CHAPTER 1

INTRODUCTION

Ideally, an electricity supply should invariably show a perfectly sinusoidal voltage signal at every customer location. However, for a number of reasons, utilities often find it hard to preserve such desirable conditions. The derivation of voltage and current waveforms from sinusoidal is described in terms of the waveform distortion, often expressed as harmonic distortion.

The increasing use of nonlinear loads in industry is keeping harmonic distortion in distribution network on the rise (Hsiung Cheng Lin 2012) (Ying-Tung Hsiao et al, 2007). The most used nonlinear device is perhaps the static power converter so widely used in industrial applications in the steel, paper and textile industries. Power quality has become an increased concern as the use of power converters has captured commercial and domestic areas through some applications like air conditioners, heaters, lifts, elevators and obviously UPS and inverters. Other applications include multipurpose motor speed control, electrical transportation systems (MRT – mass rapid transit systems) and electro-domestic appliances. A situation that has raised waveform distortion levels in distribution networks even further is the application of capacitor banks used in industrial plants for power factor correction and by power utilities for increasing voltage profile along the distribution lines. The resulting reactive impedance forms a tank circuit with the system inductive reactance at a certain frequency likely to coincide with one of the characteristic harmonics of the load. This condition will trigger large oscillatory currents and voltages that may stress the insulation. This
phenomenon is known as harmonic magnification (Roger C Dugan et al 2004). Thus it is necessary to correct excessive harmonic waveform distortion levels on the waveforms. In this modern world, use of power converters has become unavoidable and necessary too. Like industries, Power converters are used for various applications in commercial loads also (Pavel Drabek 2011).

1.1 HARMONIC DISTORTIONS

Harmonics are voltages or currents with a frequency that is an integral multiple of the fundamental supply frequency. Combined with the fundamental voltage or current, harmonics appear as a distorted waveform (Soo-Hwan Cho et al, 2012). Harmonic distortions originate in the nonlinear properties of devices and loads on the power system (Yacamini 1996) (MTE Corporation) (Xiaodong Liang et al, 2011). Even if the magnitudes of the harmonic components are approximately 20% of the fundamental magnitude, harmonic distortion can excite resonance when one of the harmonic components coincides with the natural resonant frequency of the power system.

Harmonics add to the rms and peak value of the waveform which means that the equipment could receive a damagingly high peak voltage and may be susceptible to failure. High voltage may also cause power system components to operate in the saturation regions of their characteristics, producing additional harmonics and disturbances. There are adverse effects form heating, noise and reduced life of capacitors, surge suppressors, rotating machines, cables and transformers, fuses and customers equipment (Sang-Wook Sohn et al, 2012) (Young-Sik Cho & Hanju Cha 2011). Additional losses of transmission lines, cables, generators, AC motors and transformers may occur due to harmonics. Malfunction of controllers and protective devices such as fuses and relays is possible (Tusitha Abeyasekera et al, 2003) (Uma, D et al, 2014).
As per IEEE-519, recommended harmonic distortion limits are to be verified through comparison with measurements at the Point of Common Coupling (PCC) i.e., the interface between the electric utility and the customer. A significant issue is that levels can be exceeded by 50% under start-ups or unusual conditions with durations less than an hour. The recommended limits are a function of the system voltage level. For electric networks 69kV and below, for example, the total voltage distortion is limited to 5%; no individual voltage harmonic should exceed 3%.

1.2 INTERHARMONIC DISTORTIONS

Interharmonics are voltages or currents with a frequency that is a non-integral multiple of the fundamental supply frequency. For several reasons, interharmonic components are more troublesome and harmful than harmonics (Jin Hui et al, 2012) (Kushare et al, 2007) (Lobos et al, 2000) (Mauricio Caixba, & Abner Ramirez 2010) (Roberto Langella et al 2012). Firstly, in contrast to harmonic components, interharmonics do not manifest themselves in known and/or fixed frequencies, for their frequencies can vary with the operating conditions of the interharmonic-producing load (Sharaf, AM et al, 2000). This variation presents a hazard for control and protection signals, which may suffer interference from interharmonics. Secondly, interharmonics can cause flicker in addition to distorting the waveforms (Taekhyun Kim et al, 2008) (Taekhyun Kim et al, 2009). Thirdly, interharmonics are more complex to analyze than harmonics, as they are related to the problem of waveform modulation (Yu Ji & Yunlian Sun 2010) (Zbigniew Hanzelka & Andrzej Bien 2004) (Zhaobi et al, 2013).

Barry W Kennedy (2000) has explained that the interharmonics can be observed in an increasing number of loads in addition to harmonics. These loads include static frequency converters, cycloconverters, sub-synchronous converter cascades, adjustable speed drives for induction or synchronous
motors, EAF, and all loads not pulsating synchronously with the fundamental power system frequency. Adjustable Speed Drives (ASDs) based on double stage conversion systems generate interharmonic current components in the supply system side, the DC link and output side, in addition to harmonics typical for single stage converters (Won Jin Cho, BS 2010). Under ideal supply conditions, interharmonics are generated by the interaction between the two conversion systems through the inter-modulation of their harmonics. When unbalances, background harmonic and interharmonic distortions are present in supply voltages more complex intermediation phenomenon take place.

According to the IEC recommendations the voltage interharmonics are limited to 0.2% for the frequency range from DC component to 2 kHz. The standard gives immunity test levels for interharmonics in various frequency ranges. Depending on the equipment class the voltage levels are contained within 1.5% $U_1$ (1000-2 000 Hz). Test levels for interharmonics above 100 Hz are within 2-9%.

As for interharmonic limits, the first proposal of standards was in fixing a very low value (i.e., 0.2%) for interharmonic voltages of weekly 95th percentile short time values at low frequencies. Such a low-value limit would guarantee compliance of interharmonic voltage distortion with lighting systems, induction motors, thyristor apparatus, and remote control systems. Due to measurement difficulties the alternative solution, still under discussion, is: 1) to limit individual interharmonic component voltage distortion to less than 1%, 3%, or 5% (depending on voltage level) from 0 Hz up to 3 kHz, exactly as for harmonics; 2) to adopt limits correlated with a short-term flicker severity value, equal to 1.0, to be checked by IEC flickermeter for frequencies at which these limits are more restrictive than those previously evidenced; and 3) to develop appropriate limits for
equipment and system effects, such as generator mechanical systems, signaling and communication systems, and filters, on a case-by-case basis with using specific knowledge of the supply system and connected user loads. Therefore, different limits are necessary for different ranges of frequency and two kinds of measurements- interharmonic components and light flicker are simultaneously needed (De M Koster 1999) (Testa, A et al, 2007). Regarding interharmonic distortions, a large volume of interharmonic research have been done on various subjects including identification of interharmonic sources, their possible effects, and methodologies of measurements (Zhenmei Li et al, 2008) (Zhongdong Liu et al, 2005).

1.2.1 Voltage versus Current Distortion

Roger et al (2004) explained it is common to hear that an adjustable-speed drive cannot operate properly because of one of the following reasons.

1. The harmonic voltages are too great for the control to properly determine firing angles.

2. The harmonic currents are too great for the capacity of some device in the power supply system such as a transformer, and the machine must be under rated.

3. The harmonic voltages are too great because the harmonic currents produced by the device are too great for the given system condition.

The following Figure 1.1 shows how harmonic current distortion converts into harmonic voltage distortion.
Voltage distortion is the result of distorted currents passing through the linear, series impedance of the power delivery system, although, assuming that the source bus is ultimately a pure sinusoid, there is a nonlinear load that draws a distorted current. The harmonic currents passing through the impedance of the system cause a voltage drop for each harmonic. This results in voltage harmonics appearing at the load bus. The amount of voltage distortion depends on the impedance and the current. Assuming the load bus distortion stays within reasonable limits (e.g., less than 5 percent), the amount of harmonic current produced by the load is generally constant. While the load current harmonics ultimately cause the voltage distortion, it should be noted that load has no control over the voltage distortion. The same load put in two different locations on the power system will result in two different voltage distortion values.

1.2.2 Power System Quantities under Non-sinusoidal Conditions

In the presence of harmonic distortion the power system no longer operates in a sinusoidal condition, and unfortunately many of the simplifications power engineers use for the fundamental frequency analysis do not apply (Roberto Langella, & Alfredo Testa 2011). There are three standard quantities associated with power:
- Apparent power $S$ [volt-ampere (VA)]. The product of the rms voltage and current.

- Active power $P$ [watt (W)]. The average rate of delivery of energy.

- Reactive power $Q$ [volt-ampere-reactive] (VAR)]. The portion of the apparent power that is out of phase, or in quadrature, with the active power.

The apparent power $S$ applies to both sinusoidal and non-sinusoidal conditions. The apparent power can be written as follows:

$$ S = V_{rms} \times I_{rms} \quad (1.1) $$

Where $V_{rms}$ and $I_{rms}$ are the rms values of the voltage and current. In a sinusoidal condition both the voltage and current waveforms contain only the fundamental frequency component; thus the rms values can be expressed simply as

$$ V_{rms} = \frac{1}{\sqrt{2}} V_1 \text{ and } I_{rms} = \frac{1}{\sqrt{2}} I_1 \quad (1.2) $$

Where $V_1$ and $I_1$ are the amplitude of voltage and current waveforms, respectively. The subscript “1” denotes quantities in the fundamental frequency. In a non-sinusoidal condition a harmonically distorted waveform is made up of sinusoids of harmonic frequencies with different amplitudes as shown in Figure 1.2 (Roberto Langella & Alfredo Testa 2011)
The rms values of the waveforms are computed as the square root of the sum of rms squares of all individual components, i.e.,

$$V_{rms} = \sqrt{\sum_{h=1}^{h_{max}} \left( \frac{1}{\sqrt{2}} V_h \right)^2} = \frac{1}{\sqrt{2}} \sqrt{V_1^2 + V_2^2 + V_3^2 + \ldots + V_{h_{max}}^2}$$

(1.3)

$$I_{rms} = \sqrt{\sum_{h=1}^{h_{max}} \left( \frac{1}{\sqrt{2}} I_h \right)^2} = \frac{1}{\sqrt{2}} \sqrt{I_1^2 + I_2^2 + I_3^2 + \ldots + I_{h_{max}}^2}$$

Where $V_h$ and $I_h$ are the amplitude of a waveform at the harmonic component $h$. In the sinusoidal condition, harmonic components of $V_h$ and $I_h$ are all zero, and only $V_1$ and $I_1$ remain. The active power $P$ is also commonly referred to as the average power, real power, or true power. It represents useful power expended by loads to perform real work, i.e., to convert electric energy to other forms of energy. Real work performed by an incandescent light bulb is...
to convert electric energy into light and heat. In electric power, real work is performed for the portion of the current that is in phase with the voltage. No real work will result from the portion where the current is not in phase with the voltage. The active power is the rate at which energy is expended, dissipated, or consumed by the load and is measured in units of watts. P can be computed by averaging the product of the instantaneous voltage and current, i.e.,

$$ P = \frac{1}{T} \int_0^T v(t)i(t)dt $$

(1.4)

The above Equation is valid for both sinusoidal and non-sinusoidal conditions. For the sinusoidal condition, P resolves to the familiar form,

$$ P = \frac{V I}{2} \cos \theta_1 = V_{rms} I_{rms} \cos \theta_1 = S \cos \theta_1 $$

(1.5)

Where \( \theta_1 \) is the phase angle between voltage and current at the fundamental frequency. Here the average active power is given as a function only of the fundamental frequency quantities. In the non-sinusoidal case, the computation of the active power must include contributions from all harmonic components; thus it is the sum of active power at each harmonic. Furthermore, the voltage distortion is generally very low on power systems (less than 5 percent). This approximation cannot be applied when computing the apparent and reactive power. These two quantities are greatly influenced by the distortion. The apparent power S is a measure of the potential impact of the load on the thermal capability of the system. It is proportional to the rms of the distorted current, and its computation is straightforward, although slightly more complicated than the sinusoidal case. Also, many current probes can now directly report the true rms value of a distorted waveform.
The reactive power is a type of power that does no real work and is generally associated with reactive elements (inductors and capacitors). For example, the inductance of a load such as a motor causes the load current to lag behind the voltage. Power appearing across the inductance sloshes back and forth between the inductance itself and the power system source, producing no net work. For this reason it is called imaginary or reactive power since no power is dissipated or expended. It is expressed in units of vars. In the sinusoidal case, the reactive power is simply defined as

\[ Q = S \sin \theta_1 = \frac{V_1 I_1}{2} \sin \theta_1 = V_{rms} I_{rms} \sin \theta_1 \]  

(1.6)

Hence all the Equations (1.1) to (1.6) are applicable only when the voltage is pure sinusoidal.

In case of harmonics present in the voltage or current, the waveform will get distorted. This distorted power may be denoted as “D” and known as distortion volt-amperes. It has units of volt-amperes. In this concept, Q consists of the sum of the traditional reactive power values at each frequency. D represents all cross products of voltage and current at different frequencies, which yield no average power. P, Q, D, and S are related as follows, using the definitions for S and P previously given in Equations.

\[ S = \sqrt{P^2 + Q^2 + D^2} \]

\[ Q = \sum_k V_k I_k \sin \theta_k \]

(1.7),(1.8)

Therefore, D can be determined after S, P, and Q by
With the advanced development of power-electronic technologies, there is an increasing use of voltage source inverter (VSI)-fed motor drives, especially for industrial applications in the range of low- to medium-horsepower levels (Mohan et al 1995). Various two-stage converters with separate AC/DC and DC/AC converters interconnected via a DC link (current and voltage source converters) are also sources of interharmonics because the two AC systems are not perfectly decoupled by the DC link (Seyed Reza et al 2006) (Ying Jiang & Ake Ekstrom 1997). Among them, variable-speed drives based on pulse-width-modulated (PWM) voltage-source inverters are increasingly being recognized as potential sources of interharmonics. The input power conversion part in a ASD is a three-phase diode-bridge rectifier (i.e., the front end) that converts the AC supply voltage to an unregulated DC voltage. Right after the rectifier, a large shunt capacitor is connected to the DC side of the rectifier, called the DC link, to reduce the ripple of the DC voltage. A PWM inverter then converts the DC link voltage to the three-phase AC voltage with a variable frequency/magnitude adjustable to perform the motor speed control. The disturbance current injected by the inverter into the DC link is generally low in well-designed PWM inverters. The inverter disturbance current and related rectifier input current interharmonics are typically generated if the inverter is operated in overmodulation or if the inverter load is unbalanced (Duro Basic 2010). These distorted currents in the rectifier input cause some undesired effects on power system components and loads, such as overheating, resonance, power line carrier signal interference, and induce visual flicker in display devices. Therefore, seeking effective ways to characterizing current harmonics and interharmonics produced by the ASD becomes a growing concern. For the frequency transformation analysis

\[ D = \sqrt{S^2 - P^2 - Q^2} \]  

(1.9)
through AC/DC/AC converters, the switching function concept is a commonly used tool (Guerin and Le Doeuff 2004, Alexandre B Nassif 2011). A particular problem with PWM drives with large DC bus capacitance is that propagation of the inverter disturbance current through the converter (David E Rice 1992) is affected by parallel resonance created by the interaction of the bus capacitor and power system and/or filter inductances (Guerin & Le Doeuff 2004, Alexandre B Nassif 2011). The DC bus parallel resonance can considerably amplify the disturbance current on the rectifier side, causing excessive noncharacteristics distortion in the rectifier input currents.

1.4 RESEARCH MOTIVATION

Harmonics and interharmonics have various effects on power systems (Erich W Gunther 2001). The main effects of harmonics are malfunction of control devices, telephone interferences, additional line losses and decreased lifetime and increased losses in utility equipment and customer devices.

In principle, interharmonics may also cause the same effects on power system as harmonics can do. Interharmonic currents cause interharmonic distortion of the voltage depending on magnitudes of the current components and the supply system impedance at that frequency. The greater the range of the current components’ frequencies, the greater is the risk of the occurrence of unwanted resonant phenomena, which can increase the voltage distortion and cause overloading or disturbances in the operation of customers’ equipment and installations. Among the most common, direct, effects of interharmonics are:

- Thermal effects
- Low-frequency oscillations in mechanical systems
• Disturbances in fluorescent lamps and electronic equipment operation. In practice, the operation of any equipment that is synchronised with respect to the supply voltage zero-crossing or crest voltage can be disturbed.

• Interference with control and protection signals in power supply lines. This is now the main harmful effect of interharmonics.

• Overloading passive parallel filters for high order harmonics.

• Telecommunication interference.

• Acoustic disturbance.

• Saturation of current transformers.

The unique effect of the presence of interharmonics is flickering due to variations in rms voltage magnitude. Recent studies have shown that even very small amplitude interharmonics (under 1% of the fundamental) can have significant adverse effects on important poor system components such as transformers and motors.

One of the most common methods for control of harmonic distortion in industry is the use of passive filtering techniques that make use of single-tuned or band-pass filters. Passive harmonic filters can be designed as single-tuned elements that provide a low impedance path to harmonic currents (Hu, Yacamini 1993) at a punctual frequency or as band-pass devices that can filter harmonics over a certain frequency bandwidth. The capacity of a tuned filter is calculated following the analysis of the results of a power quality survey. The total current that will flow through a tuned filter consists of both fundamental and harmonic components. The filter must to be of a capacity large enough to allow the two components to flow without overheating (Zygmunt Kusmierek & Marian Jerzy Korczynski 2003).
A tuned filter is normally used when the total harmonic current distortion is greater than 20% THD-I. In cases where the initial total harmonic current distortion is lower than this amount, the capacitance of the tuned filter may interact with power system reactance and cause a resonance problem. (Michel Verhulst 2011) In situations like this, installation of harmonic filters may be considered on the individual loads which are generating the harmonics.

When a tuned harmonic filter is applied on a system consisting of a mixture of linear and non-linear loads (service entrance or distribution transformer), it is possible to achieve distortion levels in the range from 3 to 12% THD-I. Although the filter is a very low impedance path for the tuning harmonic, there will always be some harmonic current flowing through the electrical system because the main transformer is a parallel path (from the load point of view) and the current will divide according to Ohm’s law between the filter and the main transformer. Like virtually any harmonic mitigation technology, the harmonic filter does not eliminate the tuned harmonic, it only mitigates it. However, low frequency harmonics, sub and inter-harmonics generated by ASD operation cannot be effectively eliminated with passive filters.

The more sophisticated active filtering concepts operate in a wide frequency range, adjusting their operation to the resultant harmonic spectrum. In this way, they are designed to inject harmonic currents to counterbalance existing harmonic components as they show up in the distribution system. In 1982, 800kVA shunt active filter which consisted of current-source PWM inverters using GTO Thyristors was put into practical use for harmonic compensation for the first time in the world. Nowadays, the objective of shunt active filters is to compensate reactive power, negative sequence, harmonics,
and/or flicker. In addition, active power filters can also be combined with passive filters in hybrid structure in order to decrease its rated power. There are mainly two types of active power filters: the shunt active filter and the series active filter which is shown in figures. The shunt active filter is used to filter the line currents and the series active filter is used to filter the line voltages. It is also possible to combine both types to filter both current and voltage harmonics.

1.5 RESEARCH OBJECTIVE

The inverter disturbance current and related rectifier input current interharmonics are typically generated if the inverter is operated in overmodulation or if the inverter load is unbalanced. With unbalanced loads or overmodulation, however, significant levels of interharmonic currents were found to exist. While these levels are not particularly high relative to the harmonic currents drawn by the source, their presence at non-harmonic frequencies is a cause of concern. An evaluation of the mechanism involved in the generation of interharmonics by load imbalance is done in the literature. Specific objectives of this research are described as follows:

- Analysing the effect of load unbalance in the generation of interharmonics in the rectifier input current of ASD.
- Analysing the causes of interharmonics
- Analysis of suitable mitigation methods for interharmonics.
- Analysing existing mitigation techniques
- Validating the proposed methods by using simulation.
- Formulating effective mitigation technique using simulation tool
- Mitigating interharmonics by implementing the combined technique found
- A lab experimental setup is to be done and effectiveness of the proposed scheme is verified.
- A prototype model (PTM) is to be done

The main objective of this thesis is to mitigate the interharmonics using combination of the following techniques like:

i) By using an active filter near the source

ii) By using a boost converter in the DC link

iii) By using a DC link inductor.