.535	74.535	0	12.646	39.512	83.961	0.000	11.377	26.542	54.608	89.094	0.000	5.938	21.941	41.201	65.669	90.000	0.187
0.787	14.461	74.461	0	12.698	39.362	83.855	0.000	11.349	26.522	54.506	89.030	0.000	5.987	21.975	41.031	65.524	90.000	0.185
0.788	14.387	74.387	0	12.744	39.233	83.765	0.000	11.313	26.499	54.381	88.951	0.000	6.289	22.170	40.941	65.226	90.000	0.190
0.789	14.312	74.312	0	12.759	39.189	83.734	0.000	11.255	26.467	54.186	88.829	0.000	6.122	22.021	40.832	65.138	90.000	0.183
0.790	14.238	74.238	2.22E-15	12.803	39.070	83.651	0.000	11.222	26.450	54.083	88.765	0.000	6.125	21.976	40.682	65.017	90.000	0.180
0.791	14.163	74.163	0	12.871	38.885	83.522	0.000	11.191	26.441	53.991	88.706	0.000	6.151	21.788	40.588	64.910	90.000	0.182
0.792	14.089	74.089	1.58E-11	12.892	38.831	83.484	0.000	11.157	26.425	53.887	88.641	0.000	5.388	21.975	40.148	64.983	90.000	0.155
0.793	14.014	74.014	0	12.938	38.710	83.400	0.000	11.121	26.412	53.783	88.576	0.000	5.351	22.349	39.955	64.721	90.000	0.150
0.794	13.939	73.939	0	12.990	38.578	83.308	0.000	11.058	26.393	53.609	88.467	0.000	5.313	22.290	39.844	64.580	90.000	0.147
0.795	13.864	73.864	5.88E-10	13.007	38.534	83.277	0.000	11.023	26.385	53.516	88.408	0.000	5.088	22.223	39.655	64.515	90.000	0.141
0.796	13.789	73.789	0	13.047	38.435	83.208	0.000	11.000	26.381	53.457	88.371	0.000	5.081	22.126	39.314	64.547	90.000	0.138
0.797	13.714	73.714	0	13.105	38.291	83.108	0.000	10.955	26.368	53.340	88.299	0.000	5.041	21.755	39.193	64.540	90.000	0.136
0.798	13.639	73.639	0	13.142	38.201	83.046	0.000	10.907	26.364	53.223	88.224	0.000	4.828	21.634	39.099	64.426	90.000	0.128
0.799	13.563	73.563	2.22E-15	13.189	38.090	82.969	0.000	10.817	26.355	53.011	88.091	0.000	4.784	21.549	38.942	64.325	90.000	0.125
0.800	13.479	73.491	0.000348	13.255	37.933	82.861	0.000	10.781	26.351	52.928	88.040	0.000	4.792	21.488	38.809	64.192	90.000	0.124
0.801	13.412	73.412	2.22E-15	13.309	37.809	82.776	0.000	10.754	26.351	52.869	88.002	0.000	4.463	21.424	38.520	64.198	90.000	0.115
0.802	13.337	73.337	0	13.368	37.673	82.682	0.000	10.678	26.349	52.702	87.897	0.000	4.163	21.522	38.338	64.060	90.000	0.112
0.803	13.261	73.261	4.71E-17	13.418	37.559	82.604	0.000	10.638	26.349	52.618	87.845	0.000	4.191	21.701	38.194	63.832	90.000	0.106
0.804	13.185	73.185	4.46E-07	13.429	37.536	82.589	0.000	10.557	26.352	52.451	87.740	0.000	4.230	21.778	38.077	63.639	89.989	0.103
0.805	13.109	73.109	0	13.496	37.388	82.487	0.000	10.514	26.354	52.366	87.688	0.000	4.617	22.435	38.012	63.110	90.000	0.101
0.806	13.033	73.033	1.34E-11	13.538	37.296	82.425	0.000	10.453	26.359	52.246	87.612	0.000	4.580	22.217	37.863	63.056	90.000	0.100
0.807	12.957	72.957	0	13.613	37.135	82.315	0.000	10.383	26.366	52.113	87.528	0.000	4.622	22.227	37.723	62.893	90.000	0.097
0.808	12.880	72.880	2.22E-15	13.651	37.053	82.260	0.000	10.297	26.376	51.955	87.430	0.000	4.596	22.139	37.563	62.789	90.000	0.095
0.809	12.804	72.804	0	13.711	36.926	82.173	0.000	10.277	26.379	51.918	87.407	0.000	4.590	22.153	37.439	62.616	90.000	0.093
0.810	12.728	72.728	2.22E-15	13.790	36.762	82.062	0.000	10.194	26.391	51.771	87.315	0.000	4.621	22.368	37.302	62.361	90.000	0.089

0.811	12.651	72.651	0	13.859	36.621	81.967	0.000	10.131	26.402	51.661	87.246	0.000	3.821	23.149	36.587	62.353	90.000	0.083
0.812	12.574	72.574	0	13.912	36.514	81.896	0.000	10.036	26.420	51.500	87.147	0.000	3.833	23.179	36.566	62.064	89.999	0.067
0.813	12.497	72.497	0	13.953	36.431	81.840	0.000	9.930	26.441	51.327	87.039	0.000	3.002	23.706	36.357	61.767	90.000	0.044
0.814	12.420	72.420	1.88E-16	13.995	36.348	81.784	0.000	9.875	26.454	51.240	86.985	0.000	2.790	23.645	36.179	61.670	90.000	0.042
0.815	12.343	72.343	0	14.043	36.253	81.720	0.000	9.796	26.473	51.115	86.907	0.000	1.882	24.216	36.028	61.290	90.000	0.031
0.816	12.266	72.266	0	14.111	36.121	81.633	0.000	9.755	26.483	51.052	86.868	0.000	1.870	24.333	35.628	61.248	90.000	0.019
0.817	12.189	72.189	2.22E-15	14.217	35.915	81.496	0.000	9.655	26.508	50.901	86.775	0.000	0.799	24.963	35.281	60.951	90.000	0.011
0.818	12.111	72.111	1.88E-16	14.275	35.806	81.424	0.000	9.570	26.531	50.775	86.697	0.000	0.787	24.863	35.139	60.846	89.992	0.001
0.819	12.034	72.034	2.22E-15	14.314	35.733	81.376	0.000	9.446	26.566	50.597	86.587	0.000	0.789	24.827	35.087	60.723	89.919	0.000
0.820	11.956	71.956	0	14.406	35.561	81.263	0.000	9.411	26.576	50.546	86.556	0.000	0.799	24.793	35.036	60.597	89.848	0.000
0.821	11.878	71.878	0	14.426	35.524	81.238	0.000	9.262	26.621	50.341	86.430	0.000	0.821	24.757	34.989	60.470	89.775	0.000
0.822	11.800	71.800	0	14.554	35.288	81.084	0.000	9.215	26.637	50.276	86.390	0.000	0.806	24.721	34.938	60.344	89.704	0.001
0.823	11.722	71.722	9.42E-17	14.582	35.238	81.052	0.000	9.069	26.683	50.082	86.271	0.000	1.148	24.645	34.933	60.208	89.626	0.001
0.824	11.644	71.644	0	14.673	35.075	80.946	0.000	8.989	26.709	49.978	86.207	0.000	1.061	24.626	34.879	60.086	89.546	0.001
0.825	11.566	71.566	0	14.701	35.025	80.913	0.000	8.907	26.737	49.874	86.144	0.000	1.086	24.573	34.826	59.961	89.482	0.001
0.826	11.488	71.488	2.22E-15	14.808	34.835	80.791	0.000	8.749	26.791	49.676	86.024	0.000	1.335	24.505	34.817	59.834	89.395	0.001
0.827	11.409	71.409	0	14.852	34.758	80.742	0.000	8.662	26.821	49.571	85.959	0.000	1.077	24.514	34.750	59.706	89.321	0.002
0.828	11.330	71.330	2.22E-15	14.941	34.604	80.643	0.000	8.596	26.845	49.491	85.911	0.000	1.527	24.416	34.739	59.578	89.242	0.001
0.829	11.252	71.252	0	15.008	34.488	80.569	0.000	8.495	26.881	49.371	85.839	0.000	1.612	24.345	34.717	59.441	89.176	0.001
0.830	11.173	71.173	0	15.077	34.371	80.495	0.000	8.286	26.958	49.130	85.693	0.000	1.740	24.269	34.721	59.304	89.093	0.001
0.831	11.094	71.094	9.42E-17	15.154	34.240	80.412	0.000	8.165	27.003	48.994	85.612	0.000	1.825	24.215	34.691	59.176	89.016	0.001
0.832	11.015	71.015	0	15.240	34.095	80.321	0.000	8.054	27.045	48.872	85.538	0.000	2.040	24.132	34.676	59.046	88.937	0.001
0.833	10.936	70.936	1.08E-13	15.312	33.976	80.247	0.000	8.004	27.064	48.818	85.506	0.000	2.112	24.060	34.667	58.910	88.861	0.001
0.834	10.856	70.856	0	15.459	33.735	80.097	0.000	7.771	27.153	48.570	85.358	0.000	2.303	23.945	34.681	58.771	88.787	0.001
0.835	10.777	70.777	2.22E-15	15.534	33.613	80.022	0.000	7.718	27.174	48.515	85.325	0.000	2.420	23.883	34.653	58.641	88.708	0.000
0.836	10.697	70.697	0	15.559	33.572	79.997	0.000	7.610	27.216	48.404	85.260	0.000	2.434	23.818	34.594	58.513	88.651	0.002
0.837	10.617	70.617	9.43E-14	15.644	33.436	79.913	0.000	7.415	27.292	48.208	85.144	0.000	2.547	23.762	34.618	58.377	88.546	0.002
0.838	10.537	70.537	0	15.765	33.243	79.795	0.000	7.329	27.325	48.124	85.094	0.000	2.438	23.689	34.465	58.259	88.543	0.005
0.839	10.457	70.457	0	15.871	33.075	79.694	0.000	7.092	27.418	47.897	84.961	0.000	2.988	23.518	34.641	58.101	88.395	0.001
0.840	10.377	70.377	0	15.971	32.920	79.601	0.000	6.970	27.466	47.783	84.895	0.000	3.123	23.423	34.659	57.960	88.309	0.001
0.841	10.297	70.297	0	15.989	32.892	79.585	0.000	6.860	27.509	47.682	84.836	0.000	3.339	23.291	34.684	57.819	88.230	0.000
0.842	10.217	70.217	0	16.081	32.750	79.500	0.000	6.634	27.598	47.480	84.719	0.000	3.321	23.254	34.654	57.690	88.147	0.002
0.843	10.136	70.136	0	16.232	32.519	79.364	0.000	6.534	27.637	47.392	84.668	0.000	3.659	23.062	34.715	57.540	88.069	0.000
0.844	10.055	70.055	2.22E-15	16.289	32.431	79.313	0.000	6.310	27.724	47.202	84.559	0.000	3.776	22.966	34.719	57.402	87.987	0.001
0.845	9.975	69.975	0	16.407	32.255	79.211	0.000	6.167	27.779	47.083	84.491	0.000	3.980	22.818	34.748	57.258	87.909	0.001
0.846	9.894	69.894	2.22E-15	16.496	32.121	79.134	0.000	6.020	27.835	46.964	84.423	0.000	3.953	22.789	34.723	57.129	87.822	0.003
0.847	9.812	69.812	9.42E-17	16.587	31.986	79.056	0.000	5.731	27.944	46.739	84.295	0.000	4.078	22.680	34.733	56.989	87.742	0.003
0.848	9.731	69.731	0	16.690	31.834	78.971	0.000	5.611	27.989	46.648	84.244	0.000	4.515	22.417	34.837	56.826	87.662	0.000
0.849	9.650	69.650	2.60E-15	16.785	31.696	78.893	0.000	5.405	28.066	46.495	84.159	0.000	4.443	22.403	34.800	56.700	87.575	0.003
0.850	9.568	69.568	2.36E-16	16.881	31.557	78.815	0.000	5.121	28.168	46.295	84.047	0.000	4.683	22.227	34.851	56.551	87.492	0.003
0.851	9.487	69.487	0	17.057	31.305	78.677	0.000	4.914	28.241	46.155	83.969	0.000	5.063	21.962	34.946	56.394	87.412	0.000
0.852	9.405	69.405	1.75E-05	17.135	31.193	78.616	0.000	4.597	28.349	45.950	83.857	0.000	5.252	21.823	34.974	56.251	87.324	0.001
0.853	9.323	69.323	0	17.238	31.047	78.538	0.000	4.494	28.383	45.887	83.822	0.000	5.216	21.728	34.867	56.119	87.309	0.005
0.854	9.241	69.241	0	17.390	30.834	78.425	0.000	3.998	28.541	45.598	83.666	0.000	5.263	21.703	34.959	55.974	87.156	0.006
0.855	9.159	69.159	2.22E-15	17.510	30.667	78.337	0.000	3.692	28.631	45.435	83.578	0.000	5.220	21.679	34.934	55.842	87.067	0.009
0.856	9.076	69.076	0	17.596	30.548	78.276	0.000	3.495	28.687	45.336	83.526	0.000	6.105	21.089	35.189	55.636	86.993	0.001
0.857	8.994	68.994	2.22E-15	17.696	30.411	78.206	0.000	3.213	28.763	45.204	83.456	0.000	6.098	21.040	35.176	55.504	86.903	0.003
0.858	8.911	68.911	0	17.837	30.220	78.109	0.000	2.690	28.889	44.986	83.341	0.000	6.531	20.709	35.294	55.332	86.821	0.000
0.859	8.828	68.828	0	18.063	29.916	77.959	0.000	2.252	28.980	44.833	83.261	0.000	6.584	20.623	35.296	55.196	86.731	0.003
0.860	8.745	68.745	0	18.131	29.824	77.915	0.000	1.973	29.030	44.748	83.217	0.000	6.967	20.304	35.410	55.024	86.648	0.001
0.861	8.662	68.662	0	18.343	29.545	77.781	0.000	1.123	29.145	44.558	83.120	0.000	6.842	20.338	35.366	54.896	86.556	0.006
0.862	8.579	68.579	0	18.387	29.487	77.755	0.000	0.000	29.188	44.423	83.027	0.010	7.461	19.876	35.506	54.727	86.470	0.001
0.863	8.493	68.496	6.25E-05	18.520	29.314	77.675	0.000	0.013	29.197	44.277	82.922	0.030	7.748	19.583	35.609	54.545	86.394	0.001
0.864	8.412	68.412	2.22E-15	18.719	29.056	77.558	0.000	0.006	29.195	44.181	82.846	0.045	8.035	19.331	35.675	54.388	86.303	0.001
0.865	8.328	68.328	0	18.895	28.830	77.460	0.000	0.000	29.151	44.101	82.741	0.068	8.153	19.221	35.666	54.265	86.203	0.004
0.866	8.245	68.245	2.22E-15	19.045	28.641	77.379	0.000	0.000	29.201	43.913	82.632	0.088	8.117	19.152	35.710	54.095	86.118	0.008
0.867	8.161	68.161	1.01E-07	19.201	28.445	77.298	0.000	0.203	29.196	43.820	82.553	0.103	8.560	18.759	35.826	53.918	86.031	0.006
0.868	8.076	68.076	4.71E-17	19.363	28.244	77.217	0.000	0.000	29.199	43.648	82.418	0.129	9.170	18.294	35.884	53.787	85.931	0.004
0.869	7.992	67.992	3.20E-07	19.669	27.867	77.072	0.000	0.000	29.198	43.555	82.342	0.145	9.262	18.261	35.778	53.715	85.821	0.009
0.870	7.908	67.908	0	19.729	27.794	77.045	0.000	0.012	29.203	43.465	82.273	0.161	10.187	17.272	36.206	53.368	85.769	0.000
0.871	7.823	67.823	0	20.092	27.356	76.890	0.000	0.068	29.207	43.328	82.163	0.179	10.692	16.779	36.304	53.194	85.679	0.000
0.872	7.738	67.738	1.41E-16	20.184	27.247	76.853	0.000	0.433	29.204	43.197	82.055	0.202	11.014	16.493	36.291	53.076	85.577	0.003
0.873	7.653	67.653	2.22E-15	20.451	26.932	76.753	0.000	0.005	29.218	43.080	81.966	0.218	11.116	16.446	36.178	53.011	85.464	0.009
0.874	7.568	67.568	0	20.690	26.655	76.670	0.000	0.000	29.225	42.954	81.867	0.238	11.217	16.391	36.076	52.939	85.352	0.014
0.875	7.483	67.483	4.74E-09	21.211	26.061	76.514	0.000	0.406	29.224	42.834	81.767	0.258	11.111	16.391	36.112	52.767	85.263	0.020
0.876	7.397	67.397	1.79E-15	21.280	25.983	76.495	0.000	0.838	29.134	42.796	81.651	0.286	12.019	15.664	36.038	52.712	85.144	0.020
0.877	7.312	67.312	0	21.850	25.354	76.366	0.000	0.000	29.254	42.528	81.529	0.303	12.046	15.213	36.521	52.251	85.113	0.022
0.878	7.226	67.226	0	22.228	24.946	76.301	0.000	0.133	29.268	42.375	81.406	0.327	11.941	15.250	36.520	52.106	85.015	0.028
0.879	7.140	67.140	0	23.191	23.940	76.208	0.000	0.000	29.206	42.389	81.337	0.341	13.641	13.641	36.469	52.021	84.911	0.031
0.880	7.054	67.054	0	23.583	23.585	76.070	0.008	0.000	29.272	42.215	81.273	0.355	13.239	14.229	36.194	52.066	84.766	0.037
0.881	6.967	66.967	0	23.473	23.504	76.009	0.018	0.005	29.298	41.983	81.093	0.387	13.238	14.345	35.984	52.062	84.638	0.044
0.882	6.881	66.881	2.22E-15	23.443	23.597	75.844	0.027	0.000	29.310	41.950	81.073	0.394	13.293	14.351	35.727	52.047	84.561	0.052
0.883	6.794	66.794	0	23.666	23.702	75.569	0.036	0.074	29.340	41.783	80.934	0.417	13.391	14.426	35.574	52.046	84.384	0.056
0.884	6.707	66.707	3.61E-10	23.712	23.712	75.407	0.045	0.027	29.343	41.663	80.850	0.434	13.369	14.437	35.521	51.938	84.277	0.062
0.885	6.620	66.620	0	23.738	23.738	75.247	0.054	0.019	29.284	41.620	80.744	0.455	13.387	14.621	35.214	51.991	84.136	0.068
0.886	6.533	66.533	0	23.638	23.718	75.156	0.063	0.000	29.365	41.390	80.621	0.477	14.018	14.018	35.141	51.899	84.025	0.073
0.887	6.446	66.446	0	23.731	23.842	74.926	0.071	0.000	29.399	41.266	80.540	0.492	13.916	14.075	35.126	51.768	83.922	0.079
0.888	6.358	66.358	0	23.548	24.074	74.764	0.079	0.000	29.459	41.128	80.402	0.515	13.927	14.053	35.071	51.660	83.816	0.084
0.889	6.270	66.270	0	23.746	23.914	74.609	0.087	0.000	36.199	40.923	76.560	0.521	13.250	14.901	34.778	51.695	83.677	0.090
0.890	6.182	66.182	0	23.726	23.974	74.454	0.094	0.000	36.736	40.367	76.415	0.516	13.257	14.896	34.714	51.594	83.567	0.096
0.891	6.094	66.094	2.22E-15	23.846	23.890	74.297	0.101	0.046	36.921	40.177	76.296	0.521	13.173	14.871	34.775	51.416	83.472	0.102
0.892	6.006	66.006	0	23.841	23.929	74.143	0.109	0.000	37.047	40.028	76.148	0.529	14.046	14.046	34.696	51.332	83.357	0.106
0.893	5.918	65.918	1.64E-07	23.901	23.901	73.989	0.116	2.206	38.662	38.662	75.829	0.580	13.831	13.932	35.019	50.991	83.292	0.113
0.894	5.829	65.829	4.71E-17	23.915	23.915	73.837	0.122	0.000	36.781	39.973	75.998	0.554	13.828	13.928	34.966	50.884	83.181	0.118
0.895	5.740	65.740	4.71E-17	23.927	23.929	73.685	0.129	0.042	37.852	39.143	75.633	0.545	13.807	13.922	34.938	50.761	83.073	0.124
0.896	5.651	65.651	0	23.940	23.943	73.519	0.136	0.000	36.517	40.415	75.496	0.575	13.612	13.694	35.009	50.808	82.870	0.139
0.897	5.562	65.562	0	23.920	23.930	73.406	0.142	0.281	38.478	38.478	75.366	0.556	13.611	13.707	35.312	50.244	82.904	0.137
0.898	5.472	65.472	3.40E-14	23.962	23.963	73.219	0.148	1.206	38.142	38.846	75.145	0.569	13.608	13.710	35.253	50.142	82.790	0.143
0.899	5.383	65.383	4.71E-17	23.960	23.981	73.086	0.153	0.477	38.438	38.438	75.007	0.573	13.468	13.810	35.242	50.010	82.681	0.149
0.900	5.293	65.293	2.22E-15	23.772	24.187	72.922	0.160	0.687	38.190	38.667	74.867	0.579	13.434	13.655	35.418	49.757	82.591	0.156

0.901	5.203	65.203	0	23.927	24.043	72.777	0.165	0.186	38.384	38.387	74.666	0.586	13.596	13.596	35.107	49.705	82.563	0.168
0.902	5.113	65.113	2.22E-15	23.987	23.992	72.646	0.170	0.158	38.357	38.362	74.494	0.592	13.587	13.587	35.092	49.757	82.309	0.168
0.903	5.022	65.022	4.71E-17	23.979	23.980	72.512	0.175	0.097	38.334	38.360	74.417	0.594	13.547	13.547	35.058	49.682	82.176	0.175
0.904	4.931	64.931	0	23.829	24.166	72.355	0.180	0.498	38.327	38.327	74.254	0.600	13.644	13.697	34.886	49.546	82.095	0.176
0.905	4.841	64.841	0	23.679	24.324	72.209	0.185	0.000	37.657	38.872	74.012	0.610	13.644	13.644	34.942	49.411	81.952	0.184
0.906	4.750	64.750	0	23.974	24.026	72.056	0.189	0.024	38.260	38.260	73.930	0.609	13.654	13.763	34.685	49.399	81.851	0.185
0.907	4.658	64.658	0	23.990	24.010	71.928	0.193	0.000	38.022	38.450	73.807	0.612	13.773	13.773	34.417	49.460	81.700	0.190
0.908	4.567	64.567	0	23.835	24.155	71.790	0.198	0.009	37.454	38.937	73.612	0.619	14.332	14.733	32.691	50.290	81.419	0.176
0.909	4.475	64.475	2.22E-15	23.764	24.232	71.644	0.202	0.670	38.152	38.156	73.368	0.621	14.444	14.749	32.500	50.259	81.288	0.179
0.910	4.383	64.383	0	23.979	24.009	71.507	0.205	0.671	38.152	38.155	73.351	0.621	14.286	14.710	32.660	50.038	81.193	0.185
0.911	4.390	64.283	0.000536	23.989	23.989	71.354	0.209	0.294	38.085	38.085	73.103	0.624	14.211	14.796	32.593	49.940	81.075	0.190
0.912	4.199	64.199	2.36E-16	23.983	23.983	71.230	0.213	0.654	38.052	38.113	73.047	0.625	14.229	14.847	32.466	49.874	80.949	0.193
0.913	4.106	64.106	0	23.926	24.033	71.092	0.216	0.227	38.031	38.031	72.947	0.627	14.206	14.871	32.412	49.770	80.831	0.197
0.914	4.013	64.013	0	23.950	23.994	70.941	0.220	0.207	37.990	38.003	72.748	0.627	14.077	15.284	32.038	49.832	80.680	0.197
0.915	3.920	63.920	0	23.954	23.974	70.805	0.223	0.417	37.938	37.939	72.513	0.629	14.039	15.266	32.050	49.691	80.569	0.202
0.916	3.827	63.827	0	23.955	23.955	70.669	0.226	0.000	37.868	37.981	72.481	0.628	14.064	15.257	31.983	49.595	80.448	0.206
0.917	3.734	63.734	0	23.947	23.947	70.548	0.228	0.154	37.867	37.867	72.273	0.628	14.067	15.308	31.792	49.618	80.289	0.209
0.918	3.640	63.640	0	23.932	23.936	70.416	0.231	0.000	37.463	38.207	72.163	0.628	13.983	15.438	31.767	49.441	80.197	0.212
0.919	3.546	63.546	0	23.910	23.936	70.268	0.234	2.224	37.898	37.898	71.862	0.635	14.060	15.404	31.674	49.358	80.072	0.214
0.920	3.452	63.452	2.22E-15	23.911	23.911	70.148	0.236	0.804	37.784	37.784	71.919	0.627	14.159	15.367	31.561	49.287	79.944	0.217
0.921	3.358	63.358	0	23.753	24.051	70.013	0.238	0.568	37.333	38.139	71.794	0.626	14.176	15.349	31.515	49.180	79.823	0.220
0.922	3.263	63.263	1.94E-09	23.880	23.895	69.881	0.240	0.904	37.672	37.672	71.539	0.625	14.151	15.423	31.411	49.102	79.696	0.223
0.923	3.168	63.168	0	23.873	23.873	69.750	0.242	0.974	37.649	37.650	71.427	0.625	14.158	15.437	31.339	49.009	79.571	0.226
0.924	3.073	63.073	0	23.818	23.899	69.619	0.244	0.302	37.591	37.591	71.348	0.635	14.245	15.366	31.277	48.912	79.446	0.229
0.925	2.978	62.978	0	23.828	23.857	69.489	0.245	0.073	37.091	37.961	71.174	0.618	14.257	15.374	31.208	48.819	79.320	0.231
0.926	2.882	62.882	4.71E-17	23.783	23.869	69.359	0.247	1.729	37.542	37.542	70.976	0.618	14.331	15.316	31.146	48.723	79.195	0.234
0.927	2.786	62.786	0	23.805	23.808	69.216	0.249	0.487	37.454	37.454	70.944	0.613	14.329	15.336	31.081	48.628	79.068	0.236
0.928	2.690	62.690	7.07E-16	23.790	23.790	69.101	0.250	0.616	37.393	37.395	70.753	0.609	14.328	15.352	31.017	48.532	78.941	0.239
0.929	2.688	62.589	0.000304	23.696	23.848	68.972	0.251	1.005	37.207	37.539	70.640	0.607	14.270	15.425	30.950	48.438	78.813	0.242
0.930	2.497	62.497	0	23.657	23.848	68.844	0.252	0.092	37.316	37.316	70.570	0.604	14.466	15.233	30.906	48.337	78.686	0.244
0.931	2.400	62.400	2.22E-15	23.716	23.748	68.717	0.253	0.467	37.247	37.247	70.371	0.599	14.558	15.134	30.850	48.253	78.552	0.246
0.932	2.303	62.303	0	23.615	23.808	68.590	0.254	0.000	36.242	38.119	70.252	0.601	14.393	15.331	30.783	48.146	78.429	0.248
0.933	2.206	62.206	0	23.678	23.702	68.463	0.255	0.000	36.739	37.634	70.238	0.596	14.362	15.361	30.727	48.056	78.297	0.251
0.934	2.108	62.108	0	23.583	23.752	68.337	0.255	0.200	36.242	37.968	70.027	0.592	14.601	15.134	30.686	47.948	78.170	0.253
0.935	2.010	62.010	0	23.609	23.681	68.212	0.256	0.000	36.026	38.086	69.914	0.589	14.573	15.148	30.634	47.864	78.034	0.255
0.936	2.048	61.907	0.000325	23.622	23.622	68.086	0.256	0.273	37.013	37.013	69.772	0.602	14.554	15.190	30.583	47.752	77.909	0.256
0.937	1.814	61.814	0	23.597	23.598	67.962	0.256	0.263	35.534	38.335	69.634	0.584	14.554	15.192	30.535	47.654	77.778	0.258
0.938	1.715	61.715	2.22E-15	23.573	23.573	67.837	0.257	1.252	35.102	38.686	69.461	0.585	14.561	15.174	30.491	47.562	77.643	0.260
0.939	1.616	61.616	0	23.531	23.533	67.639	0.257	0.088	35.180	38.469	69.399	0.578	14.496	15.123	30.451	47.544	77.477	0.263
0.940	1.517	61.517	2.22E-15	23.491	23.505	67.479	0.256	0.005	35.017	38.526	69.288	0.576	14.528	15.213	30.403	47.357	77.381	0.263
0.941	1.417	61.417	0	23.423	23.519	67.356	0.256	1.034	34.710	38.749	69.143	0.575	14.489	15.247	30.361	47.258	77.247	0.265
0.942	1.318	61.318	0	23.292	23.596	67.232	0.256	0.145	34.698	38.631	69.066	0.570	14.486	15.243	30.323	47.158	77.113	0.266
0.943	1.217	61.217	0	23.418	23.418	67.123	0.256	0.126	34.429	38.704	68.872	0.564	14.462	15.112	30.295	47.160	76.937	0.269
0.944	1.117	61.117	0	23.369	23.404	66.989	0.255	0.000	34.429	38.704	68.872	0.567	14.491	15.141	30.258	47.011	76.822	0.269
0.945	1.016	61.016	0	23.181	23.535	66.866	0.254	0.887	34.014	38.884	68.608	0.558	14.511	15.158	30.224	46.876	76.700	0.270
0.946	0.915	60.915	2.16E-10	23.328	23.328	66.746	0.254	0.650	33.976	38.852	68.559	0.556	14.702	14.978	30.199	46.754	76.572	0.271
0.947	0.814	60.814	2.22E-15	23.300	23.301	66.637	0.253	0.088	33.850	38.830	68.441	0.550	14.645	14.972	30.172	46.686	76.421	0.272
0.948	0.712	60.712	0	23.266	23.268	66.505	0.252	0.969	33.534	38.979	68.249	0.546	14.732	14.732	29.954	46.822	76.391	0.321
0.949	0.202	60.614	0.000196	23.194	23.277	66.384	0.251	0.353	33.604	38.882	68.261	0.544	14.799	14.799	30.005	46.495	76.193	0.282
0.950	0.508	60.508	0	23.189	23.218	66.264	0.250	0.727	33.257	38.981	68.028	0.537	14.811	14.811	30.041	46.455	75.962	0.283
0.951	0.497	60.405	6.95E-05	23.164	23.179	66.144	0.249	0.006	33.206	38.918	67.950	0.532	14.291	14.291	30.059	46.837	75.708	0.286
0.952	0.521	60.301	0.000105	23.135	23.143	66.025	0.247	3.422	32.119	40.075	67.542	0.554	14.265	14.349	30.086	46.807	75.475	0.278
0.953	0.200	60.200	0	23.080	23.131	65.906	0.246	0.449	32.919	38.963	67.737	0.524	14.267	14.414	30.066	46.639	75.362	0.278
0.954	0.096	60.096	1.30E-09	22.949	23.195	65.786	0.245	2.673	32.153	39.653	67.411	0.532	14.185	14.503	30.049	46.513	75.231	0.278
0.955	0.085	59.993	4.22E-06	23.036	23.039	65.668	0.243	0.289	32.579	38.965	67.468	0.512	14.460	14.460	30.053	46.205	75.168	0.278
0.956	0.203	59.888	1.67E-05	23.002	23.004	65.549	0.242	0.428	32.469	38.977	67.386	0.508	14.467	14.467	30.047	46.127	74.991	0.280
0.957	0.256	59.784	1.11E-05	22.954	22.982	65.431	0.240	0.359	32.288	38.971	67.242	0.501	14.467	14.467	30.047	46.127	74.991	0.329
0.958	0.321	59.679	2.22E-15	22.926	22.939	65.313	0.238	0.000	31.768	39.226	67.136	0.512	14.346	14.346	30.040	46.025	74.668	0.278
0.959	0.426	59.574	0	22.733	23.061	65.195	0.236	1.892	31.744	39.289	66.954	0.498	14.388	14.450	30.002	45.769	74.608	0.276
0.960	0.428	59.470	5.69E-05	22.759	22.961	65.077	0.234	0.003	31.946	38.947	66.969	0.487	14.307	14.307	30.088	45.861	74.318	0.279
0.961	0.453	59.365	0.000115	22.783	22.863	64.960	0.232	0.565	31.779	38.969	66.851	0.482	14.283	14.283	30.014	45.766	74.206	0.279
0.962	0.476	59.260	0.000187	22.756	22.816	64.843	0.230	1.114	31.591	39.045	66.741	0.479	14.206	14.206	30.086	45.713	74.018	0.276
0.963	0.521	59.155	0.000258	22.615	22.882	64.726	0.228	0.865	31.454	38.982	66.613	0.471	14.206	14.206	30.086	45.713	74.018	0.326
0.964	0.000	59.067	0.003131	22.666	22.754	64.609	0.226	0.684	31.367	38.944	66.533	0.466	14.003	14.003	30.095	45.741	73.624	0.274
0.965	0.225	59.052	0.000493	22.672	22.672	64.493	0.224	3.419	30.365	39.808	66.115	0.476	13.887	13.912	30.111	45.746	73.428	0.272
0.966	1.064	58.936	2.22E-15	22.555	22.711	64.376	0.221	0.019	31.107	38.861	66.309	0.451	13.765	13.836	30.014	45.711	73.320	0.269
0.967	1.171	58.829	0	22.449	22.738	64.259	0.219	3.125	30.209	39.596	65.933	0.458	13.848	13.906	30.076	45.478	73.188	0.268
0.968	1.279	58.721	2.22E-15	22.530	22.578	64.144	0.216	0.438	30.771	38.822	66.051	0.437	13.768	13.829	30.035	45.432	73.048	0.265
0.969	1.388	58.612	0	22.514	22.514	64.028	0.214	0.439	30.758	38.819	66.041	0.436	13.707	13.821	30.047	45.339	72.892	0.263
0.970	1.517	58.503	3.56E-05	22.473	22.474	63.912	0.211	0.090	30.588	38.766	65.898	0.426	13.773	13.892	30.070	45.093	72.794	0.262
0.971	1.605	58.395	0	22.424	22.442	63.796	0.208	1.869	30.131	38.994	65.665	0.422	13.896	13.896	30.088	45.033	72.694	0.295
0.972	1.281	58.299	0.000729	22.135	22.649	63.679	0.206	0.000	30.262	38.688	65.639	0.410	9.130	11.830	29.939	49.462	70.462	0.246
0.973	1.825	58.175	0	22.291	22.409	63.565	0.203	1.073	30.042	38.746	65.512	0.405	9.017	11.930	30.008	49.355	70.270	0.242
0.974	1.935	58.065	0	22.302	22.315	63.450	0.200	0.831	30.017	38.689	65.470	0.401	8.983	11.974	29.965	49.204	70.171	0.237
0.975	2.046	57.954	2.22E-15	22.257	22.275	63.335	0.197	1.531	29.768	38.776	65.334	0.396	9.015	12.013	29.996	49.032	70.039	0.233
0.976	2.343	57.835	0.000466	22.139	22.308	63.220	0.194	2.652	29.268	39.046	65.095	0.392	9.018	12.188	29.927	48.764	70.012	0.228
0.977	2.268	57.732	2.22E-15	22.171	22.190	63.105	0.191	0.482	29.671	38.536	65.175	0.379	9.191	12.198	29.942	48.514	69.933	0.224
0.978	2.380	57.620	0	22.106	22.168	62.990	0.187	0.191	29.498	38.456	65.028	0.368	9.068	12.064	29.967	48.554	69.699	0.219
0.979	2.492	57.508	0	22.093	22.103	62.887	0.185	0.907	29.404	38.500	64.982	0.367	9.262	11.939	29.994	48.382	69.577	0.214
0.980	2.605	57.395	0	22.050	22.050	62.761	0.181	0.094	29.315	38.385	64.879	0.357	9.286	11.952	29.985	48.219	69.464	0.209
0.981	2.718	57.282	0	22.010	22.010	62.657	0.178	1.069	29.061	38.398	64.717	0.348	9.135	12.149	30.011	48.057	69.321	0.204
0.982	2.832	57.168	0	21.960	21.962	62.532	0.174	1.424	28.902	38.418	64.621	0.343	9.206	12.167	30.079	47.878	69.169	0.199
0.983	2.946	57.054	0	21.689	22.144	62.416	0.171	2.587	28.442	38.657	64.416	0.339	9.236	12.151	30.054	47.725	69.062	0.195
0.984	3.060	56.940	0	21.868	21.873	62.303	0.167	1.400	28.643	38.293	64.407	0.326	11.259	11.259	31.295	47.119	68.428	0.188
0.985	3.175	56.825	0	21.816	21.835	62.189	0.163	1.983	28.472	38.406	64.341	0.326	11.147	11.147	30.774	47.221	68.441	0.195
0.986	3.290	56.710	2.22E-15	21.750	21.809	62.074	0.160	0.593	28.519	38.072	64.241	0.309	11.140	11.140	30.687	47.161	68.297	0.194
0.987	3.406	56.594	0	21.498	21.988	61.982	0.157	1.063	28.335	38.058	64.120	0.301	11.088	11.088	30.650	47.101	68.144	0.195
0.988	3.523	56.477	2.22E-15	21.671	21.703	61.846	0.152	0.370	28.322	37.951	64.069	0.294	10.974	11.194	30.577	46.610	68.330	0.170
0.989	3.639	56.361	0	21.640	21.640	61.732	0.148	1.241	28.098	37.973	63.938	0.287	10.920	11.043	30.406	46.565	68.258	0.165
0.990	3.757	56.243	0	21.598	21.598	61.629	0.145	0.852	28.051	37.864	63.865	0.279	10.947	11.059	30.266	46.347	68.254	0.162

0.991	3.641	56.144	0.000932	21.261	21.831	61.502	0.140	1.563	27.864	37.932	63.779	0.276	10.988	10.988	30.513	46.295	67.922	0.154
0.992	3.993	56.007	0	21.144	21.854	61.387	0.136	0.984	27.773	37.727	63.640	0.260	10.933	10.933	30.313	45.899	68.120	0.170
0.993	4.111	55.889	0	21.273	21.628	61.275	0.132	0.287	27.777	37.638	63.607	0.256	10.933	10.933	30.313	45.899	68.120	0.220
0.994	4.231	55.769	0	21.246	21.559	61.162	0.128	1.908	27.391	37.762	63.426	0.248	10.887	11.063	30.426	45.847	67.595	0.139
0.995	4.350	55.650	2.22E-15	21.359	21.359	61.060	0.124	0.000	27.420	37.485	63.447	0.252	11.094	11.359	31.024	45.494	67.189	0.132
0.996	4.471	55.529	0	21.305	21.305	60.935	0.119	1.339	27.257	37.499	63.249	0.229	10.976	11.290	30.781	45.413	67.182	0.128
0.997	4.592	55.408	2.22E-15	21.174	21.339	60.821	0.115	0.735	27.281	37.366	63.198	0.221	10.926	11.258	30.677	45.291	67.107	0.123
0.998	4.713	55.287	0	21.196	21.218	60.707	0.111	1.764	27.000	37.440	63.065	0.215	10.902	11.236	30.611	45.152	67.015	0.118
0.999	4.835	55.165	0	21.157	21.157	60.593	0.106	1.797	26.875	37.360	62.959	0.205	10.880	11.249	30.595	44.998	66.900	0.113
1.000	4.957	55.043	0	21.150	21.155	60.582	0.106	14.999	17.800	42.301	61.038	0.296	1.992	17.362	28.926	45.544	66.575	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

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%                                                                     %%%
%%% This function holds the truth table that creates the correct        %%%
%%% waveform to be fed into the firing signal lookup table              %%%
%%%                                                                     %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


function Signal = fcn(Angles)
    if(isequal(Angles', [1 1 1 1 1 1 1 1])==1)
        Signal = 2;
    elseif(isequal(Angles', [0 0 0 0 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 1 1 1 1 1 1])==1)
        Signal = 4;
    elseif(isequal(Angles', [0 0 0 0 0 1 1 1])==1)
        Signal = 1;
    elseif(isequal(Angles', [0 0 0 0 0 0 0 1])==1)
        Signal = 1;
    elseif(isequal(Angles', [0 0 0 0 0 0 1 1])==1)
        Signal = 0;
    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 = 2;
    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.

5-Level Hybrid-Clamped Inverter Switching States										
Voltage	Main Switches								Aux Switches	
Level	S1	S2	S3	S4	S'4	S3'	S2'	S1'	Odds	Evens
4	1	1	1	1	0	0	0	0	0	1
3	0	1	1	1	0	0	0	1	1	0
3	1	0	1	1	1	0	0	0	0	1
2	0	0	1	1	1	0	0	1	1	0
2	1	0	0	1	1	1	0	0	0	1
1	0	0	0	1	1	1	0	1	1	0
1	1	0	0	0	1	1	1	0	0	1
0	0	0	0	0	1	1	1	1	1	0

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

7-Level Hybrid-Clamped Inverter Switching States														
Voltage	Main Switches												Aux Switches	
Level	S1	S2	S3	S4	S5	S6	S6'	S5'	S4'	S3'	S2'	S1'	Odds	Evens
6	1	1	1	1	1	1	0	0	0	0	0	0	0	1
5	0	1	1	1	1	1	0	0	0	0	0	1	1	0
5	1	0	1	1	1	1	1	0	0	0	0	0	0	1
4	0	0	1	1	1	1	1	0	0	0	0	1	1	0
4	1	0	0	1	1	1	1	1	0	0	0	0	0	1
3	0	0	0	1	1	1	1	1	0	0	0	1	1	0
3	1	0	0	0	1	1	1	1	1	0	0	0	0	1
2	0	0	0	0	1	1	1	1	1	0	0	1	1	0
2	1	0	0	0	0	1	1	1	1	1	0	0	0	1
1	0	0	0	0	0	1	1	1	1	1	0	1	1	0
1	1	0	0	0	0	0	1	1	1	1	1	0	0	1
0	0	0	0	0	0	0	1	1	1	1	1	1	1	0

Table 7.3 Switching states for the 7-level hybrid-clamped inverter.

9-Level Hybrid-Clamped Inverter Switching States																		
Voltage	Main Switches																Aux Switches	
Level	S1	S2	S3	S4	S5	S6	S7	S8	S8'	S7'	S6'	S5'	S4'	S3'	S2'	S1'	Odds	Evens
8	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	1
7	0	1	1	1	1	1	1	1	0	0	0	0	0	0	0	1	1	0
7	1	0	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	1
6	0	0	1	1	1	1	1	1	1	0	0	0	0	0	0	1	1	0
6	1	0	0	1	1	1	1	1	1	1	0	0	0	0	0	0	0	1
5	0	0	0	1	1	1	1	1	1	1	0	0	0	0	0	1	1	0
5	1	0	0	0	1	1	1	1	1	1	1	0	0	0	0	0	0	1
4	0	0	0	0	1	1	1	1	1	1	1	0	0	0	0	1	1	0
4	1	0	0	0	0	1	1	1	1	1	1	1	0	0	0	0	0	1
3	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	1	1	0
3	1	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	0	1
2	0	0	0	0	0	0	1	1	1	1	1	1	1	0	0	1	1	0
2	1	0	0	0	0	0	0	1	1	1	1	1	1	1	0	0	0	1
1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	0	1	1	0
1	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	0	0	1
0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0

Table 7.4 Switching states for the 9-level hybrid-clamped inverter.

11-Level Hybrid-Clamped Inverter Switching States																						
Voltage	Main Switches																				Aux Switches	
Level	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S10'	S9'	S8'	S7'	S6'	S5'	S4'	S3'	S2'	S1'	Odds	Evens
10	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	1
9	0	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	1	1	0
9	1	0	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1
8	0	0	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	1	1	0
8	1	0	0	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	1
7	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	1	1	0
7	1	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	1
6	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	1	1	0
6	1	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	1
5	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0	0	0	1	1	0
5	1	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	1
4	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	0	0	0	0	1	1	0
4	1	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0	0	0	1
3	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	0	0	0	1	1	0
3	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0	0	1
2	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	0	0	1	1	0
2	1	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0	1
1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	0
1	1	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0	1
0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	0

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

```
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

```
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];
```