

# **Impact of System Impedance on Harmonics Produced by Variable Frequency Drives (VFDs)**

Daniel David Morton

Thesis submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Master of Science  
In  
Electrical Engineering

Jaime De La Reelopez  
Virgilio Centeno  
Arun Phadke

April 28, 2015  
Blacksburg, VA

Keywords: Harmonic Analysis, Power Electronics, Variable Frequency Drives

Copyright 2015

# **Impact of System Impedance on Harmonics Produced by Variable Frequency Drives (VFDs)**

Daniel David Morton

## **Abstract**

Variable Frequency Drives (VFDs) are utilized in commercial and industrial facilities to improve motor efficiency and provide process flexibility. VFDs are nonlinear loads that inject harmonic currents into the power system, and result in harmonic voltages across the system impedance. This harmonic distortion can negatively impact the performance of other sensitive loads in the system.

If a VFD serves a critical function, it may be necessary to supply the VFD from a Diesel Generator or Uninterruptible Power Supply (UPS). These sources have relatively high impedance when compared to a standard utility source, and will result in greater harmonic voltage distortion. This increases the likelihood of equipment failure due to harmonics. The full extent of the impact, however, is typically unknown until an extensive harmonic analysis is performed or the system is installed and tested.

This thesis evaluates the impact that source impedance has on the harmonic voltage distortion that is produced by nonlinear loads such as VFDs. An ideal system of varying source types (Utility, Generator and UPS) and varying VFD rectifier technologies (6-Pulse, 12-Pulse and 18-Pulse) is created to perform this analysis and plot the results. The main output of this thesis is a simplified methodology for harmonic analysis that can be implemented when designing a power system with a VFD serving a critical function and a high impedance source like a generator or UPS. Performing this analysis will help to ensure that other sensitive loads will operate properly in the system.

To my parents, David and Cynthia Morton,  
for teaching me to always follow through on my goals.

## **Acknowledgements**

I would like to thank Dr. Jaime De La Reelopez for serving as Chair of my graduate committee, and for his patience and support as I have worked towards earning this degree. I would also like to thank Dr. Virgilio Centeno and Dr. Arun Phadke for their support as members of my committee.

I would like to thank Bechtel Corporation for funding the majority of my graduate coursework, and my supervisors and managers who have made accommodations so I may attend class or take time away from work to write this thesis.

# Table of Contents

Abstract .....	ii
Acknowledgements .....	iv
Table of Contents .....	v
Appendices .....	vii
List of Figures .....	viii
List of Tables .....	ix
Chapter 1 – Introduction .....	1
Chapter 2 – Harmonics .....	5
2.1 Overview of Harmonics .....	5
2.1.1 Fourier Series Representation .....	5
2.1.2 Harmonic Phase Sequence .....	7
2.1.3 System Impedance .....	8
2.1.3.1 Source Impedance of a Utility Interconnection .....	9
2.1.3.2 Source Impedance of a Generator .....	10
2.1.3.3 Source Impedance of a UPS .....	11
2.1.3.4 Transformer Impedance .....	12
2.1.3.5 Cable Impedance .....	13
2.1.3.6 System Impedance at Harmonic Frequencies .....	13
2.1.4 Harmonic Indices .....	13
2.2 Effects of Harmonics .....	14
2.2.1 Transformers .....	14
2.2.2 Rotating Machines .....	15
2.2.3 Cables .....	15
2.2.4 Overcurrent Protection .....	16
2.2.5 Capacitors .....	16
2.2.6 Power Electronic Equipment .....	17
2.3 Recommended Limits .....	17
Chapter 3 – Power Electronic Equipment .....	19
3.1 Overview of Power Electronics .....	19
3.2 Variable Frequency Drives .....	19

3.2.1 Principal of Operation .....	19
3.2.2 System Components .....	20
3.2.3 Benefits.....	20
3.2.4 Harmonics.....	20
3.3 Uninterruptible Power Supplies .....	21
3.3.1 System Components .....	21
3.3.2 Line Preferred.....	22
3.3.3 Inverter Preferred.....	22
3.3.4 Harmonics.....	22
3.4 Ideal Rectifiers .....	22
3.4.1 6-Pulse Bridge Rectifier .....	22
3.4.2 Phase Multiplication.....	25
Chapter 4 – Methodology for Harmonic Analysis.....	27
4.1 Purpose.....	27
4.2 Scope.....	27
4.3 Comparison of Source Impedances.....	28
4.3.1 Case 1: VFD Fed by Utility Source.....	28
4.3.2 Case 2: VFD Fed by Generator Source .....	29
4.3.3 Case 3: VFD Fed by UPS Source.....	31
4.3.4 Summary.....	32
4.4 Calculation of Voltage THD at Load Terminals.....	33
4.5 Variation in Load Current .....	35
4.6 Implementation Using MATLAB .....	36
Chapter 5 – Results .....	37
5.1 Voltage THD for Ideal 6-Pulse VFD .....	37
5.2 Voltage THD for Ideal 12-Pulse VFD .....	38
5.3 Voltage THD for Ideal 18-Pulse VFD .....	39
5.4 Discussion of Results .....	40
Chapter 6 – Future Work .....	43
References.....	44

## Appendices

Appendix A: MATLAB Code .....	46
A.1 Development of Figure 4.4.....	46
A.2 Harmonic Analysis .....	47

## List of Figures

Figure 1.1: Typical Design Goal of the Electronic Equipment Manufacturing Industry .....	3
Figure 2.1: Fourier Series Representation of a Distorted Waveform .....	5
Figure 2.2: Individual Harmonic Voltage Drops across System Impedance .....	9
Figure 2.3: Output Impedance of UPS Based on Inverter Type .....	11
Figure 2.4: Example Cable Derating for Harmonics .....	16
Figure 3.1: Variable Frequency Drive .....	20
Figure 3.2: Uninterruptible Power Supply .....	21
Figure 3.3: 6-Pulse Diode Bridge Rectifier .....	23
Figure 3.4: Ideal 6-Pulse Bridge Rectifier DC Output Voltage Waveform.....	23
Figure 3.5: Ideal 6-Pulse Bridge Rectifier AC Input Current Waveform.....	24
Figure 3.6: Harmonic Components of the Ideal 6-Pulse Bridge Rectifier AC Input.....	25
Figure 3.7: 12-Pulse Diode Bridge Rectifier .....	26
Figure 4.1: VFD Connected to 480V Bus Fed by Utility Source .....	29
Figure 4.2: VFD Connected to 480V Bus Fed by Generator Source.....	30
Figure 4.3: VFD Connected to 480V Bus Fed by UPS Source .....	31
Figure 4.4: Comparison of Short-Circuit Current and Impedance by Source .....	33
Figure 4.5: Thevenin Equivalent for Power System Feeding VFD and Other Loads .....	34
Figure 5.1: MATLAB Plot of Voltage THD for Ideal 6-Pulse Rectifier (0-100% THD) .....	37
Figure 5.2: MATLAB Plot of Voltage THD for Ideal 6-Pulse Rectifier (0-10% THD) .....	37
Figure 5.3: MATLAB Plot of Voltage THD for Ideal 12-Pulse Rectifier (0-100% THD) .....	38
Figure 5.4: MATLAB Plot of Voltage THD for Ideal 12-Pulse Rectifier (0-10% THD) .....	38
Figure 5.5: MATLAB Plot of Voltage THD for Ideal 18-Pulse Rectifier (0-100% THD) .....	39
Figure 5.6: MATLAB Plot of Voltage THD for Ideal 18-Pulse Rectifier (0-10% THD) .....	39



## List of Tables

Table 1.1: Basic Types of Power Disturbances .....	2
Table 2.1: Sequence of Harmonics .....	8
Table 2.2: Subtransient Reactance of Three-Phase Synchronous Machines .....	10
Table 2.3: Transformer Percent Impedance at Self-Cooled Rating .....	12
Table 2.4: Current Distortion Limits for Systems Rated 120 V through 69 kV .....	18
Table 2.5: Voltage Distortion Limits .....	18
Table 4.1: Summary of Short-Circuit Current and Impedance by Source.....	32
Table 4.2: Full Load Current, 460V, 3-Phase Induction-Type Motors .....	36
Table 5.1: Application Levels for Ideal 6-Pulse VFDs on 480 V System.....	40
Table 5.2: Application Levels for Ideal 12-Pulse VFDs on 480 V System.....	41
Table 5.3: Application Levels for Ideal 18-Pulse VFDs on 480V System.....	41

## Chapter 1 – Introduction

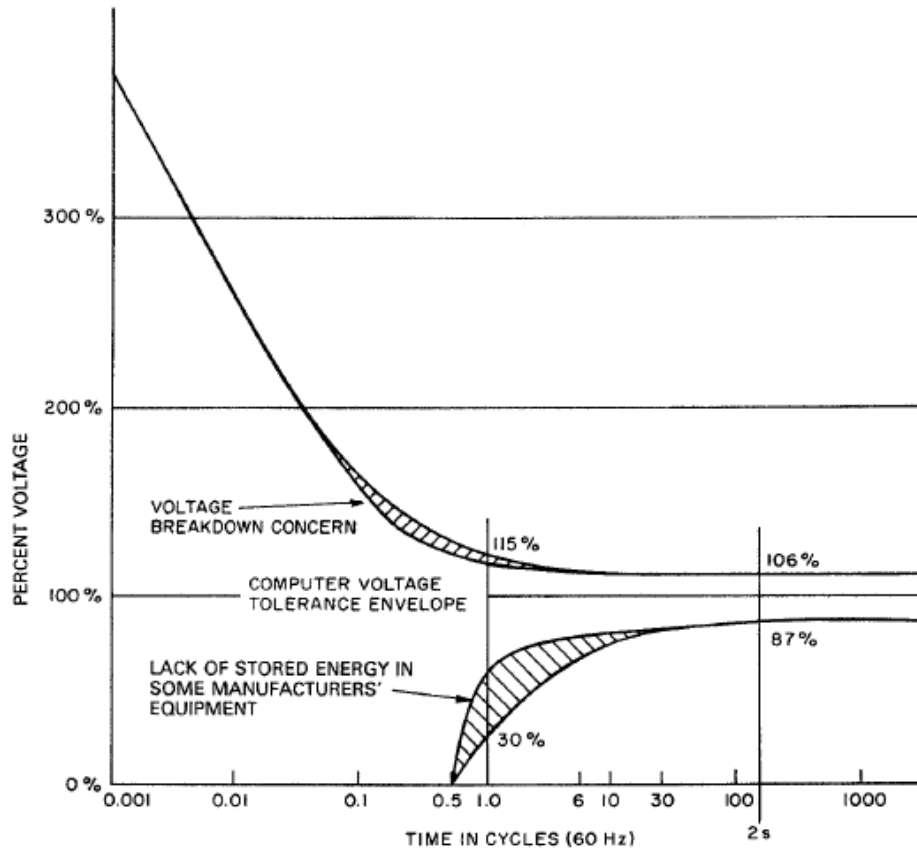
Over the last several decades, the electrical loads in commercial and industrial facilities have dramatically evolved. The demand for greater equipment efficiency and process flexibility has resulted in the application of microprocessor-based controls and power electronics technology. While these loads have increased overall productivity, they are also more sensitive to variations in the power supplied to them [1]. If the input power to a device falls outside of the design parameters, its performance will be less than optimum, or the device may not operate at all [2].

Power Quality is the term used to describe variations in a power system that results in a device's failure to perform its intended function. These variations can be categorized into three basic types of power disturbances that may occur at a facility in addition to harmonic distortion and noise [3]. As shown in Table 1.1, Type I, II, and III involve variation in the voltage magnitude over a specified period of time. Loads such as induction motors, furnaces (resistive heating devices), fluorescent lighting systems, and welding machines are tolerant of degraded power quality and unaffected by momentary outages. Microprocessor-based electronics, VFDs, switching power supplies, and other rectifier-inverter circuits, however, cannot tolerate a total power outage for more than 20 milliseconds [2].

IEEE Standard 446-1995, "Recommended Practice for Emergency and Standby Power Systems for Industrial and Commercial Applications," provides the present design goals for voltage tolerances of the electronic equipment manufacturing industry. As shown in Figure 1.1, the curve is an envelope that defines the transient and steady-state limits to which the input voltage can vary without affecting the operation of the electronic equipment or damaging it [3]. If the supply voltage falls outside of these limits and it is a critical load, a ride-through or power conditioning device, such as a UPS, should supply the equipment [2]. A critical load can be any device or equipment whose failure to operate correctly jeopardizes the health and safety of personnel, results in financial loss, or damage to property deemed critical by the user [1]. These critical loads can be found in any industry including telecommunications, process control, utilities – especially nuclear generating facilities, security, data processing, and health care [2][3].

**Table 1.1: Basic Types of Power Disturbances [3]**

Disturbance{	Type I, Transient or oscillatory overvoltage	Type II, Momentary under- or overvoltage	Type III, Sustained under- voltage, brownout, or outage	Harmonic Distortion	Noise
Typical cause of disturbance	Lighting; power network switching	Power system faults, large load changes, and utility equipment malfunctions	Excessive load; power system faults; extreme and unacceptable load changes; equipment malfunctions	Other equipment, such as adjustable- speed motor drives, large controlled rectifiers, UPS systems, or computers on the same source	Sparking appliances and same as type I
Threshold	130% of rated RMS voltage or higher (peak instantaneous above or below normal)	0-87%; 106- 130% of rated RMS voltage	Below 87% of rated RMS voltage	Greater than 5% THD	Induced from power to signal circuits
Typical duration of disturbance	Spikes 0.5- 200 microsecond duration	Range from ½ to 120 cycles depending upon type of utility distribution equipment	Restoration in a matter of seconds if correction is automatic and 30 minutes or longer if manual	Continuous	Continuous and intermittent
Effect	Latent equipment damage; errors	Shutdown; equipment damage; errors	Shutdown; equipment damage	Unnecessary shutdown; latent equipment damage due to overheating	Errors



**Figure 1.1: Typical Design Goal of the Electronic Equipment Manufacturing Industry [4]**

Harmonic distortion is also listed on Table 1.1 as a form of power disturbance. Rather than being transient or momentary in duration, harmonic distortion is periodic because it is associated with the continuous operation of a load. Harmonics are integer multiples of the power system fundamental frequency and are nearly the same cycle after cycle [1]. Microprocessor-based electronics, VFDs, switching power supplies, and other rectifier-inverter circuits, which are installed in commercial and industrial facilities to increase productivity, are also the source of additional power quality problems [2]. These devices are described as nonlinear because their input current is not proportional to the input voltage. This occurs because nonlinear devices inject harmonic currents into the power system, and when applied to the system impedance, cause a voltage drop for each harmonic. This results in voltage harmonics at the load bus [1]. The largest impact of harmonics on a power system is the overheating of components which reduces the life expectancy of equipment [2]. IEEE Standard 519-2014, “Recommended Practice and Requirements for Harmonic Control in Electric Power Systems,” sets the voltage

distortion limit for the point of interconnection at 8.0% total harmonic distortion (THD) and 5% individual harmonic [5].

While the amount of harmonic current that is injected into a system is dependent on the characteristics of the end use device, the magnitude of the voltage distortion is controlled by the system impedance. Therefore, the same nonlinear load put at two different locations in a power system will result in two different voltage distortion values. In commercial and industrial facilities, the system impedance is typically dominated by the service transformers and conductor impedances [1]. As mentioned earlier, however, there are cases when the critical function of a load requires that it be supplied by a UPS which has much higher output impedance [3]. If the critical load is a nonlinear device like a VFD, the load-induced harmonic distortion could adversely affect the UPS or other sensitive loads connected to the same bus.

This thesis will examine the interactions between high impedance power sources such as UPSs and nonlinear critical loads such as VFDs, and any impacts to other sensitive electronic devices connected to the same bus. The goal is to develop a methodology that can be used when designing such a system to guarantee that the harmonic distortion level requirements of IEEE Standard 519-2014 are satisfied to protect both the source and load equipment.

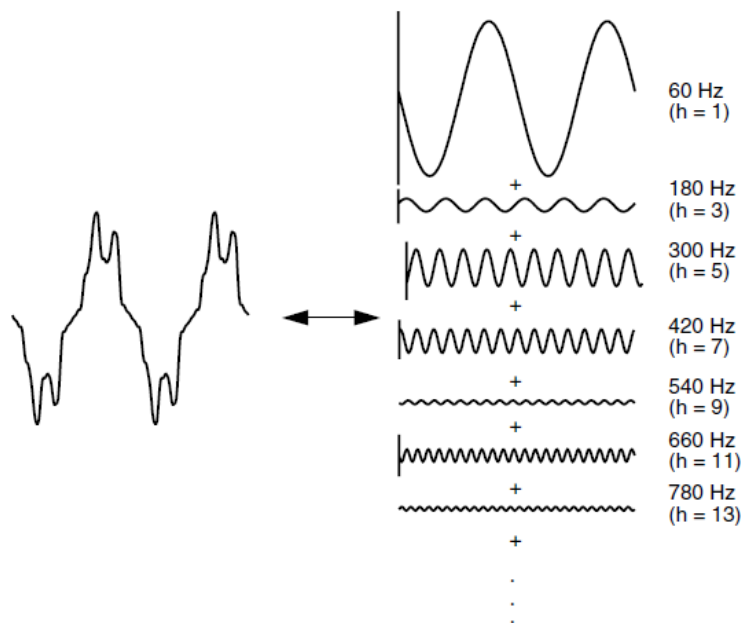
## Chapter 2 – Harmonics

### 2.1 Overview of Harmonics

Linear loads are resistive, inductive, and capacitive in nature. They draw a sinusoidal current at the fundamental frequency that is directly proportional to the sinusoidal voltage applied to the input. Nonlinear loads draw a periodically distorted current waveform that is non-sinusoidal and not proportional to the applied voltage. This can be caused by a number of devices, but commonly, power electronic equipment distorts the current waveform due to the switching on and off of semiconductors.

#### 2.1.1 Fourier Series Representation

The nonsinusoidal periodic waveform that is produced by nonlinear loads can be represented as the sum of sinusoids in which each frequency is an integer multiple of the fundamental frequency. The integer multiples of the fundamental frequency are called harmonics, and the sum of sinusoids is referred to as Fourier series. Figure 2.1 provides an illustration of how sinusoidal waveforms of different harmonic frequencies are added to the fundamental frequency to create a distorted waveform. [1]



**Figure 2.1: Fourier Series Representation of a Distorted Waveform [1]**

The Fourier series of a periodically distorted waveform can be expressed as

$$x(t) = a_0 + \sum_{n=1}^{\infty} \left( a_n \cos \frac{2\pi nt}{T} + b_n \sin \frac{2\pi nt}{T} \right)$$

where  $a_0$  is the average value (dc component) of the function  $x(t)$ , and  $a_n$  and  $b_n$  are the  $n$ th harmonic coefficients of the series. The variable  $T$  is the interval or period over which the function repeats. The dc component and harmonic coefficients of the series are given by

$$a_0 = \frac{1}{T} \int_{-T/2}^{T/2} x(t) dt$$

$$a_n = \frac{2}{T} \int_{-T/2}^{T/2} x(t) \cos \left( \frac{2\pi nt}{T} \right) dt \quad \text{for } n = 1 \rightarrow \infty$$

$$b_n = \frac{2}{T} \int_{-T/2}^{T/2} x(t) \sin \left( \frac{2\pi nt}{T} \right) dt \quad \text{for } n = 1 \rightarrow \infty$$

Since the waveform is periodic, the interval of integration can be taken more generally as  $t$  and  $t+T$ . Also, because  $\omega$  is equal to  $2\pi/T$ , the equations can be expressed in terms of angular frequency as follows:

$$x(t) = a_0 + \sum_{n=1}^{\infty} [a_n \cos(n\omega t) + b_n \sin(n\omega t)]$$

$$a_0 = \frac{1}{2\pi} \int_{-\pi}^{\pi} x(\omega t) d(\omega t)$$

$$a_n = \frac{1}{\pi} \int_{-\pi}^{\pi} x(\omega t) \cos(n\omega t) d(\omega t) \quad \text{for } n = 1 \rightarrow \infty$$

$$b_n = \frac{1}{\pi} \int_{-\pi}^{\pi} x(\omega t) \sin(n\omega t) d(\omega t) \quad \text{for } n = 1 \rightarrow \infty$$

Applying the following trigonometric identity [10]:

$$a \cos x + b \sin x = \sqrt{a^2 + b^2} \cos(x + \phi)$$

$$\phi = \tan^{-1} \left( -\frac{b}{a} \right)$$

The Fourier series equation can be rewritten as

$$x(t) = a_0 + \sum_{n=1}^{\infty} \sqrt{a_n^2 + b_n^2} \cos(n\omega t + \phi_n)$$

where

$a_0$  = dc offset

$\sqrt{a_n^2 + b_n^2}$  = magnitude of  $n$ th harmonic

$\omega$  = fundamental frequency

$\phi_n$  = phase angle of  $n$ th harmonic

The distorted waveform in Figure 2.1 possesses characteristics of symmetry. Half-wave symmetry occurs when the negative portion of a periodic waveform is an exact inverse of the positive portion. Mathematically, a function  $x(t)$  has half-wave symmetry if

$$x(t) = -x\left(t + \frac{T}{2}\right)$$

An indicator of half-wave symmetry in a distorted waveform is the presence of only odd-order harmonics as is the case in Figure 2.1. If even-order harmonics are present, the waveform does not have half-wave symmetry and there may be imbalance in the power system or there may be something wrong with the load equipment. [2][6][9]

### 2.1.2 Harmonic Phase Sequence

Harmonic orders can be further broken down by sequence in a balanced system. Positive sequence harmonics have the normal A-B-C phase rotation, and the phase sinusoids are displaced  $120^\circ$  from each other. Negative sequence harmonics have the opposite A-C-B phase



rotation, and are also displaced  $120^\circ$  from each other. Zero sequence harmonics are in phase with each other, and unlike positive and negative sequence harmonics which cancel in a balanced three-phase system, they are added together in the neutral. Also called the triplen harmonics, zero sequence harmonics can cause issues with overheating of equipment. Table 2.1 provides a summary of the lower order odd harmonics based on their sequence. [1][2]

**Table 2.1: Sequence of Harmonics [1]**

<b>Harmonic Order</b>	<b>Sequence</b>
$h = 1, 7, 13, \dots$	Positive
$h = 5, 11, 17, \dots$	Negative
$h = 3, 9, 15, \dots$ (Triplens)	Zero

### 2.1.3 System Impedance

When harmonic currents are injected into a power system by a nonlinear load, the impedance of the system creates a voltage drop at each harmonic frequency. Therefore, the total harmonic voltage distortion at the terminals of a nonlinear load is equal to the sum of these voltage drops. The impedance of the power system is typically a combination of the source impedance(s), transformer impedance(s), and cable impedance(s). Since the system impedance varies within the power system, the same load put in two different places will result in two different distorted voltage waveforms. When the power system impedance is low and the available fault current is high, the harmonic voltage distortion will be low. When the power system impedance is high and the available fault current is low, the harmonic voltage distortion will be high. It is critical when analyzing the harmonic effects produced by a nonlinear to understand the impedance of the system at its point of interconnection. [1][7][8]

Figure 2.2 provides an illustration of the impedance of a power system supplying a nonlinear load and the voltage drops at each harmonic frequency.

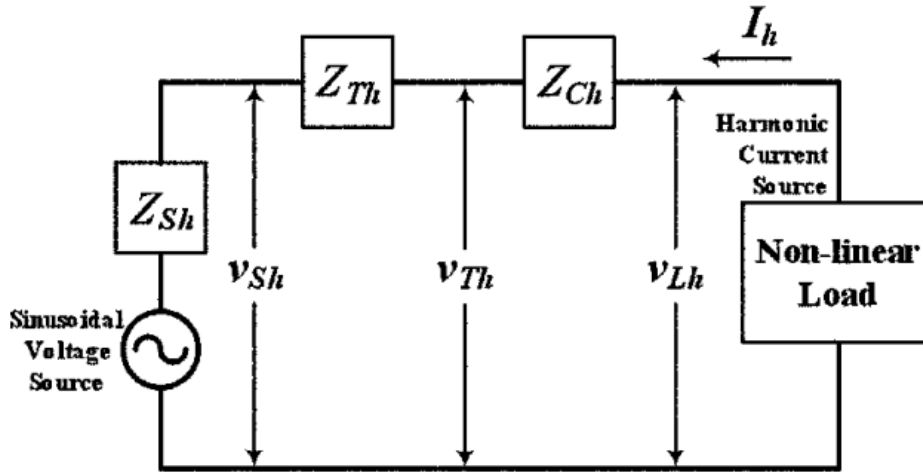


Figure 2.2: Individual Harmonic Voltage Drops across System Impedances [7]

Applying Ohm's law, the individual harmonic voltages at the load terminals, low-voltage side of the transformer, and source terminals are

$$V_{Lh} = I_h \times (Z_{Ch} + Z_{Th} + Z_{Sh})$$

$$V_{Th} = I_h \times (Z_{Th} + Z_{Sh})$$

$$V_{Sh} = I_h \times Z_{Sh}$$

where

$Z_h$  = Impedance at  $h$ th harmonic

$V_h$  = Voltage at  $h$ th harmonic

$I_h$  = Current at  $h$ th harmonic

### 2.1.3.1 Source Impedance of a Utility Interconnection

When the source of an industrial power system is a utility interconnection, its impedance at the fundamental frequency is often called its short-circuit impedance. If the three-phase short-circuit duty is provided in megavoltampere (MVA) or short-circuit current, the fundamental short-circuit impedance can be calculated as

$$Z_{SC} = \frac{kV^2}{MVA_{SC}} = \frac{kV \times 1000}{\sqrt{3}I_{SC}}$$

where

$Z_{SC}$  = short-circuit impedance in  $\Omega$

$kV$  = phase-to-phase voltage in kV

$MVA_{SC}$  = three-phase short-circuit duty in MVA

$I_{SC}$  = short-circuit current in A

If the phase information or  $X/R$  ratio of the source is not provided by the utility, it can be assumed that the impedance is purely reactive. [1]

### 2.1.3.2 Source Impedance of a Generator

It is often necessary to supply nonlinear loads from standby or emergency generators in the event that normal utility power is lost. For a generator, the source impedance at the fundamental frequency is equal to its subtransient reactance. This value can be obtained from the generator manufacturer, or in lieu of manufacturer data, it can be assumed based on typical values. IEEE Std. C57.12.00-2010, “*IEEE Standard for General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers,*” provides a table of common per-unit subtransient reactance values for three-phase synchronous machines. For generator values, see Table 2.2.

**Table 2.2: Subtransient Reactance of Three-Phase Synchronous Machines [15]**

Type of machine	Most common reactance per-unit	Subtransient reactance range per-unit
Two-pole turbine generator	0.10	0.07 to 0.20
Four-pole turbine generator	0.14	0.12 to 0.21
Salient pole generators and motors with dampers	0.20	0.13 to 0.32
Salient pole generators without dampers	0.30	0.20 to 0.50
Condensers-air cooled	0.27	0.19 to 0.30
Condensers-hydrogen cooled	0.32	0.23 to 0.36

The per-unit subtransient reactance can be converted to ohms using the following equation.

$$X_{d(\Omega)}'' = \left( \frac{kV^2}{MVA_{3\phi}} \right) \times X_{d(p.u.)}''$$

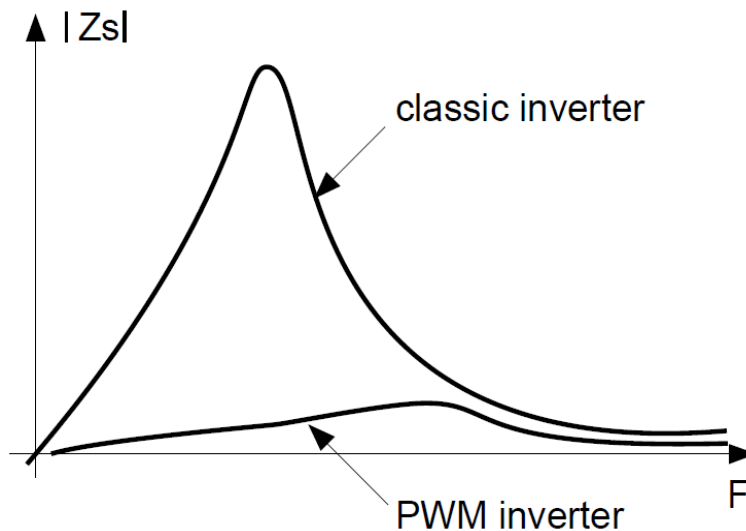
where

$kV$  = phase-to-phase voltage in kV

$MVA_{3\phi}$  = kVA rating of the generator

### 2.1.3.3 Source Impedance of a UPS

For critical applications where even a momentary loss of power can jeopardize human safety, security, or the environment, a UPS is required. Compared to an equivalent utility or generator source, the available short-circuit current from a UPS is much lower. This value is typically equal to 200% of the rated output current. It is dependent on the impedance of the output filter and the current regulation performed by the inverter. The output filter is of the L and C type. Its impedance will vary with frequency as shown Figure 2.3. If the filter component information from the UPS manufacturer is unavailable, the filter impedance can be calculated using the short-circuit current rating, and assumed to be purely reactive. [17][18]



**Figure 2.3: Output Impedance of UPS Based on Inverter Type [18]**

#### 2.1.3.4 Transformer Impedance

The transformer impedance at the fundamental frequency can be determined from the percent impedance found on its nameplate. In lieu of nameplate data, the percent impedance can be assumed based on typical values. IEEE Std. C57.12.10-2010, “*IEEE Standard Requirements for Liquid-Immersed Power Transformers*,” provides common percent impedances for transformers at their self-cooled rating. For transformer percent impedance values, see Table 2.3.

**Table 2.3: Transformer Percent Impedance at Self-Cooled Rating [16]**

High-voltage BIL (kV)	Without LTC	With LTC
≤ 110	5.5	-
150	6.5	7.0
200	7.0	7.5
250	7.5	8.0
350	8.0	8.5
450	8.5	9.0
550	9.0	9.5
650	9.5	10.0
750	10.0	10.5

The percent impedance values can be converted to ohms or adjusted to a new base if calculations are performed by per-unit analysis. The following equation can be used to convert the percent impedance of a transformer to ohms.

$$Z_{tx(\Omega)} = \left( \frac{kV^2}{MVA_{3\phi}} \right) \times Z_{tx(p.u.)}$$

where

$kV$  = phase-to-phase voltage in kV

$MVA_{3\phi}$  = kVA rating of the transformer

The  $X/R$  ratio of the transformer is needed to determine the fundamental resistance and reactance of the transformer. Otherwise, it can be assumed that the impedance is purely reactive. [1]

### **2.1.3.5 Cable Impedance**

The fundamental impedance of a cable feeding a nonlinear load can be calculated using resistance and reactance information in vendor datasheets or the National Electric Code (NEC). These sources provide the resistance and reactance per-unit length of the applicable conductor size. The actual length of the cable can then be used to approximate the cable impedance.

### **2.1.3.6 System Impedance at Harmonic Frequencies**

It is important to note that inductive reactance changes linearly with frequency. The following equation can be used to adjust the reactance value for each harmonic frequency.

$$X_h = hX_1$$

where

$X_1$  = Inductive reactance at fundamental frequency

$X_h$  = Inductive reactance at  $h$ th harmonic

For simplicity, it can be assumed that resistance does not change significantly with frequency. Additionally, if the resistance is neglected and the system is assumed to be purely reactive, this will result in a conservative prediction of the harmonic distortion. [1]

### **2.1.4 Harmonic Indices**

The effective value of a distorted waveform can be measured using one of two indices; Total Harmonic Distortion (THD) and Total Demand Distortion (TDD). THD is the root mean square (RMS) of the harmonic content of a waveform in percent of the fundamental quantity. Therefore, a waveform that is a perfect sinusoid would have a THD equal to zero. THD is most often used to describe harmonic voltage distortion as follows:

$$THD = \frac{\sqrt{\sum_{n=2}^{n_{max}} V_n^2}}{V_1}$$

Using THD as a measure of harmonic current distortion can be misleading for small loads with high harmonic distortion. In this case the significance of the distortion is low even though the THD is high. TDD is used to describe harmonic current distortion because it is the RMS of the harmonic current in percent of the maximum demand load current at the fundamental frequency. The mathematical representation of TDD is as follows:

$$TDD = \frac{\sqrt{\sum_{n=2}^{n_{max}} I_n^2}}{I_L}$$

For a new facility,  $I_L$  is estimated base on the expected load profiles. [1][2]

## 2.2 Effects of Harmonics

Harmonics are typically known for their negative effect on a power system. The most common problem with harmonics is increased heating within power system components. This increased heating causes the insulation of components to age rapidly and consequently reduces their useful life. Addition effects include reduced efficiency and malfunctioning of system or plant components. The equipment most susceptible to these effects includes transformers, rotating machines, cables, overcurrent protection, capacitors and power electronic equipment. [6]

### 2.2.1 Transformers

The main effect that harmonic current distortion has on transformers is overheating. The distorted current creates increased copper losses and iron core losses. The core losses are due hysteresis and eddy currents, and increase with the square of the harmonic frequency [1]. The additional heating in the core causes winding insulation stress which increases the likelihood of a failure. For delta-wye transformers, triplen harmonics combine in the neutral and circulate in the delta winding creating additional heat. Another problem with harmonics and transformers is audible noise which is caused by increased vibrations in the transformer. [7][8]

To prevent damage to the winding insulation, transformers that will feed nonlinear loads must be derated for the additional heating. In this case, a specialty transformer called a k-factor transformer is recommended. K-factor transformers are delta-wye transformers with an oversized delta winding and neutral to accommodate the triplen harmonics which combine and

circulate. They are also designed to reduce copper and core losses by using smaller winding conductors. [2]

### **2.2.2 Rotating Machines**

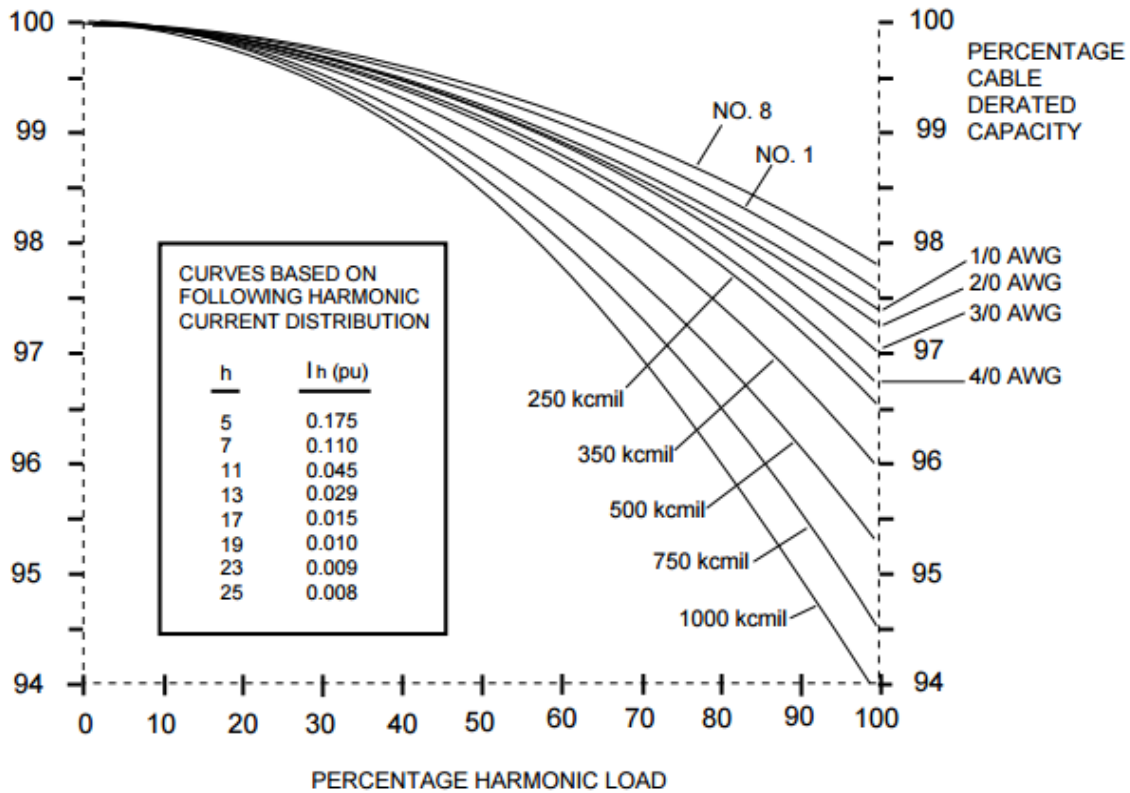
Generators and motors also experience increased heating from harmonic distortion. Similar to transformers, this heating is due to iron (eddy current and hysteresis) and copper losses in the stator and rotor windings. Generators are often oversized when supplying nonlinear loads to negate this effect. Harmonic voltage distortion can be troublesome for the voltage regulator of a generator which examines the zero crossing of the fundamental waveform. When multiple zero crossings are present due to the additional harmonic components, timing can be affected and generator instability can result. [7][8]

Motors are also uniquely affected by increased heating. Bearing lubrication can degrade over time and result in bearing collapse. Also, the effectiveness of motor insulation is reduced by 50% for every 10°C rise over rated temperature. Both of these effects reduce the life of an induction motor. Lastly, harmonics can affect the torque production of induction motors. Positive sequence components such as the 7<sup>th</sup> and 13<sup>th</sup> harmonic assist torque production, while negative sequence components such as the 5<sup>th</sup> and 11<sup>th</sup> harmonic act against torque production. This results in torque pulsations which cause vibration problems. [7][8]

### **2.2.3 Cables**

Overheating in cables is always a concern, even when harmonic distortion is not present. Cables are sized to carry load current continuously, at an expected ambient temperature, without damaging the insulation. When harmonic distortion is added, additional deration must be performed to account for the additional heat that is produced. The conductor  $I^2R$  losses which generate the heat are increased due to the skin effect and proximity effect at the higher harmonic frequencies. Also, harmonic voltage distortion can increase the dielectric stress on the insulation, and shorten the life of the cable. This increases the likelihood of a fault which results in costly repairs. Figure 2.4 provides an example of how a cable's capacity is derated based on the percentage of harmonic load that is supplied. [7][8][9]





**Figure 2.4: Example Cable Derating for Harmonics [9]**

### 2.2.4 Overcurrent Protection

Thermal-magnetic circuit breakers and fuses operate based on the heat produced from an overload condition. Harmonic current distortion also causes heat and may trigger a breaker to trip or a fuse to rupture prematurely. Therefore, breaker and fuse derating is often necessary when supplying nonlinear loads to prevent false or spurious operations. Digital relays may also be affected by harmonic distortion if they rely on detection of zero crossings. [7][8]

### 2.2.5 Capacitors

Capacitors installed in an industrial plant or commercial building for power factor correction can also experience overheating from harmonic current distortion. Because of its low impedance at frequencies higher than the fundamental frequency, a capacitor becomes a trap for harmonics. If tuned to a characteristic harmonic such as the 5<sup>th</sup> or 7<sup>th</sup>, the dielectric can fail and the capacitor can rupture. Additionally, when capacitors are connected to a network there is the

potential for parallel or series resonance. In both cases, harmonics are magnified, capacitor life is shortened, and severe voltage distortion is created. [8][9]

### **2.2.6 Power Electronic Equipment**

The proper operation of power electronic equipment such as computer power supplies and power converters is typically dependent on the accurate determination of the voltage zero crossings. Harmonic distortion of the voltage waveform can shift the zero crossing or cause imbalance in the phase-to-phase voltages. This can lead to failures and the generation of uncharacteristic harmonics. Additionally, harmonics can be magnetically coupled into equipment components. A diode rectifier is typically not affected, but capacitive circuits used for filtering may experience thermal stress because of the high harmonic currents from the supply. These harmonics can also be passed through the rectifier and impact the dc bus which is connected to logic circuits, dc loads, or inverters. Most computers, programmable logic controllers, and other sensitive electronics may not tolerate more than 5% voltage distortion, with the largest single harmonic not exceeding 3% of the fundamental. [8][11]

## **2.3 Recommended Limits**

To prevent overheating and failures of electrical equipment due to harmonic distortion, IEEE Std. 519-2014 provides recommended limits for harmonic current injection at the Point of Common Coupling (PCC) to maintain acceptable system voltage. The standard is written from the point of view of the electric utilities, and the PCC is defined as the point where the utility connects to multiple customers. In addition to limiting the harmonic current injection from individual customers, IEEE Std. 519-2014 provides limits for the overall harmonic distortion of the system voltage supplied by the utility to ensure the proper operation of electrical loads.

Within an industrial facility, the PCC can be redefined as the point between a nonlinear load and other loads. Based on the ratio of maximum short-circuit current to maximum demand load current ( $I_{SC}/I_L$ ) at each desired PCC, the maximum harmonic current distortion measured in TDD can be found from Table 2.4. The limits are based on this ratio because systems with a higher short-circuit capacity have lower voltage distortion for the same magnitude harmonic current injection than systems with lower short-circuit capacities. Based on the bus voltage at the PCC, the maximum harmonic voltage distortion measured in THD can be found from Table 2.5. [5]

**Table 2.4: Current Distortion Limits for Systems Rated 120 V through 69 kV [5]**

<b>Maximum Harmonic Current Distortion in Percent of <math>I_L</math></b>						
<b>Individual Harmonic Order (Odd Harmonics)<sup>a, b</sup></b>						
$I_{SC}/I_L$	$3 \leq h < 11$	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h \leq 50$	TDD
$< 20^c$	4.0	2.0	1.5	0.6	0.3	5.0
$20 < 50$	7.0	3.5	2.5	1.0	0.5	8.0
$50 < 100$	10.0	4.5	4.0	1.5	0.7	12.0
$100 < 1000$	12.0	5.5	5.0	2.0	1.0	15.0
$> 1000$	15.0	7.0	6.0	2.5	1.4	20.0

<sup>a</sup>Even harmonics are limited to 25% of the odd harmonic limits above.  
<sup>b</sup>Current distortions that result in a dc offset, e.g., half-wave converters, are not allowed.  
<sup>c</sup>All power generation equipment is limited to these values of current distortion, regardless of actual  $I_{SC}/I_L$ .  
 where  
 $I_{SC}$  = maximum short-circuit current at PCC.  
 $I_L$  = maximum demand load current (fundamental frequency component) at PCC under normal load operating conditions.

**Table 2.5: Voltage Distortion Limits [5]**

<b>Bus Voltage <math>V</math> at PCC</b>	<b>Individual Harmonic (%)</b>	<b>Total Harmonic Distortion THD (%)</b>
$V \leq 1.0$ kV	5.0	8.0
$1$ kV $< V \leq 69$ kV	3.0	5.0
$69$ kV $< V \leq 161$ kV	1.5	2.5
$161$ kV $< V$	1.0	1.5 <sup>a</sup>

<sup>a</sup>High-voltage systems can have up to 2.0% THD where the cause is an HVDC terminal whose effects will have attenuated at points in the network where future users may be connected.

## Chapter 3 – Power Electronic Equipment

### 3.1 Overview of Power Electronics

The term power electronics typically refers to the use of semiconductor circuits to convert electrical energy from one form to another. Rectifiers convert AC voltage to DC voltage and supply DC loads such as logic circuits or battery banks. Inverters convert DC voltage to AC voltage and typically supply critical loads or motors. Rectifiers and Inverters are used in VFDs and UPSs which are some of the most common generators of harmonic distortion in industrial power systems. [12]

### 3.2 Variable Frequency Drives

#### 3.2.1 Principal of Operation

The VFD is an electrical type of Adjustable Speed Drive (ASD) that is used to match the speed of an AC induction motor to process requirements. ASDs can also be hydraulic or mechanical in nature. Electrical ASDs are preferred over hydraulic and mechanical ASDs where reliability and low maintenance is critical. Based on the following equation, the speed of an induction motor can be controlled by adjusting the supply frequency or the number of poles.

$$n_s = \frac{120f}{p}$$

where

$n_s$  = synchronous speed of motor

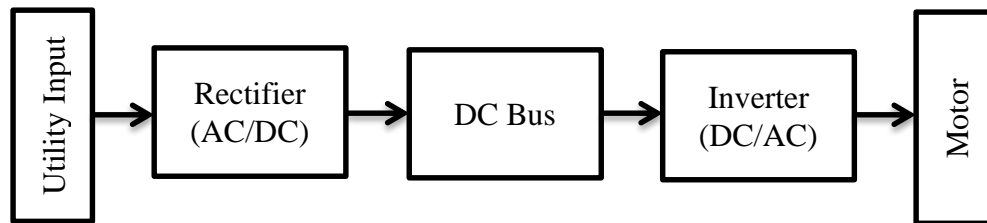
$f$  = supply frequency

$p$  = number of poles

Since the number of poles in an induction motor is typically fixed, it is much more practical to control the frequency of the source voltage applied to a motor. With the help of power electronics, this is the principle on which VFDs operate. [12][13]

### 3.2.2 System Components

As illustrated in Figure 3.1, a VFD is comprised of three main stages. In the first stage, three-phase AC voltage is fed to a rectifier which converts the voltage to DC. The DC voltage is then fed to a DC bus in the second stage where it is filtered and smoothed out. In the third stage, an inverter converts the smoothed DC voltage back to AC where the frequency varies based on input from the controller. AC squirrel cage induction motors are typically used in VFD applications because of their ruggedness. [13]



**Figure 3.1: Variable Frequency Drive**

### 3.2.3 Benefits

There are a number of benefits to using VFDs. When a motor's speed is tailored to the process needs, it draws only the energy required. This provides energy savings and process optimization which ultimately leads to higher quality. The soft starting of motors driven by VFDs results in less stress on the winding insulation and therefore reduces the maintenance costs associated with the motor. Also, VFDs allow for an increase in future production without extra capital investment. [13][14]

### 3.2.4 Harmonics

There are also a few disadvantages of using VFDs. These are mainly acoustic noise, motor heating, and supply harmonics. The supply harmonics are mostly due to the nonlinear nature of the rectifier of the VFD. The harmonic current distortion produced can range from less than 5% THD to 35% THD, or even higher. There are a number of different rectifier technologies available, each with a unique harmonic spectrum. It is important to understand the application for each VFD and the system impedance at the point of interconnection to determine the correct rectifier technology to purchase. [13][14]

### 3.3 Uninterruptible Power Supplies

#### 3.3.1 System Components

While utilities continuously strive to provide reliable power to their customers, voltage disturbances and interruptions are sometimes unavoidable. For critical systems and sensitive equipment in which an outage lasting longer than 0.5 seconds could pose a serious threat to human safety, the environment, or security, a UPS is the only solution. [3]

As illustrated in Figure 3.2, the three main stages of a UPS are similar to a VFD. The first stage is identical in that three-phase AC voltage is fed to a rectifier and converted to DC voltage. In the second stage, the DC voltage is fed to a DC bus, but also attached to the bus is a floating battery bank for energy storage. In the third stage, a static inverter converts the DC voltage back to AC where the frequency is the power system fundamental frequency. An additional feature of a UPS is a static automatic transfer switch which offers a bypass connected from the three-phase AC supply to the load bus. There are two main configurations available for UPSs; Line Preferred and Inverter Preferred. [3]

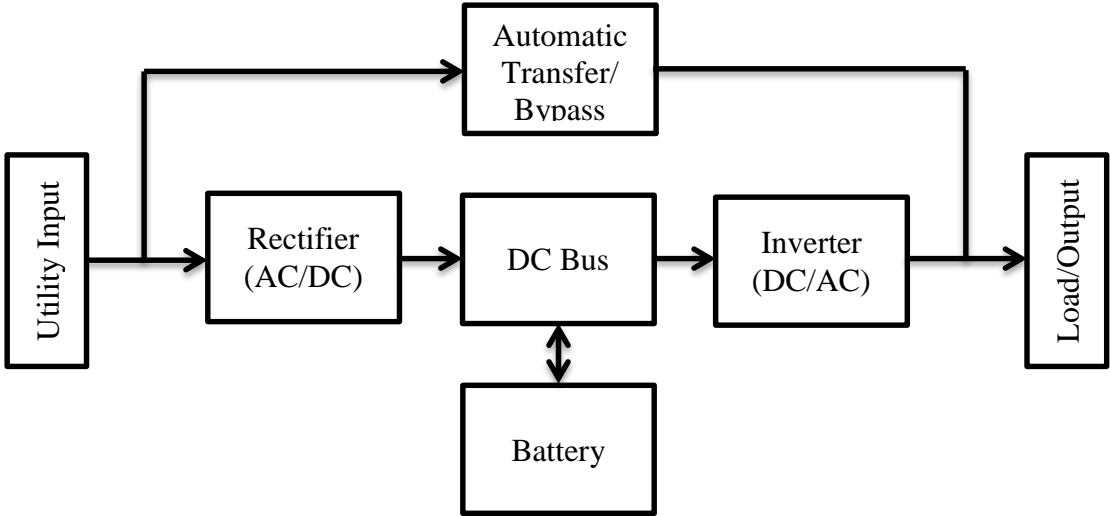


Figure 3.2: Uninterruptible Power Supply

### **3.3.2 Line Preferred**

The Line Preferred UPS configuration is also commonly referred to as an Off-line UPS. In this configuration, the loads are normally fed by the three-phase AC supply through the automatic transfer switch. At the same time, the battery charge is maintained through the rectifier and DC bus. When a disturbance occurs, the automatic transfer switch transfers the loads to the inverter which is fed by the battery until it is depleted or the AC supply is operational again. Because there is switching involved, this configuration is not used in highly critical applications. [3]

### **3.3.3 Inverter Preferred**

The Inverter Preferred UPS configuration is also commonly referred to as an On-line UPS. In this configuration, the loads are normally fed by the inverter. When a disturbance occurs, the battery bank continues to supply the inverter until it is depleted or the AC supply is returned. In this configuration, the automatic transfer switch is used to transfer the loads directly to the three-phase AC supply when a UPS failure occurs. This configuration is the industry standard for critical equipment because there is no interruption to the load when an outage of the main supply occurs. [3]

### **3.3.4 Harmonics**

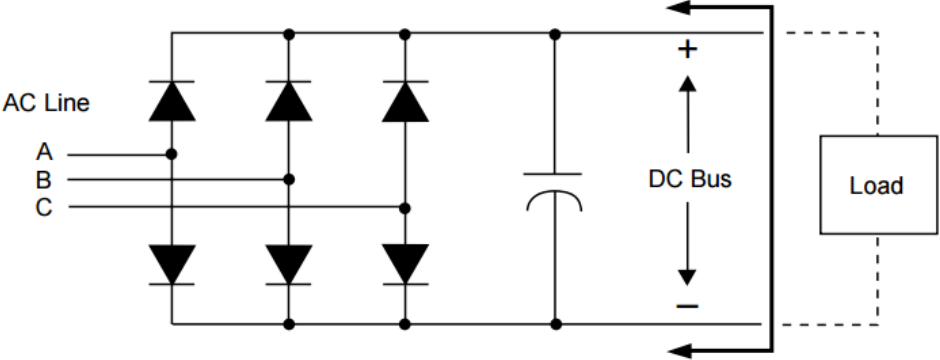
Harmonics are also an issue for UPSs at both the input and output terminals. The rectifier in the first stage of a UPS injects harmonic currents into the system. At the output terminals of the third stage inverter, harmonic voltages can be generated by nonlinear loads that are fed by the UPS. As a source, UPS systems have a much higher impedance compared to the utility and will result in a much higher voltage distortion. Oversizing the UPS is often required to reduce the impedance to achieve acceptable levels of harmonic voltage distortion. [3]

## **3.4 Ideal Rectifiers**

### **3.4.1 6-Pulse Bridge Rectifier**

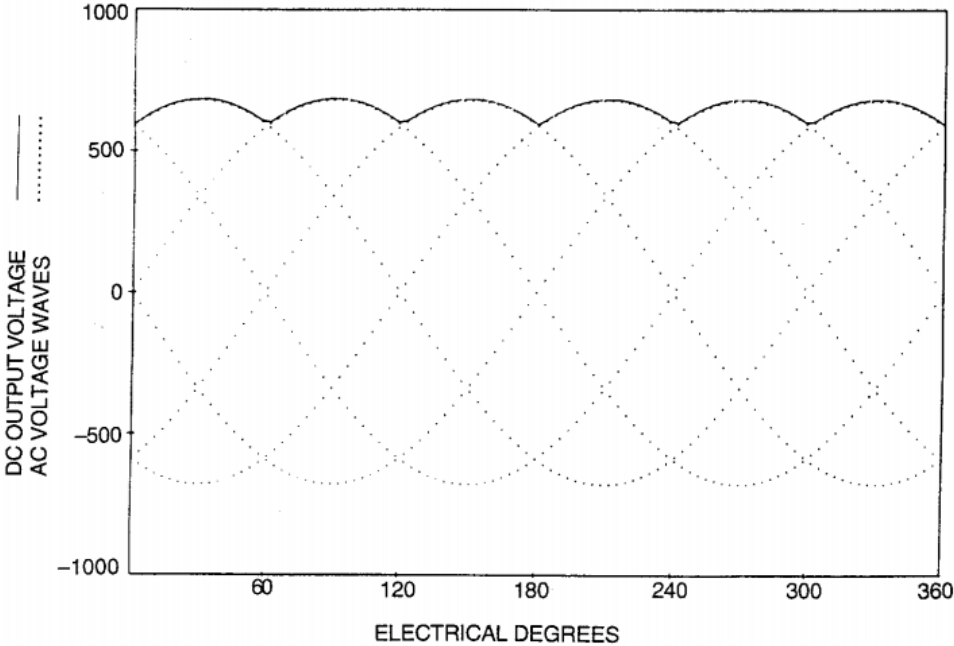
The most common rectifier circuit used in three-phase power converters and VFDs is the 6-Pulse bridge rectifier. This rectifier utilizes either six diodes or six thyristors to switch the three-phase voltages ON and OFF in sequence to produce DC voltage. A low-pass filter is

typically added to the rectifier output to smooth the DC current. Figure 3.3 illustrates the typical configuration of a 6-Pulse diode bridge rectifier. [12][13]



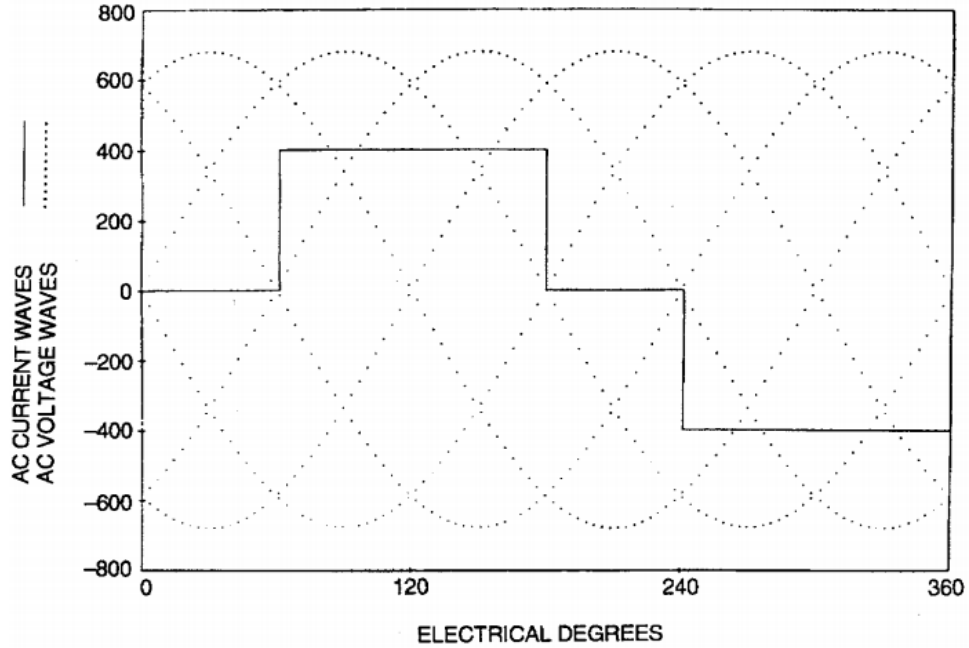
**Figure 3.3: 6-Pulse Diode Bridge Rectifier [8]**

Each diode turns ON and conducts current when there is a forward voltage across it. When thyristors are used, a gate signal is provided by an external controller to turn them ON and OFF. Figure 3.4 provides the ideal DC output voltage waveform that is created by the switching ON and OFF of the diodes in a 6-Pulse bridge rectifier. [13]



**Figure 3.4: Ideal 6-Pulse Bridge Rectifier DC Output Voltage Waveform [11]**





**Figure 3.5: Ideal 6-Pulse Bridge Rectifier AC Input Current Waveform [11]**

Figure 3.5 provides the ideal AC input current waveform for a 6-Pulse bridge rectifier. It assumes there is no DC current ripple, and the DC current is transferred between the phases instantaneously. Using Fourier series, this ideal waveform can be represented by its harmonic components. The formula for the characteristic components of a 6-Pulse bridge rectifier is

$$h = kq \pm 1$$

$$I_h = \frac{I_1}{h}$$

where

$h$  = harmonic order

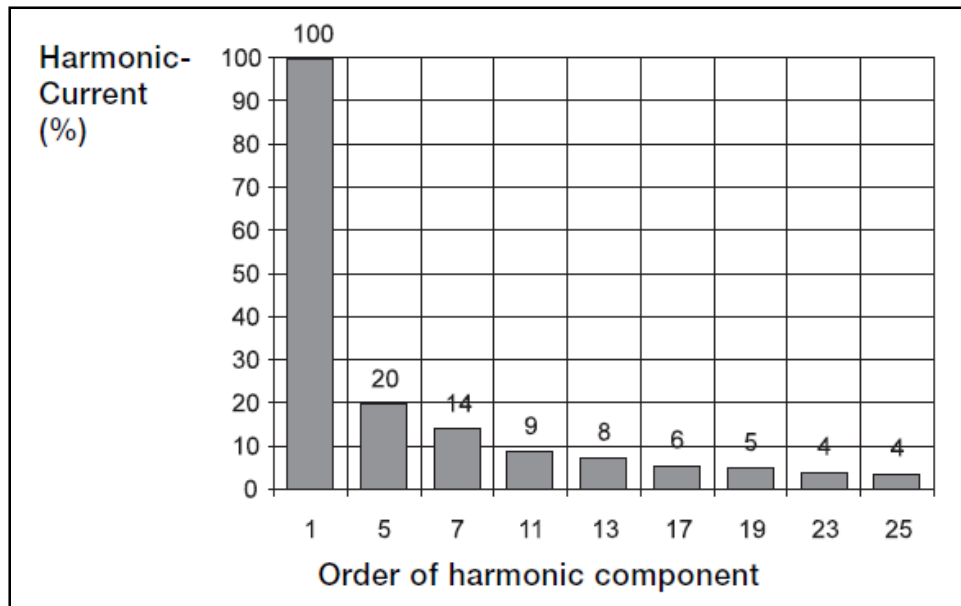
$k$  = any positive integer

$q$  = the pulse number of the rectifier circuit

$I_h$  = the amplitude of the  $h$ th harmonic current

$I_1$  = the amplitude of the fundamental current

Therefore, the harmonic spectrum for a 6-Pulse bridge rectifier consists of the 5<sup>th</sup>, 7<sup>th</sup>, 11<sup>th</sup>, 13<sup>th</sup>, 17<sup>th</sup>, 19<sup>th</sup>, 23<sup>rd</sup>, 25<sup>th</sup>, etc. harmonic components. It is important to note that the triplen harmonics are not present in three-phase bridge rectifiers. The ideal magnitude of each component is shown in Figure 3.6. Using the formula defined earlier, the total harmonic current distortion for an ideal 6-Pulse bridge rectifier is 28.9 % THD. [11][13]



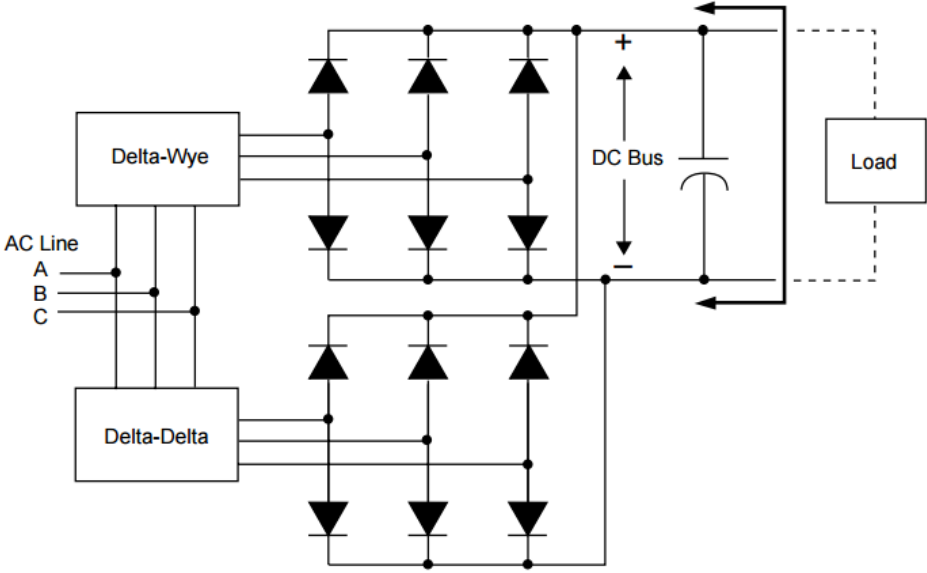
**Figure 3.6: Harmonic Components of the Ideal 6-Pulse Bridge Rectifier AC Input [13]**

In practice, there are a number of deviations from the ideal waveforms shown above. One example is that diodes are not ideal and do not turn off instantaneously when the forward voltage becomes negative. Commutation is the transfer of current from one diode to another, and commutation time is the overlap period in which both diodes remain on. This overlap along with other external factors could lead to higher levels of distortion and non-characteristic components. [12]

### 3.4.2 Phase Multiplication

An effective technique for reducing the total harmonic current distortion produced by three-phase power converters and VFDs is phase multiplication. Multiple 6-Pulse bridge rectifiers can be combined at a phase shift to form a 12 or 18-Pulse rectifier. If  $m$  is the number of 6-Pulse rectifiers that are combined, then they must be phase shifted exactly  $60/m$  degrees

from each other and equally share the dc load current. Figure 3.7 shows the configuration for a 12-Pulse diode bridge rectifier. The 30 degree phase shift is achieved by using both a delta-wye and a delta-delta transformer. [11]



**Figure 3.7: 12-Pulse Diode Bridge Rectifier [8]**

The ideal characteristic harmonic components for a 12 and 18-Pulse bridge rectifier can be calculated using the same formulas defined for a 6-Pulse bridge rectifier. The ideal harmonic spectrum for a 12-Pulse bridge rectifier consists of the 11<sup>th</sup>, 13<sup>th</sup>, 17<sup>th</sup>, 19<sup>th</sup>, 23<sup>rd</sup>, 25<sup>th</sup>, etc. harmonic components with a total harmonic current distortion of 15.4 % THD. Following the same principles, the ideal total harmonic current distortion for an 18-Pulse bridge rectifier is 9.6 % THD. [11]

## **Chapter 4 – Methodology for Harmonic Analysis**

### **4.1 Purpose**

As previously mentioned in Section 3.2, VFDs are widely used in industrial and commercial facilities for energy savings and process optimization. Their greatest negative effect on the power system, however, is harmonic current injection at the supply due to the nonlinear nature of the rectifier circuit in the VFD. This harmonic current injection can greatly impact the quality of the voltage delivered to the VFD and other loads connected to the same bus. If the other loads are sensitive power electronic devices like computer power supplies, which are dependent on the accurate determination of the voltage zero crossings, its performance will be less than optimum or it may not operate at all.

The magnitude of the voltage distortion at the supply bus is dependent on the system impedance. The system impedance is also termed the system short-circuit impedance, and it can vary greatly depending on the type of source and configuration of the distribution network. Three of the most common sources found in industrial and commercial power systems are a utility, generator, and UPS.

The purpose of this thesis is to examine the impact that system impedance has on the harmonic voltage distortion produced by VFDs that may share a common bus with other sensitive loads. Of particular interest are high impedance sources such as UPSs, which are often used to supply critical loads in the event of a power disturbance. An analysis is performed to calculate the total harmonic voltage distortion in % THD over a range of system impedance values for multiple rectifier technologies, and motor horsepower (HP) ratings. The overall goal is to use the output of this analysis to select the correct rectifier technology for a desired HP rating and system impedance that will meet or exceed the total harmonic voltage distortion limits set by IEEE Standard 519-2014.

### **4.2 Scope**

This analysis calculates the total harmonic voltage distortion in % THD over a range of system impedances that can be present at a typical 480 V industrial or commercial distribution panel. A 480 V distribution panel is used because it is the most common application level for VFDs at the HP ratings of interest. The system impedance range covers three different cases for power sources to the panel; utility, generator, and UPS. The following per-unit system

characteristics are held constant in all three cases to develop a realistic range of system impedances in Ohms.

$$\text{Apparent Power (S) Base} = 500 \text{ kVA}$$

$$\text{Voltage Base} = 480 \text{ V}$$

$$\text{Current Base} = \frac{S_{\text{base}}}{\sqrt{3} V_{\text{base}}} = 601 \text{ A}$$

$$\text{Impedance Base} = \frac{V_{\text{base}}^2}{S_{\text{base}}} = 0.4608 \Omega$$

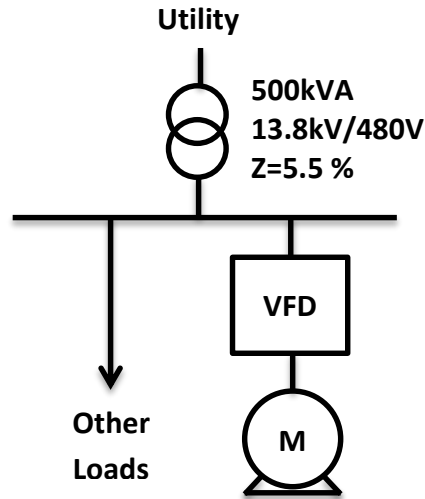
Additionally, this analysis compares the results of three different rectifiers at multiple HP ratings. For simplicity, the three rectifiers examined are the ideal 6-Pulse, 12-Pulse, and 18-Pulse rectifiers. The HP ratings compared are industry standard ratings of 10 HP, 30 HP, 75 HP, 200 HP, and 400 HP. The system impedance for all three cases at the per-unit system characteristics are calculated in the next three sections.

## 4.3 Comparison of Source Impedances

### 4.3.1 Case 1: VFD Fed by Utility Source

As explained in Section 2.1.3.1, the fundamental short-circuit impedance of a utility source can be calculated from the three-phase short-circuit duty in MVA or the short-circuit current if provided for the bus. If this information is not provided, as is the case for this example, the short-circuit impedance and current can be estimated based on the utility configuration. In commercial and industrial facilities, the short-circuit impedance is typically dominated by the service transformer as shown in Figure 4.1. The percent impedance of the transformer can be assumed from the typical values presented in Table 2.3. Therefore,

$$Z_{tx} = 0.055 \text{ p.u.}$$



**Figure 4.1: VFD Connected to 480 V Bus Fed by Utility Source**

Using the impedance base calculated in Section 4.2, the percent impedance of the transformer can be converted to ohms as follows.

$$Z_{tx(\Omega)} = Z_{tx(p.u.)} \times Z_{Base}$$

$$Z_{tx} = 0.055 \text{ p.u.} \times 0.4608 \Omega = \mathbf{0.0253 \Omega}$$

Assuming that the utility short-circuit impedance is approximately equal to the transformer impedance, and the system conductor impedances are negligible, the system short-circuit current at the 480 V panel can be calculated as

$$I_{SC} = \frac{V_{Bus}}{Z_{tx}}$$

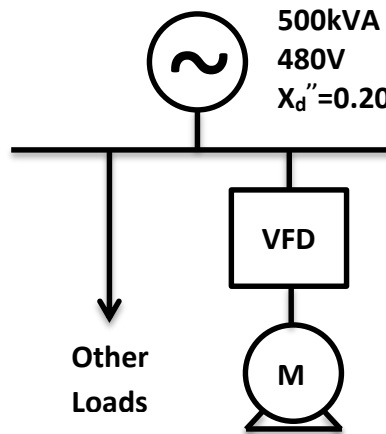
$$I_{SC} = \frac{480 \text{ V}}{0.0253 \Omega} = \mathbf{18,972 \text{ A}}$$

#### **4.3.2 Case 2: VFD Fed by Generator Source**

As explained in Section 2.1.3.2, the fundamental source impedance of a generator, as shown in Figure 4.2, is equal to its subtransient reactance. If this information is not provided by the generator manufacturer, as is the case for this example, the source impedance and short-

circuit current can be estimated based on typical values. The subtransient reactance of the three-phase synchronous generator can be assumed from the typical values presented in Table 2.2. Therefore, for a salient pole generator with dampers

$$X_d'' = 0.20 \text{ p. u.}$$



**Figure 4.2: VFD Connected to 480 V Bus Fed by Generator Source**

Using the impedance base calculated in Section 4.2, the per-unit impedance of the generator can be converted to ohms as follows.

$$X_{d(\Omega)}'' = X_{d(p.u.)}'' \times Z_{Base}$$

$$X_d'' = 0.20 \text{ p. u.} \times 0.4608 \Omega = \mathbf{0.0922 \Omega}$$

Assuming that the short-circuit impedance at the 480 V panel is approximately equal to the subtransient reactance of the generator, and the system conductor impedances are negligible, the system short-circuit current at the 480 V panel can be calculated as

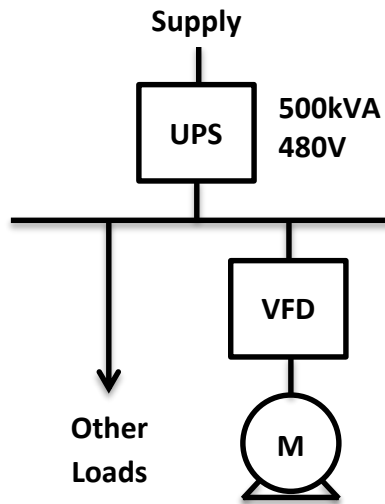
$$I_{SC} = \frac{V_{Bus}}{X_d''}$$

$$I_{SC} = \frac{480 \text{ V}}{0.0922 \Omega} = \mathbf{5,206 \text{ A}}$$

### 4.3.3 Case 3: VFD Fed by UPS Source

As explained in Section 2.1.3.3, the source impedance of a UPS source, as shown in Figure 4.3, is dependent on the impedance of the output filter and the current regulation performed by the inverter. If this information is not provided by the UPS manufacturer, as is the case for this example, the source impedance and short-circuit current can be estimated based on a typical UPS short-circuit current equal to 200 % of the UPS rated output current. Therefore,

$$I_{SC} = I_{Base} \times 2$$
$$I_{SC} = 601 A \times 2 = 1,202 A$$



**Figure 4.3: VFD Connected to 480 V Bus Fed by UPS Source**

Using the short-circuit current of the UPS, and assuming that the system conductor impedances are negligible, the UPS source impedance at the 480 V panel can be calculated as

$$Z_{UPS} = \frac{V_{Bus}}{I_{SC}}$$
$$Z_{UPS} = \frac{480 V}{1,202 A} = 0.3993 \Omega$$

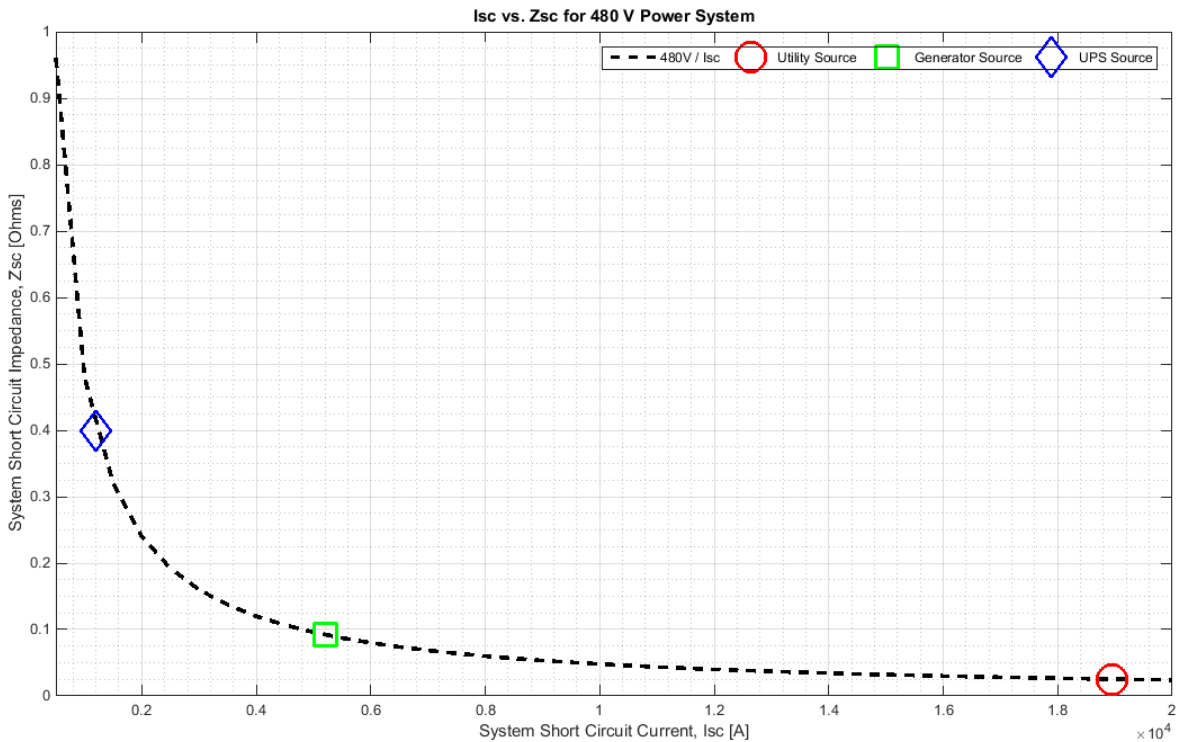


#### 4.3.4 Summary

Table 4.1 and Figure 4.4 were formed from the results of the above calculations for the system short-circuit current and impedance from a utility source, generator source, and UPS source. This data confirms that a utility source has a relatively low short-circuit impedance and is a “strong system” based on the high short-circuit current that it can supply. The data also confirms that a UPS source has a relatively high short-circuit impedance and is a “weak system” based on the low short-circuit current that it can supply. A generator source, while it has a higher short-circuit impedance than a utility source, has relatively low impedance when compared to a UPS. The next step is to determine the effect that this variation in impedance has on the total harmonic voltage distortion that is produced by different rectifier technologies at different HP ratings. Based on the results from these three sources, the voltage THD analysis will be performed over a system short-circuit current range of 500 A to 20,000 A.

**Table 4.1: Summary of Short-Circuit Current and Impedance by Source**

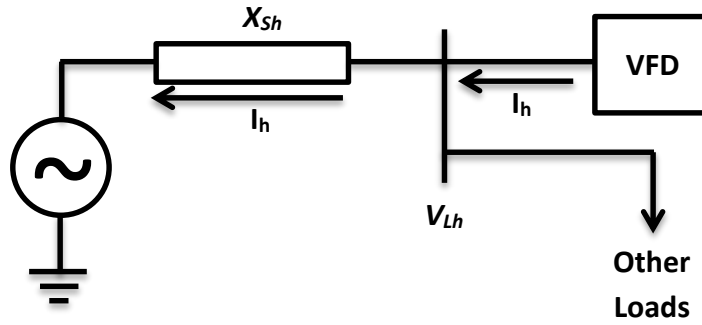
<b>Source</b>	<b>Short-Circuit Current <math>I_{sc}</math> [A]</b>	<b>Short-Circuit Impedance <math>Z_{sc}</math> [Ohms]</b>
Utility	18,972	0.0253
Generator	5,206	0.0922
UPS	1,202	0.3993



**Figure 4.4: Comparison of Short-Circuit Current and Impedance for Different Sources**

#### 4.4 Calculation of Voltage THD at Load Terminals

As discussed in Section 2.1.3, the impedance of the system creates a voltage drop at each harmonic frequency. The total harmonic voltage distortion at the load terminals is then equal to the sum of these voltage drops. Figure 4.4 provides a simplified one-line diagram of a power system that is connected to a bus feeding a VFD and other loads. In this diagram, the power system is replaced by its Thevenin Equivalent Circuit with an ideal voltage source and source impedance. As mentioned previously, when the phase information or  $X/R$  ratio of the source is not provided, it can be assumed that the impedance is purely reactive. In this analysis, the  $X/R$  ratio is unknown for all three sources. Therefore resistance is considered to be negligible, and the source impedance is replaced by the inductive reactance as shown below.



**Figure 4.5: Thevenin Equivalent for Power System Feeding VFD and Other Loads**

Furthermore, it was discussed that inductive reactance changes linearly with frequency. The voltage drop at each harmonic frequency is then calculated in this analysis using the following simplified equation.

$$V_{Lh} = I_h \times hX_{S1}$$

where

$V_{Lh}$  = load terminal voltage at  $h$ th harmonic

$I_h$  = current at  $h$ th harmonic

$h$  = harmonic order

$X_{S1}$  = source inductive reactance at fundamental frequency

Lastly, this analysis calculates the total harmonic voltage distortion in % THD that is produced by a specified nonlinear load at its input terminals for set fundamental source impedance. The voltage THD is calculated using the following equation.

$$THD = \frac{\sqrt{\sum_{h=2}^{h_{max}} V_{Lh}^2}}{V_{L1}}$$

Where for this analysis, and as an industry standard, the highest harmonic order ( $h_{max}$ ) to be considered is the 50<sup>th</sup> harmonic. Also, the fundamental voltage at the load terminals is equal to the nominal source voltage minus the voltage drop created by the fundamental load current over the fundamental source impedance. In equation form, the fundamental voltage at the load terminals for this analysis is represented as

$$V_{L1} = V_S - (I_1 \times X_{S1})$$

The methodology presented here is used in this analysis to examine how a change in the source impedance affects the voltage THD for a specified VFD rectifier technology and HP rating.

#### 4.5 Variation in Load Current

In addition to varying the source impedance, this analysis will evaluate the effect that different rectifier technologies have on total harmonic voltage distortion. The rectifiers to be evaluated are the ideal 6-Pulse, 12-Pulse, and 18-Pulse rectifiers. As discussed in Section 3.4, the harmonic load currents of these rectifiers are determined using the following formula.

$$h = kq \pm 1$$

$$I_h = \frac{I_1}{h}$$

where

$h$  = harmonic order

$k$  = any positive integer

$q$  = the pulse number of the rectifier circuit

$I_h$  = the amplitude of the  $h$ th harmonic current

$I_1$  = the amplitude of the fundamental current

The amplitude of the fundamental current is also varied in this analysis to show the total harmonic voltage distortion over the full range of possible VFD ratings. The ratings are based

on Table 430.150 of the *National Electrical Code (NEC)*. A summary of the ratings used in this analysis is provided in Table 4.2.

**Table 4.2: Full Load Current, 460V, 3-Phase Induction-Type Motors [19]**

HP	Amperes
10	14
30	40
75	96
200	240
400	477

## 4.6 Implementation Using MATLAB

Calculating the total harmonic voltage distortion in % THD at the VFD input terminals for a specified n-Pulse rectifier, motor HP rating, and system short-circuit current/impedance is fairly straightforward. This calculation requires a maximum of 50 iterations, and can be easily performed by hand. Calculating the total harmonic voltage distortion in % THD at the VFD input terminals over a range of n-Pulse rectifiers, motor HP ratings, and system short-circuit currents/impedances, however, is computationally intensive and can be very time consuming. MATLAB is employed in this analysis to calculate and plot the total harmonic voltage distortion values in % THD for each possible combination in a matter of seconds rather than hours. The MATLAB code in Appendix A of this document implements a series of nested for loops to perform the nearly 30,000 iterations necessary for this analysis. The results for each combination are stored in a three dimensional matrix so they can be easily manipulated and plotted for comparison. The hierarchy of the nested for loops used in this analysis is as follows.

- Rectifier Pulse Number (6, 12, and 18-Pulse)
  - Motor HP Rating (10, 30, 75, 200, and 400 HP)
    - System Short-Circuit Current/Impedance (500 – 20,000 A)
      - Harmonic Order (2<sup>nd</sup> –50<sup>th</sup>)

# Chapter 5 – Results

## 5.1 Voltage THD for Ideal 6-Pulse VFD

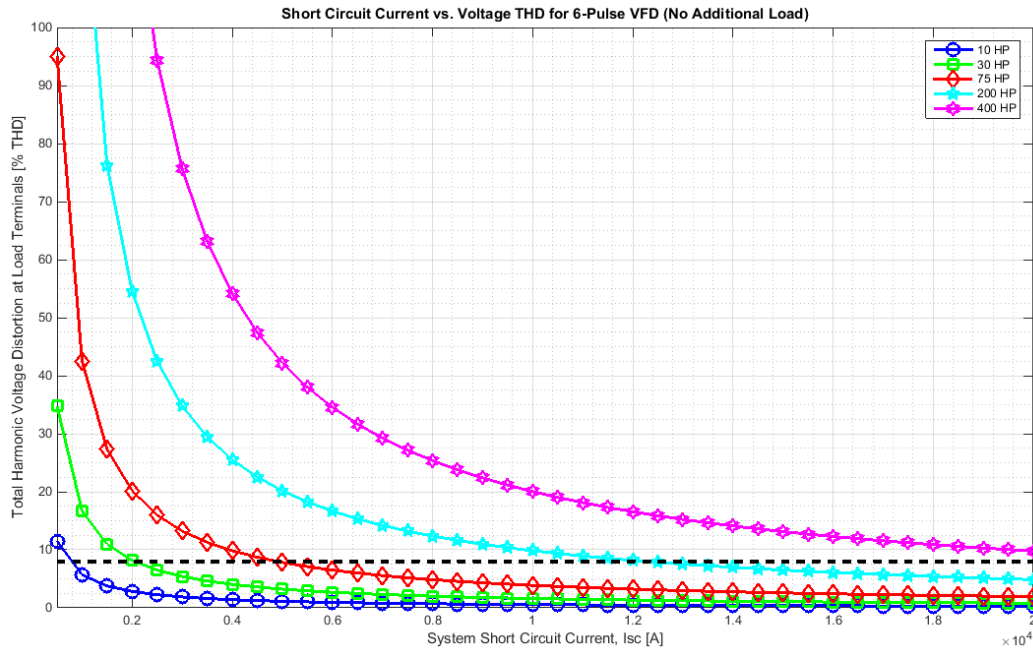


Figure 5.1: MATLAB Plot of Voltage THD for Ideal 6-Pulse Rectifier (0-100% THD)

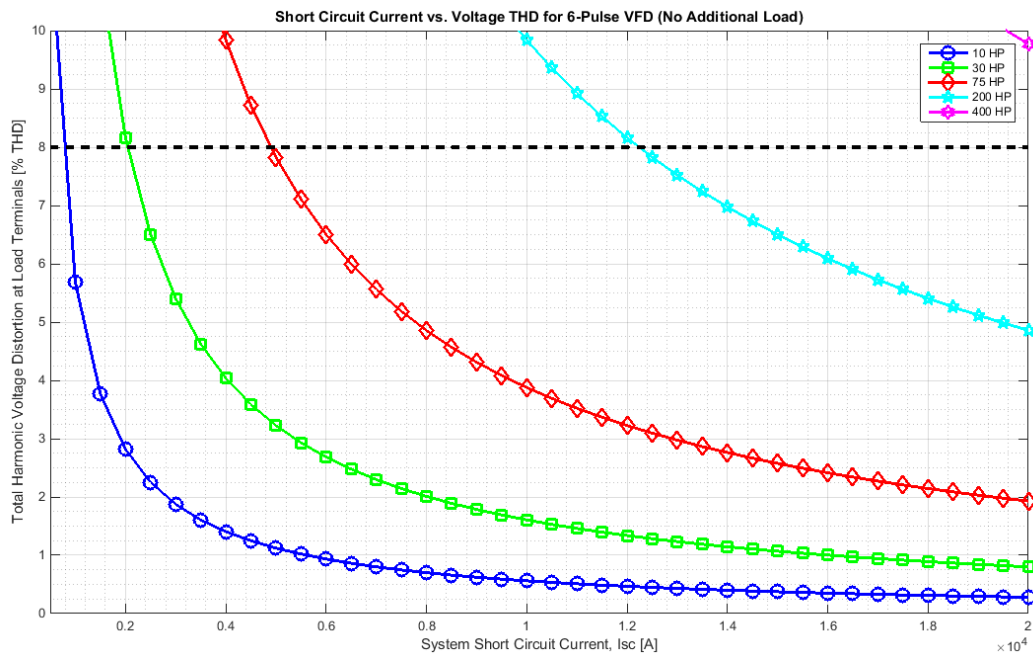


Figure 5.2: MATLAB Plot of Voltage THD for Ideal 6-Pulse Rectifier (0-10% THD)

## 5.2 Voltage THD for Ideal 12-Pulse VFD

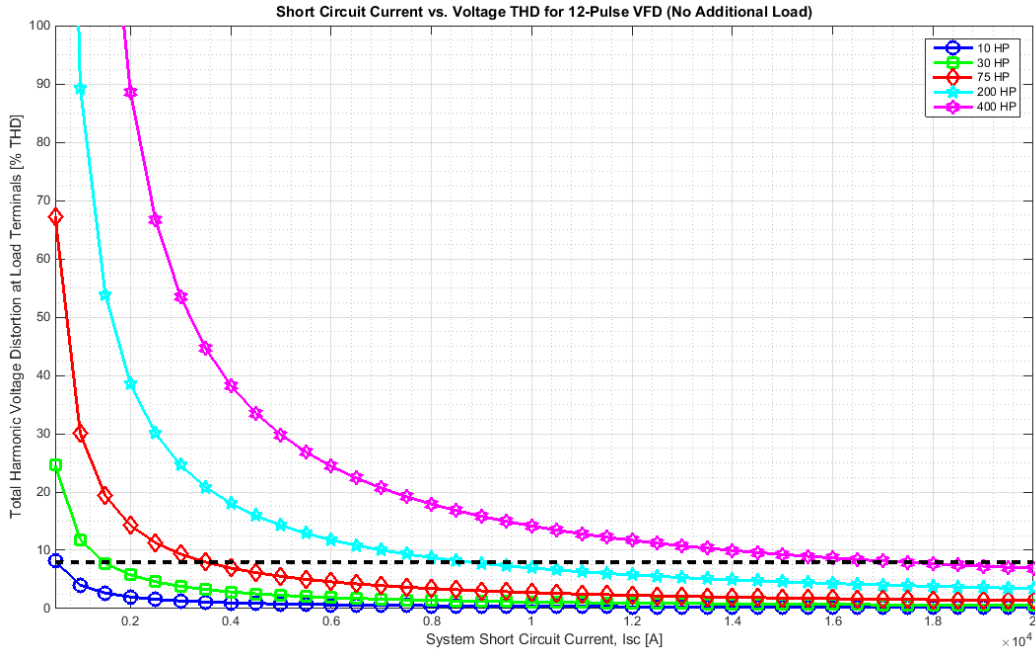


Figure 5.3: MATLAB Plot of Voltage THD for Ideal 12-Pulse Rectifier (0-100% THD)

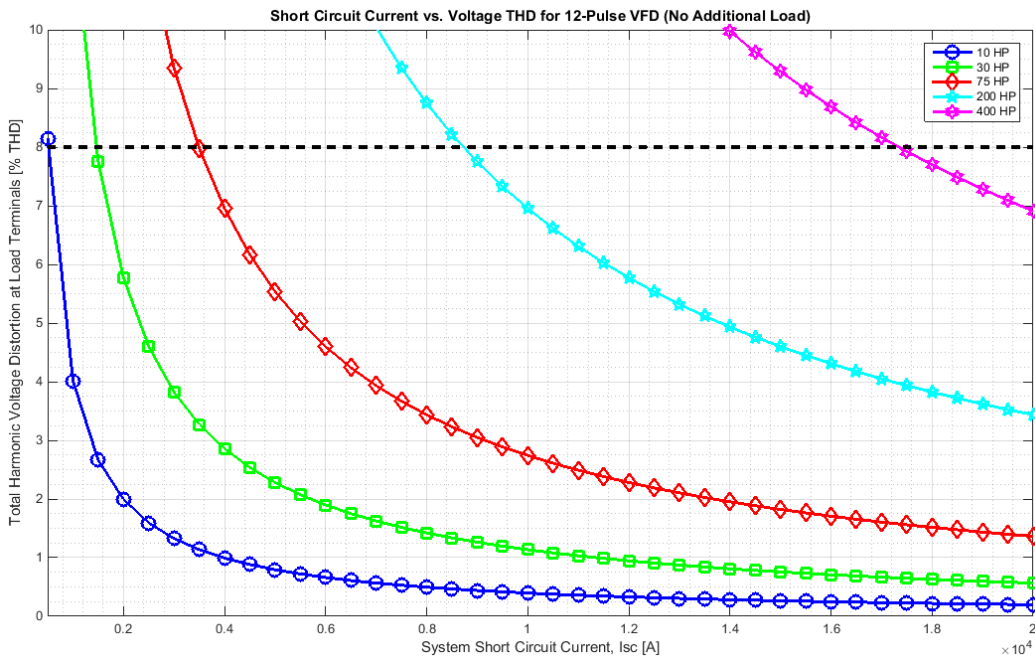


Figure 5.4: MATLAB Plot of Voltage THD for Ideal 12-Pulse Rectifier (0-10% THD)

### 5.3 Voltage THD for Ideal 18-Pulse VFD

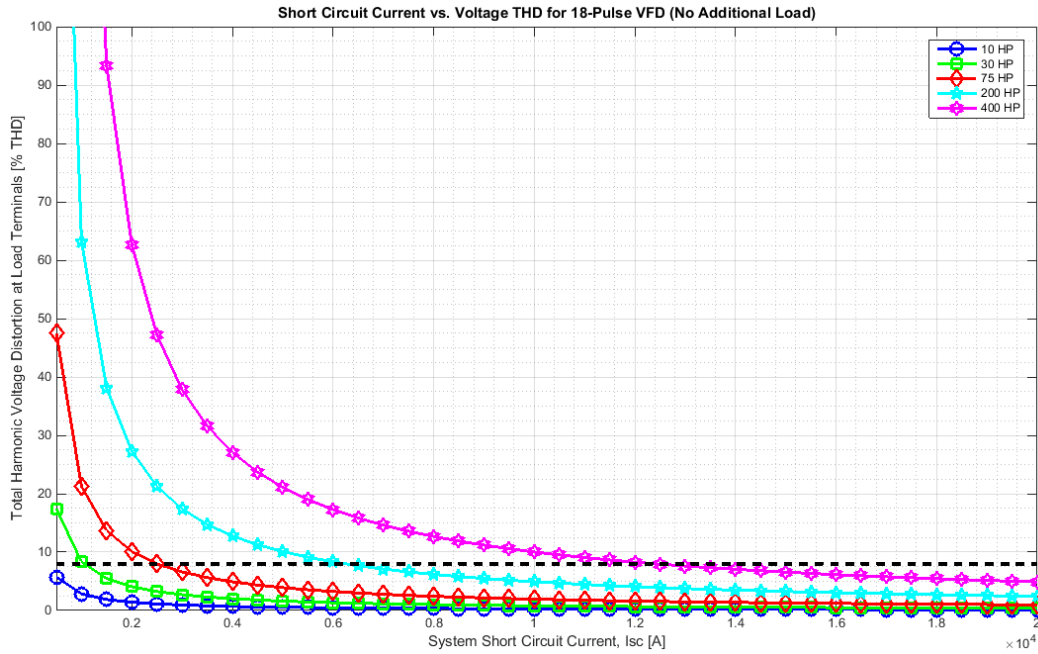


Figure 5.5: MATLAB Plot of Voltage THD for Ideal 18-Pulse Rectifier (0-100% THD)

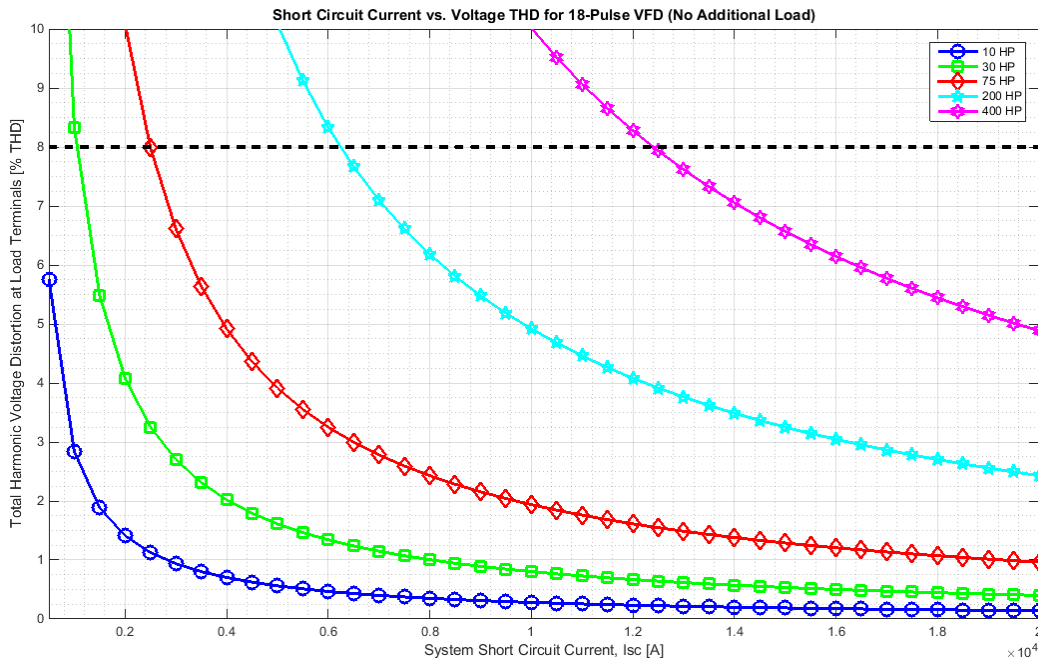


Figure 5.6: MATLAB Plot of Voltage THD for Ideal 18-Pulse Rectifier (0-10% THD)



## 5.4 Discussion of Results

Figures 5.1 and 5.2 plot the calculated voltage THD at the VFD input terminals for an ideal 6-Pulse rectifier over a range of system short-circuit currents/impedances for several different motor HP ratings. As shown in Table 2.5, the IEEE 519-2014 recommended limit for total harmonic voltage distortion at systems less than 1.0 kV is 8.0% THD. This is to ensure the proper operation of other loads connected to the same bus. When the results of this analysis are compared to the recommended limit, none of the 6-Pulse HP ratings meet the limit over the entire short-circuit current/impedance range. Table 5.1 provides the application levels for ideal 6-Pulse VFDs based on this analysis.

**Table 5.1: Application Levels for 6-Pulse VFDs on 480 V System**

Motor HP Rating	Minimum Short-Circuit Current Required to Meet IEEE 519-2014 [A]
10	1,000
30	2,500
75	5,000
200	12,500
400	Out of Range

Figures 5.3 and 5.4 plot the calculated voltage THD at the VFD input terminals for an ideal 12-Pulse rectifier over a range of system short-circuit currents/impedances for several different motor HP ratings. In general, the voltage THD values for the ideal 12-Pulse rectifier are lower than the voltage THD values for the ideal 6-Pulse rectifier. This is as expected since the current THD of an ideal 6-Pulse bridge rectifier is 28.9% and the current THD of an ideal 12-Pulse bridge rectifier is 15.4%. When the results of this analysis are compared to the IEEE 519-2014 recommended limit, although improved, there are still system short-circuit limitations at each HP rating. Table 5.2 provides the application levels for ideal 12-Pulse VFDs based on this analysis.

**Table 5.2: Application Levels for 12-Pulse VFDs on 480 V System**

Motor HP Rating	Minimum Short-Circuit Current Required to Meet IEEE 519-2014 [A]
10	500
30	1,500
75	3,000
200	9,000
400	17,500

Figures 5.5 and 5.6 plot the calculated voltage THD at the VFD input terminals for an ideal 18-Pulse rectifier over a range of system short-circuit currents/impedances for several different motor HP ratings. In general, the voltage THD values for the ideal 18-Pulse rectifier are lower than the voltage THD values for both the ideal 6-Pulse and 12-Pulse rectifiers. This is as expected since the current THD of an ideal 18-Pulse bridge rectifier is much lower at 9.6%. When the results of this analysis are compared to the IEEE 519-2014 recommended limit, although much improved, there are still system short-circuit limitations at each HP rating. Table 5.3 provides the application levels for ideal 18-Pulse VFDs based on this analysis.

**Table 5.3: Application Levels for 18-Pulse VFDs on 480 V System**

Motor HP Rating	Minimum Short-Circuit Current Required to Meet IEEE 519-2014 [A]
10	<500
30	1,500
75	2,500
200	6,500
400	12,500

Based on the results of this analysis, it is clear that the system short-circuit current and impedance plays a critical role in the magnitude of the total harmonic voltage distortion that is

seen at the VFD input terminals. When other sensitive electronic loads, which could be negatively impacted by high levels of voltage distortion, are connected to the same bus as a VFD, the system owner should perform a harmonic analysis similar to the one presented in this thesis to determine the best rectifier technology to use.

Continuing with the utility, generator, and UPS sources from Section 4.3, the following conclusions can be drawn.

- A utility source has a relatively high short-circuit current and relatively low short-circuit impedance. This makes it a “strong” source and less susceptible to high magnitude voltage distortion. At the 480 V level, a utility source that is fed by a 500 kVA distribution transformer is limited to a maximum VFD motor HP rating of approximately 400 HP to comply with IEEE 519-2014 at the VFD input terminals.
- A generator source has an intermediate short-circuit current and impedance. At the 480 V level, a generator source rated at 500 kVA is limited to a maximum VFD motor HP rating of approximately 75 HP to comply with IEEE 519-2014 at the VFD input terminals.
- A UPS source has a relatively low short-circuit current and relatively high short-circuit impedance. This makes it a “weak” source and highly susceptible to high magnitude voltage distortion. At the 480 V level, a UPS source rated at 500 kVA is limited to a maximum VFD motor HP rating of approximately 30 HP to comply with IEEE 519-2014 at the VFD input terminals.

It is important to note that these conclusions assume that only ideal 6, 12, and 18-Pulse bridge rectifiers are available. They also do not account for other harmonic reduction techniques that can be added to the VFD or system to improve the current and voltage THD.

## Chapter 6 – Future Work

The intent of this thesis was to develop a methodology that can be used when designing a system to ensure that the recommended harmonic distortion limits of IEEE Standard 519-2014 are satisfied to protect the VFD as well as other sensitive loads connected to the same bus.

Future work can include:

- Applying this methodology to non-ideal rectifiers by using actual vendor data for the VFD harmonic current spectrum.
- Comparing the results from the methodology developed in this thesis to the results from industry software for harmonic analysis.
- Comparing the results from the methodology developed in this thesis to actual test data from an operating power system.
- Examining the effect of additional fundamental and harmonic currents from other linear and nonlinear loads on the total harmonic voltage distortion at the same bus.
- Further research into the source impedance of a UPS to verify that using short-circuit current equal to 200% of the rated output current is an accurate representation of the UPS.
- Expanding the analysis over other rectifier technologies and harmonic reduction techniques, other HP ratings, and a broader range of system short-circuit currents/impedances.
- Adding harmonics from the output of a UPS and determining how this impacts the total harmonic voltage distortion at the VFD input terminals.

## References

- [1] R. C. Dugan, *Electrical Power Systems Quality*, 2nd ed. New York: McGraw-Hill, 2003
- [2] R. E. Fehr III, *Industrial Power Distribution*, Upper Saddle River, NJ: Prentice Hall, 2002, pp. 177-192.
- [3] D. C. Griffith, *Uninterruptible Power Supplies: Power Conditioners for Critical Equipment*, New York: M. Dekker, 1989
- [4] *IEEE Recommended Practice for Emergency and Standby Power Systems for Industrial and Commercial Applications*, IEEE Standard 446-1995, Dec. 1995.
- [5] *IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems*, IEEE Standard 519-2014, Mar. 2014.
- [6] J. Arrillaga and N. R. Watson, *Power System Harmonics*, 2nd ed. Hoboken, NJ; West Sussex, England: J. Wiley & Sons, 2003
- [7] N. Shah, "Harmonics in Power Systems: Causes, Effects and Control," Siemens Industry, Inc., Alpharetta, GA, May 2013.
- [8] "Power System Harmonics – Causes and Effects of Variable Frequency Drives – Relative to the IEEE 519-1992 Standard," Square D, Raleigh, NC, Bulletin No. 8803PD9402, Aug. 1994.
- [9] "The Origin, Effect, and Suppression of Harmonics in Industrial Electrical Networks," Square D, Laverne, TN, Bulletin No. 0140PD9502, Mar. 1997.
- [10] P. C. Krause and O. Wasynczuk, *Electromechanical Motion Devices*, McGraw-Hill, Inc, 1989
- [11] *IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems*, IEEE Standard 519-1992, Apr. 1993.
- [12] M. Barnes, *Practical Variable Speed Drives and Power Electronics*, Amsterdam; Boston: Newnes, 2003.
- [13] "ABB Drives – Technical Guide Book," ABB, 3AFE64514482 Rev. H, Sep. 2014.
- [14] M. H. Rashid, *Power Electronics Handbook – Devices, Circuits, and Applications*, 3<sup>rd</sup> ed. Burlington, MA. Elsevier, 2011.
- [15] *IEEE Standard for General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers*, IEEE Standard C57.12.00-2010, Jun. 2010.

- [16] *IEEE Standard Requirements for Liquid-Immersed Power Transformers*, IEEE Standard C57.12.10-2010, Jan. 2011.
- [17] “Understanding UPS Overload Capabilities in Data Centers,” Eaton, White Paper WP10-13, 2010.
- [18] J. N. Fiorina, “Inverters and Harmonics (Case Studies of Nonlinear Loads),” Cahier Technique Merlin Gerin, France, n° 159, Sep. 1993.
- [19] *National Electrical Code Handbook*, 2014 ed.

## Appendix A: MATLAB Code

### A.1 Development of Figure 4.4

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%   Impact of System Impedance on Harmonics Produced by VFDs
%   Daniel David Morton
%   Copyright 2015
%   Morton_DD_T_2015_1.m
%
%   Description: This file calculates the short-circuit current and
%   impedance for three different types of sources and plots results for
%   comparison.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

clc
clear all

% Define base values for per-unit analysis
S_base = 500000;
V_base = 480;
Z_base = (V_base^2)/S_base;
I_base = S_base/(sqrt(3)*V_base);

% Calculate utility (transformer) impedance and short-circuit current
Z_xfmr_pu = 0.055;
Z_xfmr_ohm = Z_xfmr_pu*Z_base;
Isc_xfmr = V_base/Z_xfmr_ohm;

% Calculate generator impedance and short-circuit current
Z_gen_pu = 0.20;
Z_gen_ohm = Z_gen_pu*Z_base;
Isc_gen = V_base/Z_gen_ohm;

% Calculate UPS short-circuit current and impedance
Isc_ups = I_base*2;
Z_ups_ohm = V_base/Isc_ups;

% Calculate system impedance over a range for short-circuit current
Isc = 500:500:20000;
Zsc = zeros(1,length(Isc));

for n=1:length(Isc)

    Zsc(n) = V_base/Isc(n);

end

% Plot utility, generator, and UPS data over curve of short-circuit
% impedance vs. short-circuit current
plot(Isc,Zsc,'k--',Isc_xfmr,Z_xfmr_ohm,'ro',Isc_gen,Z_gen_ohm,'gs',...
     Isc_ups,Z_ups_ohm,'bd','markersize',20,'linewidth',2);
title('Isc vs. Zsc for 480 V Power System')
```

```

xlabel('System Short-circuit Current, Isc [A]')
ylabel('System Short-circuit Impedance, Zsc [Ohms]')
legend('480V / Isc','Utility Source','Generator Source','UPS Source',...
       'Orientation','horizontal')
axis([500 20000 0 1])
grid ON
grid minor

```

## A.2 Harmonic Analysis

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%   Impact of System Impedance on Harmonics Produced by VFDs
%   Daniel David Morton
%   Copyright 2015
%   Morton_DD_T_2015_2.m
%
%   Description: This file plots the total harmonic voltage distortion in
%   %THD for ideal n-Pulse rectifiers over a range of system impedances
%   and for multiple horsepower (HP) ratings.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

clc
clear all

% Define nominal system voltage
Vs = 480;

% Define impedance range of interest
Isc_min = 500;
Isc_max = 20000;
Isc_step = 500;
Isc = Isc_min:Isc_step:Isc_max;

% Define maximum harmonic order to include in analysis
h_max = 50;

% Define ideal n-Pulse rectifier types and motor HP ratings to analyze
P = [6 12 18];
I1 = [14 40 96 240 477];

% Initialize matrices to use in calculations
THD_V = zeros(length(I1),length(Isc),length(P));
IEEE519 = zeros(1,length(Isc));

% This for loop creates array at the IEEE 519-2014 recommended limit for
% total harmonic voltage distortion to be plotted with results
for n=1:length(Isc)

    IEEE519(1,n) = 8;

end

% The following uses nested for loops to calculate the voltage %THD for

```



```

% multiple ideal n-Pulse rectifiers, multiple horsepower (HP) ratings, and
% over a range of system short-circuit currents/impedances. The results
% are stored in a three dimensional matrix.

% First for loop to iterate through n-Pulse rectifiers
for z=1:length(P)

    % Second for loop to iterate through motor HP ratings
    for y=1:length(I1)

        % Initialize and build array for harmonic current spectrum based on
        % number of pulses and HP full load current
        Ih = zeros(h_max,1);
        Ih(1,1) = I1(y);

        for n=1:(h_max-1)/P(z)

            h = n*P(z)-1;
            Ih(h,1) = Ih(1,1)/h;
            h = n*P(z)+1;
            Ih(h,1) = Ih(1,1)/h;

        end

        % Third for loop to iterate through range of system short-circuit
        % currents/impedances
        for x=1:length(Isc)

            % Fourth for loop iterates through harmonic orders and
            % calculates the root mean square (RMS) of the harmonic voltage
            % drops for each combination of pulse number, HP rating, and
            % system short-circuit current/impedance
            Sum_Vh2 = 0;

            for h=2:h_max

                Vh = Ih(h,1)*(Vs/Isc(x))*h;
                Sum_Vh2 = Sum_Vh2 + Vh^2;

            end

            % Divide RMS of harmonic voltage drops by fundamental voltage
            % magnitude at load terminals to calculate %THD and store in
            % three dimensional matrix
            THD_V(y,x,z) = sqrt(Sum_Vh2)/(Vs-(Ih(1,1)*(Vs/Isc(x))))*100;

        end

    end

end

% Plot figures over two ranges for each combination pulse number;
% 0-100% THD and 0-10% THD

```

```

figure(1)
plot(Isc,THD_V(1,:,1),'bo-',...
      Isc,THD_V(2,:,1),'gs-',...
      Isc,THD_V(3,:,1),'rd-',...
      Isc,THD_V(4,:,1),'cp-',...
      Isc,THD_V(5,:,1),'mh-',...
      Isc,IEEE519,'k--',...
      'linewidth',2,'markersize',10);
title('Short-circuit Current vs. Voltage THD for 6-Pulse VFD (No Additional
Load)')
xlabel('System Short-circuit Current, Isc [A]')
ylabel('Total Harmonic Voltage Distortion at Load Terminals [% THD]')
legend('10 HP','30 HP','75 HP','200 HP','400 HP')
axis([500 20000 0 100])
grid ON
grid minor

```

```

figure(2)
plot(Isc,THD_V(1,:,1),'bo-',...
      Isc,THD_V(2,:,1),'gs-',...
      Isc,THD_V(3,:,1),'rd-',...
      Isc,THD_V(4,:,1),'cp-',...
      Isc,THD_V(5,:,1),'mh-',...
      Isc,IEEE519,'k--',...
      'linewidth',2,'markersize',10);
title('Short-circuit Current vs. Voltage THD for 6-Pulse VFD (No Additional
Load)')
xlabel('System Short-circuit Current, Isc [A]')
ylabel('Total Harmonic Voltage Distortion at Load Terminals [% THD]')
legend('10 HP','30 HP','75 HP','200 HP','400 HP')
axis([500 20000 0 10])
grid ON
grid minor

```

```

figure(3)
plot(Isc,THD_V(1,:,2),'bo-',...
      Isc,THD_V(2,:,2),'gs-',...
      Isc,THD_V(3,:,2),'rd-',...
      Isc,THD_V(4,:,2),'cp-',...
      Isc,THD_V(5,:,2),'mh-',...
      Isc,IEEE519,'k--',...
      'linewidth',2,'markersize',10);
title('Short-circuit Current vs. Voltage THD for 12-Pulse VFD (No Additional
Load)')
xlabel('System Short-circuit Current, Isc [A]')
ylabel('Total Harmonic Voltage Distortion at Load Terminals [% THD]')
legend('10 HP','30 HP','75 HP','200 HP','400 HP')
axis([500 20000 0 100])
grid ON
grid minor

```

```

figure(4)
plot(Isc,THD_V(1,:,2),'bo-',...
      Isc,THD_V(2,:,2),'gs-',...
      Isc,THD_V(3,:,2),'rd-',...

```

```

    Isc,THD_V(4,:,2),'cp-',...
    Isc,THD_V(5,:,2),'mh-',...
    Isc,IEEE519,'k--',...
    'linewidth',2,'markersize',10);
title('Short-circuit Current vs. Voltage THD for 12-Pulse VFD (No Additional
Load)')
xlabel('System Short-circuit Current, Isc [A]')
ylabel('Total Harmonic Voltage Distortion at Load Terminals [% THD]')
legend('10 HP','30 HP','75 HP','200 HP','400 HP')
axis([500 20000 0 10])
grid ON
grid minor

figure(5)
plot(Isc,THD_V(1,:,3),'bo-',...
    Isc,THD_V(2,:,3),'gs-',...
    Isc,THD_V(3,:,3),'rd-',...
    Isc,THD_V(4,:,3),'cp-',...
    Isc,THD_V(5,:,3),'mh-',...
    Isc,IEEE519,'k--',...
    'linewidth',2,'markersize',10);
title('Short-circuit Current vs. Voltage THD for 18-Pulse VFD (No Additional
Load)')
xlabel('System Short-circuit Current, Isc [A]')
ylabel('Total Harmonic Voltage Distortion at Load Terminals [% THD]')
legend('10 HP','30 HP','75 HP','200 HP','400 HP')
axis([500 20000 0 100])
grid ON
grid minor

figure(6)
plot(Isc,THD_V(1,:,3),'bo-',...
    Isc,THD_V(2,:,3),'gs-',...
    Isc,THD_V(3,:,3),'rd-',...
    Isc,THD_V(4,:,3),'cp-',...
    Isc,THD_V(5,:,3),'mh-',...
    Isc,IEEE519,'k--',...
    'linewidth',2,'markersize',10);
title('Short-circuit Current vs. Voltage THD for 18-Pulse VFD (No Additional
Load)')
xlabel('System Short-circuit Current, Isc [A]')
ylabel('Total Harmonic Voltage Distortion at Load Terminals [% THD]')
legend('10 HP','30 HP','75 HP','200 HP','400 HP')
axis([500 20000 0 10])
grid ON
grid minor

```