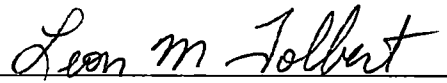


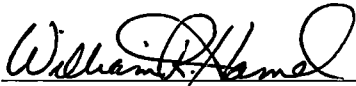
To the Graduate Council:

I am submitting herewith a thesis written by Tim Cunnyngnam entitled "Cascade multilevel inverters for large hybrid-electric vehicle applications with variant dc sources." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Electrical Engineering.

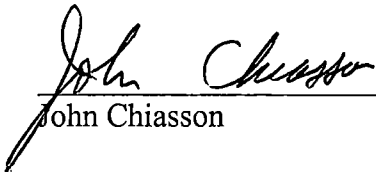


Leon M. Tolbert, Major Professor

We have read this thesis
and recommend its acceptance:



William R. Hamel



John Chiasson

Accepted for the Council:



Interim Vice Provost and
Dean of The Graduate School

**CASCADE MULTILEVEL INVERTERS FOR
LARGE HYBRID-ELECTRIC VEHICLE APPLICATIONS
WITH VARIANT DC SOURCES**

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Tim Cunnyngnam
May 2001

Copyright © 2001 by Tim Cunnyngnam

All rights reserved

ABSTRACT

This thesis investigates using the cascade multilevel inverter as an alternative to conventional pulse width modulated inverters for large hybrid-electric vehicle (HEV) drivetrain applications. Previous research considered constant and equal dc sources with invariant behavior; however, this research extends earlier work to include variant dc sources, which are typical of lead-acid batteries when used in HEVs. This thesis also investigates methods to minimize the total harmonic distortion of the synthesized multilevel waveform and to help balance the battery voltage. The harmonic elimination method was used to eliminate selected lower dominant harmonics resulting from the inverter switching action. Switching points (angles) were determined using an iterative technique to solve the system of nonlinear transcendental equations. The total harmonic distortion was investigated over a wide range of possible output control voltages and number of voltage levels used to synthesize the output waveform.

As expected, the line-to-line voltage of the three-phase multilevel inverter's voltage was observed to be zero when used with an ideal low-pass filter; however, the total harmonic distortion increased significantly for both the phase- and line-voltages as the number of synthesis voltage levels decreased. Also, a switching pattern that would help balance and equalize the individual battery voltages within an HEV battery pack was developed. The individual batteries with the higher voltages would be assigned the longer duty cycle, and the batteries with the lower voltages would be skipped or assigned the lower duty cycles.

TABLE OF CONTENTS

1 INTRODUCTION	1
1.1 HYBRID-ELECTRIC VEHICLES	1
1.1.1 The Series HEV Configuration	2
1.1.2 The Parallel HEV Configuration	2
1.1.3 Other Configurations	4
1.2 THE DEMAND FOR LARGE HEV APPLICATIONS.....	5
1.2.1 Application Requirements	6
1.2.2 Increase in Component Size using Common Techniques	7
1.3 ADVANCED POWER ELECTRONICS	7
1.4 OUTLINE OF THESIS	9
2 MULTILEVEL INVERTERS	11
2.1 TYPES OF MULTILEVEL INVERTERS	12
2.1.1 Diode-Clamped Inverter	13
2.1.2 Capacitor-Clamped Inverter	16
2.1.3 Cascade H-Bridge Inverter	19
2.2 WAVEFORM GENERATION USING SEPARATE IDEAL DC SOURCES	22
2.2.1 Waveform Synthesis	23
2.2.2 Fourier Analysis	25
2.2.2.1 <i>Eliminating Selected Lower Dominant Harmonics</i>	27
2.2.2.2 <i>Minimizing the Total Harmonic Distortion</i>	29
2.3 SWITCHING ANGLES WHEN DC SOURCES VARY	31

3 SWITCHING ANGLES WITH VARIANT DC SOURCES	32
3.1 THE LEAD-ACID BATTERY AS A DC SOURCE	32
3.2 SORTING DC VOLTAGE SOURCES	33
3.3 MULTILEVEL WAVEFORM ANALYSIS OF VARIANT DC VOLTAGE SOURCES	35
3.3.1 Switching Order with Perturbed dc Sources	38
3.3.2 Determining Switching Angles for Different Voltages	44
<i>3.3.2.1 Varying the Control Voltage</i>	<i>45</i>
3.3.3 Comparison of the Two Methods	48
3.3.4 Equations and Vector-Matrix Notation	51
4 CONTROL VOLTAGE AND THREE-PHASE ANALYSIS	52
4.1 CONTROL VOLTAGE	52
4.1.1 Sorting the dc Sources and Reducing the Number of Steps	54
<i>4.1.1.1 Using 4-of-5 dc Sources</i>	<i>55</i>
<i>4.1.1.2 Using 3-of-5 dc Sources</i>	<i>62</i>
<i>4.1.1.3 Using 2-of-5 dc Sources</i>	<i>66</i>
<i>4.1.1.4 Using 1-of-5 dc Sources</i>	<i>69</i>
4.1.2 Summary	71
4.2 THREE-PHASE ANALYSIS	74
4.2.1 Simulation Using an Ideal Low-Pass Filter	75
5 CONCLUDING REMARKS	81
5.1 A BRIEF SUMMARY	81
5.2 CONCLUSION.....	83

5.3 FUTURE RESEARCH	84
BIBLIOGRAPHY	86
VITA	89

LIST OF TABLES

<u>Table</u>	<u>Page</u>
2-1 Diode-clamp three-level converter voltage and corresponding switching states...15	
2-2 A capacitor-clamped three-level converter voltage and switching states18	
3-1 THD _v and sorted permutations for the five-step waveform42	
3-2 A comparison of the methods used from Chapters 2 and 350	
4-1 THD _v and sorted permutations for the four-step waveform58	
4-2 THD _v and sorted permutations for the three-step waveform64	
4-3 THD _v and sorted permutations for the two-step waveform67	
4-4 THD _v for the phase and line voltage vs. harmonics.....78	

LIST OF FIGURES

<u>Figure</u>	<u>Page</u>
1-1 Series configuration	3
1-2 Parallel configuration.....	3
1-3 Dual-mode configuration.....	5
2-1 Example multilevel sinusoidal approximation using 11-levels	12
2-2 A five-level diode-clamped multilevel inverter: (a) inverter topology; (b) switch representation.....	14
2-3 An m-level diode-clamped multilevel inverter	15
2-4 A five-level capacitor-clamped multilevel inverter	17
2-5 An m-level capacitor-clamped multilevel inverter	18
2-6 Single H-bridge configuration	20
2-7 Cascade H-bridges m-level multilevel inverter	20
2-8 Waveform Synthesis: (a) five-step, 11-level; (b) ten-step, 21-level; (c) fifteen-step, 31-level; (d) twenty-step, 41-level	24
2-9 Illustration of increased number of steps versus the THD _v	25
3-1 Multilevel waveforms	36
3-2 Synthesis of a multilevel waveform.....	39
3-3 Illustration of the THD _v vs. the permutations of v_a	42
3-4 Harmonics of the multilevel waveform with different voltage sources.....	44
3-5 Switching angles versus the control voltage over a finite region	45
3-6 Total harmonics distortion of the waveform versus the control voltage	46
3-7 Harmonics of the multilevel waveform with selected harmonics eliminated.....	47

<u>Figure</u>	<u>Page</u>
4-1 Total harmonic distortion of the waveform versus the control voltage	53
4-2 Illustration of the THD _v vs. the sorted permutations of four dc sources	57
4-3 Switching angles vs. V_p for a four-step waveform.....	60
4-4 THD _v vs. V_p for a four-step waveform.....	61
4-5 Illustration of the THD _v vs. the sorted permutations of three dc sources	63
4-6 Switching angles vs. V_p for a three-step waveform	65
4-7 THD _v vs. V_p for a three-step waveform	65
4-8 Illustration of the THD _v vs. the sorted permutations of three dc sources	66
4-9 Switching angles vs. V_p for a two-step waveform	68
4-10 THD _v vs. V_p for a two-step waveform	68
4-11 Switching angle vs. V_p for a one-step waveform	69
4-12 THD _v vs. V_p for a one-step waveform.....	70
4-13 THD _v vs. the switching angle for a one-step waveform	70
4-14 THD _v vs. V_p over a wide range on control voltage	73
4-15 Phase- and line-voltages using an ideal low-pass filter with $h > 13^{\text{th}}$ completely filtered	76
4-16 Phase voltage ripple for $n = 13$	76
4-17 Phase- and line-voltages using an ideal low-pass filter with $h > 21^{\text{st}}$ completely filtered	79
4-18 Phase voltage ripple for $n = 21$	79
4-19 Line voltage ripple for $n = 21$	80

1 Introduction

1.1 Hybrid-Electric Vehicles

Battery powered electric vehicles (BEV or EV) have been around since the 1960's when the demand was revived due to air pollution and ecology. However, limited technological advances and specific component requirements caused the popularity of electric vehicles to fade in-and-out. During the past ten years, the digital age has brought forth the capability to advance this technology using a combination of advanced electric drive systems, new battery technologies, fuel cells, microturbine power units, and the internal combustion engine to mix the battery powered electric vehicle with conventional automotive drive systems. This gave birth to the hybrid-electric vehicle (HEV).

In the past thirty years, there has been a desire to reduce vehicle emissions and improve fuel economy. Due to inflated fuel prices since 1999 and the mandate for cleaner, fuel-efficient vehicles, the timing for the HEV could not be better. The future of using hybrid-electric vehicles may become reality, especially since several EVs and HEVs have been used for the past decade.

The HEV can have several different configurations, where the chemical, mechanical, and electrical sources of energy supplement each other to yield an overall system with a particular advantage. The HEV offers additional flexibility to reduce emissions and improve the fuel economy of the vehicle. The two basic HEV system configurations are the series and parallel, where the power flow of the system determines the type.

1.1.1 The Series HEV Configuration

In the series HEV configuration, as depicted in Figure 1-1, the accessory power unit (APU) supplements the energy storage system (ESS), usually batteries, to store energy, which is used by the main propulsion system. The power flows from the APU, to the ESS, then to the propulsion system. The vehicle's overall performance is determined by the main propulsion system, ESS characteristics, APU capability, and its system controller to manage the power flow. For the HEV to meet its performance criteria, properly sized components are chosen such that the APU can replenish the ESS and maintain it within acceptable operating limits.

The series HEV is usually simple to control because the APU does not mechanically couple with the drive system. Since the APU is not mechanically coupled to the drive system, it can operate at a constant speed where it is most efficient, significantly extending the range of the vehicle, or produce the least amount of emissions. However, it has all the disadvantages of multi-state conversion [1].

1.1.2 The Parallel HEV Configuration

In the parallel HEV configuration, as shown in Figure 1-2, the APU is mechanically coupled with the electric drive system. This is usually mechanically complicated and involves a complicated control structure for the system. The overall propulsion system is considered as a "power assist" when compared to the series configuration, where the overall system is deemed a "range extender."

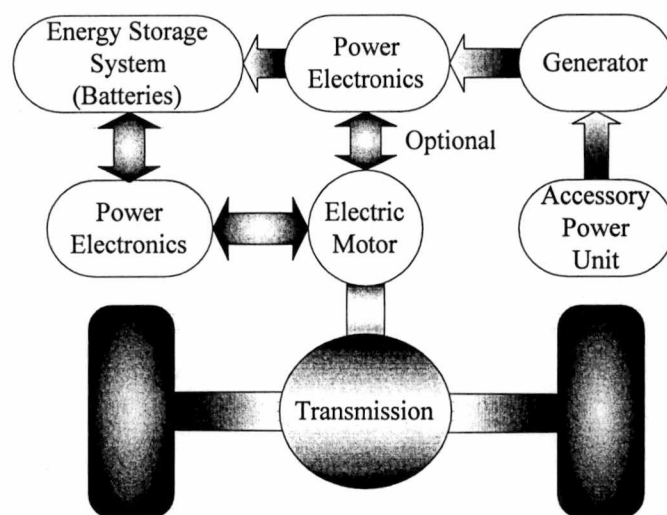


Figure 1-1: Series configuration

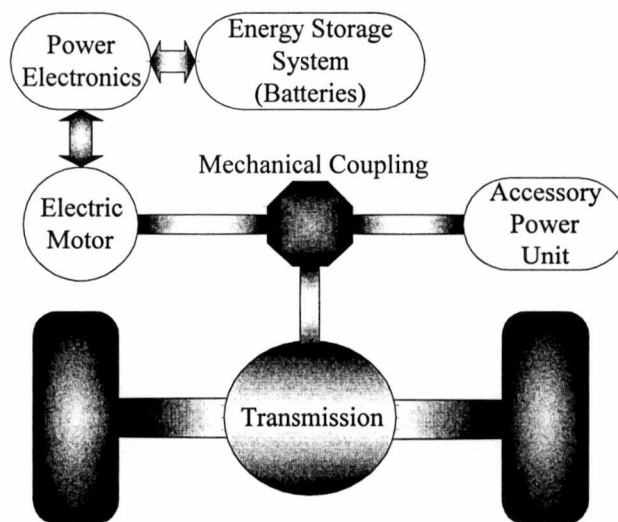


Figure 1-2: Parallel configuration

The size of the ESS and electric drive system can be significantly reduced, which has several advantages over the series arrangement. The APU is smaller when compared to a conventional automotive engine because the power from the APU and the electric motor combine to produce an equivalent power. The parallel configuration may also be operated in three modes: (1) as a pure EV using the electric motor only, (2) as a conventional vehicle using only the APU, (3) or both using the APU and the electric motor. The electric motor can also be used as a generator, where it supplies energy to the ESS, thus, the APU is used as the main propulsion system and power is shared with the generator. The main advantage of the parallel HEV is flexibility; the APU and electric motor operate together optimizing efficiency, performance, and emissions requirements.

1.1.3 Other Configurations

Although, the series or parallel configuration can improve fuel economy and reduce emissions, other configurations have advantages over the series or parallel arrangements. Mixed configurations can achieve better performance, but their control complexity increases. For example, the dual-mode hybrid, as used in the Toyota Prius, is a popular mixed configuration [2]. It is basically a parallel hybrid with a separate generator that can recharge the batteries or assist the drivetrain, as shown in Figure 1-3.

The terms ESS, APU, and propulsion system were used in general because they describe a variety of devices. The ESS may consist of different battery types, ultra-capacitors, flywheels, or other energy storage elements. The typical APU is an internal combustion engine (ICE), but may be an alternative fuel ICE, efficient diesel engine, multi-fuel microturbine, fuel-cell, etc. The main propulsion system typically consists of

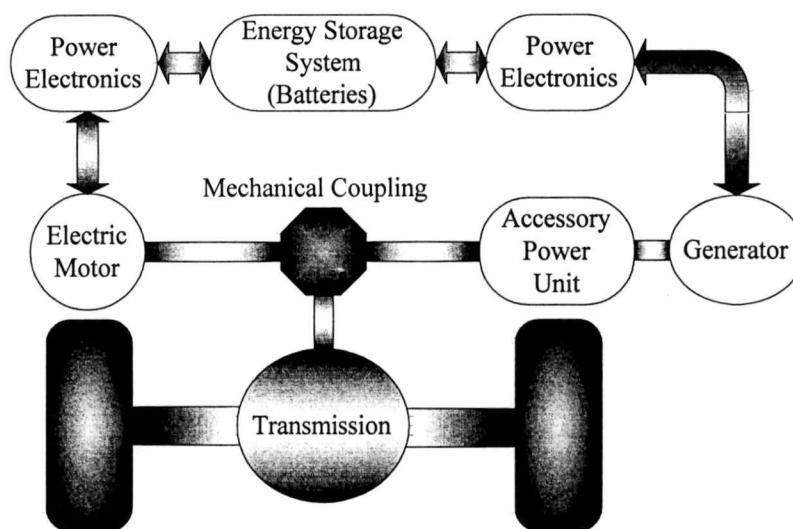


Figure 1-3: Dual-mode configuration

ac induction motors, but a variety of other electric motors have also been used. In the past, dc motors were used and are still prime movers in some EVs. Switch reluctance motors, due to their simple, rugged construction and price advantages, are candidates for future drive systems.

1.2 The Demand for Large HEV Applications

Although, the popular automotive vehicle has been the center of discussion up to now, it is not the only vehicle to use a hybridized propulsion system. Large HEV applications such as transit buses, recreational vehicles, heavy-duty trucks, school buses, military vehicles, etc., are additional areas that would benefit from a hybrid system. Although some research has been done in these areas, the overall system implementation becomes more difficult because the vehicles are larger and obviously require a larger ESS, APU, and drive system.

In addition, these larger components are more expensive and less reliable because the semiconductor switching dV/dt is considerably higher, the devices dissipate more heat due to higher switching losses, and higher rated components tend to cost more (especially when replaced several times during the life of the application). The high frequency switching of popular pulse width modulation (PWM) schemes, which is common in modern power electronic equipment, increases the electromagnetic interference (EMI), and induces internally circulating currents into the motor bearing causing failure and stator winding insulation breakdown of the traction motors [3].

1.2.1 Application Requirements

Large HEV applications require considerably larger components and storage units in comparison to the majority of the diesel engines used. The average continuous power range expected is 150kW-300kW for the majority of applications, however some applications may be larger than 1MW. Thus, an expected average or continuous power that exceeds 150kW will be used to define large HEV applications.

The most common applications today are the electric and alternative fuel transit bus. The cyclic operations of the transit bus are ideally suited for EVs and HEVs. The electric transit bus has been successful and considerable research and development time has been spent in the electric transit industry, hence, the move to larger hybrid systems is inevitable. However, the need for a larger drive system that compares with the performance of presently used diesel buses is a fundamental requirement.

1.2.2 Increase in Component Size using Common Techniques

The common techniques used for large HEVs would be similarly scaled from the automotive HEV. Using this arrangement, the components become excessively large and expensive, therefore, the viable application becomes less realizable. Although the application may be achieved, if it is not economically feasible, then the demand for the application diminishes.

Heavy-duty design of power electronic inverters for the drive system would be required to compensate for the larger working voltage, current, and heat dissipation. Since the switching inverters have semiconductors and other components that are dependent on the operating voltage and current, the result is more expensive and less efficient inverters. Common methodologies appear to close the door for larger applications because the components become expensive, bulky, inefficient, and overall not reliable. Improvements on these drive systems are imperative before large HEV applications become successful.

Therefore, the work in this thesis is to investigate a new type of inverter approach for large HEV drive systems, which has several advantages over the present technology that is commonly used in dc-ac inversion. Some advantages are high efficiency, smaller power electronic modules, scalable and modular systems, and system redundancy improving reliability for drive system critical applications.

1.3 Advanced Power Electronics

The Multilevel Inverter approach allows the use of high-power and high-voltage electric motor drive systems. Using a multilevel inverter, a “divide and conquer”

approach to HEV system design allows more flexibility and control over the discrete components that make up the system. Inherently, several modular units may be embedded and controlled using the multilevel approach with a microcontroller or DSP chip.

The goal of the inverter is to produce an ac waveform from a dc supply. The dc supply usually consists of several batteries connected in series. In typical applications, the input voltage for the inverter is the same as the dc supply voltage. Also, power is the product of voltage and current; larger applications require more power from the dc supply thus posing a design barrier. The power may be maintained by increasing the voltage and decreasing the current by the same proportion, or decreasing the voltage and increasing the current by the same proportion. If the dc supply voltage is increased (adding more batteries in series to maintain or decrease the current) for the larger power requirement, the components must be able to withstand the maximum dc supply voltage. A high supply voltage results in a slower switching frequency because of the semiconductor's characteristics. If the designer chooses to deal with a larger current, then heat dissipation, and switching dV/dt become a problem, in addition to EMI problems. However, by using multiple switching levels, the components are exposed to a smaller voltage, as compared to PWM inverters, and assembled to produce the desired output waveform.

The multilevel inverter uses the individual batteries from the battery pack to generate the desired sinusoidal waveform by combining the individual dc sources at specified times. Generally 12-volt batteries are available, so there are multiple switching levels composed of the series batteries used in the multilevel inverter which allows for

scalable high power applications that result in highly efficient power conversion. Thus, the overall objective of converting dc to ac for motor control has been accomplished using the multilevel inverter with additional benefits of high efficiency, smaller components, fundamental switching frequency, very low EMI, scalable and modular systems, and the ability to use any separate dc source. It is important to note that the ESS may consist of many different types of dc sources and the discrete level of the voltage is limited to the desired performance of the semiconductor switches. Using 2, 6, 12, 24, 48 volt, or any other dc level may be selected based on the desired performance criteria; however, the same dc level is usually desired for each available source.

1.4 Outline of Thesis

The following chapters investigate using multilevel inverters with variant dc sources. The variation was assumed to be within reasonable bounds (10%) and was not expected to change rapidly, as in a series connection of lead-acid batteries. The fundamental theory was based on invariant separate dc sources, as in Chapter 2.

Chapter 2 provides an introduction to waveform synthesis using multiple switching levels and develops the fundamental theory based on invariant separate dc sources. Several types of multilevel topologies will be introduced.

In Chapter 3, the fundamental theory that was developed in Chapter 2 will be expanded to include variant dc sources. The optimum switching angles will be investigated for the variant case to determine if the computation can be performed in real-time. Other alternatives will be considered such as a pre-computed look-up table stored in memory.

Chapter 4 discusses redundancy, another advantage of multilevel conversion. The loss of a level and the ability to bypass the failed component and continue operation will be discussed. Several issues will be examined to determine redundant operation and performance tradeoffs in three-phase traction motors.

Chapter 5 summarizes the advantages of using multiple switching level waveform synthesis over present inverter design methodology for large HEV applications, and discusses future research direction for using the multilevel topology for hybrid-electric vehicles.

2 Multilevel Inverters

This chapter presents a brief introduction to the three main types of multilevel converters: diode-clamped, capacitor-clamped, and cascade H-bridges. For this thesis, the cascade multilevel inverter is discussed for use in large HEV drive systems because the available batteries make this inverter favorable. Additional features such as its battery management capability, redundant inverter operation, and scalability make the cascade inverter the multilevel converter of choice.

In section 2.2, the multilevel waveform is examined using invariant dc voltage sources with equal magnitudes. The Fourier analysis of the multilevel waveform is used to compare two types of harmonic minimization: (1) eliminating selected lower dominant harmonics, and (2) minimizing the total harmonic distortion of the voltage waveform. Finally, the variant case is introduced, which is the discussion of Chapter 3, where the dc sources vary like a typical battery.

Multilevel inverters divide the main dc supply voltage into several smaller dc sources which are used to synthesize an ac voltage into a staircase, or stepped, approximation of the desired sinusoidal waveform. A waveform generated with five dc sources each with a one-volt magnitude approximates the desired sinusoid, as shown in Figure 2-1. The five dc sources (five steps) produced a peak-to-peak voltage of 10 volts using 11 discrete levels.

Figure 2-1 illustrates an example multilevel waveform. Using multiple levels, the multilevel inverter can yield operating characteristics such as high voltages, high power levels, and high efficiency without the use of transformers [4, 5]. The multilevel inverter

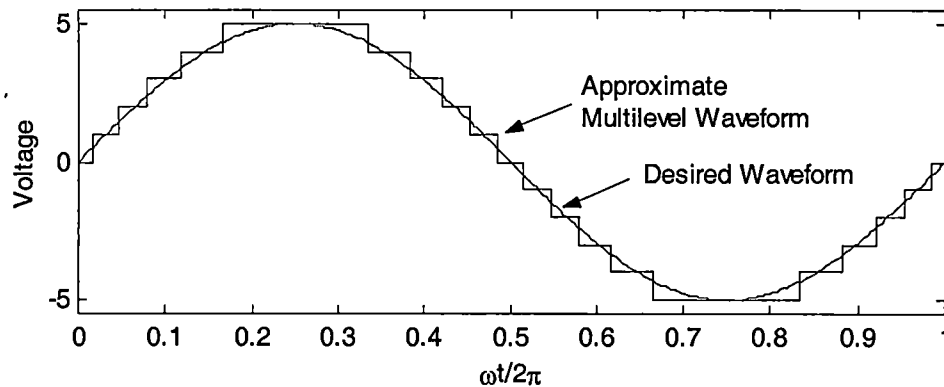


Figure 2-1: Example multilevel sinusoidal approximation using 11-levels.

combines individual dc sources at specified times to yield a sinusoidal resemblance; by using more steps to synthesize the sinusoidal waveform, the waveform approaches the desired sinusoid and the total harmonic distortion approaches zero.

2.1 Types of Multilevel Inverters

There are three main types of multilevel inverters: (1) diode-clamped inverter, (2) capacitor-clamped inverter, and (3) cascade inverter [3, 4]. Applications that have been proposed include static VAR (volt-ampere reactive) compensation, back-to-back high-voltage intertie, and adjustable speed drives [4, 5]. However, using the multilevel inverter as an application for EV and HEV drive systems is a relatively new concept [3, 5-6]. The multilevel inverter may be implemented at the discrete component level dividing the main dc supply voltage into several smaller voltages. The advantages and disadvantages for each configuration of the multilevel converter will be presented.

2.1.1 Diode-Clamped Inverter

Examples of a three-level converter will be used because three levels can be obtained from both conventional PWM and a multilevel inverter. For PWM, the three-level inverter is classified as unipolar PWM switching where the three discrete levels are $+V_{dc}$, 0, or $-V_{dc}$. However, for the multilevel inverter – three levels are just the beginning.

The simplest diode-clamped inverter is commonly known as the neutral point clamped converter (NPC) [4, 7]. The NPC consists of two pairs of series switches (upper and lower) in parallel with two series capacitors where the anode of the upper diode is connected to the midpoint (neutral) of the capacitors and its cathode to the midpoint of the upper pair of switches; the cathode of the lower diode is connected to the midpoint of the capacitors with its anode connected to the midpoint of the lower pair of switches. The capacitors divide the main dc voltage into smaller voltages, for this example, one-half of the main dc voltage. Thus, the three outputs are 0, $\frac{1}{2}V_{dc}$, or V_{dc} . Although, the output phase voltage, V_{an} , was not negative, another phase (or leg) was added to generate the negative portion, $-V_{bn}$, of the wave to yield 0, $-\frac{1}{2}V_{dc}$, or $-V_{dc}$. Therefore, two legs connected to the capacitors, as shown in Figure 2-2, yield a five-level output V_{ab} : V_{dc} , $\frac{1}{2}V_{dc}$, 0, $-\frac{1}{2}V_{dc}$, or $-V_{dc}$. For a three-phase inverter, an extra phase c is introduced for a total of three legs connected to the capacitors.

The five-level output voltage V_{ab} may be generated by controlling the switches, where Table 2-1 shows the proper switching states. The switches (S_{a1} AND $S_{a'1}$) AND (S_{a2} AND $S_{a'2}$) are complementary pairs. When S_{a1} is on ($S_{a1}=1$) $S_{a'1}$ is off ($S_{a'1}=0$), likewise

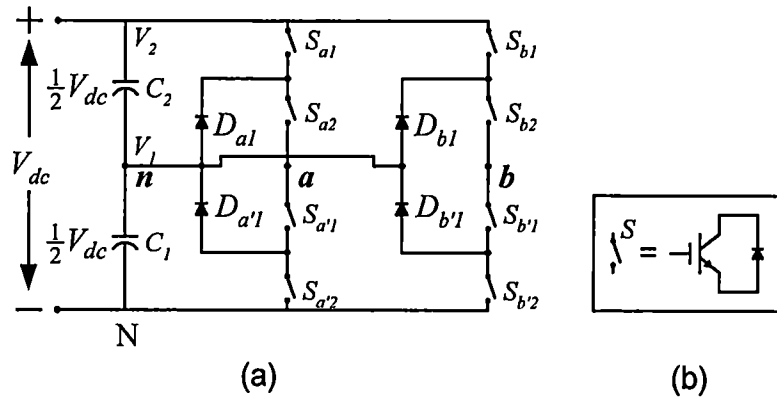


Figure 2-2: A five-level diode-clamped multilevel inverter: (a) inverter topology; (b) switch representation.

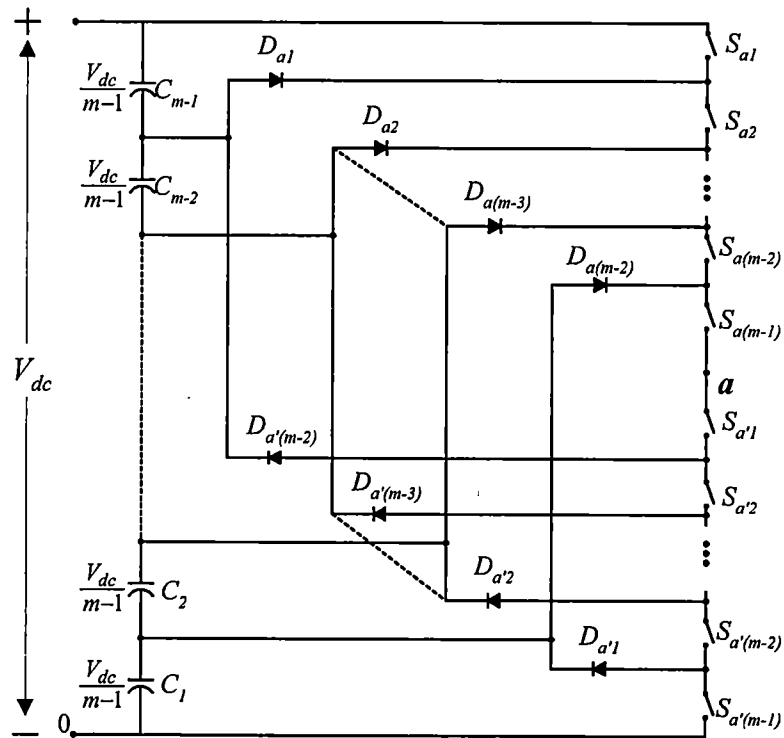
for the other switch pairs. Although a simple example was used, Tolbert et al. implemented a three-phase six-level diode-clamped inverter structure [6].

Some drawbacks of the diode-clamped multilevel inverter may be observed. Using extra diodes in series becomes impractical when the number of levels increase, requiring $(m-1)(m-2)$ diodes per phase [3, 4, 6]. Note that in Figure 2-3, the diode labeled D_{a2} requires two series-connected diodes because it blocks two capacitor voltages, and $D_{a(m-2)}$ requires $(m-2)$ series-connected diodes because it blocks $(m-2)$ capacitor voltages. Also, the switch duty cycle is different for some of the switches requiring different current ratings; the switches block one capacitor voltage level V_{dc} [3, 6]. In addition, the capacitors do not share the same discharge or charge current resulting in a voltage imbalance of the series capacitors [3, 6]. The capacitor voltage imbalance may be controlled using a back-to-back topology as illustrated by Tolbert et al. [3, 5], connecting resistors in parallel with capacitors, or using redundant voltage states [8].

Table 2-1

Diode-clamp three-level converter voltage and corresponding switching states.

S_{a1}	S_{a2}	$S_{a'1}$	$S_{a'2}$	S_{b1}	S_{b2}	$S_{b'1}$	$S_{b'2}$	V_{ab}
0	0	1	1	1	1	0	0	$-V_{dc}$
0	0	1	1	0	1	1	0	$-\frac{1}{2}V_{dc}$
1	1	0	0	1	1	0	0	0
0	0	1	1	0	0	1	1	0
0	1	1	0	0	0	1	1	$\frac{1}{2}V_{dc}$
1	1	0	0	0	0	1	1	V_{dc}

**Figure 2-3:** An m -level diode-clamped multilevel inverter.

The advantages and disadvantages of the m -level diode-clamped multilevel inverter are as follows [4]:

Advantages:

- A large number of levels m yields a small harmonic distortion.
- All phases share the same dc bus.
- Reactive power flow can be controlled.
- High efficiency for fundamental switching frequency
- The control method is relatively simple.

Disadvantages:

- Excessive clamping diodes $(m-1)(m-2)$ are required per phase.
- Real power flow is difficult because of the capacitors' imbalance.
- Different current ratings for switch devices are required due to their conduction duty cycle.

2.1.2 Capacitor-Clamped Inverter

The capacitor-clamped multilevel inverter (formerly flying-capacitor) is similar to the diode-clamped structure, however, the capacitor-clamped multilevel topology allows more flexibility in waveform synthesis and balancing voltage across the clamped capacitors. The three-level inverter is used, as shown in Figure 2-4, for illustration. Essentially, the capacitor-clamped structure produces the same three positive output levels (0 , $\frac{1}{2}V_{dc}$, or V_{dc}), as discussed in section 2.1.1, from a single leg. To generate the negative portion of V_{ab} , $-V_{bn}$ (0 , $-\frac{1}{2}V_{dc}$, or $-V_{dc}$), phase b was introduced, as in the diode-

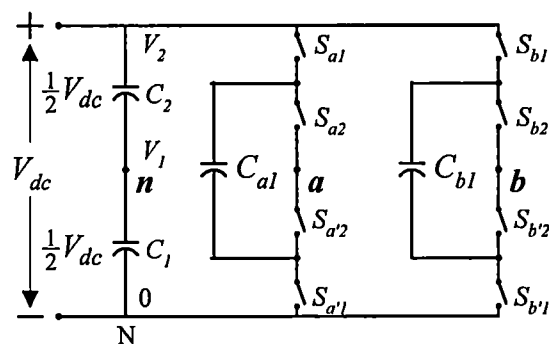


Figure 2-4: A five-level capacitor-clamped multilevel inverter.

clamped structure. Likewise for the diode-clamped inverter structure, a three-phase inverter may be produced by adding another leg or phase c .

Table 2-2 shows the possible switch combinations to generate the five-level output waveform. Note that one is not limited to a set of switching states to generate the output waveform, as in the diode-clamped inverter. The output wave may be produced using different combinations of switching states for the inner voltage levels. This topology allows increased flexibility in how the majority of the voltage levels may be chosen. In addition, the switches may be chosen to charge or discharge the clamped capacitors, which balance the capacitor voltage.

The general m -level capacitor-clamped multilevel inverter, as shown in Figure 2-5, has an m -level output phase voltage. Thus, two phases would produce a $(2m-1)$ level output voltage, or line voltage. The capacitors have different voltage requirements similar to the blocking requirement of the diodes discussed in section 2.1.1. Assuming all capacitors are identical, extra capacitors may be used in series to spread the working voltage evenly. However, this arrangement requires a large number of capacitors per

phase $\frac{1}{2}(m-1)(m-2)$ which results in a bulky, and expensive inverter when compared to the diode-clamped inverter.

The advantages and disadvantages of the m -level capacitor-clamped multilevel inverter is as follows [4]:

Advantages:

- Large m allows the capacitors extra energy during long discharge transient.
- Flexible switch redundancy for balancing different voltage levels.
- Lower total harmonic distortion when the number of levels m is high.
- Real and reactive power flow can be controlled.

Disadvantages:

- Large number of capacitors are bulky and generally more expensive than the clamping diodes used in the diode-clamped multilevel inverter.
- Complex control is required to maintain the capacitors voltage balance.
- Poor switching utilization and efficiency for real power transmission.

2.1.3 Cascade H-Bridges Inverter

The cascade H-bridges inverter is a cascade of H-bridges, or H-bridges in a series configuration. The three-level converter has the same configuration as a single H-bridge inverter, a single-phase full-bridge inverter used in unipolar PWM. A single H-bridge is shown in Figure 2-6, and the cascade of H-bridges is shown in Figure 2-7. The four switches S_1 , S_2 , S_3 , and S_4 are controlled to generate three discrete outputs V_{ab} with levels of $-V_{dc}$, 0, or $+V_{dc}$. When S_2 AND S_3 are on the output is $-V_{dc}$; when either pair S_1 AND S_2 OR S_3 AND S_4 are on the output is 0; when S_1 AND S_4 are turned on the output is $+V_{dc}$.

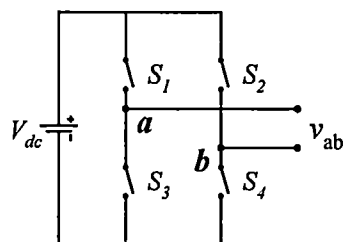


Figure 2-6: Single H-bridge configuration

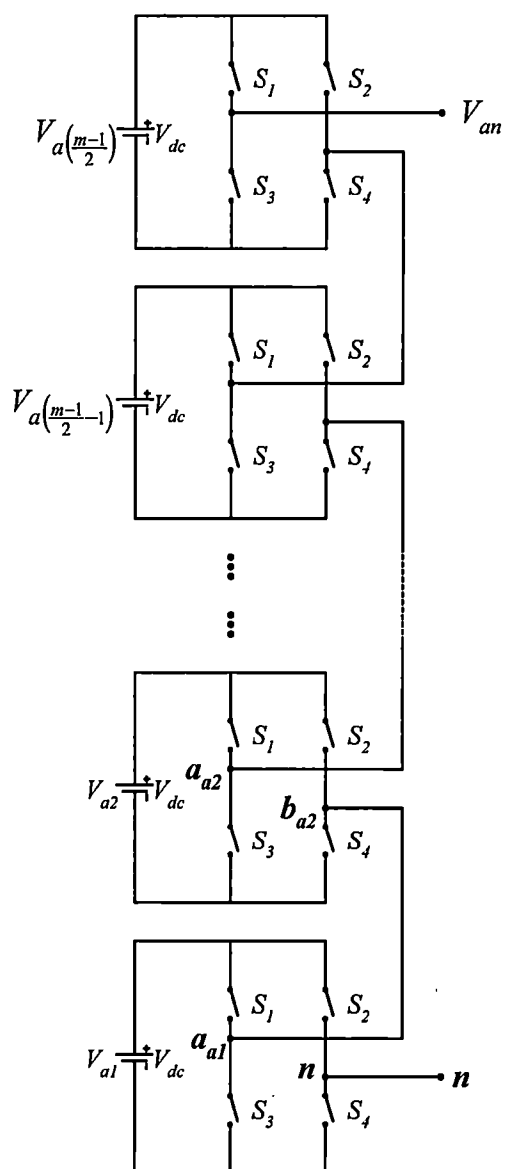


Figure 2-7: Cascade H-bridges m -level multilevel inverter.

The cascaded H-bridge multilevel inverter uses a separate dc source for each H-bridge, as illustrated by the single-phase structure in Figure 2-7. The output of each H-bridge can have three discrete levels, which when combined at specified times result in a staircase waveform, V_{an} , as shown in Figure 2-1. The number of output phase voltage levels m in a cascade inverter with s separate dc sources is $m = 2s+1$ possible levels.

Tolbert showed that the duty cycle for each voltage level can be rotated so that each dc source and bridge share the same load [3]. Because the switches do not share the same load when generating the multilevel waveform, they must be rotated to actively share the duty cycle.

The advantages and disadvantages of a cascade multilevel H-bridge inverter with s separate dc sources per phase is as follows [4]:

Advantages:

- The series structure allows a scalable, modularized circuit layout and packaging since each bridge has the same structure.
- Requires the least number of components considering there are no extra clamping diodes or voltage balancing capacitors.
- Switching redundancy for inner voltage levels is possible because the phase voltage output is the sum of each bridge's output.
- Potential of electrical shock is reduced due to the separate dc sources.

Disadvantages:

- Limited to certain applications where separate dc sources are available.

The goal of an HEV drive system is to perform highly efficient power conversion, sustain ease and flexibility in the control method, and maintain reliability and performance. This is critical for large HEV applications. The cascade multilevel inverter has several advantages well suited for large HEV applications (e.g., transit industry, military applications). Some additional advantages of HEV drive systems using the cascade inverter are as follows: (1) redundant switching operation to balance battery use, (2) limp home capability which operates using a minimal number of levels, and (3) worst case operability which maintains operation at reduced performance. The separate dc sources (batteries) can be switched on various ways to synthesize the output voltage, thus, enhancing HEV drive system operability, and systems management flexibility.

In summary, a minimal number of sources may be used to operate the drive system at reduced performance, which would default to a limp home or worst case mode. The advantageous cascaded multilevel inverter is preferred for large HEV drive systems over PWM and conventional variations thereof.

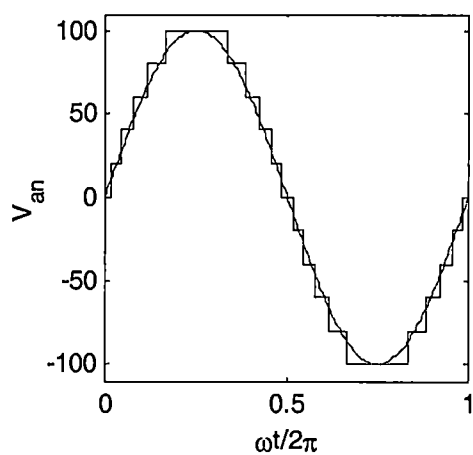
2.2 Waveform Generation using Separate Ideal dc Sources

This section introduces the staircase waveform of a cascade inverter, or any other topology discussed, using separate ideal dc sources. In section 2.2.1, analysis of the waveform using different levels of sinusoid approximation and its significant reduction of the total harmonic distortion of the voltage waveform (THD_v) as the number of levels increased is illustrated. Following, section 2.2.2 presents the Fourier analysis of the staircase waveform for s steps and the importance of selecting the proper switching times to combine the dc sources.

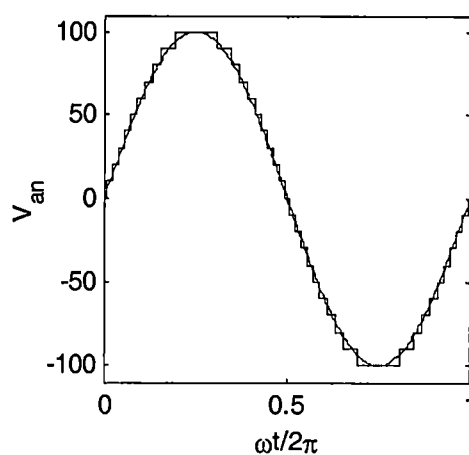
2.2.1 Waveform Synthesis

A five-, ten-, fifteen-, and twenty-step multilevel waveform comparison is shown in Figure 2-8. Notice that the staircase waveform better approximates the desired sinusoid as the number of steps increased. As this approximation improved, due to the increased resolution, the total harmonic distortion of the waveform decreased; that is, the inverter's voltage waveform improved. The switching times were chosen to minimize the THD_v , which is defined by (2-4), and discussed in section 2.2.2.2. The THD_v for the five- and ten-step multilevel waveform, displayed in Figure 2-8(a) and (b), was found to be 7.26% and 3.79% respectively. Thus, using twice the number of steps resulted in a 47.8% reduction in the THD_v . Similarly, for a five- and fifteen-step THD_v of 7.26% and 2.57%, a 64.6% reduction in the THD_v was found. Increasing the step size to twenty produced a THD_v of 1.94%, which was a 74.6% reduction in the total harmonic distortion by using four times as many steps to synthesize the sinusoidal voltage.

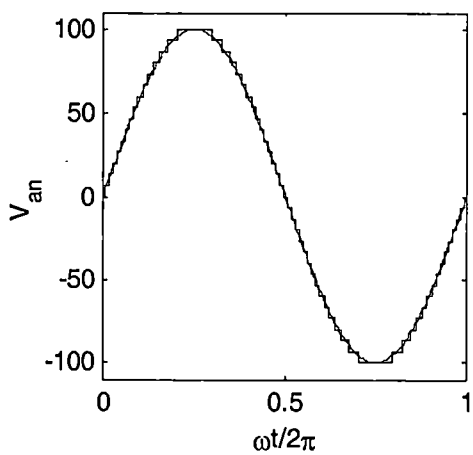
To briefly summarize, increasing the number of steps from 5 to 10, 15, and 20 resulted in a decrease to 0.522, 0.354, and 0.268 of the THD_v of the five-step inverter, respectively. One may assume an even larger number of steps would essentially eliminate the total harmonic distortion, but also requires increased hardware and control requirements. Thus, a "significant" reduction in the THD_v also implies a "significant" tradeoff between the number of hardware devices, control or performance requirements, and the THD_v allowed. In Figure 2-9, the THD_v was plotted versus the number of steps. Increasing the number of steps obviously decreased the THD_v , but at 40 steps the THD_v was found to be less than 1%. In addition, at 8 and 13 steps the THD_v was less than 5%



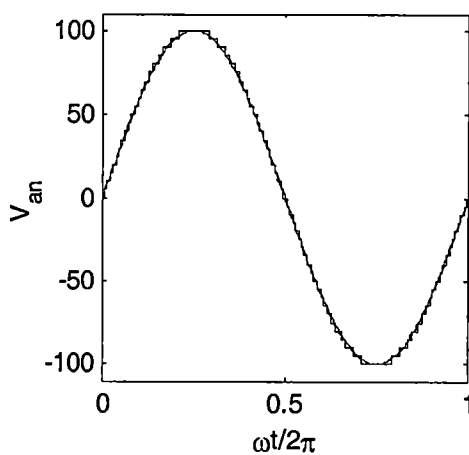
(a)



(b)



(c)



(d)

Figure 2-8: Waveform Synthesis: (a) five-step, 11-level; (b) ten-step, 21-level; (c) fifteen-step, 31-level; (d) twenty-step, 41-level.

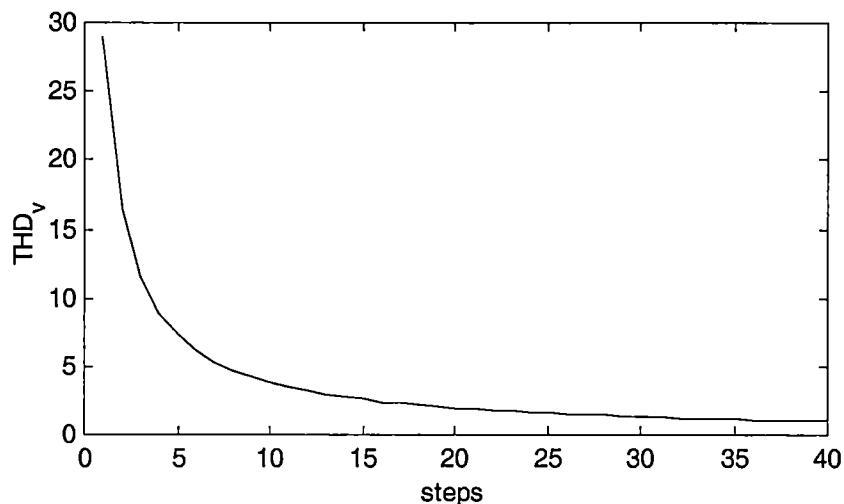


Figure 2-9: Illustration of increased number of steps used versus the THD_v .

and 3%, respectively. The switching angles were found to minimize the total harmonic distortion of the waveform without any filtering, as discussed in section 2.2.2.2.

2.2.2 Fourier Analysis

The Fourier analysis of a multilevel waveform allows the frequency spectra of the waveform to be determined, in particular the unwanted harmonics. In this section, the fundamental equations that describe the multilevel waveform using Fourier analysis are presented [3, 6]. In the two subsections that follow, two methods that determine the switching angles are compared: (1) eliminating the lower dominant harmonics, and (2) minimizing the total harmonic distortion.

The Fourier series of a cascade multilevel waveform with separate equal dc sources may be expressed as

$$\begin{aligned}
f(t) &= f_{\theta_1}(t) + f_{\theta_2}(t) + f_{\theta_3}(t) + \cdots + f_{\theta_s}(t) \\
&= \frac{4V_{dc}}{\pi} \sum_{\substack{h=1 \\ \text{odd}}}^{\infty} [\cos(h\theta_1) + \cos(h\theta_2) + \cos(h\theta_3) + \cdots + \cos(h\theta_s)] \frac{\sin(h\omega t)}{h} \quad (2-1) \\
&= \frac{4V_{dc}}{\pi} \sum_{\substack{h=1 \\ \text{odd}}}^{\infty} \left[\sum_{k=1}^s \cos(h\theta_k) \right] \frac{\sin(h\omega t)}{h}
\end{aligned}$$

where,

h – is the odd harmonic order (1, 3, 5, 7, 9,...).

s – is the number of dc sources, or steps.

k – is an integer > 0 (1, 2, 3,..., s)

θ_k – is the k^{th} switching angle.

and $f_{\theta_s}(t)$ is the Fourier series for θ_s .

The total rms value for the multilevel waveform with s steps was found by integrating the multilevel waveform over one cycle. Because the waveform has s discrete steps over one-quarter of a cycle, the integration consisted of separating the s intervals into s separate integrals using the odd quarter-wave symmetry of the waveform. The root-mean-square of the cascaded multilevel waveform with s steps is

$$[f(t)]_{rms} = V_{dc} \sqrt{\left[s^2 - \frac{2}{\pi} \sum_{k=1}^s (2k-1)\theta_k \right]} \quad (2-2)$$

The fundamental rms value is

$$[f_1(t)]_{rms} = \frac{V_{dc} 2\sqrt{2}}{\pi} \sum_{k=1}^s \cos(\theta_k) \quad (2-3)$$

From (2-2) and (2-3), the THD% was determined as

$$THD\% = 100 \cdot \sqrt{\left(\frac{[f(t)]_{RMS}}{[f_1(t)]_{RMS}}\right)^2 - 1} \quad (2-4)$$

The quality of a multilevel waveform depends on the choice of switching angles; varying the switching angles to control the magnitude of the rms waveform also affects the THD_v. Ideally, one desires only the fundamental component of the multilevel waveform, and to eliminate or filter the residual frequencies. However, choosing the proper switching angles can be an exhaustive task. Assuming the dc sources are constant and are equal, the analysis may be simplified.

2.2.2.1 Eliminating Selected Lower Dominant Harmonics

The most popular technique to reduce the harmonic distortion is to eliminate the lower dominant harmonics and filter the higher residual frequencies [3, 6]. Typically, this method is preferred because a system of equations may be developed using (2-1) which can be solved for the switching angles that eliminate selected harmonics, and retain a single degree of freedom to control the magnitude of the fundamental-frequency component [3, 6]. For example, the switching angles for a three-phase five-step (11-level) multilevel inverter can be determined using (2-5), where the lower dominant harmonics are eliminated and control over the fundamental-frequency component is retained. Note that for a three-phase system, the lower dominant harmonics are the 5th, 7th, 11th, and 13th. Using (2-1) to write the equations for the lower dominant harmonics and normalizing with respect to V_{dc} , a system of nonlinear transcendental equations was determined as

$$\begin{aligned}
\cos(\theta_1) + \cos(\theta_2) + \cos(\theta_3) + \cos(\theta_4) + \cos(\theta_5) &= K \\
\cos(5\theta_1) + \cos(5\theta_2) + \cos(5\theta_3) + \cos(5\theta_4) + \cos(5\theta_5) &= 0 \\
\cos(7\theta_1) + \cos(7\theta_2) + \cos(7\theta_3) + \cos(7\theta_4) + \cos(7\theta_5) &= 0 \\
\cos(11\theta_1) + \cos(11\theta_2) + \cos(11\theta_3) + \cos(11\theta_4) + \cos(11\theta_5) &= 0 \\
\cos(13\theta_1) + \cos(13\theta_2) + \cos(13\theta_3) + \cos(13\theta_4) + \cos(13\theta_5) &= 0
\end{aligned} \tag{2-5}$$

where

$$K = \frac{\pi V_p}{4} \tag{2-6}$$

V_p is defined by

$$V_{\min} < V_p < \frac{4s}{\pi} \tag{2-7}$$

and

V_p – is the desired peak magnitude of the phase voltage's fundamental frequency.

$V_{\min}$ – is a minimum value determined by discretion where an advantage is gained by reducing the number of steps.

s – is the number of steps (for this example $s = 5$).

Note that K may be defined several different ways depending on the application and control method. Tolbert defines K as sM_i , where M_i is the modulation index [6]. The modulation index is $V_L^*/V_{L\max}$ where V_L^* is the amplitude command of the output phase voltage, and $V_{L\max}$ is the maximum attainable amplitude of the inverter [6]. The fundamental-frequency component of the waveform is controlled by the switching angles that correspond to M_i . Also, the maximum V_p in (2-7) occurs when (2-5) has no solution for the switching angles as V_p approaches $4s/\pi$. The multilevel inverter can operate in the

square wave mode (when $V_p = 4s/\pi$), however, (2-5) is only valid over a selected range that was not determined in this study.

Using this technique to solve for the angles is computationally intensive and requires an iterative technique [3, 6]. For $V_p = 5.00$ and using step-sizes of unity magnitude, the angles were determined to be

$$\theta_1 = 7.86^\circ, \theta_2 = 19.37^\circ, \theta_3 = 29.65^\circ, \theta_4 = 47.68^\circ, \theta_5 = 63.21^\circ.$$

The angles were determined such that the peak magnitude of the fundamental-frequency voltage component was 5.00 volts, and the lower dominant harmonics (5th, 7th, 11th, and 13th) for three-phase systems equal zero. Theoretically, for three-phase systems, a filter that eliminates the upper harmonics above the 15th would yield a THD of zero in the line voltage.

2.2.2.2 Minimizing the Total Harmonic Distortion

The switching angles may also be solved to minimize the total harmonic distortion. Equation (2-4) was squared to yield

$$THD^2 = \left(\frac{[f(t)]_{RMS}}{[f_1(t)]_{RMS}} \right)^2 - 1 \quad (2-8)$$

To minimize (2-8), the partial derivative of (2-8) was taken with respect to each switching angle and set equal to zero. A generalized formula was developed, by substituting (2-3) and (2-4) into (2-8) and differentiating (2-8) to determine the partial derivatives. This was a time consuming process, but saved considerable time because the s system of equations could be written. It can be shown that the simplified general formula is

$$\frac{\partial THD^2}{\partial \theta_n} = (2n-1) \sum_{k=1}^s \cos(\theta_k) + \left[2 \sum_{k=1}^s (2k-1) \theta_k - \pi s^2 \right] \sin(\theta_n) = 0 \quad (2-9)$$

where n is the n^{th} switching angle. Using (2-9) for a five-step waveform produced five nonlinear transcendental equations with five variables whose solutions are the angles that minimize the total harmonic distortion (2-8).

The optimal angles for a five-step multilevel waveform were determined to be

$$\theta_1 = 5.49^\circ, \theta_2 = 16.68^\circ, \theta_3 = 28.58^\circ, \theta_4 = 42.06^\circ, \theta_5 = 59.46^\circ.$$

Again in (2-9), the peak magnitude of the fundamental-frequency component cannot be selected, as it was in (2-5), to yield a set of optimum angles. However, a more complicated method can be used, but it requires one to determine the optimum angles subject to a constraint on the magnitude of the fundamental-frequency component.

The angles from (2-5) were determined by adjusting the value of K to have the same magnitude as the fundamental component from (2-9), $V_p = 5.1973$ V. The angles from (2-5), elimination of the lower dominant harmonics, were determined as:

$$\theta_1 = 5.30^\circ, \theta_2 = 18.65^\circ, \theta_3 = 24.53^\circ, \theta_4 = 42.20^\circ, \theta_5 = 60.80^\circ.$$

The angles from (2-9), minimizing the total harmonic distortion, were determined to be:

$$\theta_1 = 5.49^\circ, \theta_2 = 16.68^\circ, \theta_3 = 28.58^\circ, \theta_4 = 42.06^\circ, \theta_5 = 59.46^\circ.$$

Thus, the difference was slight (< 5 degrees for all of the angles). The total harmonic distortion of the two methods was 7.26% and 8.19% without filtering, the larger was from the elimination method. Thus, using the elimination method and a filter to reduce the upper harmonics is the method of choice because the magnitude of the fundamental

frequency component can be controlled. The magnitude and frequency of the sinusoidal waveform is the prime mover of the ac induction machine and must be controlled in real-time. The ideal case was assumed where the dc sources are invariant and equal in magnitude. Typical batteries in HEV drive systems are not ideal; they vary with time, and generally, are not equal.

2.3 Switching Angles when dc Sources Vary

In the next chapter, the switching angles are determined for variant dc sources using the harmonic elimination method. This method was chosen because, it can reduce the THD_v of the waveform to near zero when used with a filter, and retains control over the fundamental frequency component.

3 Switching Angles with Variant dc Sources

This chapter investigates variant dc voltage sources when used in a cascade multilevel inverter. A method to determine how to properly arrange the dc voltage sources to minimize the THD, and balance their usage while maintaining control over the fundamental-frequency component is developed, and the tradeoffs between operating at optimal and near-optimal positions are examined for real-time deployment.

3.1 The Lead-Acid Battery as a dc Source

In many HEV applications, the primary energy storage component is the lead-acid battery. In this thesis, the separate dc sources were assumed to behave similar to the lead-acid battery, furthermore, its nominal voltage of 12.0 V was normalized to 1.0 V to simplify the calculations and discussion.

In the cascade multilevel inverter, as was shown in Chapter 2 (Figure 2-7), the batteries are separated and independently connected to an H-bridge. Thus, in a real application, the duty cycle for each voltage level must be rotated to ensure that the batteries discharge equally [3, 4, 6]. In the simplest case, the duty cycle can be rotated using a set pattern if the batteries have equal magnitudes. However, several independent batteries do not have equal magnitudes, and vary with time and load, therefore, rotating the duty cycle must consider the voltage variation from the lowest to the highest dc voltage source. Ideally, the lowest battery voltage is assigned the lowest duty cycle, meaning that it is on the least amount of time, and the highest battery voltage is assigned the highest duty cycle.

In general, lead-acid batteries have slightly different voltages due to their individual load imbalance and nonlinear characteristics, where the nominal voltage of a standard lead-acid battery is 12.0 V and was assumed to vary from 10.8 to 13.2 V when discharged or charged, respectively. Several definitions are used to define the terminal voltage which classifies the state of a lead-acid cell, however, for this discussion, assuming 10.8 V as the discharged state and 13.2 V as the charged state is reasonable [9, 10]. Therefore, the normalized battery voltage is 0.90 to 1.10 for the discharged and charged state, respectively. Although, most of the batteries may vary by less than 2% from the mean battery voltage, for analysis, the worst case assumes a 10% variation, that is, one battery is mostly discharged (0.90 V), another is mostly charged (1.10 V), and the remaining batteries are evenly distributed in between.

The analysis will be discussed using a 5-step multilevel waveform to determine the proper method to sort the independent voltage sources. One may assume that arranging the dc voltage sources from the highest battery voltage with the longest duty cycle to the lowest battery voltage with the shortest duty cycle is the ideal order. However, the order in which the independent batteries are used to generate the multilevel waveform changes the harmonic content and the switching angles must be properly determined for the voltage source pattern.

3.2 Sorting dc Voltage Sources

In Chapter 2, the separate dc sources were considered constant with unity magnitude and the angles were found to eliminate the 5th, 7th, 11th, and 13th harmonics. In this chapter, the THD, and harmonic content is examined using the harmonic elimination

method. This method was chosen as the primary tool for calculating the switching angles when the dc sources vary for several reasons. First, the general equation (modified from (2-1) and introduced in section 3.3.4) is simpler to program and modify than the optimal equation (2-9), and the Jacobian matrix can be calculated which aids in solving the system of nonlinear equations. Second, it yields a greater reduction in the THD_v when combined with a filter to remove the higher harmonics because it eliminates selected lower dominant harmonics. Finally, a single degree of freedom can be used to control the magnitude of the fundamental-frequency component.

Two variations of the harmonic elimination method are examined. The first uses fixed switching angles with perturbed dc sources, and the second case calculates the switching angles using different voltage magnitudes for the dc sources. The THD_v of the multilevel waveform will be different for the two cases because varying either the battery voltage or the switching angles affects the harmonic content. The first case is similar to using ideal batteries whose unity magnitudes are perturbed, however, the order that the batteries are switched on to synthesize the multilevel waveform is unique. In addition, the batteries' voltage must be balanced to ensure that they are within a safe operating range and to avoid damage due to over discharging. Using this technique also functions as a battery management system, where the duty cycle of the individual batteries can be controlled, or skipped in case of failure. In the second case, the switching angles are solved for a selected order of the dc voltage sources.

3.3 Multilevel Waveform Analysis of Variant dc Voltage Sources

In this section, the Fourier series of the multilevel waveform using variant dc sources will be introduced. In section 3.3.1, the switching order is investigated using perturbed dc sources, and in section 3.3.2, the switching angles are calculated using the harmonic elimination method with variant dc sources. Then, a discussion and summary of the two methods is presented in section 3.3.3. Also, the equations that were used to simplify the analysis are presented in a vector and matrix-based form in section 3.3.4.

The vector representation is included for completeness and allows the equations to be expressed in a condensed form using matrices, which can be programmed for computer simulation or implemented with a DSP chip. There was also a motivation to use a DSP chip to calculate the switching angles in real-time for minimal total harmonic distortion using the harmonic elimination method and a filter to remove the higher frequencies; also, the vector and matrix environment is ideal for programming and data manipulation. However, solving the s nonlinear transcendental systems of equations is computational intensive because the process requires an iterative approach. The speed by which the solution must converge is in the microsecond range, determined by the desired switching frequency, which is not attractive for DSP chips (modern computers with a 450MHz processor can solve a system of 5 nonlinear transcendental equations within a second). In addition, a good initial guess to the solution is required for convergence.

A multilevel waveform with variant dc sources, as shown in Figure 3-1, may be expressed as

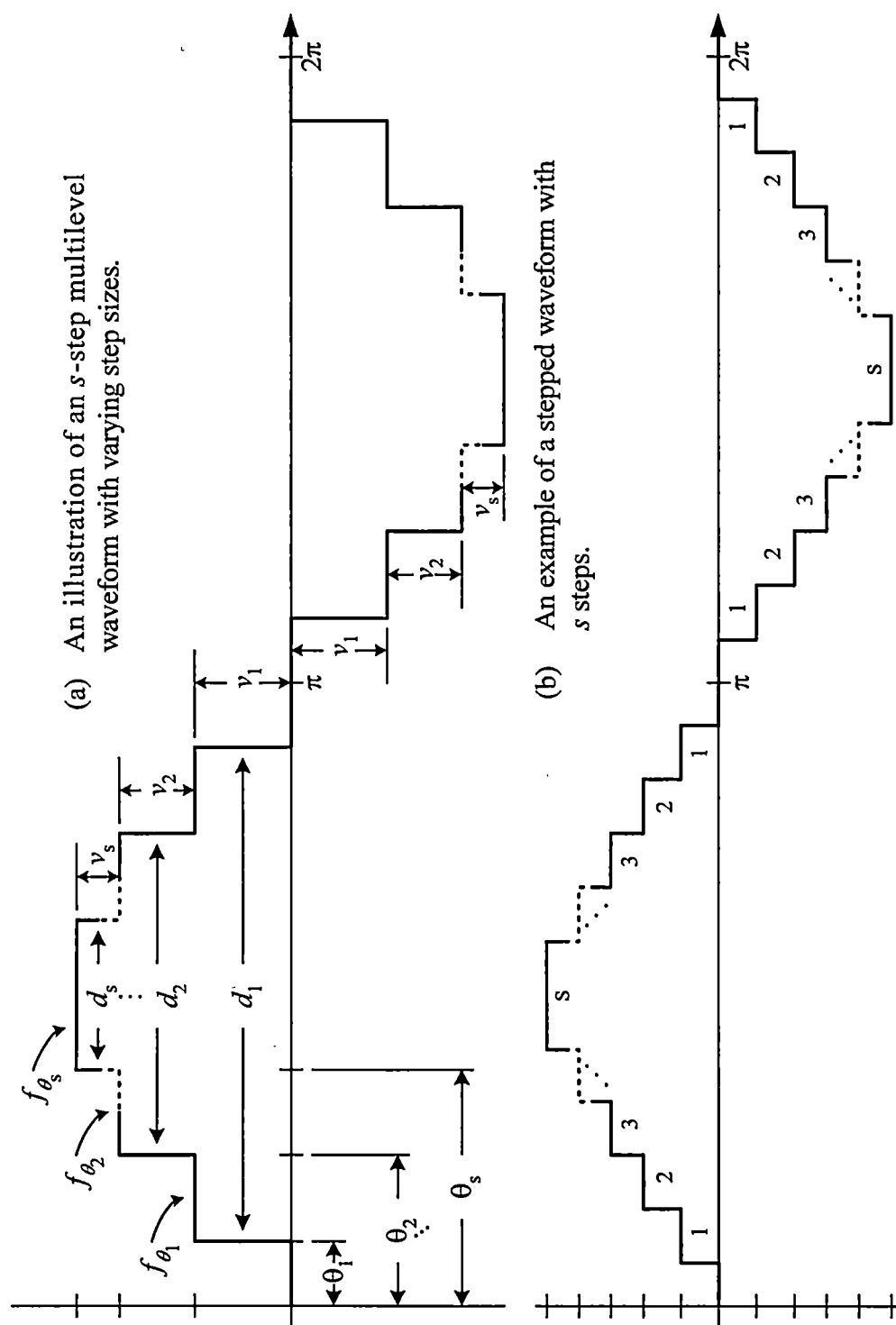


Figure 3-1: Multilevel Waveforms.

$$\begin{aligned}
 f(t) &= f_{\theta_1}(t) + f_{\theta_2}(t) + \cdots + f_{\theta_s}(t) \\
 &= \frac{4}{\pi} \sum_{\substack{h=1 \\ \text{odd}}}^{\infty} [v_1 \cos(h\theta_1) + v_2 \cos(h\theta_2) + \cdots + v_s \cos(h\theta_s)] \frac{\sin(h\omega t)}{h} \quad (3-1)
 \end{aligned}$$

where v_1, v_2 , etc. are the magnitudes of the dc voltage sources. Equation 3-1 was modified from (2-1) by allowing the magnitudes of each step to vary. Note that in Chapter 2, the dc sources were assumed constant with unity magnitudes.

Let the s separate dc voltage sources for phase a of a cascade multilevel inverter be defined as

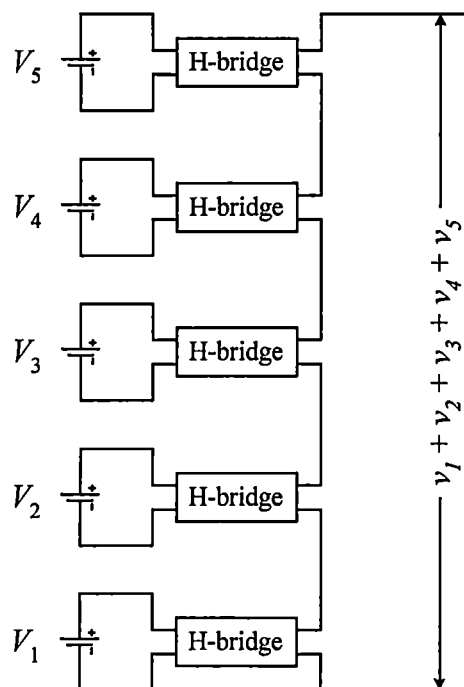
$$\mathbf{V}_a = [V_{a1} \quad V_{a2} \quad \cdots \quad V_{as}]^T \quad (3-2)$$

where the individual voltage sources can be switched at various times and duty cycles to produce the multilevel waveform, as shown in Figure 3-2. The individual voltage source V_{ai} will be used to identify a particular battery, for example, V_{a1} , and V_{a2} , denote their permanent physical location and can be used in the synthesized waveform anywhere by controlling the switching patterns. Also, let the magnitude of the voltage of each battery be variable with a range

$$v_{\min} \leq v_{nom} \leq v_{\max} \quad (3-3)$$

where the nominal voltage is 1.0 V, normalized to represent 12.0 V. The selected minimum and maximum values are 0.90 V and 1.10 V. For example, the voltage source V_1 can have a value anywhere between 0.90 and 1.10 V, V_2 can also have the same range, and so on for the s dc sources. Let the individual steps of the multilevel waveform have measured values, defined by

$$\mathbf{v}_a = [v_{a1} \quad v_{a2} \quad \cdots \quad v_{as}]^T. \quad (3-4)$$



Each voltage source is independent and may be connected at various times and duty cycles to produce the multilevel waveform. For example, if the individual voltages are measured to be

$$\mathbf{V} = [V_1 \ V_2 \ V_3 \ V_4 \ V_5]^T$$

$$= [0.90 \ 1.10 \ 0.95 \ 1.05 \ 1.00]^T$$

the desired multilevel waveform can be synthesized using the voltage sources as shown below.

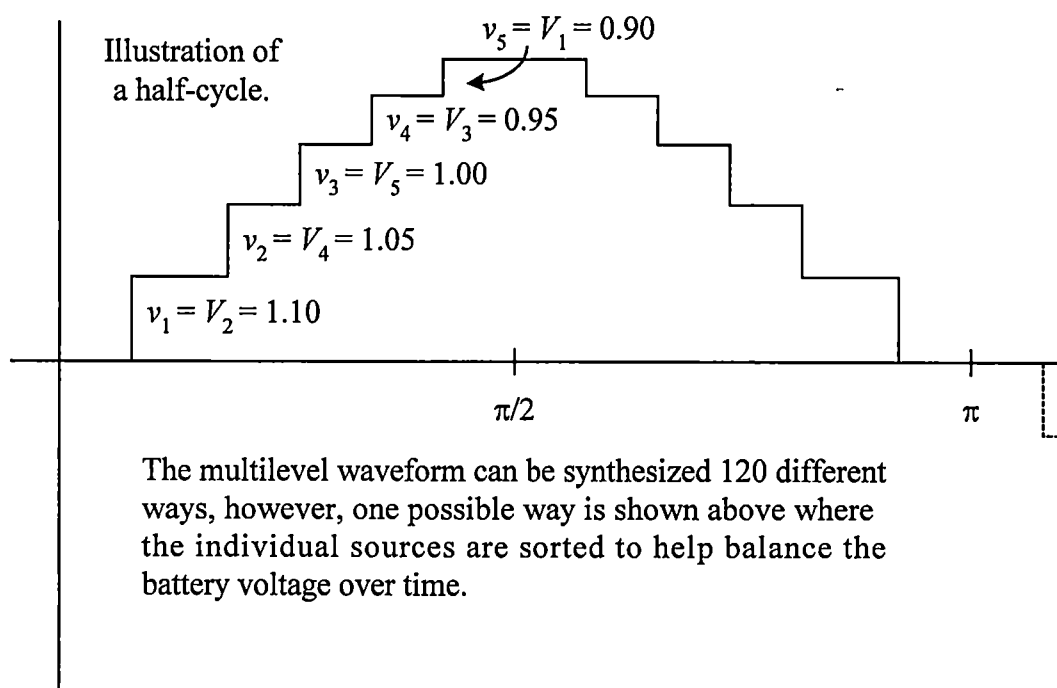


Figure 3-2: Synthesis of a multilevel waveform.

Now, the voltage magnitudes in $\mathbf{v}_a$ correspond to the stepped waveform. The next step is to sort the voltage sources $\mathbf{V}_a$ in the proper order to synthesize the multilevel waveform. In an application, the order of $\mathbf{V}_a$ will be controlled and rotated based on duty cycle and voltage. Let the duty cycle of each step of the multilevel waveform be defined as

$$\mathbf{d}_a = [d_1 \quad d_2 \quad \cdots \quad d_s] \quad (3-5)$$

where $d_1 = \pi - 2\theta_1$, $d_2 = \pi - 2\theta_2$, and $d_s = \pi - 2\theta_s$ represent the duty cycles (or the pulse widths) of a half-cycle and depends only on the switching angles

$$\boldsymbol{\Theta} = [\theta_1 \quad \theta_2 \quad \cdots \quad \theta_s]^T. \quad (3-6)$$

Initially, the analysis will be done using a single phase, however, the three-phase system will be examined later because it becomes more complicated with three dependent systems which contain three times as many dc sources and control requirements.

3.3.1 Switching Order with Perturbed dc Sources

In this section, the switching angles were determined from unity dc voltage sources and fixed so that the effect of perturbing voltages can be examined. When batteries have unlike voltages, combining them in a particular order is important because it changes the harmonic content and qualities of the waveform (THD_v, voltage ripple, and fundamental frequency magnitude) and it also affects the voltage of the individual batteries. For example, V_1 can be turned on as the first step with the longest on time, or it can be turned on as the last step with the shortest duty cycle. The other batteries can be switched in a finite number of ways resulting in the overall multilevel waveform, however, the different voltage-step patterns affect the THD_v of the multilevel waveform and duty cycle

of the batteries. Therefore, one desires a pattern that minimizes the THD_v and optimizes the duty cycle such that the batteries can be balanced with equal magnitudes.

For a s -step multilevel waveform there exists a finite number of ways to use the s batteries. A three-step multilevel waveform can be combined using $2 \cdot 3 = 6$ different switching patterns, and a five-step multilevel waveform can be combined using $2 \cdot 3 \cdot 4 \cdot 5 = 120$ different voltage-step patterns. The maximum possible voltage-step permutations for a s -step multilevel waveform can be determined by $s! = 2 \cdot 3 \cdot 4 \cdots s$, where s represents the number of steps of the multilevel waveform. Therefore, considering that the switching angles are fixed, the THD_v is investigated for each switching pattern using a predetermined set of perturbed dc voltage sources.

The THD_v is calculated for each permutation and sorted in increasing order. For example, a three-step waveform can have the following six voltage arrangements for V_a :

$$\begin{array}{lll} (1) [V_1 & V_2 & V_3] \quad (3) [V_2 & V_1 & V_3] \quad (5) [V_3 & V_1 & V_2] \\ (2) [V_1 & V_3 & V_2] \quad (4) [V_2 & V_3 & V_1] \quad (6) [V_3 & V_2 & V_1] \end{array} \quad (3-7)$$

The voltage sources in (3-7) can be switched in any order, however, to simplify the discussion, the voltage of each individual step of the multilevel waveform is varied instead of attempting to arrange the batteries in the proper order. The same result is achieved by assuming that the batteries are arranged in a fixed order with only their magnitudes determined from the permutations. For example, the 5-step waveform has 120 different possibilities, which means that each of the five batteries can have five different values, but their order does not change. In actuality, the H-bridges are switched at selected times to produce the desired voltage-step pattern. Assuming the desired voltages v_a are known, the THD_v can be calculated for each permutation of v_a and sorted

by increasing THD_v . It should be pointed out that the fundamental's magnitude V_p is dependent on the order, the voltages v_a , and the switching angles. The desired operating point for balancing battery voltage is when the largest voltage has the longest duty cycle, and the smallest voltage has the smallest duty cycle.

Let the dc voltage sources have the following magnitudes for a 5-step waveform

$$\mathbf{v}_a = \mathbf{V}_a = [1.10 \quad 1.05 \quad 1.00 \quad 0.95 \quad 0.90]^T \quad (3-8)$$

which is the desired voltage-step pattern because the duty cycle allows the batteries to be balanced by assigning the smaller battery voltage to the shortest duty cycle and the higher battery voltage to the longer duty cycle. Note that there are 120 different ways of arranging the voltages in (3-8), and each permutation produces a particular THD_v and fundamental frequency magnitude. A plot of the 120 permutations vs. the THD_v for a single-phase multilevel waveform is shown in Figure 3-3.

In Figure 3-3, the THD_v was determined for each permutation of (3-8) and sorted from lowest THD_v to highest. The order in (3-8) was shown to occur at the 2nd sorted permutation, which is the desired voltage pattern. The plot was determined using the switching angles calculated for $V_p = 5.00$ V and using step-sizes of unity magnitude. Therefore, by varying only the magnitudes and assuming that the angles were fixed, the desired operating point occurred near the lower portion of the THD_v curve for the permutations. It should also be noted that the THD_v was determined without any filtering of the phase voltage. The first 20 of the 120 sorted permutations are shown in Table 3-1.

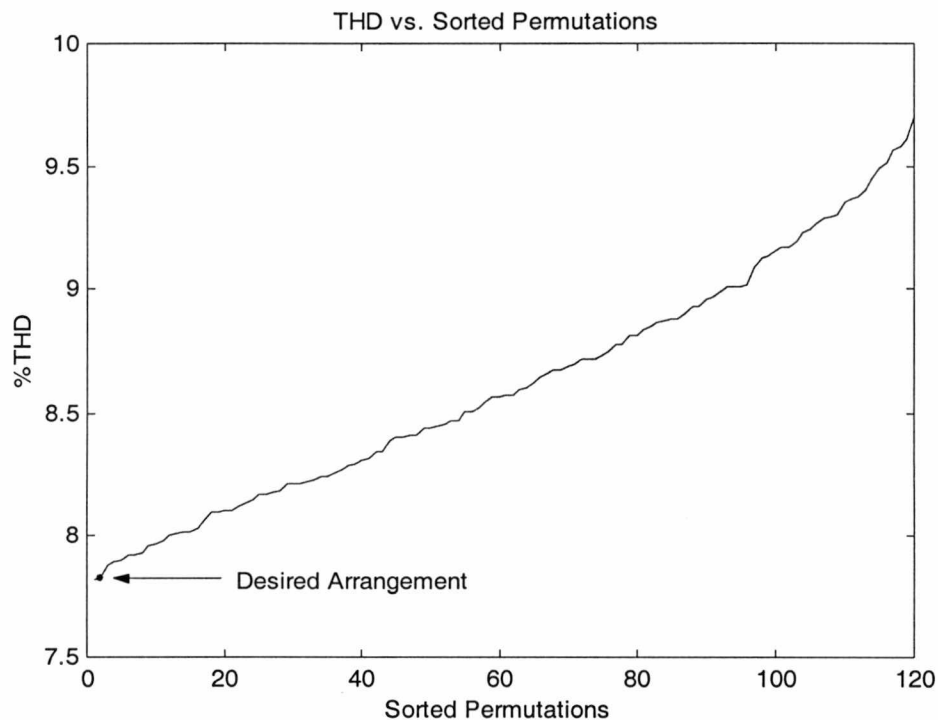


Figure 3-3: Illustration of the THD_v vs. the permutations of v_a .

Table 3-1
 THD_v and sorted permutations for the five-step waveform.

THD	V1	V2	V3	V4	V5
7.8157	1.1000	1.0000	1.0500	0.9500	0.9000
7.8190	1.1000	1.0500	1.0000	0.9500	0.9000
7.8735	1.1000	1.0500	0.9500	1.0000	0.9000
7.8882	1.1000	0.9500	1.0500	1.0000	0.9000
7.8992	1.0500	1.1000	1.0000	0.9500	0.9000
7.9154	1.1000	1.0000	1.0500	0.9000	0.9500
7.9183	1.0500	1.0000	1.1000	0.9500	0.9000
7.9219	1.1000	1.0500	1.0000	0.9000	0.9500
7.9517	1.0500	1.1000	0.9500	1.0000	0.9000
7.9608	1.1000	1.0000	0.9500	1.0500	0.9000
7.9788	1.1000	0.9500	1.0000	1.0500	0.9000
7.9995	1.0500	1.1000	1.0000	0.9000	0.9500
8.0049	1.0000	1.1000	1.0500	0.9500	0.9000
8.0123	1.0500	0.9500	1.1000	1.0000	0.9000
8.0123	1.0500	1.0000	1.1000	0.9000	0.9500
8.0272	1.0000	1.0500	1.1000	0.9500	0.9000
8.0551	1.1000	1.0500	0.9000	1.0000	0.9500
8.0941	1.1000	1.0500	0.9500	0.9000	1.0000
8.0963	1.1000	0.9500	1.0500	0.9000	1.0000
8.0995	1.0000	1.1000	1.0500	0.9000	0.9500

In Table 3-1, the order that the dc sources are turned on to synthesize the sinusoid affects the THD_v of the waveform. Also, as discussed earlier to simplify the analysis, the location and order of the voltage sources are assumed fixed, but the magnitude varies depending on the particular permutation. The THD_v of the voltage waveform was 7.82% for the desired charge-balancing order.

In Chapter 2, the fundamental magnitude could not be adjusted for the optimal case, which yielded a THD_v of 7.26%, so for a proper comparison, the magnitude of the fundamental for the harmonic elimination method was adjusted to be the same as the optimal case, which yielded 8.19%. The THD_v of the waveform using the harmonic elimination method (previously determined in Chapter 2, where $V_p = 5.0$ V and using unity magnitude voltage sources) was 8.48%, but using the order in (3-8) resulted in a THD_v of 7.82%. Therefore, properly sorting the perturbed voltage sources actually decreased the THD_v , but the switching angles were fixed (assuming equal dc sources). Although, the THD_v of the waveform decreased, the desired harmonics chosen to be eliminated from the three-phase system were not equal to zero because the angles were determined assuming the voltage sources were unity, but the unity voltage sources were perturbed and replaced by (3-8). The magnitude of the fundamental component also changed, it increased from $V_p = 5.0$ to 5.086 V.

The harmonics of the waveform with perturbed voltage sources and fixed switching angles, determined from unity sources, is illustrated in Figure 3-4. The fundamental component has a magnitude of 5.086 V and is off scale to emphasize the harmonics. The 5th, 7th, 11th, and 13th harmonics are not eliminated because the voltage

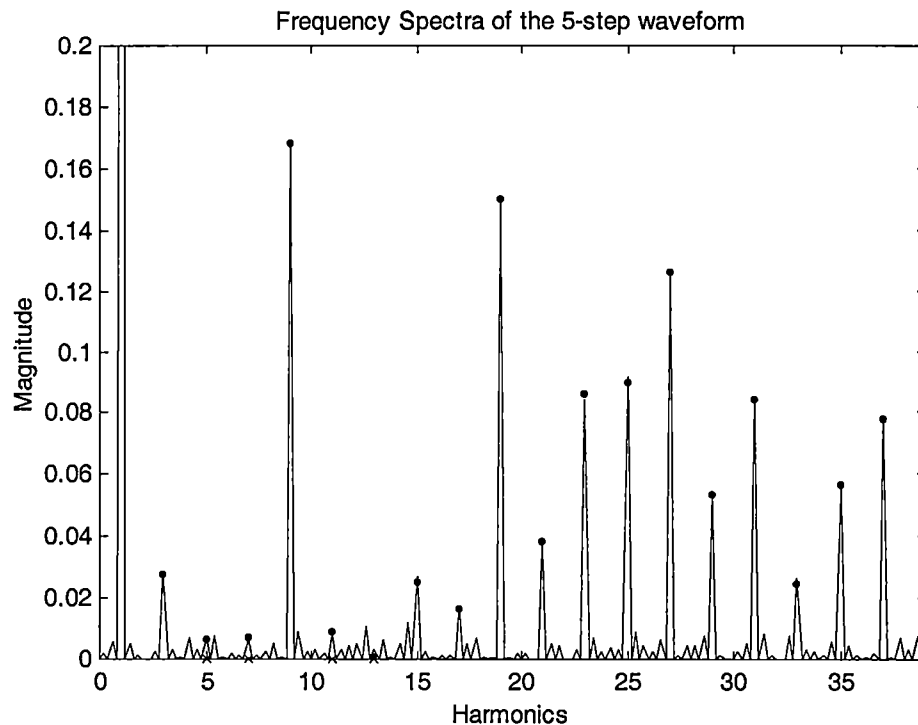


Figure 3-4: Harmonics of the multilevel waveform with different voltage sources.

sources are not unity. However, the next section determines the switching angles to eliminate the desired harmonics due to the different voltages.

3.3.2 Determining Switching Angles for Different Voltages

In this section, the switching angles are determined to eliminate the 5th, 7th, 11th, and 13th harmonics for the multilevel waveform using different voltage magnitudes, given by (3-8), and using the control voltage V_p to control the peak magnitude of the fundamental-frequency component. The switching angles are determined by varying V_p and keeping the desired voltage switching order as in (3-8).

3.3.2.1 Varying the Control Voltage

First, the switching angles are investigated as a function of the control voltage V_p given the switching order defined by (3-8). The switching angles and THD_v as a function of V_p are shown in Figure 3-5 and 3-6. The switching angles are shown over a finite region where the bottom curve is θ_1 , the curve above it is θ_2 , and so on to the top curve which is θ_5 , in other words, $\theta_1 < \theta_2 < \theta_3 < \theta_4 < \theta_5$. Note that near $V_p = 4.85$ and $V_p = 5.45$ V, the switching angles θ_1 and θ_2 converge to the same point, likewise for θ_4 and θ_5 . This causes the iterative routine to diverge and fail to return a valid solution; a solution outside of this range requires a different starting guess to determine the switching angles, and V_p

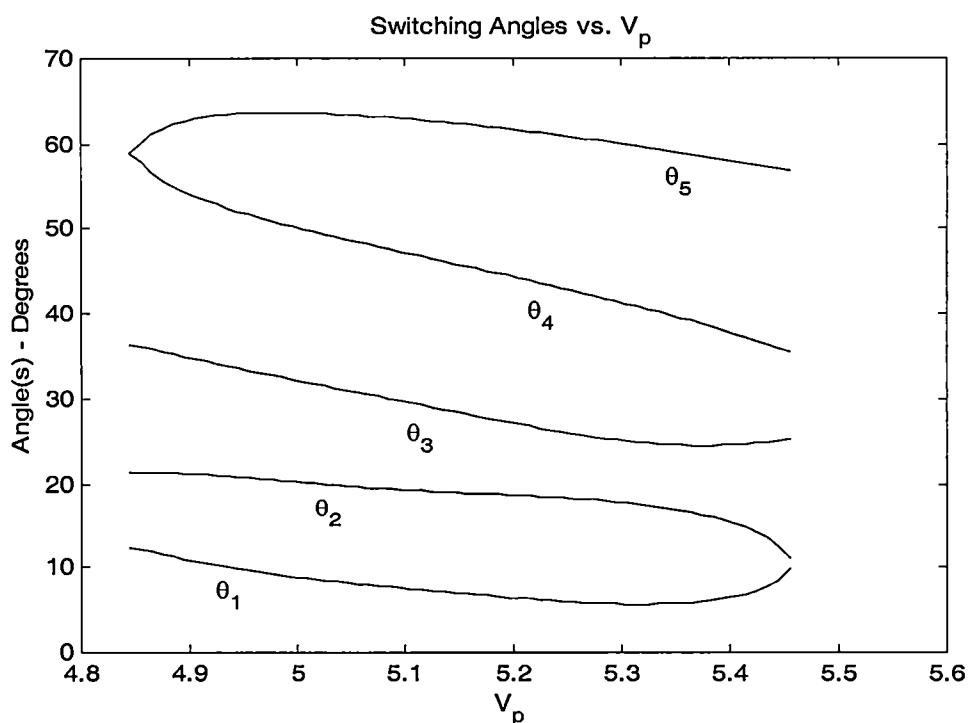


Figure 3-5: Switching angles versus the control voltage over a finite region.

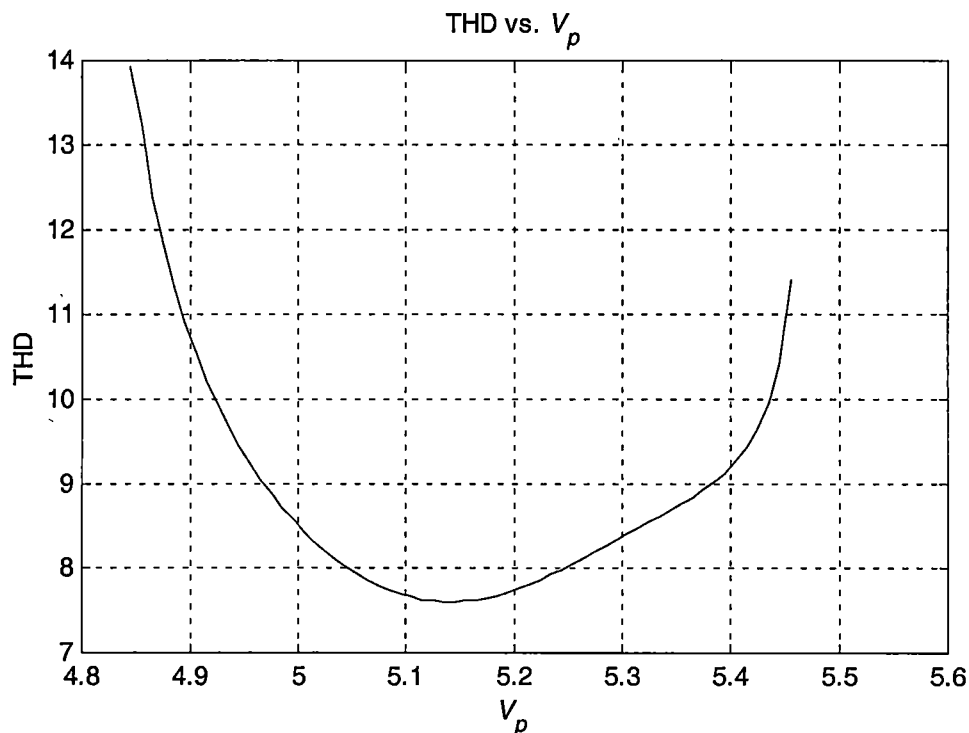


Figure 3-6: Total harmonic distortion of the waveform versus the control voltage.

outside of this range and may produce drastically different angles that still satisfy the system of equations. Also, an initial guess that is used to solve the system of nonlinear equations may yield different switching angles within this range.

The minimum THD_v in Figure 3-6 is 7.60% ($V_p = 5.145$ V), which was determined by calculating the switching angles over a finite range of V_p to eliminate the selected harmonics. The THD_v at $V_p = 5.0$ V was 8.49% which is higher than before (Table 3-1) when the switching angles were determined from unity voltage sources and the voltage pattern selected based on (3-8). Thus, the THD_v increased from 7.82% to 8.49%, however, it varied slightly from the invariant unity case which yielded a THD_v of 8.48%. The harmonics are shown in Figure 3-7 with $V_p = 5.0$ V.

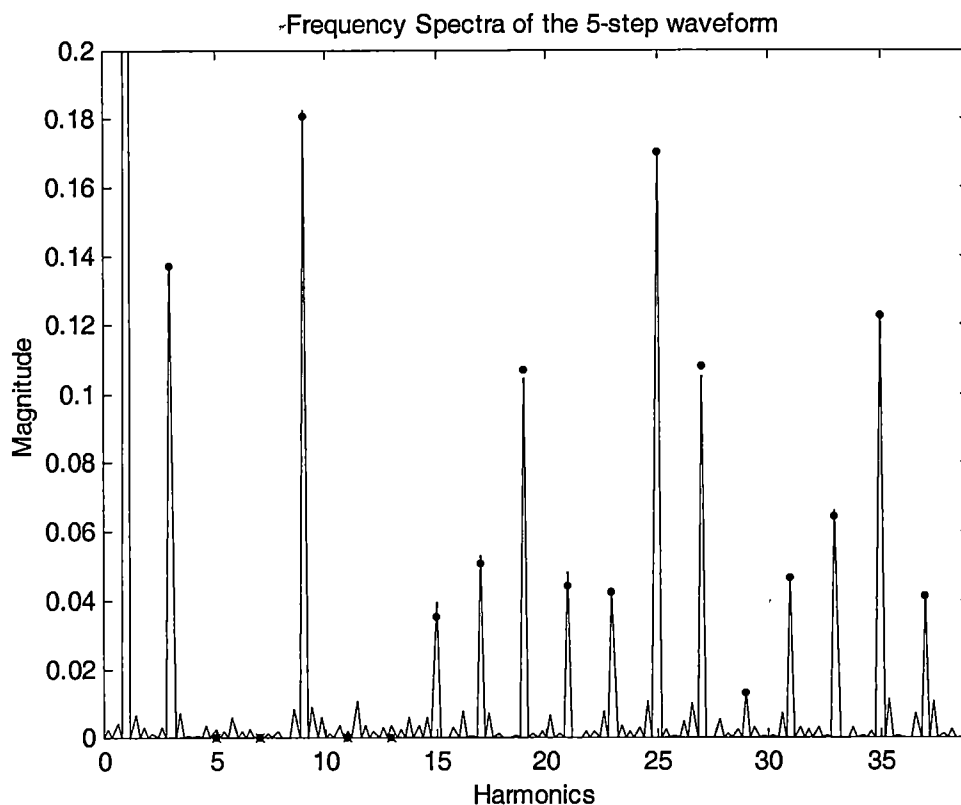


Figure 3-7: Harmonics of the multilevel waveform with selected harmonics eliminated.

The 5th, 7th, 11th, and 13th harmonics are eliminated because the switching angles were chosen to eliminate them subject to the voltage order in (3-8). The fundamental-frequency component magnitude is 5.00 V (off scale). The THD_v was calculated from a single phase, and it should be noted that the harmonics that are a multiple of 3 are eliminated in a balanced three-phase system, thus, the THD in the three-phase line voltage would be much less than that calculated for phase voltage. Figure 3-6 (discussed in Ch. 4) shows the THD_v as V_p varies using the switching angles in Fig. 3-5.

3.3.3 Comparison of the Two Methods

In this section, the two methods of section 3.2.1 and 3.2.2 are discussed. Although there are several ways to minimize the THD_v , the basic strategy was to compare the THD_v of the phase voltage for the two methods and consider their computational requirements.

First, the simplest case was examined by perturbing only the magnitudes of the multilevel steps and observing the THD_v associated with each permutation. In this method, the switching angles were determined in Chapter 2 and remained fixed during the analysis. A decrease in the total harmonic distortion was observed due to sorting the multilevel steps, and the 5th, 7th, 11th, and 13th harmonics had *nonzero* values of 6.5, 6.6, 9.1, 0.7 mV, respectively, as was illustrated in Figure 3-4. The partial harmonic distortion of the 5th, 7th, 11th, and 13th harmonics was

$$\frac{\sqrt{6.5^2 + 6.6^2 + 9.1^2 + 0.7^2} \text{ mV}}{5.086 \text{ V}} (100\%) = 0.26\%.$$

The batteries were perturbed to unequal values, where the most charged battery had the highest duty cycle, and the battery with the least charge was assigned the lowest duty cycle to help balance their voltage.

In the second case, the switching angles were solved for the different magnitudes of the multilevel steps and the THD_v was observed and compared to the previous case. The desired magnitude of the fundamental-frequency component V_p was varied, and the switching angles over a finite range were plotted as a function of the control voltage. Also, the THD_v of the waveform was plotted as a function of the control voltage to

illustrate the minimum harmonic distortion. The harmonics were examined to verify that the 5th, 7th, 11th, and 13th harmonics had zero values.

In both cases, the computational requirement was exhaustive, but the first case, using perturbed dc sources, exhibited the best scenario for real-time implementation using a DSP chip. This was because the switching angles were not determined with each variation, which allows a faster control time. The total harmonic distortion actually was reduced using the desired voltage order in (3-8) (the 2nd of 120 sorted combinations for the THD_v). The results are summarized in Table 3-2.

Table 3-2 shows the total harmonic distortion, peak magnitude of the fundamental frequency component, and the switching angles for the 5-step multilevel waveforms discussed in Chapters 2 and 3. The table compares five cases and is divided into two sections by the double vertical line: Invariant (Ch. 2) and Variant (Ch. 3).

I. The optimal case was determined by solving for the angles that minimized the THD_v of the waveform without control over the fundamental frequency component. It had the smallest total harmonic distortion of all the methods.

II. The Harmonic Elimination Method (HEM) was used to calculate the switching angles eliminating the 5th, 7th, 11th, and 13th harmonics with the same fundamental magnitude as the optimal case. Although, the lower dominant harmonics were eliminated, the THD_v was higher than the optimal case for the phase voltage waveform.

III. The harmonic elimination method was repeated for a peak fundamental-frequency magnitude of five volts. The switching angles increased and were within 5.48°

Table 3-2
A comparison of the methods used from Chapters 2 and 3.

	Invariant dc sources with unity magnitude			Variant dc sources	
	I	II	III	IV	V
Variables	Optimal (unity dcs)	HEM (unity dcs)	HEM (unity dcs)	Fixed Angles	HEM
THD _v	7.26%	8.19%	8.48%	7.82%	8.49%
V _p	5.1973	5.1973	5.00	5.086	5.00
θ_1	5.49°	5.30°	7.86°	7.86°	8.82°
θ_2	16.68°	18.65°	19.37°	19.37°	20.21°
θ_3	25.58°	24.53°	29.65°	29.65°	32.19°
θ_4	42.06°	42.20°	47.68°	47.68°	50.10°
θ_5	59.46°	60.80°	63.21°	63.21°	63.68°

of the angles calculated from the previous case, however, the peak magnitude decreased by 0.20 volts, which is reasonable for a small voltage change.

IV. The switching angles from II were fixed and the different voltages of (3-8) were reordered, that is, permuted. This decreased the total harmonic distortion of the waveform and increased the magnitude of the fundamental frequency component. The desired voltage pattern was the 2nd of 120 different patterns when arranged by increasing THD_v.

V. The switching angles were determined to eliminate the selected harmonics to produce the desired 5.00 V magnitude of the fundamental frequency component for a

direct comparison to **III**. This waveform had the highest harmonic distortion and was similar to **III**, with the switching angles within approximately 2.5° of those in **III**.

3.3.4 Equations and Vector Matrix Notation

In this section, the equations that were used to solve for the switching angles for variant dc sources are illustrated. Similar to (2-5), the system of nonlinear transcendental equations to eliminate the 5^{th} , 7^{th} , 11^{th} , and 13^{th} harmonics for a 5-step multilevel waveform is represented by

$$\begin{aligned} v_1 \cos(\theta_1) + v_2 \cos(\theta_2) + v_3 \cos(\theta_3) + v_4 \cos(\theta_4) + v_5 \cos(\theta_5) &= K \\ v_1 \cos(5\theta_1) + v_2 \cos(5\theta_2) + v_3 \cos(5\theta_3) + v_4 \cos(5\theta_4) + v_5 \cos(5\theta_5) &= 0 \\ v_1 \cos(7\theta_1) + v_2 \cos(7\theta_2) + v_3 \cos(7\theta_3) + v_4 \cos(7\theta_4) + v_5 \cos(7\theta_5) &= 0 \quad (3-9) \\ v_1 \cos(11\theta_1) + v_2 \cos(11\theta_2) + v_3 \cos(11\theta_3) + v_4 \cos(11\theta_4) + v_5 \cos(11\theta_5) &= 0 \\ v_1 \cos(13\theta_1) + v_2 \cos(13\theta_2) + v_3 \cos(13\theta_3) + v_4 \cos(13\theta_4) + v_5 \cos(13\theta_5) &= 0 \end{aligned}$$

where K was defined by (2-6). Note that the system in (3-9) may be written in a generalized compact form as

$$\mathbf{v}_a^T \cos(\mathbf{h}\mathbf{\Theta}^T) = \mathbf{K} \quad (3-10)$$

where $\mathbf{v}_a$, $\mathbf{\Theta}$, $\mathbf{h}$, and $\mathbf{K}$ are s -vectors defined in (3-9) as

$\mathbf{v}_a = [v_{a1} \ v_{a2} \ v_{a3} \ v_{a4} \ v_{a5}]^T$ = the independent dc voltage sources

$\mathbf{\Theta} = [\theta_1 \ \theta_2 \ \theta_3 \ \theta_4 \ \theta_5]^T$ = the switching angles

$\mathbf{h} = [1 \ 5 \ 7 \ 11 \ 13]^T$ = the fundamental and selected harmonics to eliminate

$\mathbf{K} = [K \ 0 \ 0 \ 0 \ 0]^T$ = the parameter used to control the fundamental's magnitude and eliminate selected harmonics (5^{th} , 7^{th} , 11^{th} , and 13^{th}).

4 Control Voltage and Three-Phase Analysis

In this chapter, the total harmonic distortion of the multilevel waveform is examined over a wider range of control voltage V_p than that used in Chapter 3, and the total harmonic distortion of the line-to-line voltage of a three-phase multilevel waveform is determined.

4.1 Control Voltage

In Chapter 3, the control voltage was used to adjust the peak magnitude of the fundamental frequency component and was varied over a finite range. Also in Chapter 3, the switching angles were solved to eliminate the 5th, 7th, 11th, and 13th harmonics over a finite range of the control voltage (which was illustrated in Figures 3-5 and 3-6), and the total harmonic distortion was determined based on the switching angles and the control voltage, which is shown again in Figure 4-1.

In Figure 4-1, the THD_v was minimal at $V_p = 5.145 \text{ V}$ and increased as V_p varied. At both endpoints, the THD_v increased significantly, which appears that operating over a finite range of V_p is less than desirable because of the increased THD_v . However, it also suggests that the five-step multilevel waveform can be reduced to a four-step waveform, or a three-step waveform and so on depending on the specific control requirements. It is intuitively obvious that reducing the number of steps to synthesize the waveform will reduce the magnitude of the fundamental-frequency component, however, it is not obvious how the THD_v varies by reducing the number of steps. Also, by choosing 4-of-5, or 3-of-5, etc., of the available dc sources allows more flexibility in combining the dc

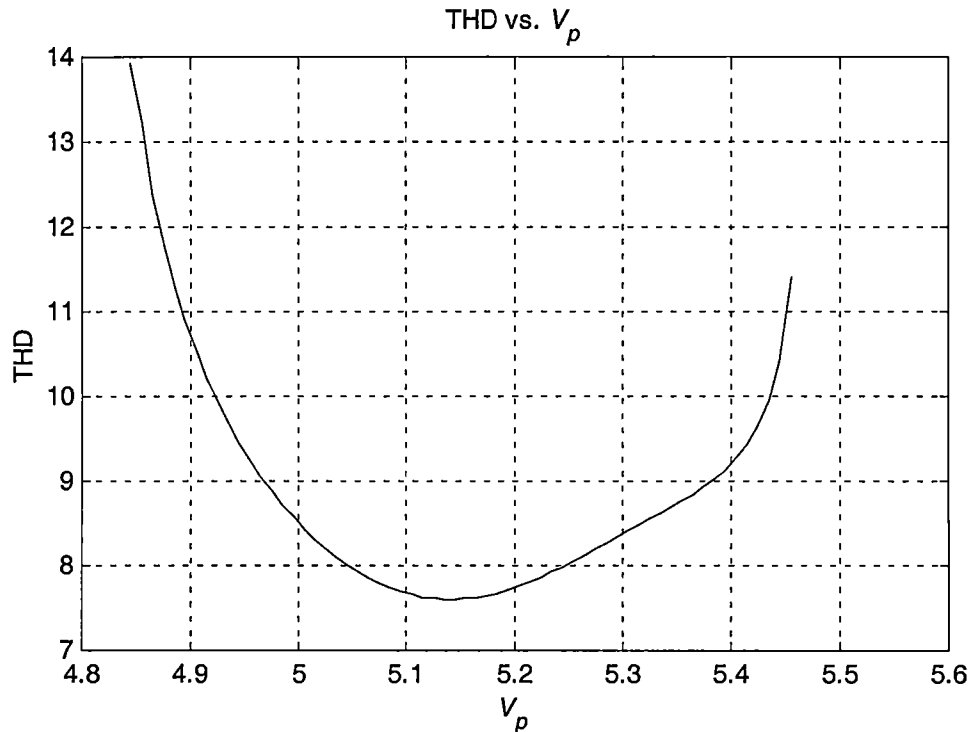


Figure 4-1: Total harmonic distortion of the waveform versus the control voltage

sources, which allows some to be skipped or used frequently depending on their battery voltage.

In this section, the switching angles and the THD_v of the multilevel waveform will be investigated over a wider range of control voltage. Expanding the range of the control voltage requires using less of the dc sources to synthesize the multilevel waveform, or reducing the number of steps used to synthesize the multilevel waveform. Step dropping is used to reduce the magnitude of the fundamental-frequency component while maintaining minimal THD_v and voltage balance of the individual dc sources.

4.1.1 Sorting the dc Sources and Reducing the Number of Steps

When the number of steps are reduced in a multilevel waveform the number of dc sources required also decrease. For example, in a five-step waveform there are 120 different ways to combine five dc sources to synthesize the multilevel waveform. However, using only 2-of-5 dc sources yields 20 different ways to synthesize the waveform and using 1-of-5 dc sources yields five ways to generate a single alternating pulse. This allows the dc sources to be rotated and combined in such a way to minimize the THD_v of the multilevel waveform. The THD_v can be calculated for each permutation as before to determine the best operating point and combination of dc sources. Although, a desired method to regulate the battery voltage is to allow the battery with the highest voltage be assigned the longest duty cycle and the battery with the lowest battery voltage to be skipped. It should also be noted that the H-bridge can be used to charge a weak battery at the expense of the other batteries, however, this is generally not preferred because some of the energy is lost during the transfer and charging, resulting in a poor efficiency.

Although, in addition to using conventional friction (brake pads) to slow down a moving vehicle, the propulsion system may be operated as a generator. During regeneration (regenerative braking), when the propulsion system operates as a generator slowing the vehicle down, the weaker batteries can be charged by assigning them a longer duty cycle. The energy transfer using this method is moderately conservative because the energy required to slow the vehicle down goes through an energy transformation where the kinetic energy is transferred to electrical energy and then

converted to chemical energy in the batteries. This is also termed 'free energy' but it is really a basic principle of conservation. A primary advantage of using a multilevel inverter is that the weaker batteries (ones with the lowest voltage) can be charged using the longest duty cycle and the batteries with the highest voltage can be charged with the shortest duty cycle, or skipped if using less steps. Thus, it has the advantage of charging and balancing the battery voltage independently. The control scheme can become quite complex initiating the proper sequence of battery usage, switching angles, duty cycles, the number of steps to use, and other drive system control requirements.

In the next section, the five sources will be analyzed using a 4-step waveform by dropping a step and analyzing the dc sources taken 4 at a time. The THD_v and switching angles will be determined as a function of V_p , as in Chapter 3.

4.1.1.1 Using 4-of-5 dc Sources

In this section, only four dc sources from the original five are used to generate the multilevel waveform. The total harmonic distortion, switching angles, and analysis of sorting the different dc sources are investigated.

First, the dc sources are independent and have different voltages as given by

$$\mathbf{v}_a = [1.10 \quad 1.05 \quad 1.00 \quad 0.95 \quad 0.90]^T \quad (4-1)$$

which was originally defined by (3-8). Because any four of the five batteries available can be used, they may be combined in several different ways to synthesize the voltage waveform. The number of ways that the waveform can be synthesized is given by

$$P_r^n = \frac{n!}{(n-r)!} \quad (4-2)$$

which represents the number of permutations of r batteries taken from the original set of n batteries. In this example, $n = 5$ and $r = 4$ resulting in 120 different ways to synthesize the four-step multilevel waveform. Thus, the batteries can be arranged in 120 different ways, which allows flexibility in synthesizing the multilevel waveform by managing the batteries due to load imbalance and thermal considerations. However, when a battery failure occurs, it permanently reduces the five-step waveform to a four-step waveform reducing both the number of dc sources available and the possible combinations.

For a five-step multilevel waveform, skipping a failed battery (only 4 dc sources available) reduces the possible ways to synthesize the multilevel waveform from 120 to 24. Furthermore, battery failure disrupts a balanced three-phase system because all phases were assumed equal, therefore, battery failure in any one of the three phases disrupts the balanced system. Allowing any phase to have a different number of steps results in an unbalanced system, therefore, introducing harmonic content into the line voltage that was assumed to be zero by (1) superposition of the three phases, (2) adjusting the switching angles to eliminate selected harmonics, and (3) using a low-pass filter to retain the fundamental-frequency component. One way to maintain a balanced three-phase system is to reduce all of the phases evenly by the same number of steps. For example, if a battery in phase a fails, then skipping a battery in phases b and c will help to balance the system.

The plot in Figure 4-2 illustrates the total harmonic distortion of the four-step multilevel waveform for the 120 permutations. The switching angles were calculated using constant unity dc sources, which remained fixed, and the THD, was determined for

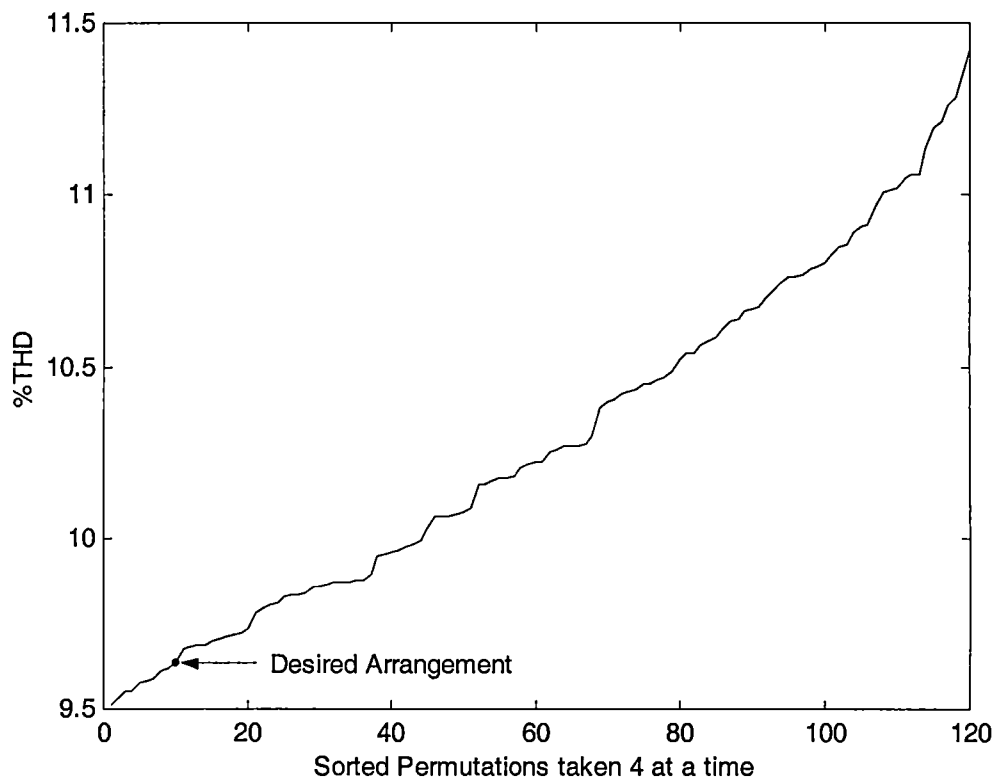


Figure 4-2: Illustration of the THD_v vs. the sorted permutations of four dc sources.

every permutation of the different voltage sources. The permutations were then sorted from the lowest to the highest THD_v , where the desired dc voltage source pattern was [1.10, 1.05, 1.00, 0.95], where 1.10 V was assigned the longest duty cycle and 0.95 V was assigned the shortest duty cycle respectively. The desired pattern occurred at the 10th sorted permutation and is shown in Figure 4-2; it represents where the 10th permutation occurred in relation to the other 120 possible ways to synthesize the waveform when sorted from the lowest THD_v to the highest.

The first 20 of the 120 sorted permutations are shown in Table 4-1. Although only four dc sources were used to synthesize the multilevel waveform, they were chosen

Table 4-1
THD_v and sorted permutations for the four-step waveform.

ORDER	THD	V1	V2	V3	V4
1	9.5119	1.1000	1.0500	1.0000	0.9000
2	9.5300	1.1000	1.0500	0.9500	0.9000
3	9.5518	1.1000	1.0000	0.9500	0.9000
4	9.5551	1.1000	1.0000	1.0500	0.9000
5	9.5741	1.0500	1.1000	1.0000	0.9000
6	9.5823	1.0500	1.1000	0.9500	0.9000
7	9.5891	1.1000	0.9500	1.0000	0.9000
8	9.6107	1.1000	0.9500	1.0500	0.9000
9	9.6181	1.0500	1.0000	0.9500	0.9000
10	9.6359	1.1000	1.0500	1.0000	0.9500
11	9.6731	1.0000	1.1000	0.9500	0.9000
12	9.6802	1.0500	0.9500	1.0000	0.9000
13	9.6876	1.0000	1.0500	0.9500	0.9000
14	9.6894	1.1000	1.0500	0.9000	0.9500
15	9.6982	1.1000	1.0000	1.0500	0.9500
16	9.7035	1.0500	1.1000	1.0000	0.9500
17	9.7125	1.0500	1.0000	1.1000	0.9000
18	9.7151	1.0000	1.1000	1.0500	0.9000
19	9.7215	1.1000	1.0000	0.9000	0.9500
20	9.7373	1.0500	1.1000	0.9000	0.9500

from five independent sources. The magnitudes of the independent voltage sources are shown in Table 4-1 where a particular combination produced a specific THD_v. It should be noted that for analysis, the magnitudes of the multilevel steps were sorted based on the voltage of the independent dc sources, however, the dc voltage sources were also assumed to have any value in (4-1). This simplified the analysis by assuming that the dc voltages can take on the values in Table 4-1, and do not need to be physically sorted based on their voltage, but would be sorted in an actual implementation. For example, in the first sorted order, V_1 is 1.10 V and V_2 is 1.05 V, however, in the 5th order V_1 is 1.05 V and V_2 is 1.10 V. The voltage sources represent the steps in the multilevel waveform and the magnitude of the voltage source specified by the order in Table 4-1. In an actual implementation, the dc sources may have a different position within the multilevel

waveform and a different voltage. Also, the desired voltage source pattern occurred at the 10th permutation in Table 4-1. Although, other patterns achieve minimal THD_v, in addition to minimizing the THD_v, one also desires to manage the batteries by balancing the voltages and rotating the duty cycles. It was assumed that the dc sources could be arranged in a pattern that would balance the battery voltages, as illustrated in Table 4-1 by the 10th sorted permutation.

Next, the equations were solved for the switching angles to eliminate the 5th, 7th, and 11th harmonics as shown by (4-3). Reducing the number of steps also reduced the number of equations and variables required. Thus, a four-step multilevel waveform required 4 equations to determine the 4 unknowns, and the same iterative process was required to solve for the switching angles.

$$\begin{aligned}
 v_1 \cos(\theta_1) + v_2 \cos(\theta_2) + v_3 \cos(\theta_3) + v_4 \cos(\theta_4) &= K \\
 v_1 \cos(5\theta_1) + v_2 \cos(5\theta_2) + v_3 \cos(5\theta_3) + v_4 \cos(5\theta_4) &= 0 \\
 v_1 \cos(7\theta_1) + v_2 \cos(7\theta_2) + v_3 \cos(7\theta_3) + v_4 \cos(7\theta_4) &= 0 \\
 v_1 \cos(11\theta_1) + v_2 \cos(11\theta_2) + v_3 \cos(11\theta_3) + v_4 \cos(11\theta_4) &= 0
 \end{aligned} \tag{4-3}$$

where $K = \pi V_p/4$, and V_p is the peak magnitude of the fundamental-frequency component, and $\mathbf{v}_a = [1.10 \ 1.05 \ 1.00 \ 0.95]^T$. It should be noted that less harmonics were eliminated which increased the THD_v of the waveform because the 13th harmonic was not eliminated, as in (3-9).

The switching angles were solved over a varying range of V_p and are illustrated in Figure 4-3. The switching angles were calculated over a finite range of V_p and the corresponding THD_v of the multilevel waveform is shown in Figure 4-4. In Figure 4-3, the switching angles are such that $\theta_1 < \theta_2 < \theta_3 < \theta_4$. At the endpoints, the iterative

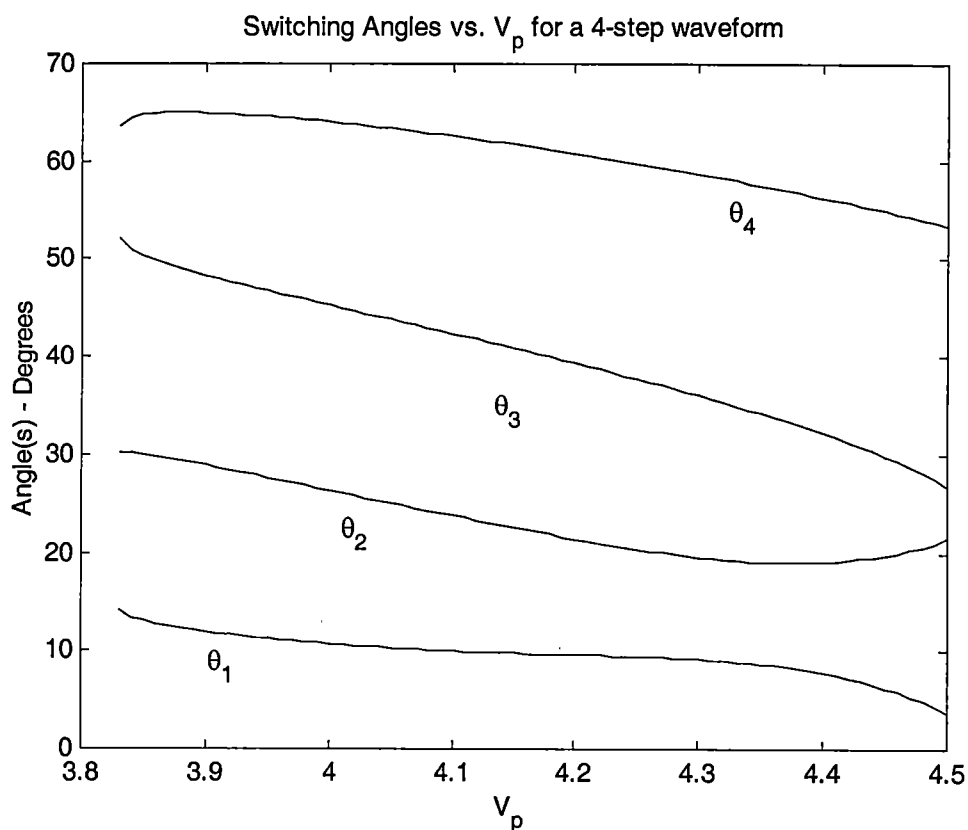


Figure 4-3: Switching angles vs. V_p for a four-step waveform.

solution converged to a single point and failed to render a solution outside of this range without a different guess. The switching angles were determined by using an initial guess that was close to a solution at the end of the boundary and then incrementing V_p while using the previously determined switching angles as an initial guess. This allowed the solution to converge quicker over the interval because the initial guess was the previous switching angles before V_p was incremented.

The plot in Figure 4-4 allows the THD_v of the multilevel waveform to be observed and one can notice that the total harmonic distortion is minimal at approximately 4.22 V. However, as illustrated in Figure 4-1, the total harmonic

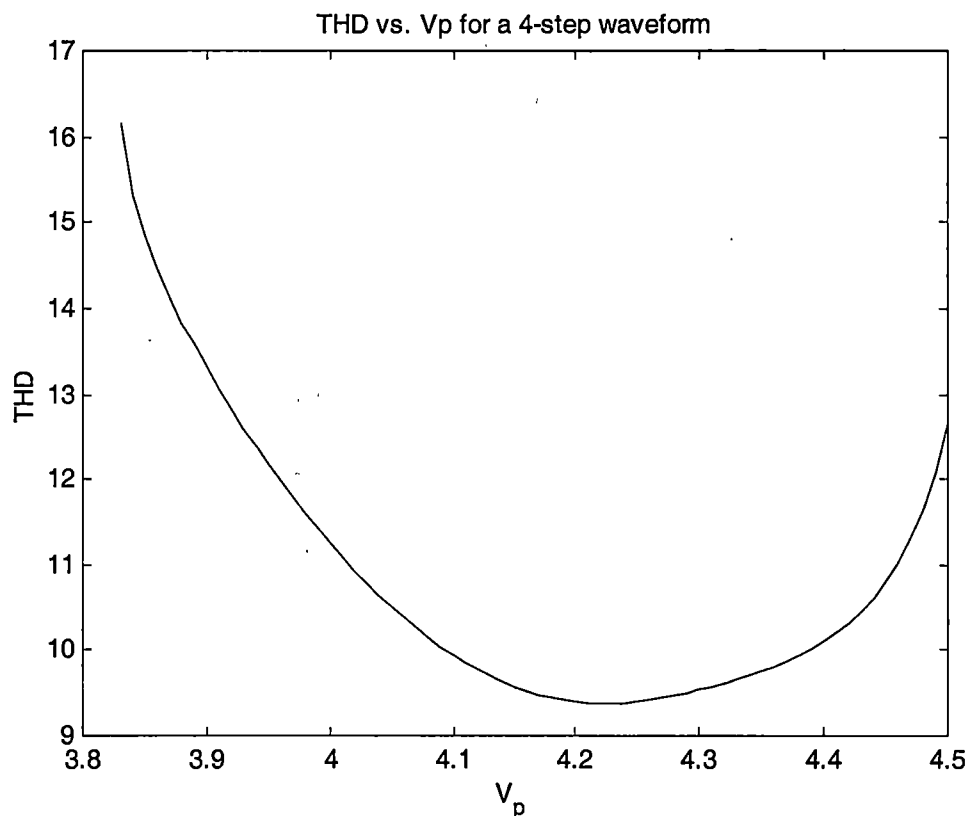


Figure 4-4: THD_v vs. V_p for a four-step waveform.

distortion increases near the endpoints. Thus, one may deduce, in order to obtain minimal THD_v and control V_p over the entire range, the number of dc sources used to synthesize the multilevel waveform must be reduced to obtain a 4-step, 3-step, etc. multilevel waveform. However, by decreasing the number of steps, the total harmonic distortion increased because some of the lower dominant harmonics cannot be eliminated. Only, a maximum of $(s - 1)$ selected harmonics can be eliminated when using the harmonic elimination method.

In the next sections, the original five-step multilevel waveform is dropped to a three-step and two-step waveform. The three-step multilevel waveform is analyzed in

section 4.1.1.2, and the two-step waveform is analyzed in section 4.1.1.3 by generating plots similar to section 4.1.1.1. The dc sources with the highest voltage are used for the longest duty cycle and the lower voltage sources are skipped. Thus, maintaining battery management was also considered a priority because HEV performance is strongly dependent on the condition of the batteries. Properly managing the batteries extends the cycle life and increases reliability; it also reduces operating cost. A detailed analysis of the control scheme, specifically, investigating the tradeoffs between duty cycle and voltage synthesis is required to optimize the parameters of the complete system, but is beyond the scope of this thesis. Several other combinations of the discrete steps can be favorable, which may yield a lower harmonic distortion than the pattern used in this thesis. However, it was also assumed that the switching angles and harmonic distortion was determined to balance the batteries using the pattern given by (4-1) over a wide range of control voltage.

4.1.1.2 Using 3-of-5 dc Sources

In this section, the original five-step waveform was reduced to a three-step waveform. The total harmonic distortion of the waveform was determined by varying only the voltage sources, and the switching angles remained fixed and were determined using unity dc sources, as shown in Figure 4-5.

In the plot of Figure 4-5, the desired arrangement was chosen as the first three elements in (4-1) because the goal was to balance the dc voltage sources, and it occurred at the 15th permutation from the lowest THD_v to the highest. The first 20 of the total 60 permutations are shown in Table 4-2 to illustrate how the voltage sources can be used at

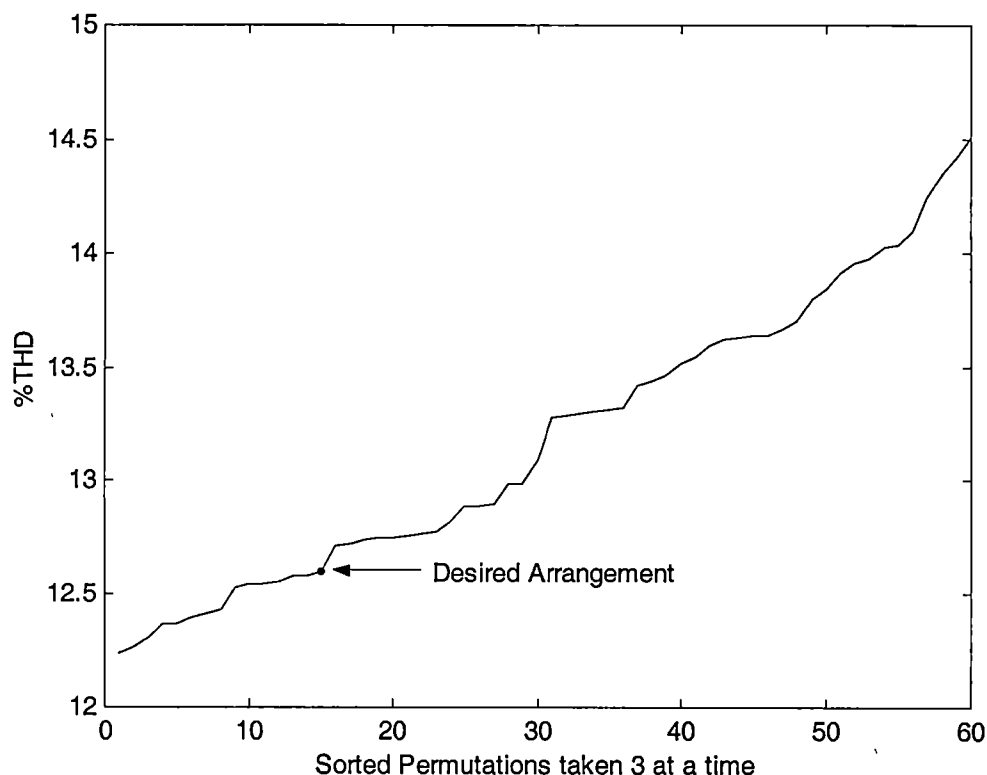


Figure 4-5: Illustration of the THD, vs. the sorted permutations of three dc sources.

different levels to synthesize the multilevel waveform. One may observe from Table 4-2 that the synthesized waveform uses the largest voltage during the first step, and the smallest voltage as the last step near the apex of the sinusoid. The same phenomena can be observed in Tables 4-1 and 3-1. Therefore, the highest harmonic distortion resulted when the lowest voltage step was used as the first step and the highest voltage was used as the last step. However, this was determined by using angles for the unity dc sources and then perturbing the dc sources to determine the overall effect on the waveform's total harmonic distortion.

Table 4-2
THD_v and sorted permutations for the three-step waveform.

ORDER	THD	V1	V2	V3
1	12.2386	1.1000	1.0500	0.9000
2	12.2621	1.1000	1.0000	0.9000
3	12.3104	1.1000	0.9500	0.9000
4	12.3707	1.0500	1.1000	0.9000
5	12.3736	1.0500	1.0000	0.9000
6	12.3979	1.1000	1.0500	0.9500
7	12.4110	1.0500	0.9500	0.9000
8	12.4337	1.1000	1.0000	0.9500
9	12.5287	1.0000	1.0500	0.9000
10	12.5478	1.0500	1.1000	0.9500
11	12.5482	1.0000	1.1000	0.9000
12	12.5585	1.0000	0.9500	0.9000
13	12.5790	1.0500	1.0000	0.9500
14	12.5816	1.1000	0.9000	0.9500
15	12.5980	1.1000	1.0500	1.0000
16	12.7092	1.0500	0.9000	0.9500
17	12.7200	1.1000	0.9500	1.0000
18	12.7391	0.9500	1.0000	0.9000
19	12.7454	0.9500	1.0500	0.9000
20	12.7521	1.0000	1.0500	0.9500

Next, the switching angles are determined for the three-step case over a finite range of control voltage by (4-4) and illustrated in Figure 4-6.

$$\begin{aligned}
 v_1 \cos(\theta_1) + v_2 \cos(\theta_2) + v_3 \cos(\theta_3) &= K \\
 v_1 \cos(5\theta_1) + v_2 \cos(5\theta_2) + v_3 \cos(5\theta_3) &= 0 \\
 v_1 \cos(7\theta_1) + v_2 \cos(7\theta_2) + v_3 \cos(7\theta_3) &= 0
 \end{aligned}
 \tag{4-4}$$

The 5th and 7th lower dominant harmonics are eliminated and the switching angles were determined using an iterative process to generate the plot in Figure 4-6.

The total harmonic distortion of the waveform was determined by varying the control voltage and using the switching angles from Figure 4-6 to generate the plot in Figure 4-7.

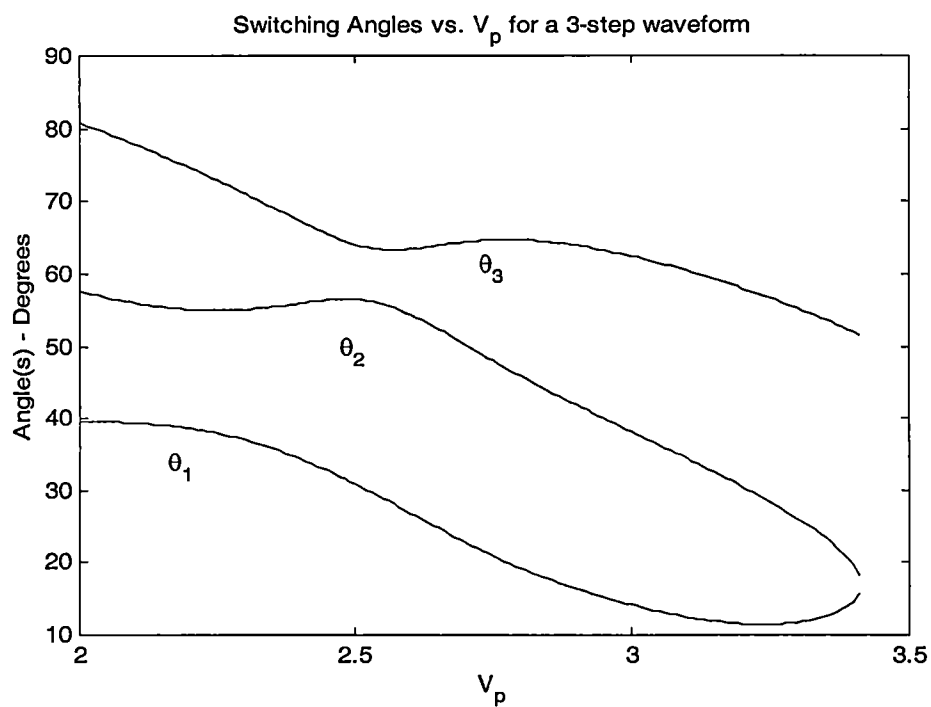


Figure 4-6: Switching angles vs. V_p for a three-step waveform.

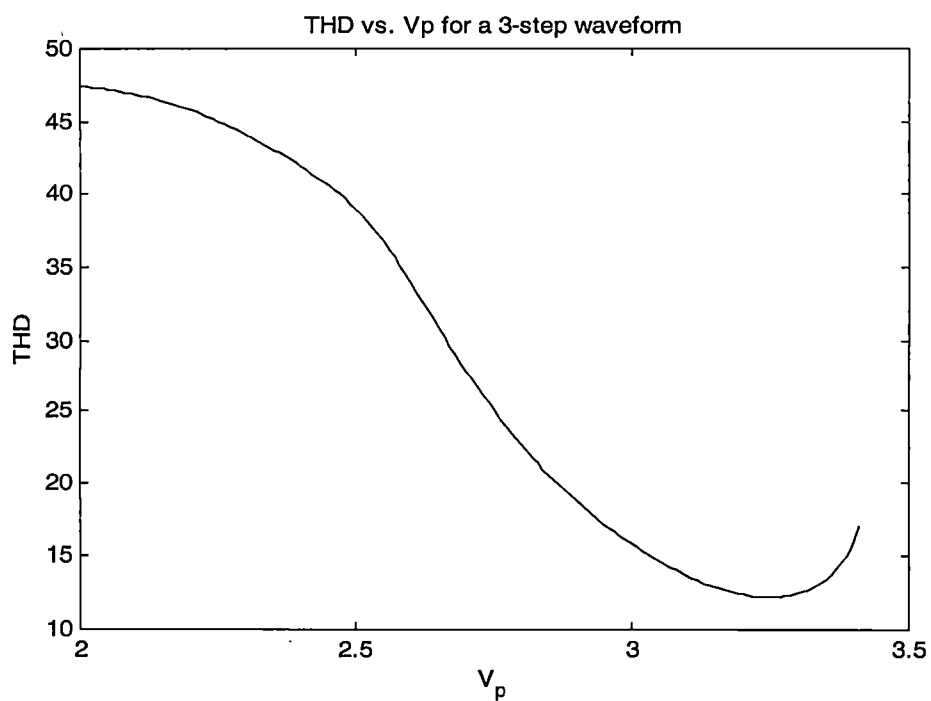


Figure 4-7: THD_v vs. V_p for a three-step waveform.

The THD_v increased overall when compared to the four-step waveform in Figure 4-4 because less resolution was used to synthesize the three-step waveform; however, when V_p was adjusted to less than 3 V, the THD_v increased unreasonably, as in Figure 4-7. One way to reduce the THD_v when approaching 2 V is to drop the three-step waveform and use a two-step synthesis method. Another way is to use pulse width modulation (PWM) to generate the ac waveform.

4.1.1.3 Using 2-of-5 dc Sources

In this section, the same techniques are applied to the two-step waveform to generate the relevant plots. The THD_v due to perturbing the dc sources and combining any two of the five are shown in Figure 4-8. The desired voltage pattern was selected as

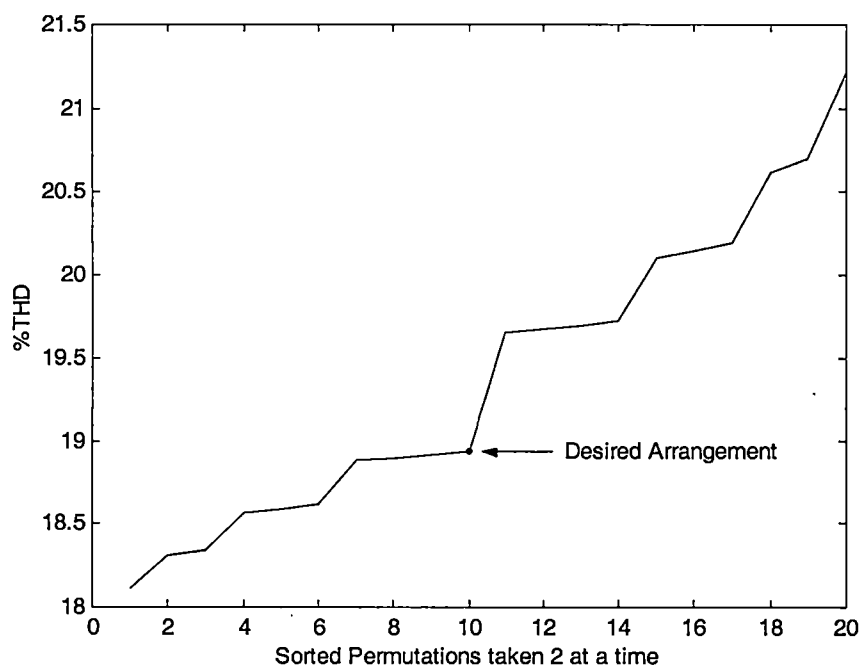


Figure 4-8: Illustration of the THD_v vs. the sorted permutations of two dc sources.

the first two elements of (4-1) and occurred at the 10th permutation. The 20 different combinations can be observed in Table 4-3 and it should be noted that the combination that yielded the least THD_v occurred when the largest voltage was used as the first step and the smallest voltage was used as the last step. The combination that yielded the largest THD_v was the just the opposite, the smallest voltage was used as the first step, and the largest voltage was used for the last step.

The switching angles were determined for the two-step case over a finite range of control voltage by (4-5) and is illustrated in Figure 4-9.

$$\begin{aligned} v_1 \cos(\theta_1) + v_2 \cos(\theta_2) &= K \\ v_1 \cos(5\theta_1) + v_2 \cos(5\theta_2) &= 0 \end{aligned} \quad (4-5)$$

The 5th harmonic was eliminated and the two switching angles were determined using an iterative process to generate the THD_v of the waveform, as illustrated in Figure 4-10.

Table 4-3
THD_v and sorted permutations for the two-step waveform.

ORDER	THD	V1	V2
1	18.1109	1.1000	0.9000
2	18.3066	1.0500	0.9000
3	18.3425	1.1000	0.9500
4	18.5597	1.0000	0.9000
5	18.5900	1.0500	0.9500
6	18.6179	1.1000	1.0000
7	18.8785	0.9500	0.9000
8	18.8973	1.0000	0.9500
9	18.9144	1.0500	1.0000
10	18.9299	1.1000	1.0500
11	19.6567	1.0500	1.1000
12	19.6765	1.0000	1.0500
13	19.6985	0.9500	1.0000
14	19.7230	0.9000	0.9500
15	20.1040	1.0000	1.1000
16	20.1501	0.9500	1.0500
17	20.2015	0.9000	1.0000
18	20.6205	0.9500	1.1000
19	20.7003	0.9000	1.0500
20	21.2133	0.9000	1.1000

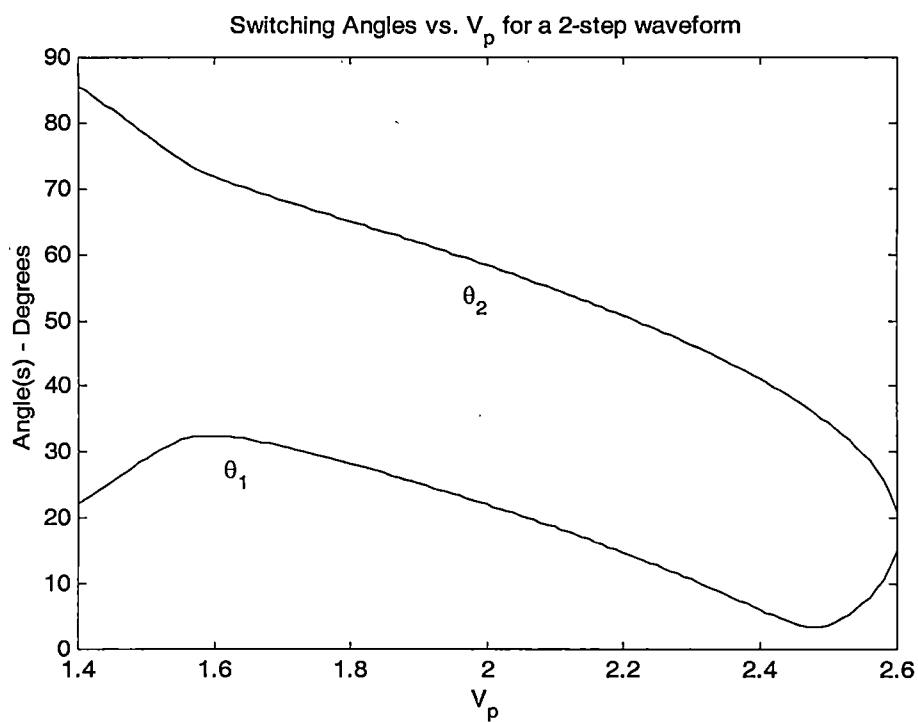


Figure 4-9: Switching angles vs. V_p for a two-step waveform.

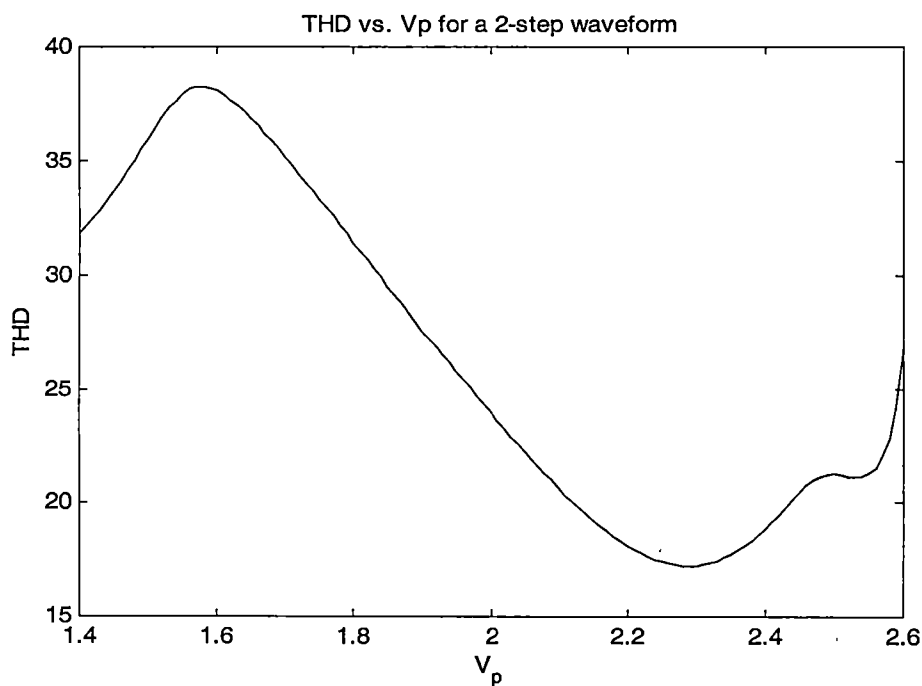


Figure 4-10: THD_v vs. V_p for a two-step waveform.

The plot in Figure 4-10 illustrates how the total harmonic distortion varies with the control voltage. By dropping the number of steps used to synthesize the multilevel waveform, the THD_v can be reduced over a wider range of control voltage. For example, when using three steps to synthesize the waveform the THD_v increased when the control voltage decreased below 2.6 volts (Figure 4-7). However, by using two steps to synthesize the waveform, the control voltage was extended below 2.6 volts at a lower THD_v than that of the three-step waveform.

4.1.1.4 Using 1-of-5 dc Sources

In this section, the single-step waveform is analyzed. First, the switching angle and THD_v are plotted against the control voltage ($V_p = 1.10V$) in Figures 4-11 and 4-12. Second, the two graphs are combined to illustrate the variation of the THD_v versus the switching angle, as shown in Figure 4-13.

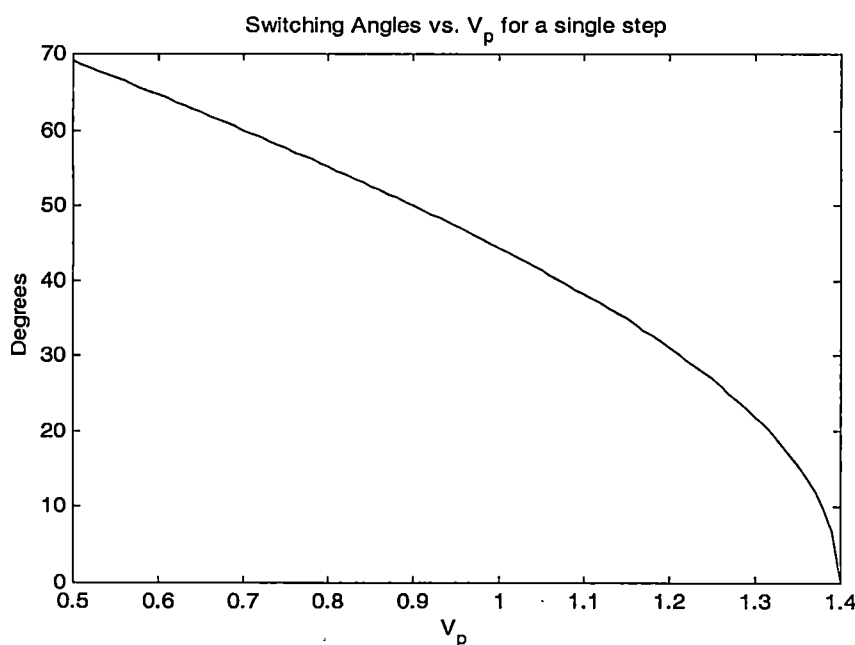


Figure 4-11: Switching angle vs. V_p for a one-step waveform.

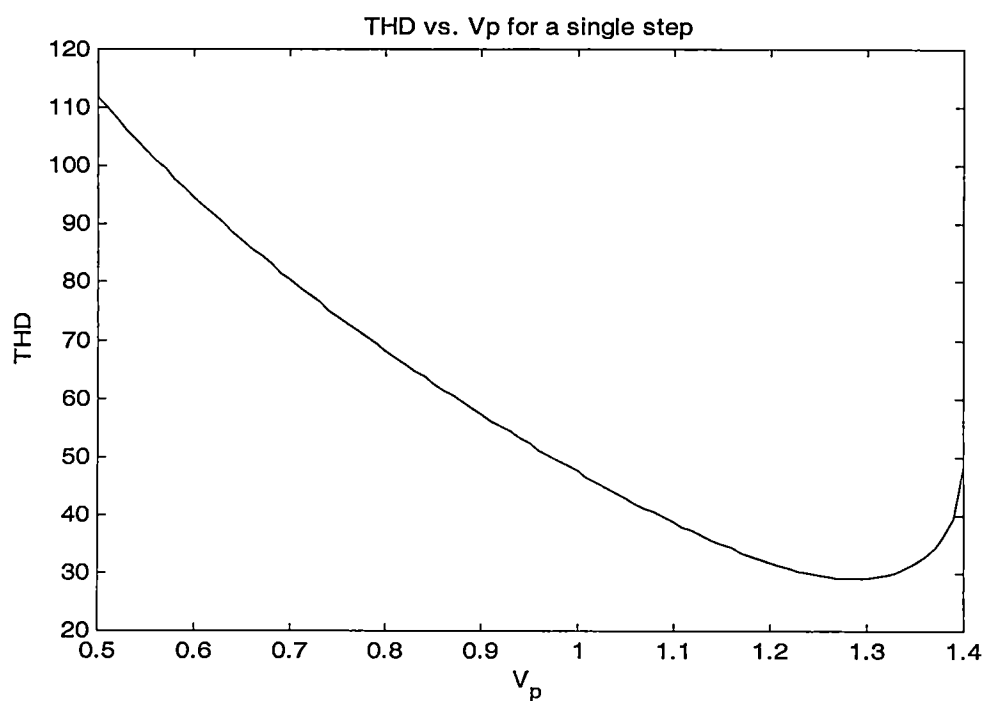


Figure 4-12: THD_v vs. V_p for a one-step waveform.

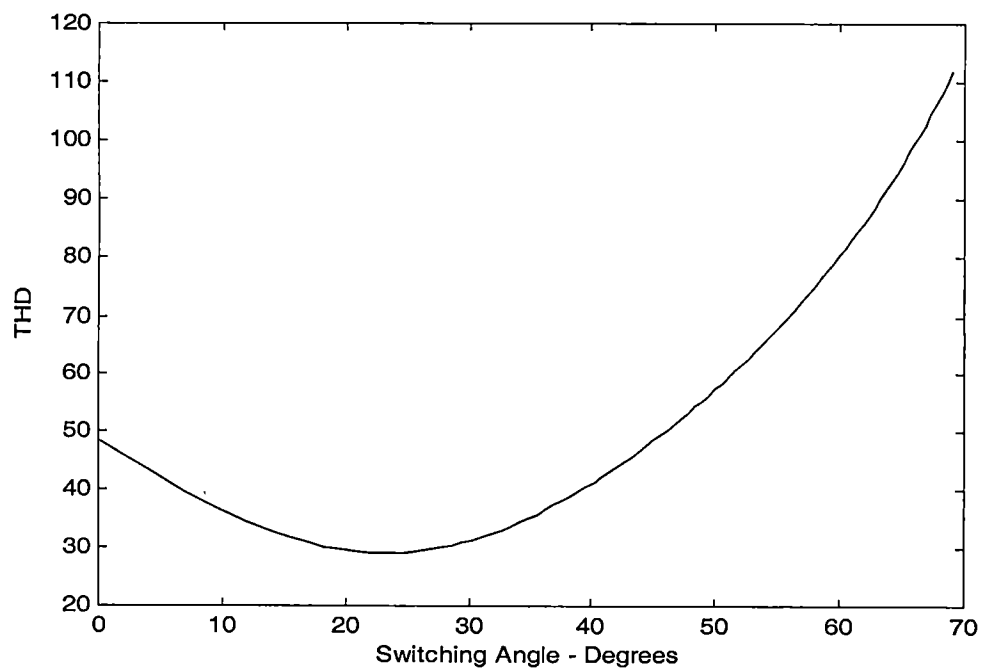


Figure 4-13: THD_v vs. the switching angle for a one-step waveform.

The switching angle increased as the control voltage was reduced. The single step was generated using the highest voltage of 1.10 V to balance the battery voltage. However, as the control voltage was reduced, the total harmonic distortion significantly increased to above 100%, as shown in Figure 4-12.

A noticeable trend that was introduced in Chapter 2 is that the total harmonic distortion increased when fewer steps were used to synthesize the sinusoidal waveform; however, alternative switching schemes, such as PWM, can be used to reduce the THD_v for smaller voltage requirements. Using a cascade multilevel inverter for high power applications reduces the switching voltage across the semiconductor device when compared to PWM techniques, thus, PWM may be desirable only at lower control voltages. Ideally, the combination of multilevel and PWM control techniques may be integrated into the complete system allowing the drive system to be continuously variable over its operating range.

Figure 4-13 illustrates the total harmonic distortion of a single alternating pulse of various widths determined by the switching angle. For the majority of switching angles the THD_v was above 30% indicating an alternative scheme may be desirable.

In the next section, the reduced stepped waveforms are summarized and a plot of the THD_v vs. the control voltages is illustrated over a wide range of control voltage.

4.1.2 Summary

The main point of section 4.1.1 was that the THD_v of the waveform increased by reducing both the control voltage and the number of steps used to synthesize the multilevel waveform. In addition, the battery voltages were balanced by choosing a

desired pattern such that the highest voltage had the highest duty cycle and the lowest voltage had the lowest duty cycle. For a reduced number of steps, the highest voltages were used to synthesize the multilevel waveform and the lowest voltages were skipped. In addition to multilevel switching strategies, PWM control techniques may be used at lower control voltages, instead of reducing the number of steps, to minimize the total harmonic distortion.

In Figure 4-14, the total harmonic distortion for all of the steps was superimposed on the graph to illustrate the impact of reducing the number of steps over a wide range of control voltage. The control voltage was varied from 0.5 V to 5.0 V, and the total harmonic distortion was shown for 7 different regions. From this graph, one may determine the transition point where the number of steps used to synthesize the waveform should be used. The choice for the transition point was where the total harmonic distortion was the least for any overlapping regions. For example, the 2-to-3-step transition point should be at 2.6 V. So for a control voltage below 2.6 V, the two-step waveform would be used, and for a control voltage above 2.6 V, the three-step waveform should be used. It should also be noted that in Figure 4-14 there are two graphs that were not discussed previously. These plots were used to maintain continuity over the variation of the control voltage by arbitrarily choosing one of the angles and solving for the others. Additional transition points are at 3.41, 3.90, 4.50, and 4.90 V. The alternative four-step curve was generated in a similar way and exploration of using this technique to expand the control voltage is beyond the scope of this thesis and may be investigated in future work.

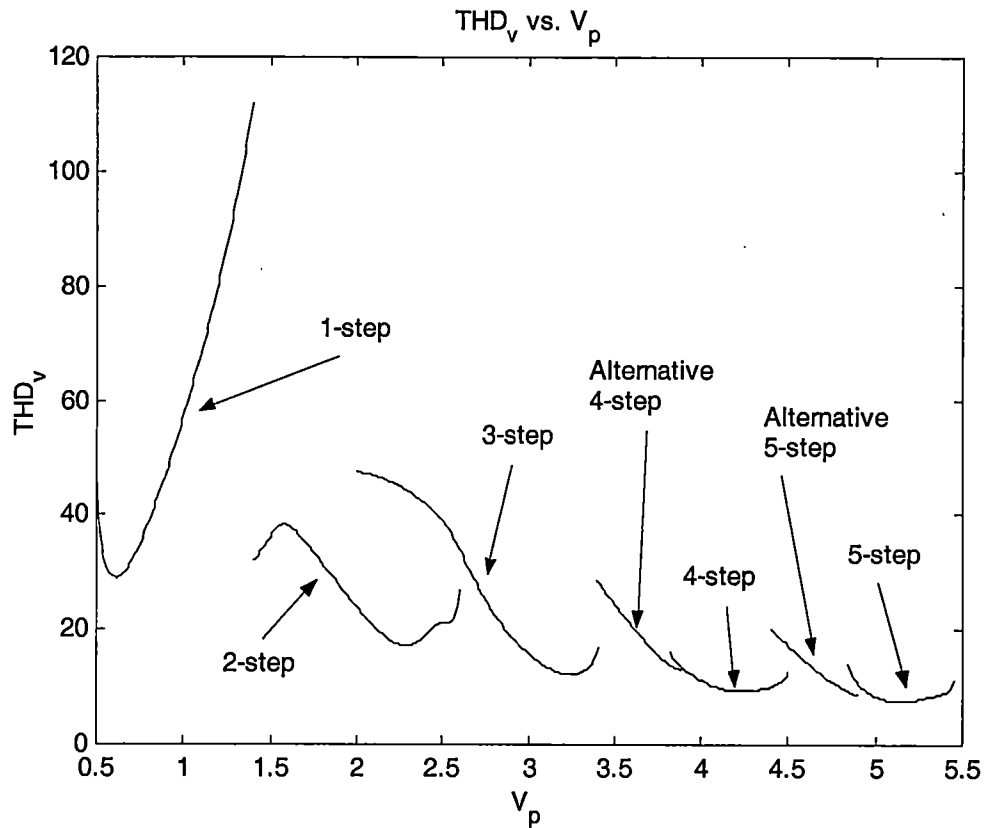


Figure 4-14: THD_v vs. V_p over a wide range of control voltage.

Also, by perturbing only the magnitudes of the dc sources to different values, the total harmonic distortion naturally progressed to a minimal state when the highest voltage was used as the first step and the lowest voltage was used as the last step. The extra sources were distributed in between, however, a precedence of balancing the voltages at the expense of a slightly higher harmonic distortion was used. In the next section, the phase- and the line-voltages are analyzed for the three-phase multilevel waveform using an ideal low-pass filter to illustrate the significance of eliminating selected harmonics.

4.2 Three-Phase Analysis

The five-step multilevel waveform is used to illustrate the significance of eliminating selected harmonics with an ideal filter. The ideal low-pass filter was assumed to remove all the harmonics above its cutoff frequency $f_c = hf_s$. In the previous sections, the THD_v was shown for the phase-voltages and in some cases it was determined to be above 20%. However, even with a high THD_v , it will be illustrated that the THD_v of the line-voltages when used with an ideal low-pass filter is zero. A balanced three-phase system was assumed for analysis, and the switching angles were determined by solving (3-10) to eliminate the 5th, 7th, 11th, and 13th harmonics for a control voltage of $V_p = 5.0$ V.

Let the phase-to-neutral voltages of the cascade multilevel inverter in a three-phase system be described by the Fourier Series for the multilevel waveform by

$$v_a(\omega t) = \frac{4}{\pi} \sum_{\substack{h=1 \\ \text{odd}}}^n \left[\sum_{k=1}^5 v_{ak} \cos(h\theta_{ak}) \right] \frac{\sin(h\omega t - h\phi_a)}{h} \quad (4-6)$$

$$v_b(\omega t) = \frac{4}{\pi} \sum_{\substack{h=1 \\ \text{odd}}}^n \left[\sum_{k=1}^5 v_{bk} \cos(h\theta_{bk}) \right] \frac{\sin(h\omega t - h\phi_b)}{h} \quad (4-7)$$

$$v_c(\omega t) = \frac{4}{\pi} \sum_{\substack{h=1 \\ \text{odd}}}^n \left[\sum_{k=1}^5 v_{ck} \cos(h\theta_{ck}) \right] \frac{\sin(h\omega t - h\phi_c)}{h} \quad (4-8)$$

where ϕ_a , ϕ_b , and ϕ_c are the phase angles 0, $2\pi/3$, and $4\pi/3$ respectively; n is the number of harmonics to include in the analysis; v_{ak} , v_{bk} , and v_{ck} are the magnitudes of the 5 dc

sources for each phase [1.10, 1.05, 1.00, 0.95, 0.90]; and θ_{ak} , θ_{bk} , and θ_{ck} are the switching angles for each phase [7.86° 19.37° 29.65° 47.68° 63.21°].

The line-to-line voltages can be determined from equations (4-6) to (4-8) as the difference $v_{ab} = v_a - v_b$; line voltages v_{bc} and v_{ca} can be found similarly. However, the THD_v for the line voltage is significantly lower than the phase voltage because the 5th, 7th, 11th, and 13th harmonics were eliminated from both the phase and line voltages. The harmonics that are a multiple of three were eliminated from the line-to-line voltage because those harmonics combine to zero due to superposition of all three phases.

4.2.1 Simulation Using an Ideal Low-Pass Filter

First, the best case scenario is illustrated showing that the THD_v of the line-to-line voltage for v_{ab} is zero. In Figure 4-15, n was chosen to be 13 in (4-6) to (4-8), and the line-to-line voltage of only v_{ab} was shown because the others are identical, but displaced by $2\pi/3$ and $4\pi/3$. Although the line-to-line voltage yielded a THD_v of zero, the phase voltages yielded a THD_v of 4.54%, as shown in Figure 4-16. The ripple is the difference between the actual and its fundamental waveform and was shown only for the phase-voltages. Some of the triplin harmonics – harmonics that are a multiple of three – appear in the line-neutral voltage, but these cancel in the line-to-line voltage in a three-phase system. Therefore, voltage ripple does not appear in the line-to-line voltages when used with an ideal low-pass filter. However, ideal low-pass filters are not practical for high power applications, but they simplify the analysis because one can observe the harmonic content by choosing the cutoff point at higher harmonics, thus, allowing the harmonic content below the filters cutoff point to be determined.

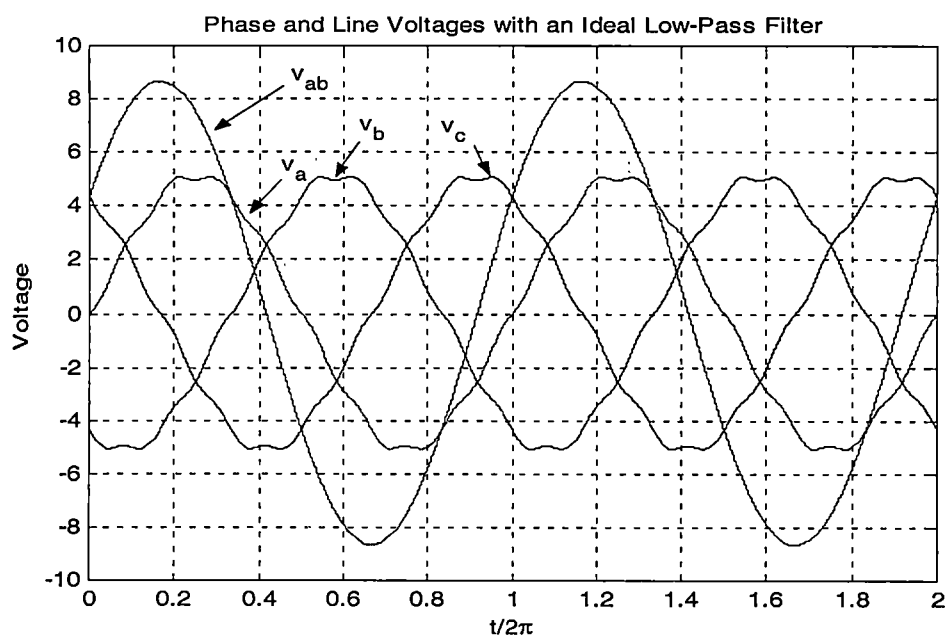


Figure 4-15: Phase- and line-voltages using an ideal low-pass filter with $h > 13^{\text{th}}$ completely filtered.

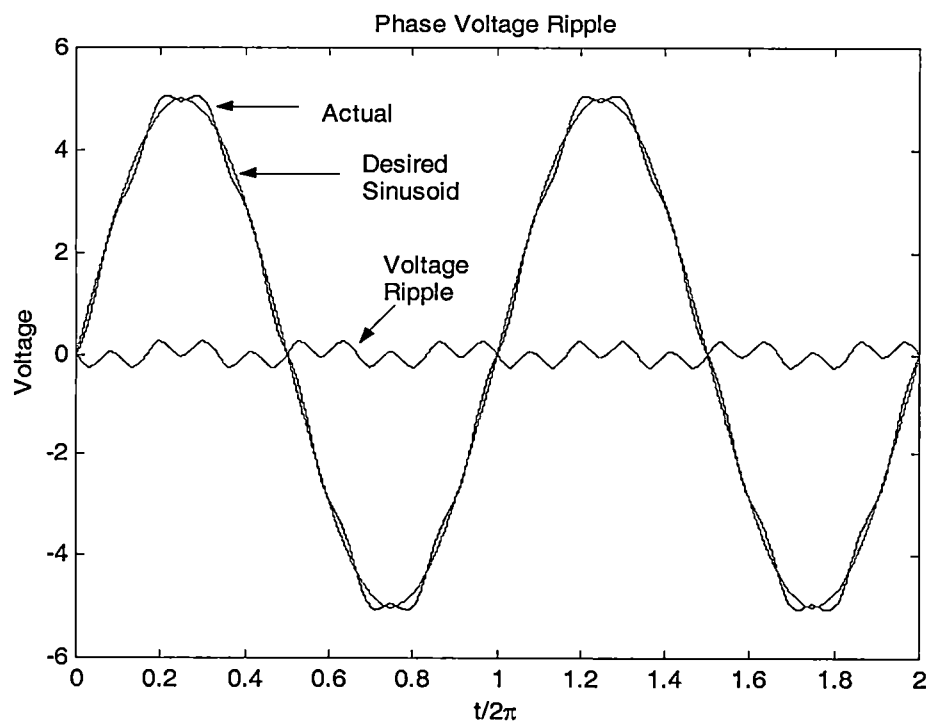


Figure 4-16: Phase voltage ripple for $n = 13$.

As n in (4-6) to (4-8) increases, the total harmonic distortion of the phase-to-neutral voltages increases. When $n > 15$ the total harmonic distortion in the line-to-neutral voltage increases, but for $n \leq 15$ the line THD_v is zero, as illustrated in Table 4-4.

In Table 4-4, the THD_v for the phase and line voltages are shown up to $n = 99$. The harmonics that are a multiple of three are highlighted because they combine to zero in the line-to-line voltages. Also, the line voltage has zero THD_v when used with an ideal low-pass filter to remove harmonics above the 15th. Therefore, combining a low-pass filter with the harmonic elimination method, the THD_v can be minimized.

The THD_v for the phase and line voltages is illustrated in Figure 4-17 for $n = 21$ using (4-6) to (4-8), and from Table 4-4 the THD_v was 5.24% for the phase-neutral voltages and 2.36% for the line-neutral voltages. Assuming that an ideal low-pass filter removed all of the harmonics greater than $h = 21$, the ripple for the phase voltages is illustrated in Figure 4-18, and the ripple for the line voltages is shown in Figure 4-19.

The ripple is the difference between the actual and the desired waveform and was observed to be the least in the line-to-line voltages because the triplen harmonics were eliminated by superposition of the three phases, and the lower dominant harmonics were eliminated using the harmonic elimination method.

Table 4-4
THD_v for the phase and line voltage vs. harmonics

Harmonics	Phase THD	Line THD
3	2.7421	0
5	2.7421	0
7	2.7421	0
9	4.5386	0
11	4.5386	0
13	4.5386	0
15	4.5921	0
17	4.7006	1.0043
19	5.1639	2.3619
21	5.2373	2.3619
23	5.3047	2.5079
25	6.3042	4.2300
27	6.6638	4.2300
29	6.6688	4.2377
31	6.7333	4.3386
33	6.8534	4.3386
35	7.2805	4.9859
37	7.3260	5.0522
39	7.3291	5.0522
41	7.3291	5.0522
43	7.3502	5.0828
45	7.4078	5.0828
47	7.4283	5.1126
49	7.4317	5.1175
51	7.4657	5.1175
53	7.4728	5.1279
55	7.4762	5.1328
57	7.5252	5.1328
59	7.5845	5.2194
61	7.7410	5.4443
63	7.7871	5.4443
65	7.8003	5.4630
67	7.8025	5.4662
69	7.8033	5.4662
71	7.8038	5.4669
73	7.8195	5.4893
75	7.8207	5.4893
77	7.8212	5.4900
79	7.8734	5.5641
81	7.8746	5.5641
83	7.8907	5.5868
85	7.9056	5.6079
87	7.9222	5.6079
89	7.9376	5.6297
91	7.9547	5.6537
93	7.9554	5.6537
95	7.9663	5.6691
97	7.9979	5.7134
99	8.0160	5.7134

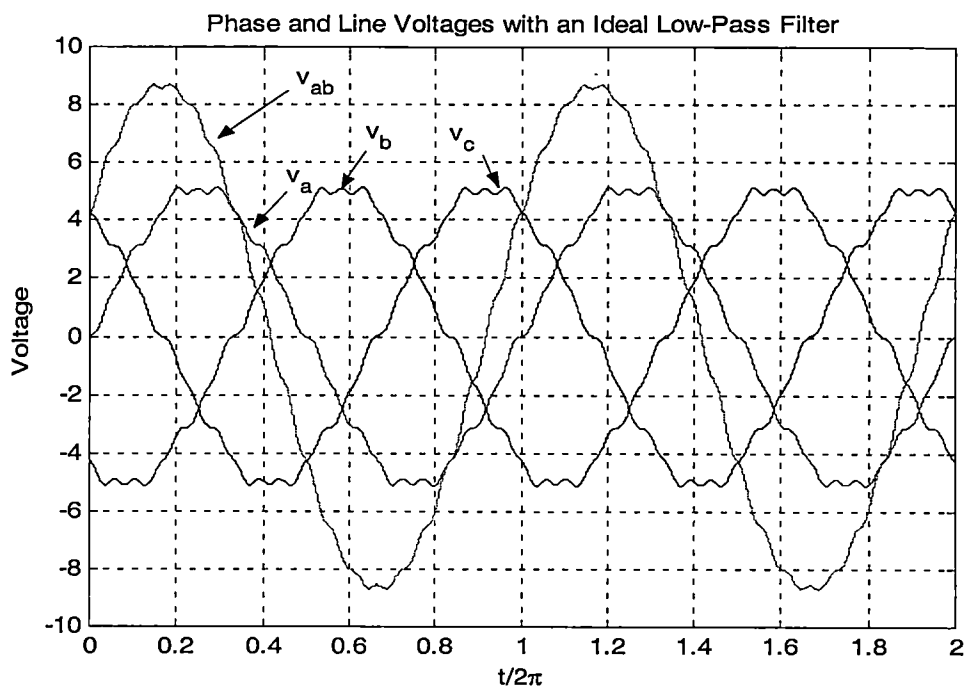


Figure 4-17: Phase- and line-voltages using an ideal low-pass filter with $h > 21^{\text{st}}$ completely filtered.

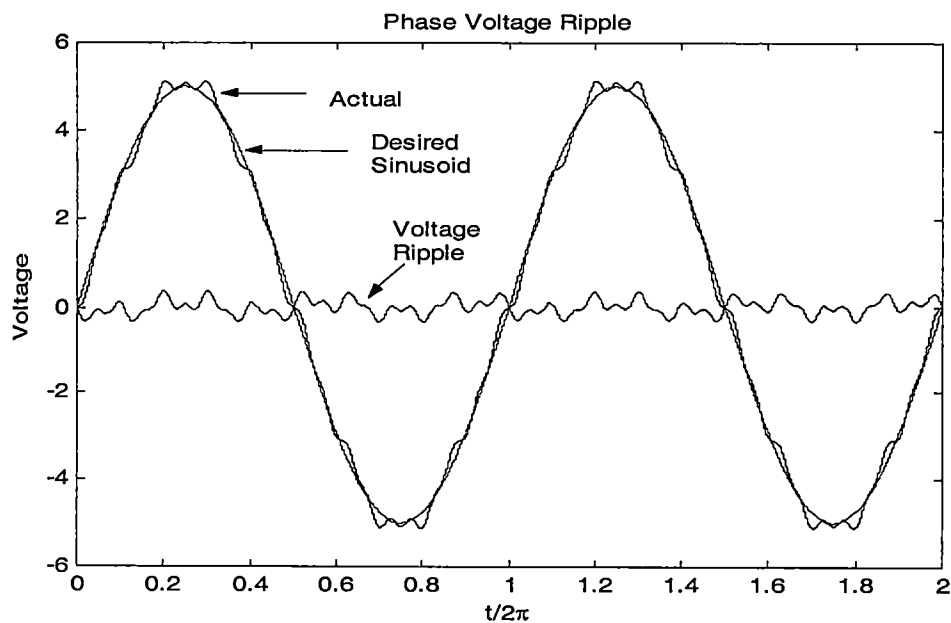


Figure 4-18: Phase voltage ripple for $n = 21$.

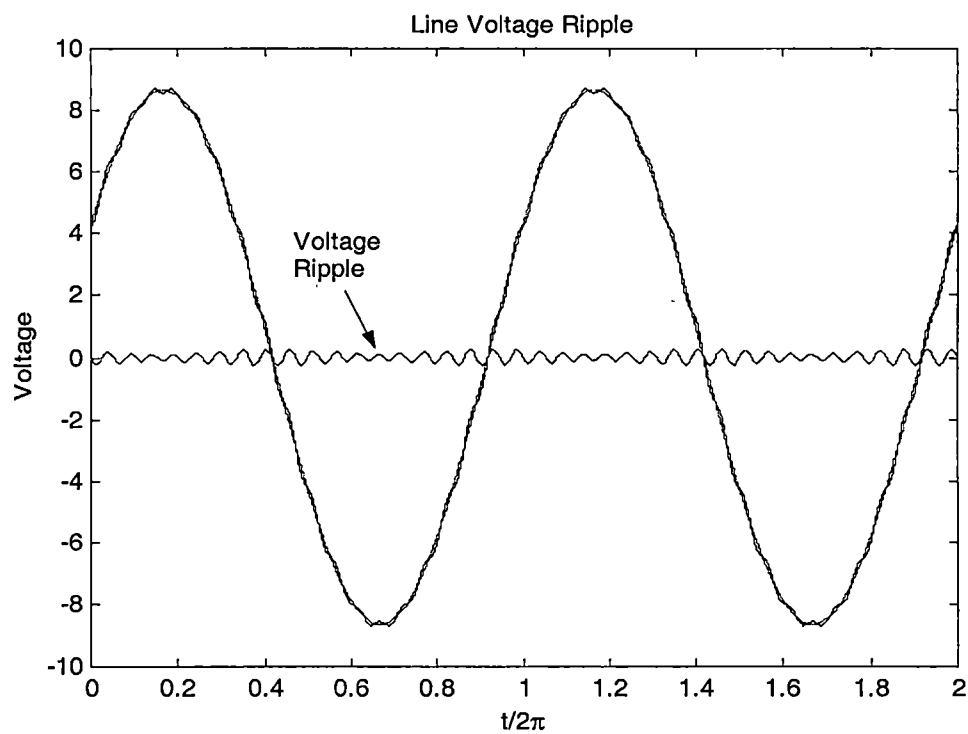


Figure 4-19: Line voltage ripple for $n = 21$.

5 Concluding Remarks

5.1 A Brief Summary

In summarizing the contributions of this research endeavor, the chief motivation of this work was based on finding an alternative to conventional PWM techniques for use in large hybrid-electric drivetrains. The cascade multilevel inverter topology allows operation at a much higher voltage and power level than conventional PWM techniques because the voltage across the semiconductor device is reduced by dividing the battery pack into individual batteries that are switched at various times and duty cycles. Specific advantages of the cascade multilevel inverter over using PWM in hybrid-electric drivetrains was introduced in Chapters 1, and several other advantages of the multilevel inverter topology were generally introduced in Chapter 2.

Additionally, previous research was reviewed and discussed in Chapter 2, and the switching angles were determined using unity and equal dc sources. Originally, the switching angles were desired to be calculated in real-time and implemented on a digital signal processing chip, however, the switching angles were solved using an iterative numerical optimization technique to render the solutions of the nonlinear transcendental equations and stored in a look-up table. This was judiciously approached by examining the present method used, which was the harmonic elimination method, and by also introducing an alternative method to find the optimal switching angles. This method was derived on the basis that all of the harmonics in the multilevel waveform were to be minimized by finding the appropriate switching angles, that is, minimizing the ripple in

the waveform. Without a filter, the alternative method produced the least amount of total harmonic distortion and approximated the desired sinusoid the best with the least amount of ripple. However, the harmonic method was preferred because the lower dominant harmonics can be eliminated and the magnitude of the fundamental frequency component could be controlled. Thus, with a low-pass filter, the harmonic elimination method was used to determine the switching angles.

This led to the introduction of variant dc sources meaning that the dc sources are not unity or equal, but can have different values. For simplicity, the dc sources were normalized about 1.0 V to represent 12.0 V and they varied by $\pm 10\%$ of their nominal value of 1.0 V. The direct implication of variant dc sources insinuated they must be sorted because they cannot be chosen at random in the control scheme, and specific combinations of the dc values improved the synthesis by reducing the total harmonic distortion. First, the dc values were assumed unity and equal, but the magnitudes were perturbed by $\pm 10\%$ and the total harmonic distortion of the phase voltage was determined for each permutation. The total harmonic distortion was minimal when the dc sources were perturbed and sorted by the largest and smallest voltage having the longest and shortest duty cycle, respectively, and the other voltage sources distributed in between. The highest total harmonic distortion occurred when the dc sources were sorted in the opposite order as the minimal case. Next, the dc sources were sorted to balance their voltage and the switching angles were solved over a finite range of control voltage.

The switching angles and the total harmonic distortion of the phase voltage were determined using the harmonic elimination method, where the dc sources were sorted in

an order to achieve a balanced state, and investigated over a finite sweep of control voltage. It was determined that the total harmonic distortion varied over the range of control voltage and yielded a minimum operating point. However, with an ideal low-pass filter, the line-to-line voltage yielded a total harmonic distortion of zero for the five-step multilevel waveform when used with a cutoff frequency of $15 f_s$ and 1.00% at $17 f_s$.

Lastly, the total harmonic distortion was superimposed onto a single graph by varying the control voltage from 0.5 volt using the one-step waveform to greater than 5.00 V using the five-step waveform to illustrate where the transition from increasing or decreasing the number of steps may be used. This also illustrated that a reduced number of steps increased the total harmonic distortion of the waveform significantly, however, the multilevel inverter may be operated in a pulse width modulated mode at those lower voltages reducing the total harmonic distortion and maintaining the control voltage.

5.2 Conclusion

In conclusion, a combination of using multilevel-pulse-width-modulated control techniques is the method of choice for implementing the cascade multilevel inverter into large hybrid-electric drivetrains. Using this combination increases the flexibility of operation by adding control over each independent dc source in the cascade configuration to double as a battery management system. On the other hand, a disadvantage of using a multilevel inverter control scheme can become quite complex in initiating battery management, switching algorithms for multilevel synthesis and pulse width modulation, and integrating it into the infrastructure of the hybrid-electric vehicle's existing system and components. However, planning the hybrid configuration around the multilevel

topology maintains freedom in designing a complete propulsion system for large hybrid-electric vehicles.

5.3 Future Research

The first suggestion for future research begins with analyzing the solution space for the switching angles over the range of variant dc voltage sources. The switching angles are difficult to solve using the nonlinear technique because a good initial guess is required for convergence, and the solutions must be stored in a look-up table. The size of the look-up table can become excessive for variant dc sources by storing the switching angles for the reduced number of steps that are to be used, that is, switching angles for the five-step, four-step, three-step, etc. waveforms.

Next, explore a real-time implementation of the multilevel-pulse-width-modulated inverter. This includes using multilevel techniques for high-voltage and pulse-width-modulated control for the lower voltages over a complete range of the control voltage. In addition, determine the semiconductor's switching stress and other component stress for high-power deployment of this mixed control scheme and compare the high-power multilevel technique to the low voltage pulse-width-modulated technique.

Lastly, investigate an integrated control scheme to include a battery management system. Incorporating a battery management system in this mixed topology increases the systems flexibility and attractiveness for hybrid-electric vehicles because the electronic package will continue to decrease in size over time resulting in a cheaper and more reliable unit. Most battery management systems incorporate a warning indicator that indicates a possible failure, but control over the independent dc source can not be

integrated using conventional techniques. However, using the mixed multilevel and pulse width modulated techniques, and the cascade topology, the battery management system can be integrated with complete control over each independent dc source.

BIBLIOGRAPHY

Bibliography

- [1] T. C. Moore, "Tools and Strategies for Hybrid-Electric Drivesystem Optimization," JSAE 961660, 1996.
- [2] A. Nagasaka, M. Nada, H. Hamada, S. Hiramatsu, Y. Kikuchi, "Development of the Hybrid/Battery ECU for the Toyota Hybrid System," JSAE 98122, 1998.
- [3] L. M. Tolbert, F. Z. Peng, T. G. Habetler, "Multilevel Converters for Large Electric Drives," *IEEE Transactions on Industry Applications*, Vol. 35, No. 1, Jan./Feb. 1999, pp. 36-44.
- [4] J. S. Lai, F. Z. Peng, "Multilevel Converters – A New Breed of Power Converters," *IEEE Transactions on Industry Applications*, Vol. 32, No. 3, May 1996, pp. 509-517.
- [5] L. M. Tolbert, F. Z. Peng, and T. G. Habetler, "Multilevel Inverters for Electric Vehicle Applications," in *Proc. IEEE Workshop Power Electron. Transportation*, Dearborn, MI, Oct. 22-23, 1998, pp. 79-84.
- [6] L. M. Tolbert, F. Z. Peng, D. J. Adams, J. W. McKeever, "Multilevel Inverters for Large Automotive Electric Drives," in *Conf. Rec. All Electric Combat Vehicle 2nd Int. Conf.*, Dearborn, MI, June 8-12, 1997, Vol. 2, pp. 209-214.
- [7] F. Z. Peng, "A Generalized Multilevel Inverter Topology with Self Voltage Balancing," IEEE/IAS Annual Meeting, Oct. 8-12, Rome, Italy, 2000.

- [8] G. Sinha, and T. A. Lipo, "A Four-Level Rectifier Inverter System for Drive Applications," *IEEE Industry Applications Magazine*, Jan./Feb. 1998, pp. 66-74.
- [9] T. R. Crompton, *Battery Reference Book*, Butterworth-Heinemann, Second Edition, 1997.
- [10] H. Bode, *Lead-Acid Batteries*, R. J. Brodd and K. V. Kordesch, translators, John Wiley & Sons, New York, 1977.
- [11] L. M. Tolbert, F. Z. Peng, and T. G. Habetler, "Multilevel PWM Methods at Low Modulation Indices," *IEEE Transactions on Power Electronics*, Vol. 15, No. 4, July 2000, pp. 719-725.
- [12] G. A. Hubbard, "Modeling and Control of a Hybrid-Electric Vehicle," M. S. thesis, Massachusetts Institute of Technology, Cambridge, MA, 1996.
- [13] Q. Jiang, and T. A. Lipo, "Switching Angles and DC Link Voltages Optimization for Multilevel Cascade Inverters," *Electric Machines and Power Systems*, 2000, Vol. 28, pp. 605-612.
- [14] L. M. Tolbert, F. A. Peng, "A Multilevel Converter-Based Universal Power Conditioner," *IEEE Transactions on Industry Applications*, Vol. 36, No. 2, Mar./Apr., 2000, pp. 596-603.
- [15] J. W. McKeever, S. Das, L. M. Tolbert, and L. D. Marlino, "Life-Cycle Cost Sensitivity to Battery-Pack Voltage of an HEV," JSAE 2000-01-1556, 2000.

Vita

Tim Cunnyngnam has actively been involved in the hybrid-electric and alternative fuel transit industry since 1998. He received a fellowship from the Graduate Automotive Technology Education program at The University of Tennessee in 2000. He plans to continue his career in the hybrid-electric and alternative fuel vehicle industry.