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# Harmonics in commercial building power systems

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# HARMONICS IN COMMERCIAL BUILDING POWER SYSTEMS

By

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in the program of

Electrical and Computer Engineering

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# Abstract

# HARMONICS IN COMMERCIAL BUILDING POWER SYSTEMS

**Master of Engineering 2007**

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**Electrical and Computer Engineering**
**Ryerson University**

Harmonics are increasingly becoming a major source of power quality problems in today's commercial power distribution systems. Although they have been present in power distribution system since the early days of AC power systems, their level has dramatically increased and the effect on power distribution systems has been more and more noticeable in the last decade. This dramatic increase of harmonic levels is mainly contributed to the introduction of non linear loads such as personal computers, servers, variable frequency drives and UPS systems. Harmonic problems are especially common in commercial buildings housing large computer rooms where the concentration of nonlinear loads per square foot is very high, and continue to grow higher as the footprint of network and communication equipment becomes smaller.

This report will provide a deep look at harmonics in power distribution systems in commercial buildings, their sources and the different ways by which they can affect today's electrical systems and power quality. Some of the solutions commonly used to deal with the problem of harmonics are reviewed and a critical analysis of their effectiveness is provided. Computer simulations using Matlab Simulink have been developed to illustrate key points when possible.

## Acknowledgements

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# CHAPTER 1

# 1. INTRODUCTION

Most of what constitute the electrical load in today's commercial buildings is considered non linear load. In general, a load is considered non-linear if its impedance changes with the applied voltage, in which case the current drawn does not follow the applied voltage and will not be sinusoidal even when it is connected to a sinusoidal voltage. The non-sinusoidal current contains harmonic currents that interact with the impedance of the power distribution system to create voltage distortion that can affect both the distribution system equipment and the loads connected to it.

Non linear loads make up 50% of the total load in most commercial buildings today [1]. Personal computers, servers, laser printers are only few examples of such equipment used extensively in a typical office building. These loads are nonlinear mainly because of the use of switch mode power supplies (SMPS). Cooling systems in these same buildings further contribute to the problem because of the use of variable frequency drives to control fans, compressors or pumps.

Non-linear loads in commercial office buildings are expected to make up around 80% of the loading on the utility distribution systems in less than a decade [1]. It is therefore evident that power quality problems associated with harmonics will continue to impose challenges for engineers, manufacturers and regulatory institutions in their effort to maintain a good control on the impact of harmonics on power distribution systems.

## 1.1 Standards and Regulations for Harmonic Control in Power Systems

The institute of electrical and electronic engineer (IEEE) standard 519-1992 [2] defines the acceptable levels of harmonic distortions in high quality power.

IEEE Std. 519-1992 states that:

*"Computers and allied equipment such as programmable controllers frequently require AC sources that have no more than a 5% harmonic voltage distortion factor, with the largest single harmonic being no more than 3% of the fundamental voltage. Higher levels of harmonics result in erratic, sometimes subtle, malfunctions of the equipment that can, in some cases, have serious consequences."*

Table 10.3 from IEEE 519-1992 [2] defines the levels of harmonic currents that can be injected into the utility distribution.

| **Maximum Harmonic Current Distortion in % of $I_L$<br>Individual Harmonic Order (Odd Harmonics) (1),(2)** | | | | | | |
|---|---|---|---|---|---|---|
| $I_{SC}/I_L$ | <11 | 11 ≤h ≤17 | 17 ≤h ≤23 | 23 ≤h ≤35 | 35 ≤h | TDD |
| <20(3) | 4.0 | 2.0 | 1.5 | .6 | .3 | 5.0 |
| 20 < 50 | 7.0 | 3.5 | 2.5 | 1.0 | .5 | 8.0 |
| 50 < 100 | 10.0 | 4.5 | 4.0 | 1.5 | .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 |

(1) Even harmonics are limited to 25% of the odd harmonic limits above.
(2) Current distortions that result in a DC offset, e.g., half-wave converters, are not allowed.
(3) 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 and $I_L$ = maximum demand load current (fundamental frequency component) at PCC.

**IEEE Table 10.3: Current Distortion Limits for General Distribution Systems (120V through 69KV)**

Table 11.1 from IEEE 519-1992 [2] defines the voltage distortion limits that can be reflected back onto the utility distribution system

| **Bus Voltage at PCC** | **Individual Voltage Distortion (%)** | **Total Harmonic Voltage Distortion THD (%)(1)** |
|---|---|---|
| 69 kV and below | 3.0 | 5.0 |
| 69.0001 kV through 161 kV | 1.5 | 2.5 |
| 161.001 kV and above | 1.0 | 1.5 |

(1) High voltage systems can have up to 2.0% THD where the cause is an HVDC terminal that will attenuate by the time it is tapped for a user.

**IEEE Table 11.1 Voltage Distribution Limits**

Electronics equipment manufacturers respect in their designs and specifications the requirements and guidelines set by regulatory institutions. However, due to the accumulative effect of multiple numbers of equipments present in a typical distribution system and how these equipments are integrated into the power system, the overall distortion level in the power system does not always remain within the recommended levels.

## 1.2 Why Should We Be Concerned

Voltage and current waveform distortion is not a new phenomenon. It has been a problem even in the early days of AC systems where non-linear loads existed in heavy industrial applications, mainly in large motor drives, heavy rectification equipment and arc furnaces. But harmonics at that time were isolated in those industrial power systems where they were controlled and dealt with effectively. Nowadays, harmonic problems have extended beyond industrial distribution systems and are now found in most commercial buildings. The main cause are switch mode power supplies (SMPS) which can be found in most electronic devices used in an office building, in personal computers, copiers, monitors, etc. As a result, it has been increasingly challenging in recent years to maintain the distortion at an acceptable level. Some studies have shown that the harmonic distortion levels in power distribution systems have been increasing at a constant rate with an increase of THD (total harmonic distortion) of the order of 0.1% per year [3].

Harmonic currents flowing through power systems cause heat losses and utilize the system capacity and lead to power quality problems. High level of harmonic currents lead to a decrease in the electrical system efficiency, an unnecessary energy cost and ultimately causes failures in the electrical system components. When the level of distortion in the supply voltage approaches 10% the duration of the service life of equipment is significantly reduced. The reduction has been estimated at [3]:

- 32.5% for single phase machines
- 18% for three phase machines
- 5% for transformers.

Unnecessary energy cost is another concern from high level harmonics in power systems. In addition to kilowatt-hours charges, consumers are typically charged a demand charge in every billing period by the utility plus a low power factor penalty if the power factor at the consumer load is lower than the minimum set by the utility. Presence of harmonics often lead to momentary over peak demands and a lower than desired power factor. As a result these extra charges and penalties will be applied by the utility. These extra charges and penalties can substantially increase the monthly bill especially in high power consumption buildings. For example a building with an actual power demand of 2000KW and an apparent power of 2500KVA having a power factor of 0.80 could be charged a penalty of (0.9-0.8)*2500 = 250KW if the penalty is applied at lower than 0.9 power factor.

## 1.3 Power Demand in the Information Technology (IT) Industry

Power demand in the IT industry has been rising continuously since the early nineties and has not shown any signs of slowing down [4]. In fact, the power demand in the IT industry is still at its infancy stages as has been suggested in some recent studies [4] and it will only continue to rise as we become more and more reliant on the internet in every aspects of our daily life. Every sector of our society has become dependant on the world wide web. Industries can not be competitive without it and all government sectors are reconfiguring their infrastructures and their way of doing business around it. The education system whether public or private relies more and more on the internet as a tool for research and knowledge. If anything, this is an indication that the demand for web hosting facilities and collocation spaces will continue to increase, increasing with it the level of non linear loads and consequently the level of harmonics.

Increased Power consumption of internal components of IT devices further contributes to the increase of power demand in the IT industry, resulting in the increase of harmonic levels. Faster circuitry, voltage reduction and increased processing time continue to increase the power density which is expected to quadruple in just few years [1]. This increase in power density will lead to a reduction in the equipment foot print allowing IT personals to put more equipment per square footage. This phenomenon will have a double impact on the increase in the level of harmonics in power systems, that is, an increase in the number of non linear loads per square-foot will require more UPS power and cooling equipment to support this increase in power density. These support equipment are also harmonic generating equipment and will further contribute to the problem.

Expected future changes are indicated in the following table [1]:

| | ***Present*** | ***Future*** |
|---|---|---|
| *Microprocessor :* | 2.9-5V | 1.3-1.8V |
| *Logic & Memory:* | 3.3V | 1.2-1.8V |
| *Electromechanical devices: (CD ROM, Hard drives, Fans)* | 12V | 12V |
| *Microprocessor speed:* | 1GHz | 5GHz |
| *Buss speed:* | 10-200MHz | 500MHz |
| **Power density:** | **2W/Cu.in** | **10W/Cu.in** |

## 1.4 How is this Report Organized?

This report is organized as follow: Chapter 2 provides a mathematical overview of harmonics with a brief review of Fourier series. Chapter 3 covers the origin of harmonics. Chapter 4 provides an analysis of the impact of harmonics on power distribution systems and in the operation of certain equipment and devices. Finally, Chapter 5 provides an overview of some of the solutions being used in the industry to deal with harmonics with a critical analysis of their effectiveness.

# CHAPTER 2

# 2. MATHEMATICAL OVERVIEW OF HARMONICS

A waveform that is periodic and sinusoidal can be represented mathematically by the following function: $\text{A}\sin(\frac{2\pi}{T}t+\phi)$ where A is the amplitude, T is the function period and $\phi$ is the phase displacement. When a function is periodic but not sinusoidal it can be represented by an infinite series of sinusoids referred to as Fourier series by the following function:

$$f(t)=\frac{a_0}{2}+\sum_{n=1}^{\infty}(a_n\cos n\omega_0 t+b_n\sin n\omega_0 t)$$

where

$$a_n=\frac{2}{T}\int_{t_0}^{t_0+T}f(t)\cos n\ \omega_0 t\,\text{dt},\ \text{n=0,1,2,.....}$$

$$b_n=\frac{2}{T}\int_{t_0}^{t_0+T}f(t)\sin n\ \omega_0 t\,\text{dt},\ \text{n=0,1,2,.....}$$

An alternate simplified representation of the Fourier series is given by:

$$f(t)=\frac{a_0}{2}+\sum_{n=1}^{\infty}(A_n\cos(n\omega_0 t+\phi_n)$$

where

$$A_n=\sqrt{a_n^2+b_n^2}\ \text{and}\ \phi_n=-\tan^{-}\frac{b_n}{a_n}.$$

Looking at the function representation of the non sinusoidal waveform we see that this function could contain an infinite number of frequencies $0, f_0, 2f_0, \ldots. nf_0$. Each term $a_n\cos n\omega_0 t+b_n\sin n\omega_0 t$ is referred to as a harmonic. The harmonic resulting from n=1 is called first harmonic or fundamental with fundamental frequency $f_0$. Similarly in the case of n=2, the resulting harmonic is referred to as a second harmonic and so on. Figure 2.1 shows the fundamental with the third and fifth harmonic.

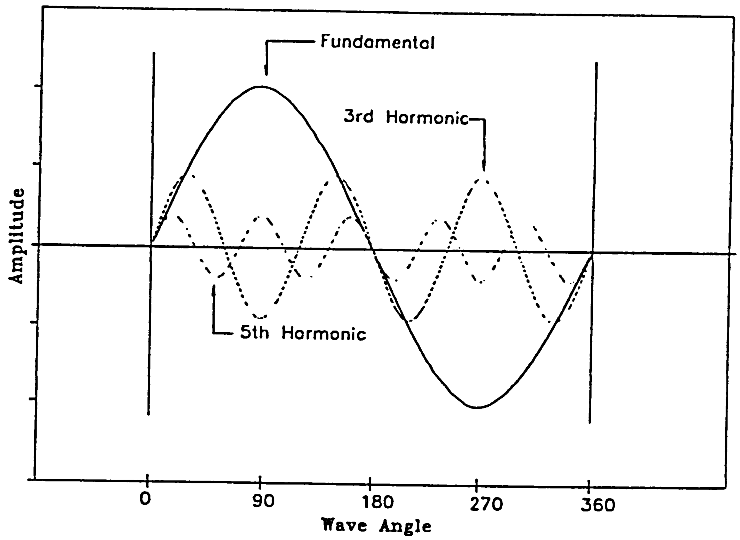



Figure 1 - Waveform Showing Fundamental with the Third and the Fifth Harmonics.

**Simplification through symmetry:**

Through some mathematical manipulation, the equations:

$$a_n = \frac{2}{T}\int_{t_0}^{t_0+T} f(t)\cos n\,\omega_0 t\,\mathrm{dt}, \text{ and } b_n = \frac{2}{T}\int_{t_0}^{t_0+T} f(t)\sin n\,\omega_0 t\,\mathrm{dt}$$

can be rewritten as:

$$a_n = \frac{2}{T}\int_{t_0}^{T/2} [f(t) + f(-t)]\cos(\frac{2\pi nt}{T})\,\mathrm{dt}, \qquad (2.1)$$

and

$$b_n = \frac{2}{T}\int_{t_0}^{T/2} [f(t) - f(-t)]\sin(\frac{2\pi nt}{T})\,\mathrm{dt}, \qquad (2.2)$$

Which provide the following useful simplifications:

*Odd Symmetry:*

A function representing a waveform is said to have odd symmetry when $f(-t) = -f(t)$. This will result in the terms $a_n$ for all n becoming zero as seen from equation (2.1), leading to the Fourier series for an odd function having no cosine terms. An odd function is symmetrical about the origin (Figure 2).

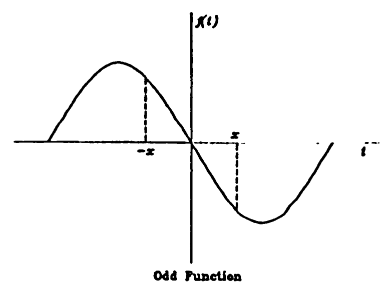



Figure 2- Waveform with Odd Symmetry

*Even Symmetry:*

A function representing a waveform is said to have even symmetry when $f(-t)=f(t)$. This results in the terms $b_n$ for all n becoming zero as seen from equation (2.2), leading to the Fourier series for an even function having no sine terms. An even function is symmetrical about the Y axis (Figure 3).

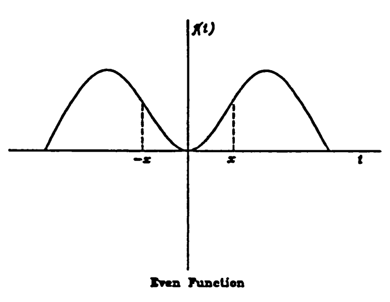



Figure 3- Waveform with Even Symmetry

*Half wave Symmetry:*

A function representing a waveform is said to have half wave symmetry when $f(t)=-f(t-\frac{T}{2})$. Waveforms with half wave symmetry contain only odd harmonics multiple of the fundamental. This can be proven using the identities $\cos(x-n\pi)=(-1)^n\cos(x)$ and $\sin(x-n\pi)=(-1)^n\sin(x)$. Sine wave, Cosine wave, Square wave and triangular wave have all half wave symmetry. In power distribution systems, because of half wave symmetry, even harmonics are ignored.

# CHAPTER 3

# 3. ORIGINS OF HARMONICS

Harmonics in the early days of power distribution systems were mainly the product of magnetization devices and arcing devices [5]. The introduction of semiconductor products in recent decades introduced other sources of harmonics, mainly from power electronic devices. These latest sources have had the greatest impact on voltage and current distortion.

This chapter introduces the major sources of harmonics with an analysis of how they generate these harmonics.

## 3.1 Switch Mode Power Supplies (SMPS)

Switch mode power supplies (SMPS) are found in most of today's electronic devices. They can be found in personal computers, laptops, servers, scanners, fax machines, copiers and the list goes on. Switch mode power supplies are probably the number one source of harmonics in commercial buildings designated for office use.

### 3.1.1 Older Type Power Supplies

Switch mode power supplies have evolved over the years from the traditional type which utilizes a step down transformer and a rectifier to achieve the required DC voltage, to the most recent ones using direct controlled rectification of the supply to charge a capacitor bank from which the output current and voltage is controlled through switching devices.

#### 3.1.1.1 Simulations With Matlab Simulink

Using Matlab Simulink, we constructed a model of the traditional type power supply (Figure4). In this model, the 120V AC is stepped down to 24V AC before it is rectified through a two pulse rectifier. The output at the rectifier is then fed through a filter before it supplies the load. Figure 5 shows the waveforms obtained after running the simulation. The waveforms are the output DC voltage at the rectifier, the output voltage after the filter at the load, and the line current at the 120V side. The harmonic profile of the line current is shown in Figure 6. The harmonic profile indicates a high level presence of lower order odd harmonics with the third being the dominant.

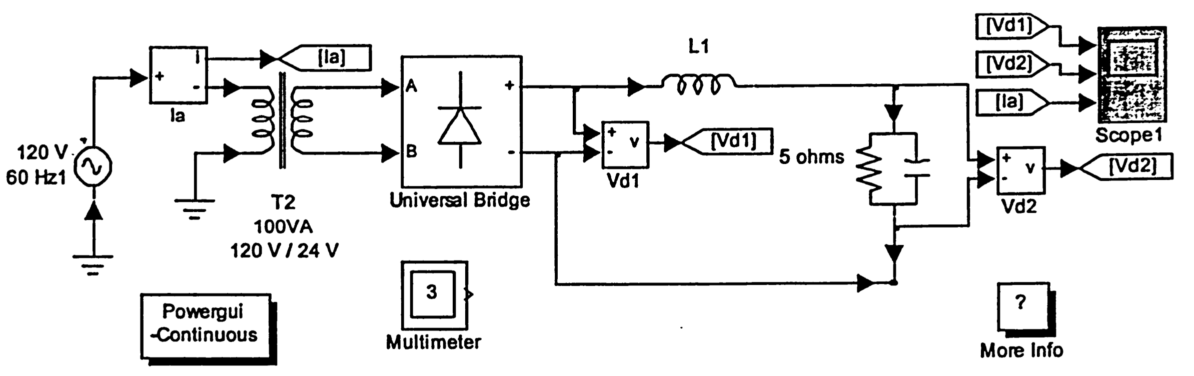



Figure 4 - Matlab Simulink Model of an Older Type Power Supply

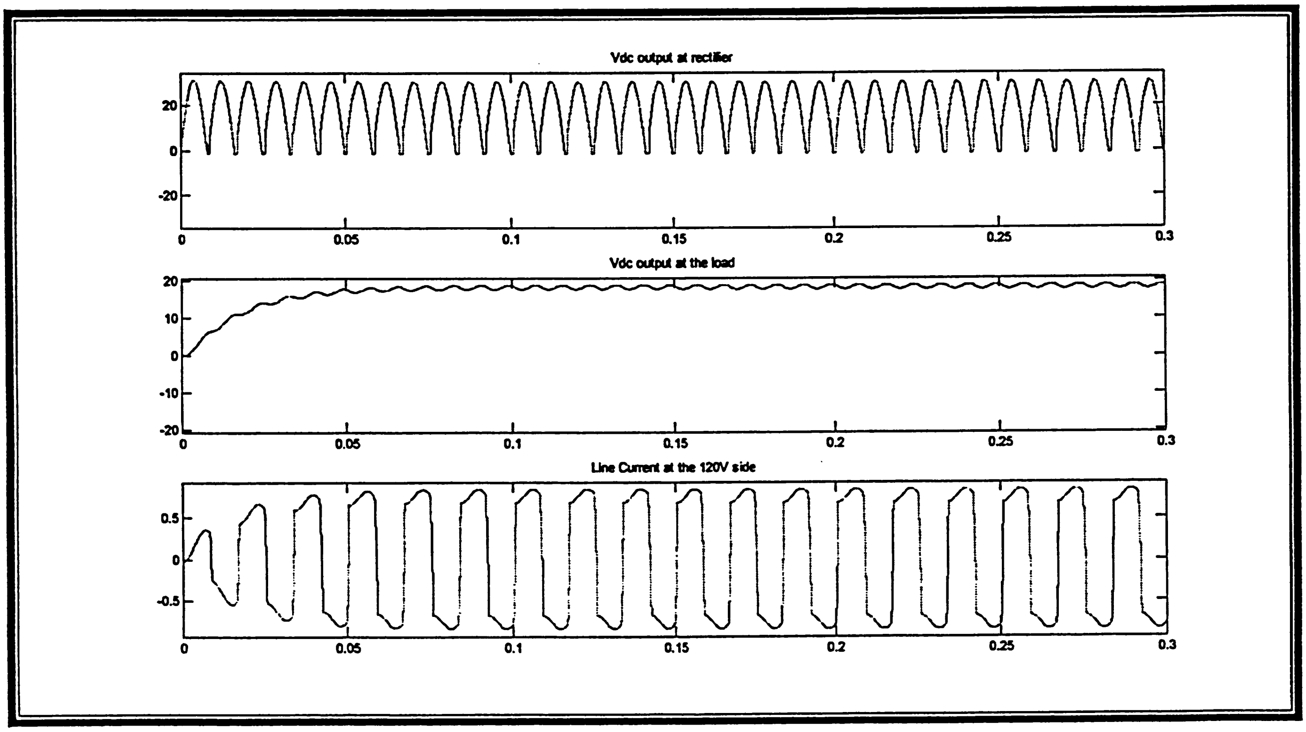



Figure 5- Output Waveforms of Simulink Model of Figure4: *a) Output DC Voltage at the Rectifier, b) Output Voltage at the Load, c) Line Current at the 120V Side.*

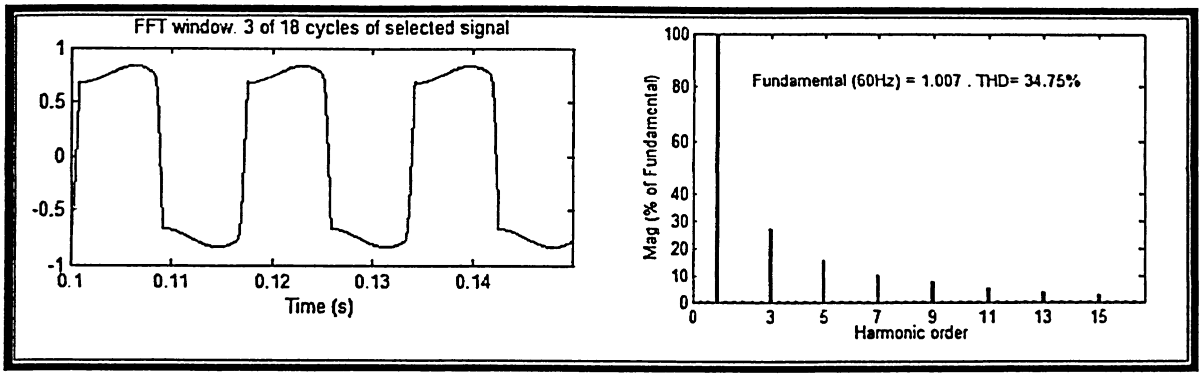


Figure 6 - Line Current at the 120V Side and its Harmonic Profile.

### 3.1.2 Newer Type Power Supplies

The elimination of the step down transformer in the newer type SMPS made them much smaller in size and significantly reduced their weight resulting as well in the reduction of manufacturing cost. Moreover, the use of controlled high switching devices gave this type of SMPS the ability to provide a wider range of output DC voltages. Their main disadvantage however, was the higher level of third harmonics that they generated compared to the traditional type power supplies.

In the newer type SMPS (Figure 7), the 120V AC input is directly converted to DC through a two pulse rectifier to charge a capacitor. Twice per cycle, a pulse of current is drawn to recharge the capacitor to the peak value of the supply voltage. Between voltage peaks the capacitor discharges to support the load and the SMPS does not draw current from the source. As a result, the supply voltage peak is flattened by the instantaneous voltage drops throughout the distribution system caused by the simultaneous current pulses drawn by the multiple SMPS units. The flattened voltage waveform contains a lowered fundamental voltage component plus 3rd, 5th, 7th, 9th and higher voltage harmonics.

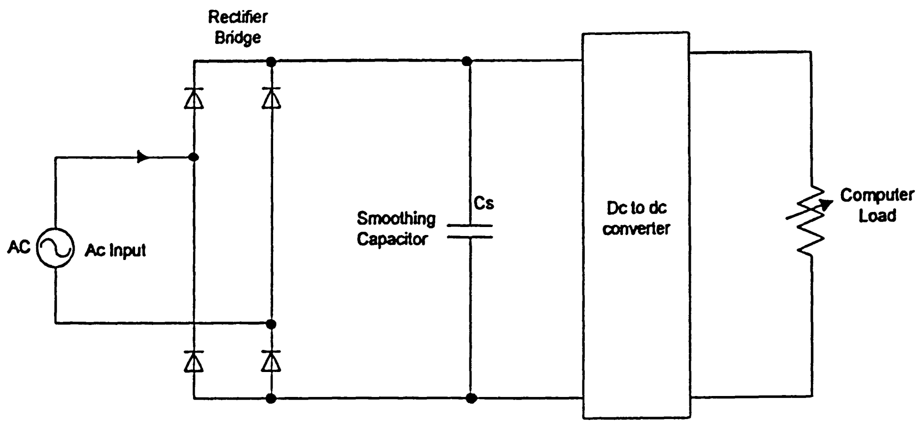



Figure 7 - Typical PC Power Supply Structure

3.1.2.1 Simulations with Matlab Simulink

Using Matlab Simulink, we built a model of the newer type power supply (Figure 8). At the DC to DC conversion we used a resonant type converter. The resulting waveforms are shown in Figure 3.6. The waveforms show the output DC voltage at the rectifier after filtering, the output DC voltage at the load after the DC to DC conversion, the line current at the 120V side and its harmonic profile, and the 120V AC input and its harmonic profile. As was expected, the harmonic profile of the line current shows a much higher level of third harmonic than was the case with the traditional power supply

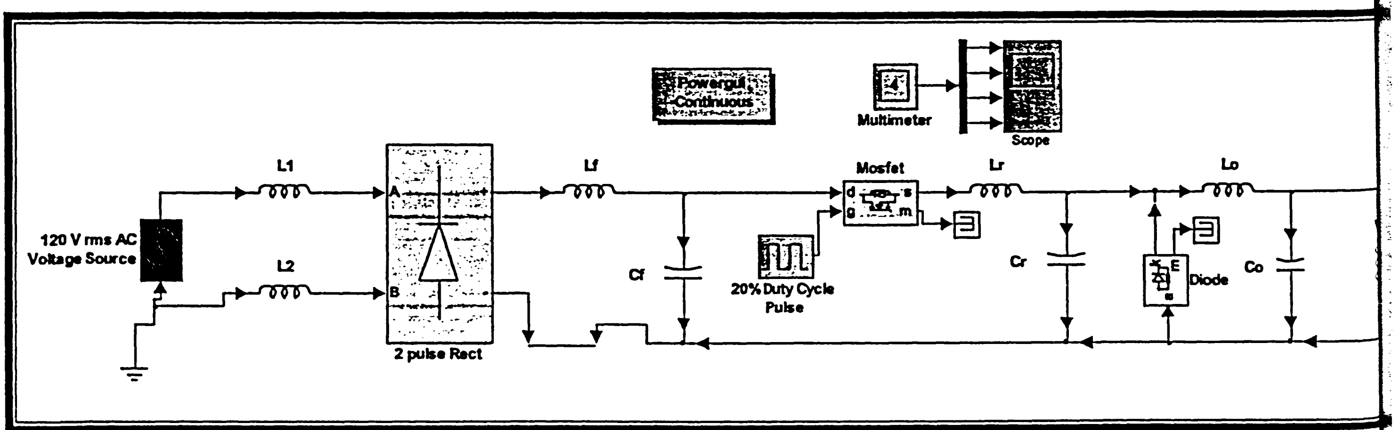



Figure 8 - Matlab Simulink Model of Switch Mode Power Supply

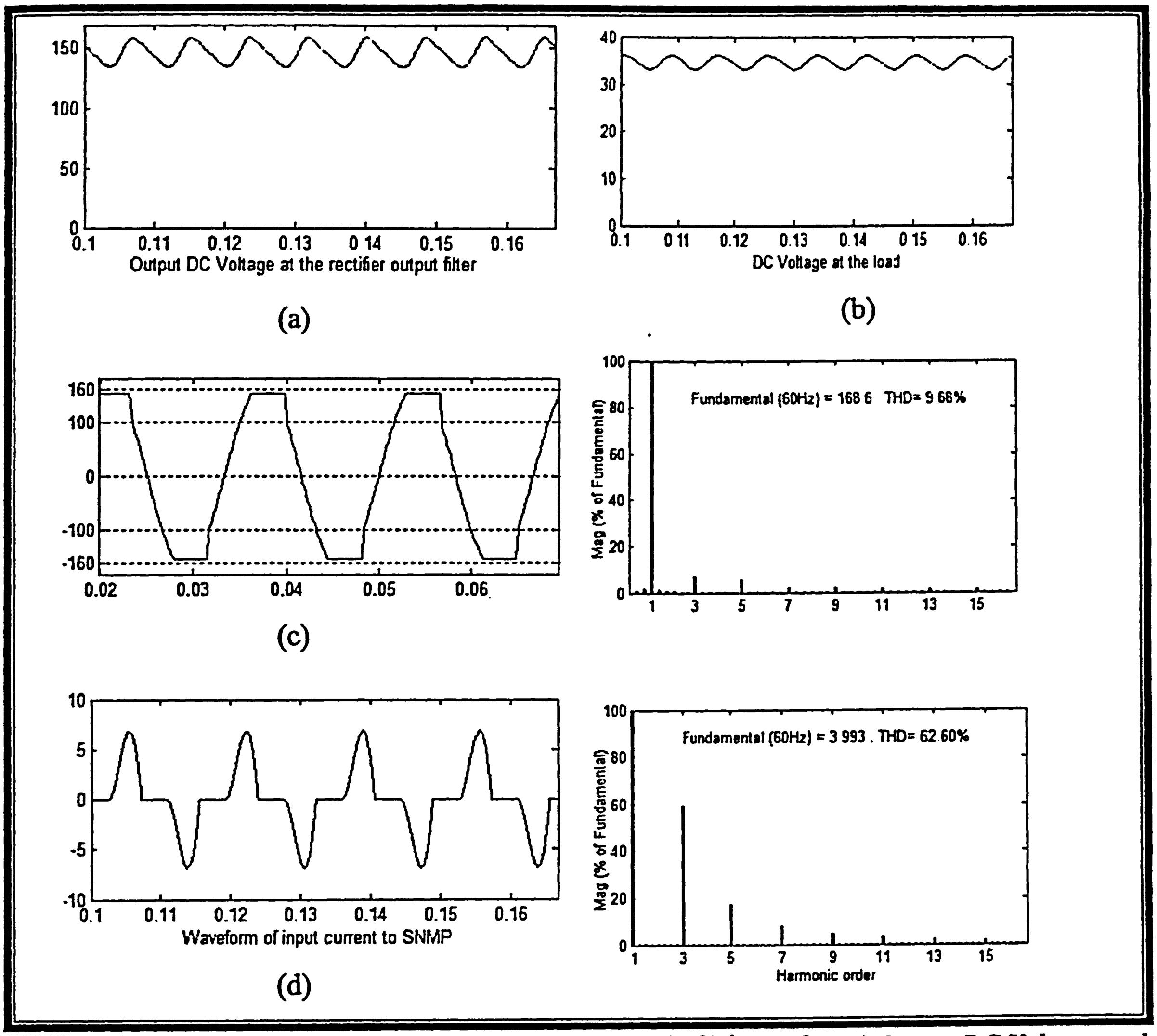



Figure 9 - Output Waveforms of Simulink Model of Figure 8. : *a) Output DC Voltage at the Rectifier Output Filter, b) Output DC Voltage at the Load, c) Line Voltage and its Harmonic Spectrum d) Line Current at the 120V Side and its Harmonic Spectrum of the line Current*

### 3.1.3 The Effect of Diversity on Harmonic Profile.

In a recent study [6], it was found that the harmonic profile of the line current obtained when multiple SMPSs were supplied from the same phase was significantly different from the one obtained when a single SMPS was connected to the same circuit. The study showed a significant reduction in the 3$^{rd}$ and 5$^{th}$ harmonics. For example: a reduction from 76% to 24% was observed for the 3$^{rd}$ harmonic [6]. This reduction was attributed to the attenuation effect resulting from the widening of the current pulse.

## 3.2 Three Phase Diode Rectifiers

The six pulse rectifier shown in Figure 10 is widely used in high power rectification such as in motor drives and large KVA UPS systems. The six pulse rectifier utilizes six diodes and exhibits 6 pulses per cycle on the dc voltage. Higher pulse rectifiers (12, 18, etc..) are constructed using 6 pulse rectifiers connected in parallel through phase shifting transformers.

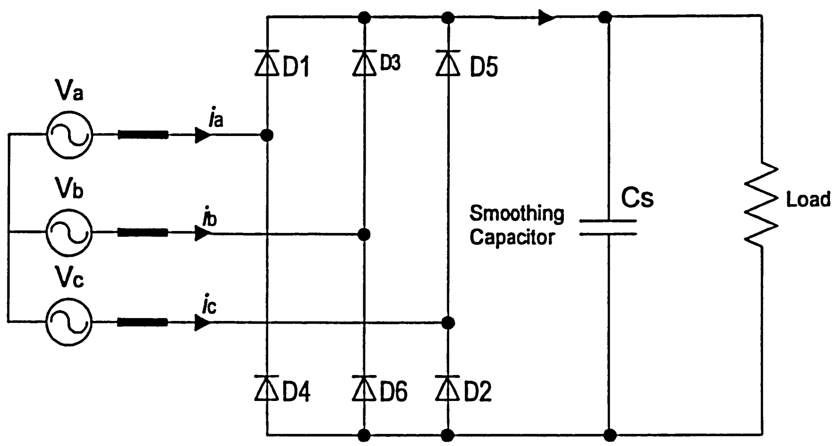



Figure 10 - Six Pulse Rectifier Diagram

### 3.2.1 Mode of Operation

Figure 11 shows the voltage waveforms of the line voltages of the system in Figure 10. Looking at Figure 10, each diode would conduct for one third of each 360° of the supply voltage. From $\frac{\pi}{6}$ to $\frac{5\pi}{6}$, $V_a$ is most positive and $D_1$ is forward biased and is turned on. The current is supplied to the load through $D_1$, the negative return current will flow back through the most negative voltage, first through $D_6$ to $V_b$ from $\frac{\pi}{6}$ to $\frac{\pi}{2}$ then through $D_2$ to $V_c$ from $\frac{\pi}{2}$ to $\frac{5\pi}{6}$. Similarly from $\frac{5\pi}{6}$ to $\frac{3\pi}{2}$, $V_b$ is most positive and $D_3$ is forward biased and is turned on. The current is supplied to the load through $D_3$ and returns through $D_2$ from $\frac{5\pi}{6}$ to $\frac{7\pi}{6}$ and through $D_4$ from $\frac{7\pi}{6}$ to $\frac{3\pi}{2}$. Finally from $\frac{3\pi}{2}$ to $\frac{13\pi}{6}$, $D_5$ is forward biased for the supply current and $D_4$ and $D_6$ are forward biased for the return current.

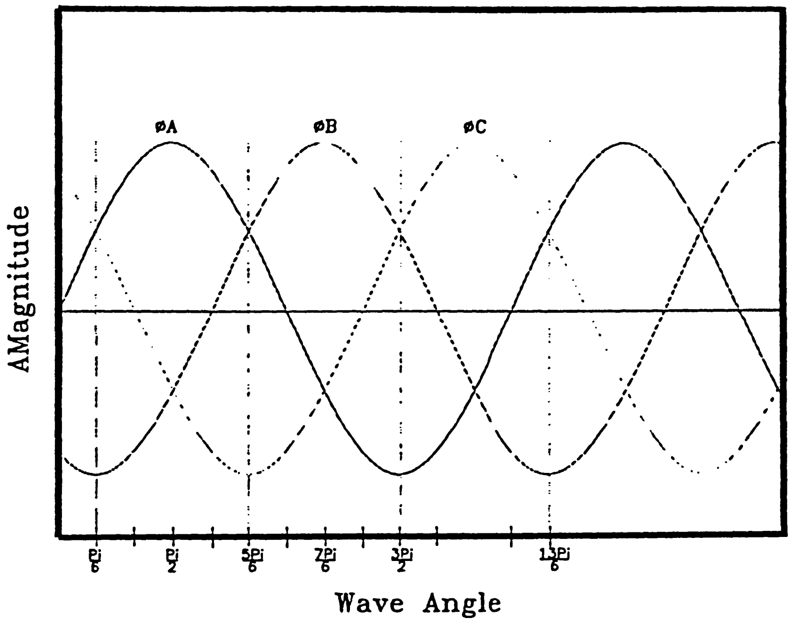



Figure 11- Waveforms of Line Voltages of the Rectifier of Figure 10.

Just as in the SMPS, the current in the three phase rectifier is drawn from the supply in pulses during peak line to line voltage, and the line current would have the waveform shown in the Figure 13. It is evident that the line current is not sinusoidal.

The line current is described by the following equation [7]:

$$I_{\phi}=\frac{2\sqrt{3}}{\pi}I_D\left(\cos\omega t-\frac{1}{5}\cos 5\omega t+\frac{1}{7}\cos 7\omega t-\frac{1}{11}\cos 11\omega t+\ldots\right)$$

The six pulse bridge therefore produces harmonics of the order of n=6k +/- 1 where k is an integer and where those harmonics of orders 6k+1 are of positive sequence and the ones of orders 6k-1 are of negative sequence. We also notice the absence of triple harmonics, although this would not be the case if the system was unbalanced. We would therefore expect the following harmonics in the six pulse rectifier (5,7,11,13, etc.).

3.2.1.1 Simulations With Matlab Simulink

Using Matalb Simulink, we built a model of the three phase six pulse rectifier (Figure 12). The AC side line current and its harmonic profile are shown in Figure 13. As expected, the harmonic profile indicates the presence of the $5^{th}$, $7^{th}$, $11^{th}$, etc.

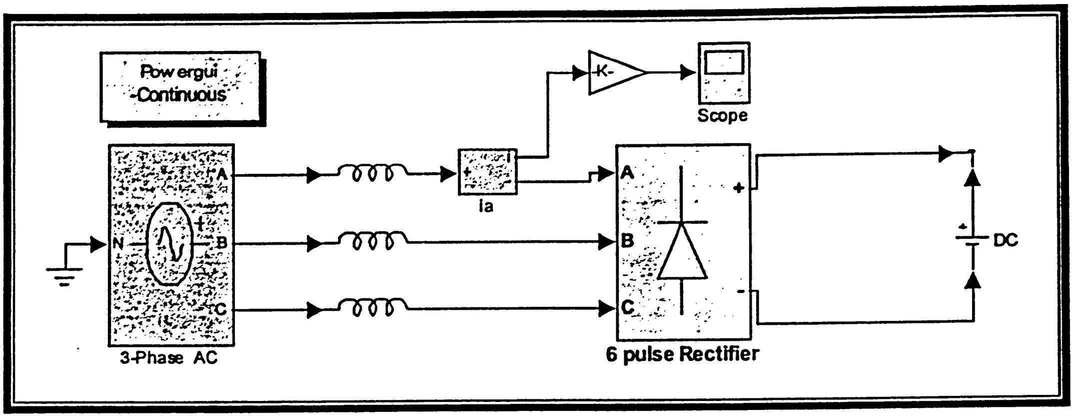



Figure 12- Matlab Simulink Model of a Six Pulse Rectifier

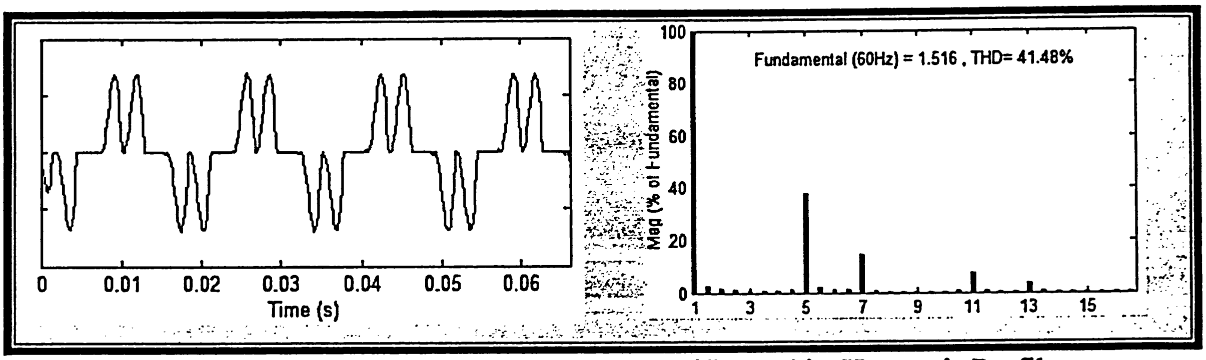



Figure 13- Line Current in Six Pulse Rectifier and its Harmonic Profile

## 3.3 Magnetic materials

The magnetic material used in a transformer core, exhibits a nonlinear behavior when an alternating magnetomotive force is applied to it. This can be seen from the hysteresis loop shown in Figure 14.

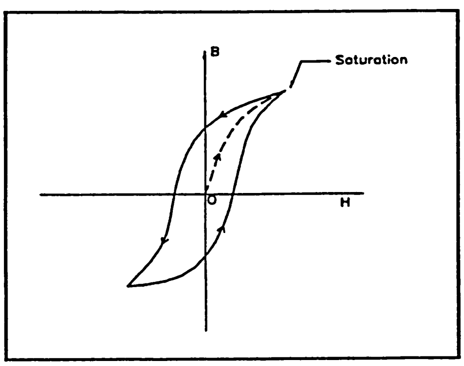



Figure 14- Hysteresis Loop

As it can be seen from the hysteresis curve, the flux density magnitude does not follow the field intensity magnitude when an alternating current is applied. When H and B are both equal to zero and an alternating current is applied, B and H first follow the dashed curve in the hysteresis loop. When the current reaches the maximum, both B and H reach their maximum. Beyond this point the magnetic flux begins to become flat and a small increase in B require a large increase in H. As a result, the current starts to get distorted showing harmonic components [5].When the current decreases, B and H follow a different curve and H reaches zero while B is still lagging (residual magnetism). As H becomes negative, B continue to decrease until it reaches zero, then both B and H become negative until they both reach their maximum negative values and start to decrease in the negative direction in the same way as in the positive direction.

To reduce the cost and the physical size of the transformer, transformer manufacturers design the transformers to operate at or above the knee of the saturation curve, resulting in a distorted magnetizing current rich in 3rd harmonic (Figure 15a and 15b). The higher the operation is on the saturation curve, the greater the amount of distortion [8]. This is especially true when the transformer is operated beyond the rated power or above nominal voltage.

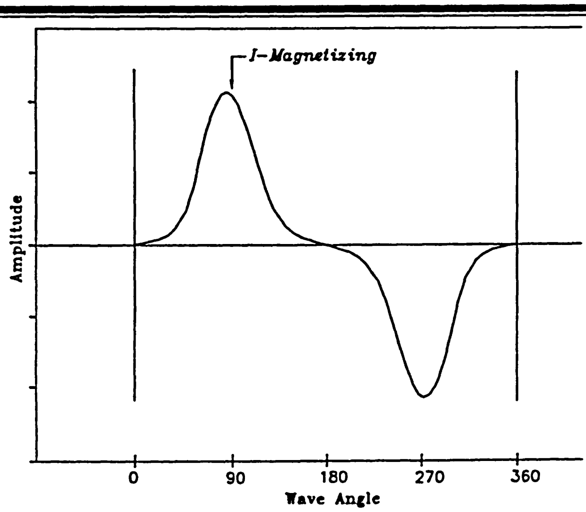



Figure 15a- Typical Waveform for a Transformer Magnetizing Current

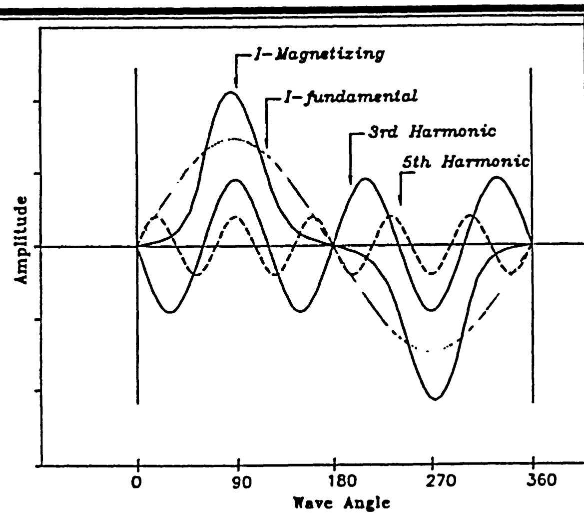



Figure 15b- Harmonics in Magnetizing Current

### 3.3.1 Simulations With Matlab Simulink

Using Matalb Simulink, we built the model shown in Figure 16 in order to obtain the harmonic profile of the magnetizing current. The simulation was run without any load on the transformer in order to obtain mostly the magnetizing current. The magnetizing current and its harmonic profile are shown in Figure 17.

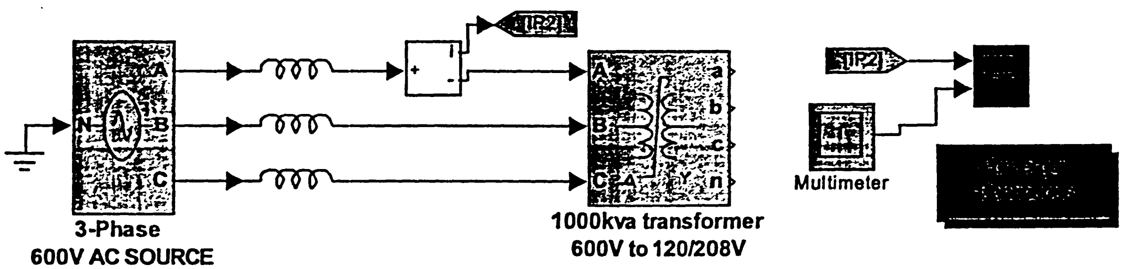



Figure 16- Matlab Simulink Model to Obtain the Transformer Magnetizing Current

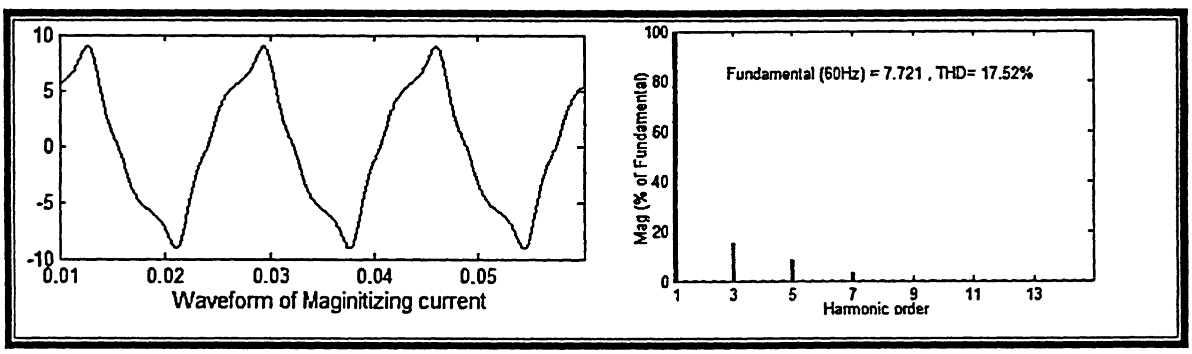



Figure 17- Transformer Magnetizing Current and its Harmonic Profile

It should be noted that harmonics from transformers or magnetizing devices generally have much lesser effect on the power distribution system compared to rectifiers, inverters and switch mode power supplies except when resonance occur.

## 3.4 Ballasts in Fluorescent Lamps

Fluorescent lighting is widely used in industrial and commercial applications because of the high efficiency and longer lifespan that it provides compared to incandescent lighting.

Fluorescent lamps require ballast to control current flow through electrodes. There are two types of lighting ballasts, magnetic and electronic ballasts.

Magnetic ballasts used in conventional fluorescent lighting systems, operate from the source using a simple series choke as the ballast which function is to create sufficient voltage with the glow starter to start the lamp and also to limit the lamp current after it has started. Magnetic ballasts are simple to make and offer low manufacturing cost, and they are three to four times more efficient than incandescent lamps, but they have some drawbacks. Some of these drawbacks are low input power factor, audible humming noise, extra losses in the choke, delayed start and no dimming control.

Electronic Ballasts on the other hand, make use of power electronic devices to convert the lamp operating frequency from 60Hz to 20-40 kHz. The high frequency operation reduces internal losses in the lamp and conserves energy. Electronic ballasts for fluorescent lamps result in a further 20-30% in efficiency over the magnetic ballasts. However, their main disadvantage is the high level of harmonics that their inverter generates especially in large applications. Magnetic ballasts do generate harmonics also, but at a lower level compared to the electronic ones. Figure 18 shows a typical waveform of the current drawn by fluorescent lamp through the ballast [3]. The harmonic profile of the line current is shown in Figure 19 [3]. This harmonic profile shows a high level presence of lower order odd harmonics.

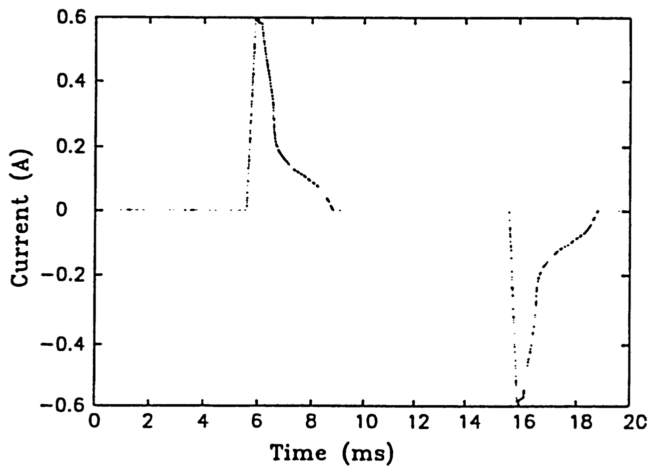



Figure 18 - Current Waveform in a Fluorescent Lamp with High Efficiency Electronic Ballast

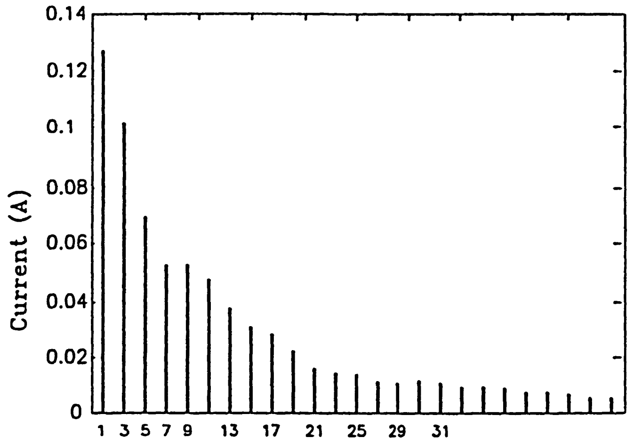



Figure 19- Harmonic Spectrum of the Current Waveform of Figure 18

# CHAPTER 4

# 4. EFFECTS OF HARMONICS IN POWER DISTRIBUTION SYSTEMS

High level presence of harmonics in power distribution systems can lead to serious problems. Many sudden failures of power distribution equipment are attributed to the presence of high levels of harmonics which remained in the power system for a prolonged period of time without any actions being taken to suppress them until they've caused serious damage to the equipment insulation or proper operation.

In this section, we will address some of the negative ways that harmonics affect power distribution systems.

## 4.1 Voltage Distortion

When the load current contains high level of harmonics, it becomes distorted. This distorted load current flowing through the power source and line impedance will cause voltage drops at these harmonics causing the line voltage to become distorted as well. The resultant distorted voltage when applied to other loads connected to the same circuit, causes harmonic current to flow in them even if they are linear loads.

A power distribution system containing nonlinear loads can be modeled with the circuit shown in Figure 20 [9]. In this model, the non linear load is modeled by a linear load for the fundamental (60hz) current and a current source for all other harmonic currents feeding back into the source.

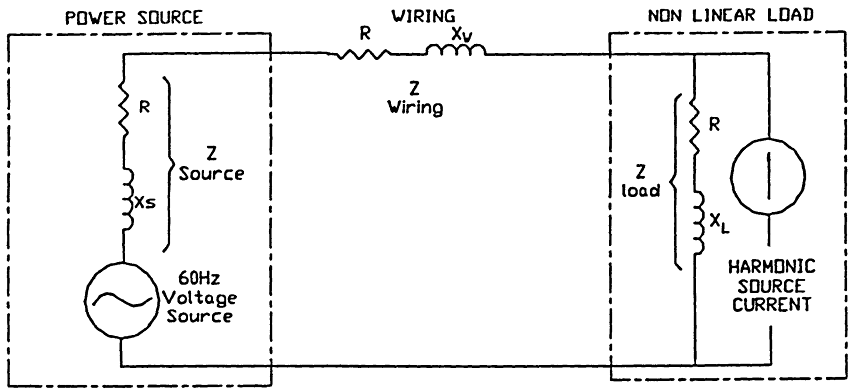



Figure 20 - Equivalent Circuit of Non Linear Load.

The system impedance at the harmonic frequency is defined as:

$$Z_n = R_t + X_{t.n}$$

Where

$R_t = R_{(wire)} + R_{(source)}$ and $X_{tn} = X_{n(wire)} + X_{n(source)}$

Because the inductive impedance $X_{tn}$ is frequency dependent, the introduction of harmonic currents into the system increases the total impedance Z.

Current harmonics flowing through the system impedance create harmonic voltages which are vectorially added to the source voltage causing it to be distorted. The resulting source voltage as seen by the load is defined as:

$$V = I_1 Z_1 + I_3 Z_3 + I_5 Z_5 + \ldots.. = \sum_{n=0}^{\infty} I_{2n+1} Z_{2n+1}$$

Where

$I_1$ is the current at the fundamental frequency.

$I_3$ is the current at the 3rd harmonic.

$I_5$ is the current at the 5th harmonic, etc.

And

$Z_1$ is the system impedance at the fundamental frequency.

$Z_3$ is the system impedance at the 3rd harmonic.

$Z_5$ is the system impedance at the 5th harmonic, etc.

The major ill effect of voltage distortion is low power factor. In a power system with just linear loads, the apparent power $S$ in terms of real power $P$ and reactive power $Q$ is expressed as $S^2 = P^2 + Q^2$. Since harmonic currents in non linear loads produce no useful work, they are considered reactive as well and the apparent power is expressed as: $S^2 = P^2 + Q^2 + Q_H^2$.

The power factor $P_f$ which is equal to $\frac{P}{S}$ is no longer equal to $\cos\phi$. Figure 21 shows the power diagram for linear and non linear loads.

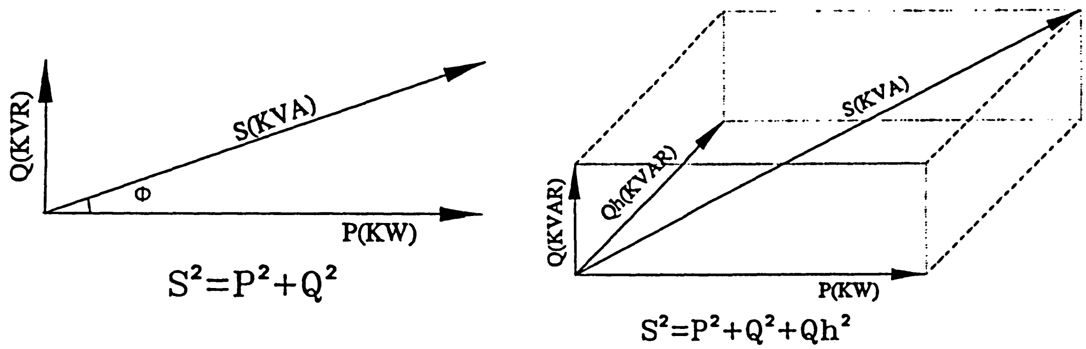



Figure 21- Power Diagram for Linear Load (left ) and Non Linear Load (right)

To better appreciate the effect of harmonics on the power factor we need to look at it from a mathematical viewpoint.

First the voltage total harmonic distortion is defined as:

$$THD_V = \frac{1}{V_{1(rms)}}\sqrt{\sum_{h=2}^{\infty} V_{h(rms)}^2} \Rightarrow \sum_{h=2}^{\infty} V_{h(rms)}^2 = THD_V^2\, V_{1(rms)}^2 \quad (1)$$

Similarly, the current total harmonic distortion is defined as:

$$THD_I = \frac{1}{I_{1(rms)}}\sqrt{\sum_{h=2}^{\infty} I_{h(rms)}^2} \Rightarrow \sum_{h=2}^{\infty} I_{h(rms)}^2 = THD_I^2\, I_{1(rms)}^2 \quad (2)$$

Where

$V_{1(rms)}$ and $I_{1(rms)}$ are the fundamental rms voltage and current respectively.

$$V_{(rms)} = \sqrt{\sum_{h=1}^{\infty} V_{h(rms)}^2} = \sqrt{V_{1(rms)}^2 + \sum_{h=2}^{\infty} V_{h(rms)}^2} \quad (3)$$

And

$$I_{(rms)} = \sqrt{\sum_{h=1}^{\infty} I_{h(rms)}^2} = \sqrt{I_{1(rms)}^2 + \sum_{h=2}^{\infty} I_{h(rms)}^2} \quad (4)$$

Substituting (1) into (3), and (2) into (4) we get the following:

$$V_{(rms)} = V_{1(rms)} \sqrt{THD_V^2 + 1} \quad (6)$$

And

$$I_{(rms)} = I_{1(rms)} \sqrt{THD_I^2 + 1} \quad (7)$$

The apparent power per phase is:

$$S = V_{(rms)} I_{(rms)}$$

Substituting for $V_{(rms)}$ and $I_{(rms)}$ from equation (6) and (7) we get:

$$S = V_{1(rms)} I_{1(rms)} \sqrt{THD_V^2 + 1} \sqrt{THD_I^2 + 1}$$

$$= S_1 \sqrt{THD_V^2 + 1} \sqrt{THD_I^2 + 1}$$

$S_1$ is the apparent power at the fundamental frequency.

The power factor is therefore:

$$P_f = \frac{P}{S} = \frac{P}{S_1} \times \frac{1}{\sqrt{THD_I^2 + 1}\sqrt{THD_V^2 + 1}} = P_{f(disp)} \times P_{f(dist)}$$

Where

$P_{f(disp)} = \frac{P}{S_1}$ is referred to as the displacement power factor

And:

$P_{f(dist)} = \frac{1}{\sqrt{THD_I^2 + 1}\sqrt{THD_V^2 + 1}}$ is referred to as the distortion power factor

As we can see from the above equation for $P_f$ for power systems containing non linear loads, the displacement power factor can have a negative affect on the overall power factor. For example a power system with only linear loads, and having a power factor of 0.9 (which is considered a good power factor), will have its power factor reduced to 0.85 by a displacement power factor of just 0.95.

High voltage distortion due to harmonics can also cause multiple zero crossings for the voltage wave. This zero crossing noise can lead to operation errors in equipment which relay in their timing on the zero crossing [9]. Many electronic controllers detect the point at which the supply voltage crosses zero volts to determine when loads should be turned on. This is done because switching reactive loads at zero voltage does not generate transients, so reducing electromagnetic interference (EMI) and stress on the semiconductor switching devices. When harmonics or transients are present on the supply, the rate of change of voltage at the crossing becomes faster and more difficult to identify, leading to erratic operation. To rectify this problem, electronic designers in the recent years have been implementing internal clocks for timing in their designs so not to be susceptible to multiple zero crossing [9].

### 4.1.1 Simulations with Matlab Simulink

To further illustrate how current harmonics and system impedance causes voltage distortion, we built the circuit model shown in Figure 22 using Matlab Simulink. In this model, we used a 120V single phase source. The model created in chapter 3 for a SMPS was made into a block and used to simulate a single phase non-linear load. We captured the voltage at panel-1 at the source, and at panel-2 feeding the non-linear load located further downstream from the source. The simulation was repeated for different source and line impedances to see how the changes affect the voltage distortion. Table 4.1 shows the simulation results.

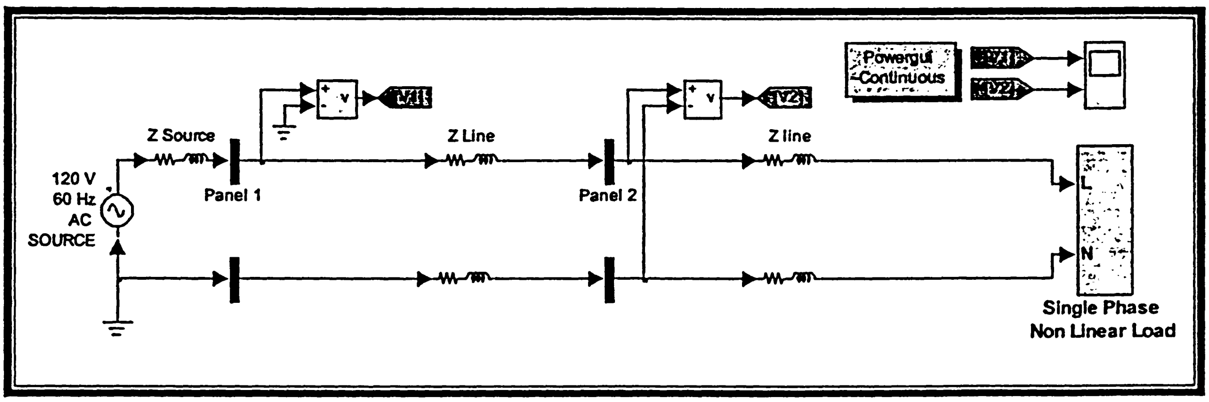



Figure 22- Matlab Simulink Model to See the Effect of Source and Line Impedance on Voltage Distortion

| **Source Impedance** ($R_{(\Omega)}$,$L_{(H)}$) | **Line Impedance** ($R_{(\Omega)}$,$L_{(H)}$) | $V_{THD}$ **(@ Panel 1)** | $V_{THD}$ **(@ Panel 2)** |
|---|---|---|---|
| $(0.03,\ 4\times10^{-3})$ | $(0.2,\ 7\times10^{-3})$ | 1.43% | 6.49% |
| $(0.06,\ 8\times10^{-3})$ | Unchanged | 2.48% | 6.88% |
| $(0.09,\ 12\times10^{-3})$ | Unchanged | 3.3% | 7.19% |
| Unchanged | $(0.4,\ 14\times10^{-3})$ | 2.33% | 7.83% |
| Unchanged | $(0.6,\ 21\times10^{-3})$ | 1.80% | 8.18% |

Table 4.1- Results From the Simulation Obtained From Simulink Model of Figure 4.2

From the results shown in table 4.1 we can conclude the following:

a) An increase in the source impedance will result in an increase in the voltage distortion at the source and at the load.

b) As the line impedance increases, the voltage distortion at the load increases while it decreases at the source. This is to be expected as the current harmonic could be seen as a current source at the non-linear load with the harmonic current flowing from the nonlinear load towards the source resulting in voltage drop in the opposite direction in comparison with the voltage drop due to the fundamental frequency.

In the next Simulink Simulations, we will show how a distorted voltage resulting from a non linear load will be applied to other loads connected to the same circuit, causing harmonic current to flow in them even if they are linear loads.

First, we built the circuit model shown in Figure 4.4. In this model, a single phase linear load was connected to a 120V rms single phase source through a downstream distribution panel which we labeled 'Panel2'. The resulting voltage and current waveforms are shown in Figure24. As expected, the waveforms are not distorted.

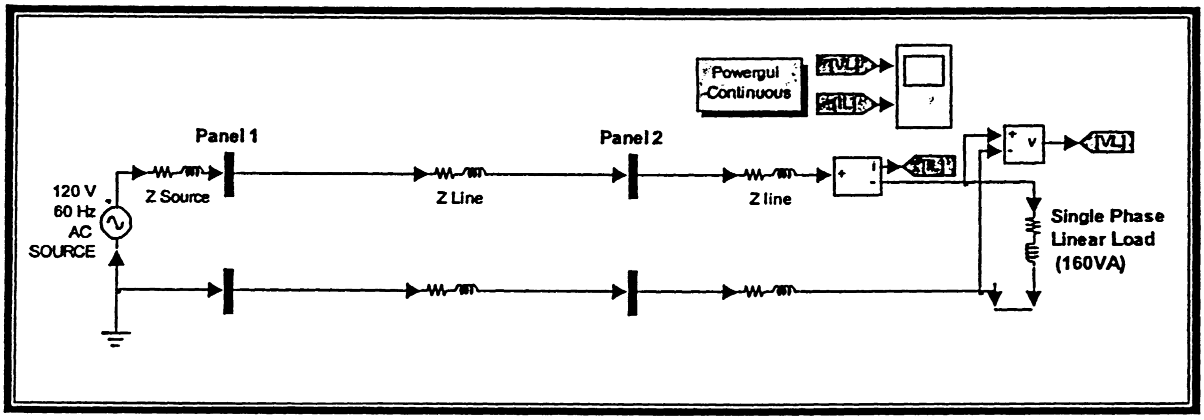
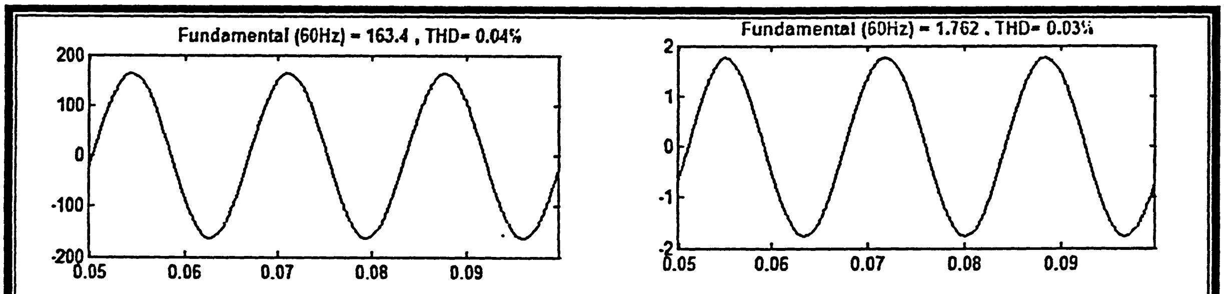



Figure 23- Matlab Simulink Model of a Simplified Single Phase Distribution System with Only Linear Loads




a) Voltage waveform seen at the linear load b) Current waveform seen at the linear load

Figure 24- Voltage and Current Measured at the Linear Load of Figure 23.

Next, we connected a nonlinear load to the same panel 'panel2' feeding the linear load as shown in Figure 25. The resulting voltage and current waveforms are shown in Figure 26. As we can see from the simulation results, the voltage applied to the linear load has now a 3.9% THD caused by the non linear load connected to the same bus. This voltage THD distortion at the linear load has resulted in a current distortion of 2.67%, and we can see from the harmonic profile of the linear load current that there are harmonic currents now flowing through the load even though the load is linear.

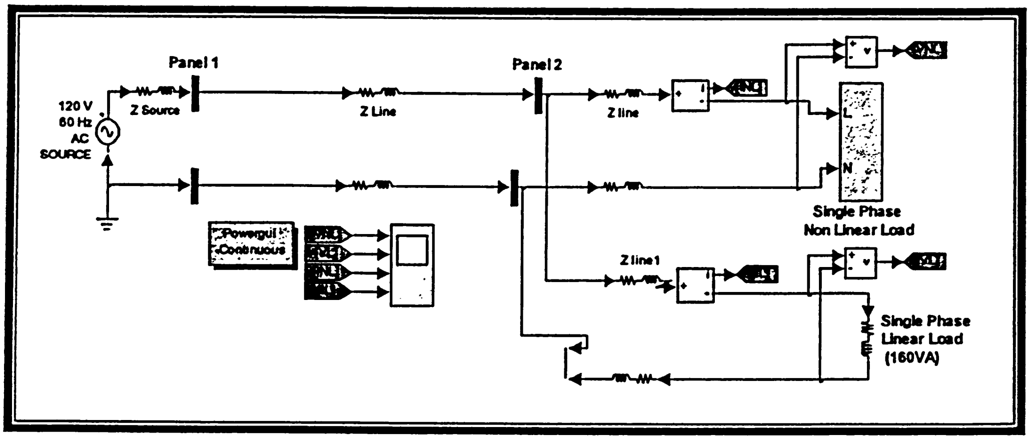
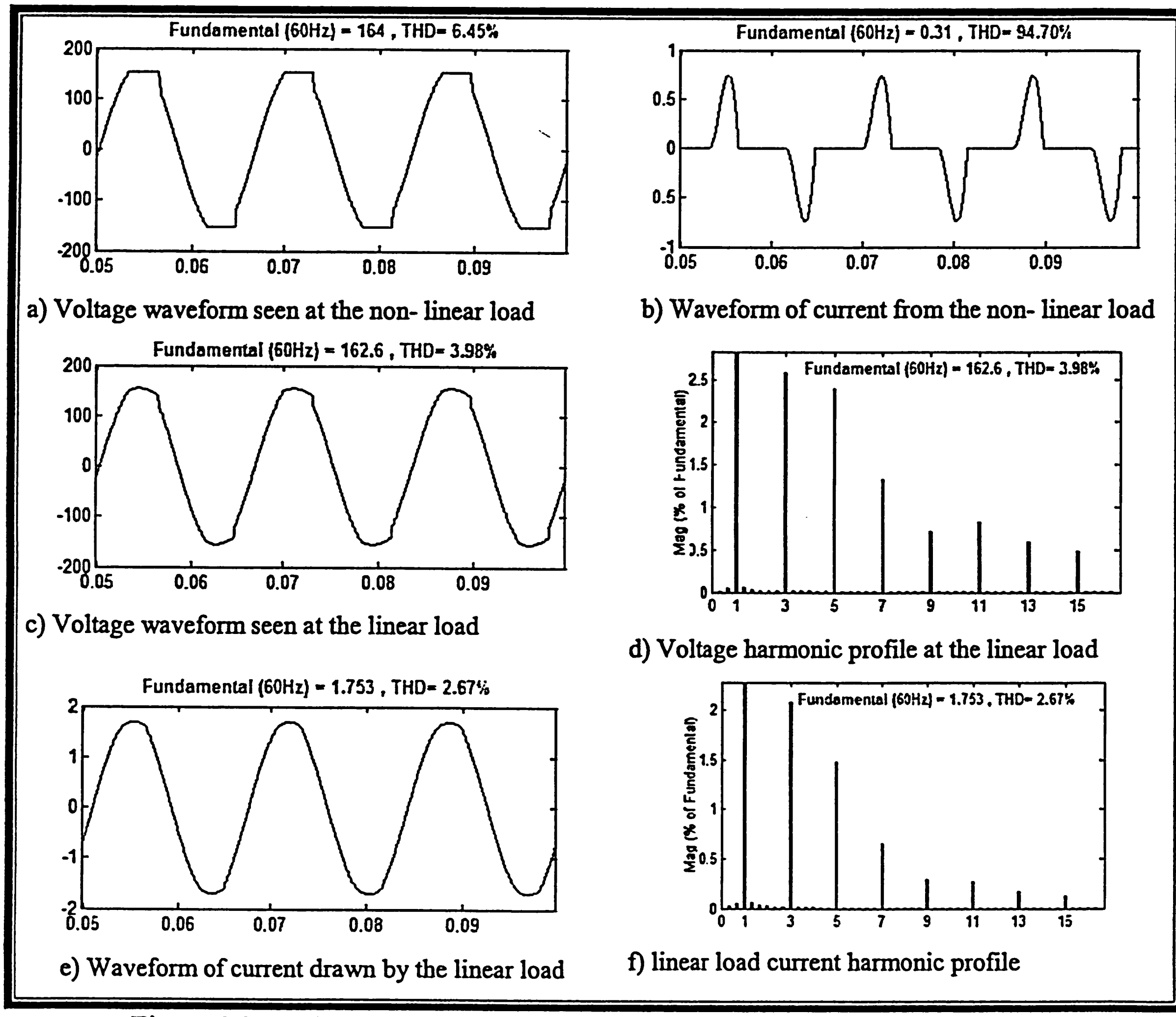



Figure 25 - Matlab Simulink Model of a Simplified Single Phase Distribution System with Linear Loads and Non Linear Loads Fed From a Common Bus.




a) Voltage waveform seen at the non- linear load

b) Waveform of current from the non- linear load

c) Voltage waveform seen at the linear load

d) Voltage harmonic profile at the linear load

e) Waveform of current drawn by the linear load

f) linear load current harmonic profile

Figure 26 - Voltages and Currents Measured at the Linear and Nonlinear Load of Figure25 with Their Harmonic Profiles

## 4.2 Harmonic Effects on the neutral wire and transformers

### 4.2.1 Effects of 3rd harmonic current on the neutral in a 4wire system

The majority of equipments that make up the load in an office space or a computer room are computers, servers, printers, etc. Most of these equipments are single phase loads. The current drawn by such equipment (Figure 27) is rich with $3^{rd}$ harmonic as has been outlined in chapter 3. Third harmonic currents are particularly troublesome in three phase four wire distribution systems. Unlike the 60Hz currents, which cancel out in the neutral wire in a three phase system (assuming a balanced system), the $3^{rd}$ harmonic currents do not cancel out in the neutral, instead they add up (Figure 28). A 50% $3^{rd}$ harmonic current presence in each phase with respect to the fundamental would translate to 150% $3^{rd}$ harmonic current in the neutral. This becomes a very serious problem if the neutral is not properly sized to handle that much current especially since the neutral is generally not protected with any type of over current protection device.

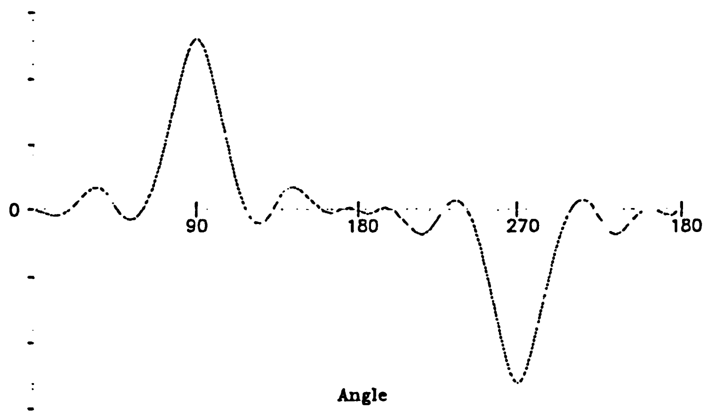



Figure 27- Typical Current Drawn by a Personal Computer

To further illustrate this effect with a real life example, consider an office building with 500 computer users, each with 300VA power consumption for his or her PC. The total connected load would be 300x500= 150KVA. At 208V/3phase the total demand load would be $\frac{150 \times 1000}{208\sqrt{3}}$ = 416Amps and each phase on the secondary of the transformer will be carrying that amount of current. If we assume the following harmonic levels: $3^{rd}$ harmonic (50%), $5^{th}$

harmonic (40%), 7th harmonic (30%), 9th harmonic (15%), which would be a good assumption for a typical PC power supply, then the harmonic currents per phase would be:

$I_3 = 416 \text{ x } 0.7 = 291$

$I_5 = 416 \text{ x } 0.6 = 249$

$I_7 = 416 \text{ x } 0.4 = 166$

$I_9 = 416 \text{ x } 0.2 = 83$

The total demand distortion is:

$$TDD = \frac{\sqrt{291^2 + 249^2 + 166^2 + 83^2}}{416} = 1.02 \text{ or } 102\%$$

If a transformer was provided to support this load but was not sized properly to accommodate the level of harmonics, then it will clearly be overloaded. The neutral wire would also be overloaded because of the 3rd and 9th harmonics

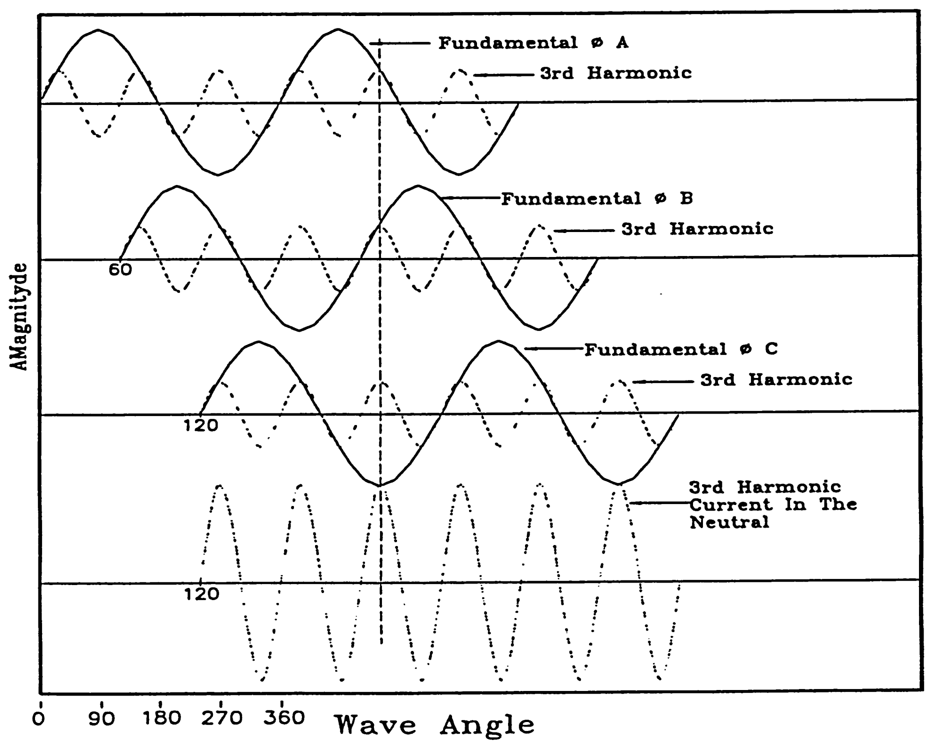



Figure 28- 3RD Harmonic Current in the Neutral in a 4wire System

4.2.1.1 Simulations With Matlab Simulink

Using Matlab Simulink, we built the circuit model shown in Figure 29 to simulate a three phase 4 wire distribution system feeding single phase linear loads. To simulate a single phase non linear load, we used the model created in chapter 3 for a SMPS and made it into a block. The measured currents on phase A, B, C, the neutral and their harmonic profiles are shown in Figure 30. The harmonic profile on the neutral clearly shows how the third harmonics in each of the phase were added at the neutral.

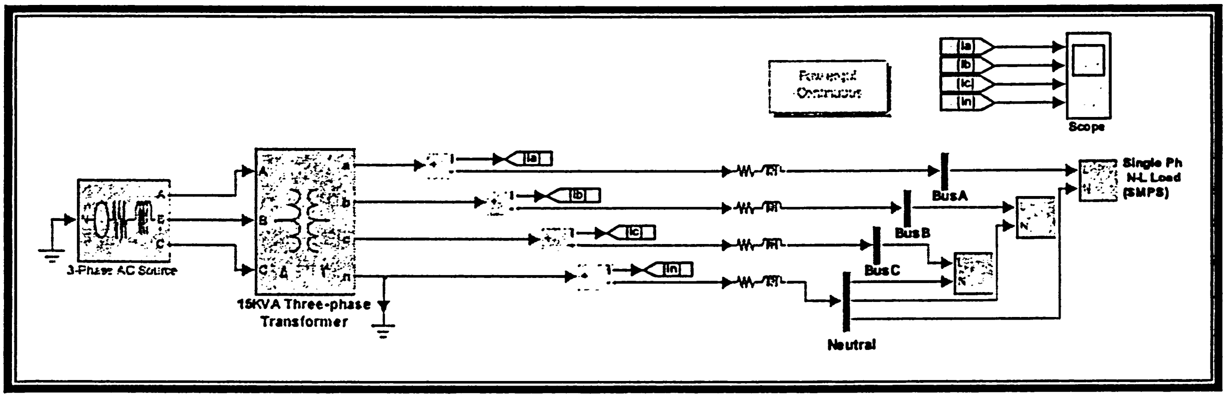
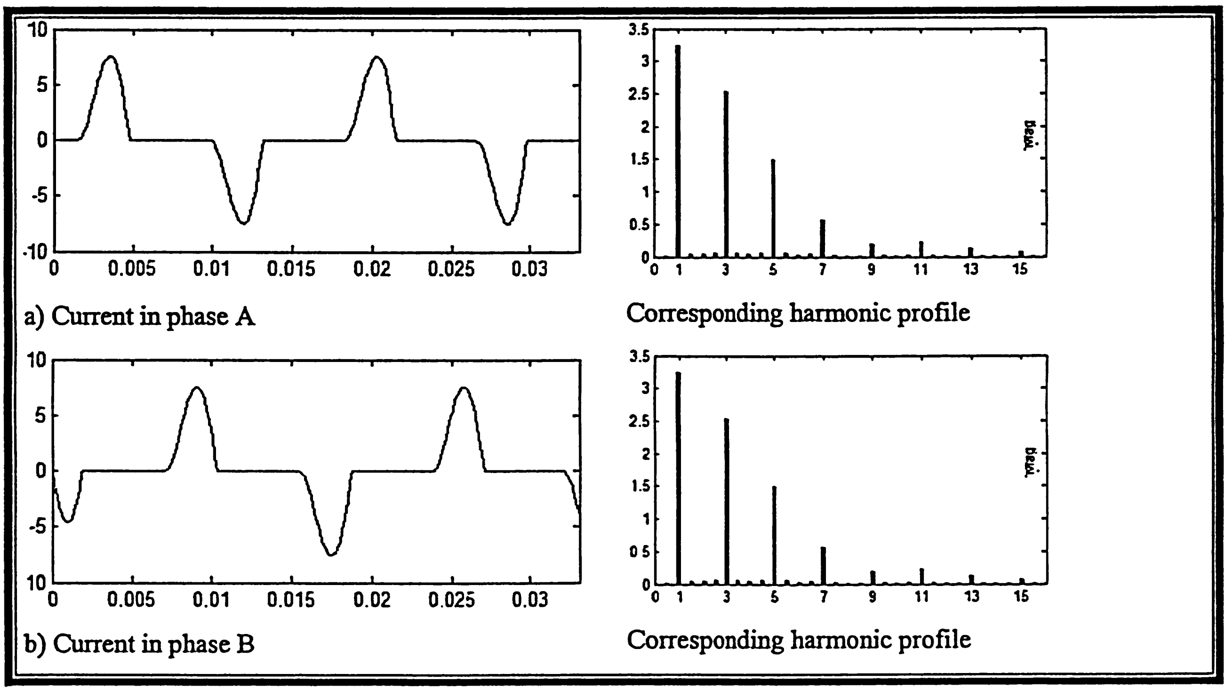



Figure 29- Matlab Simulink Model Depicting a Three Phase, 4wire Distribution System Feeding Single Phase Non-linear Loads.



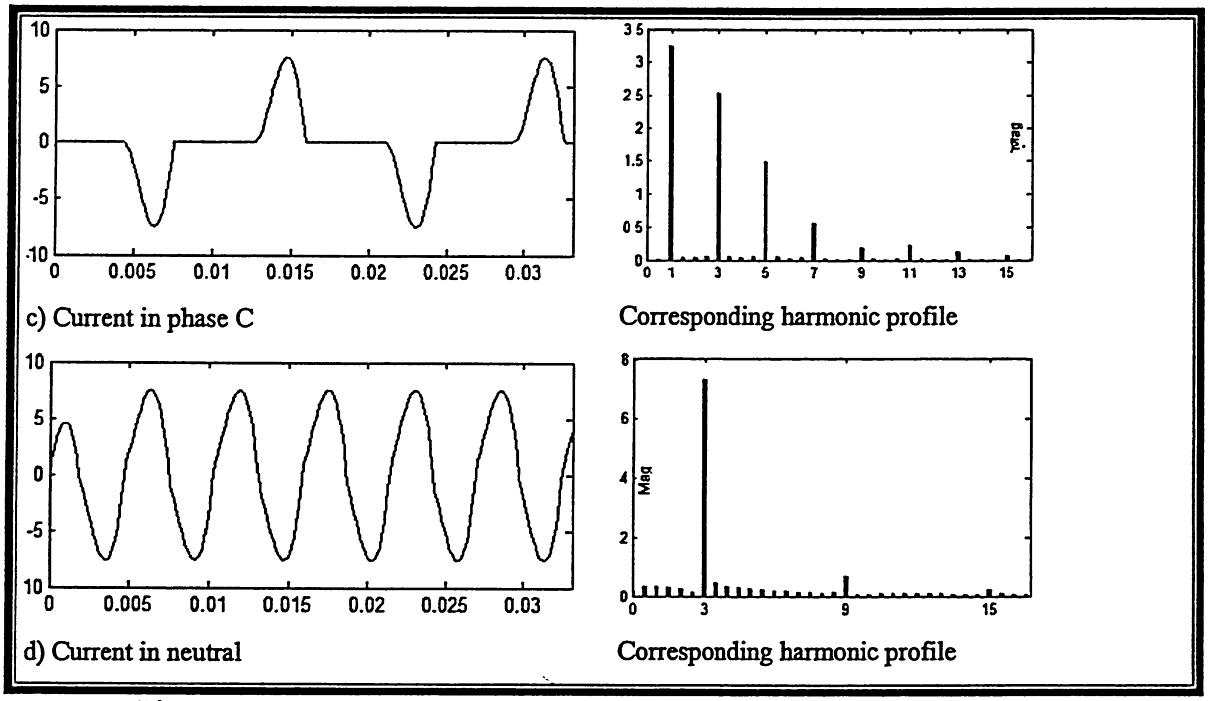



Figure 30- Waveforms of the Current Measured at the Phases and the Neutral of Figure29

### 4.2.2 Effects of Harmonic Current on a Delta/Wye Transformer

Delta/Wye step down transformers are widely used in commercial buildings to step the voltage down from 600V to 120/208V or 480V to 120/208V in the case of the United States. Harmonics can have damaging effects on a delta/wye transformer that is not properly de-rated or specially selected to cope with harmonics. Depending on the level of current harmonics present in the system, the transformer would experience an increase in the eddy current losses up to twice or three times the level if harmonics were not present. As with the neutral wire, the third harmonic current is especially troublesome in the transformer because it is a zero sequence current and therefore gets trapped in the primary windings, and as it circulates it causes the transformer to overheat (Figure 31). The increase of the operating temperature of the transformer will overtime reduce its operating life.

The increase in eddy current loss can be seen from the following equation:

$$P_{e,T} = P_{e1}\sum_{h=1}^{n} I_h^2 h^2 \text{ [9]}$$

Where;

$P_{e,T}$ is the total eddy current loss

$P_{e1}$ is the eddy current loss at the fundamental frequency

$h$ is the harmonic order

$I_h$ is the RMS current at harmonic h as a percentage of rated fundamental current.

In a similar way, the transformer stray losses are calculated as:

$$P_{s,T} = P_{s1} \sum_{h=1}^{n} I_h^2 h^{0.8} \text{ [9]}$$

Where;

$P_{s,T}$ is the total stray loss

$P_{s1}$ is the stray loss at the fundamental frequency

$h$ is the harmonic order

$I_h$ is the RMS current at harmonic h as a percentage of rated fundamental current

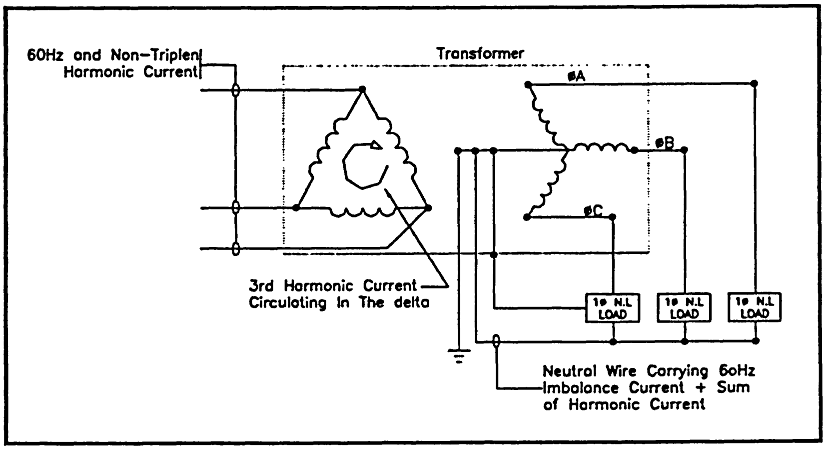



Figure 31- 3RD Harmonic Current in a Delta/Wye Transformer

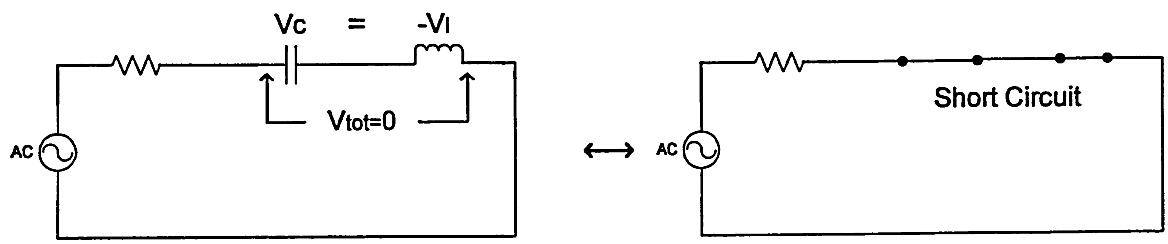
## 4.3 Resonance

A more serious problem with harmonics in power distribution systems is resonance. Resonance can occur because of capacitors used for power factor correction or due to capacitance from power distribution cables or both. Industrial buildings where induction motors make up most of the system load are known for the integration of power factor correction capacitors in their power distribution system to improve the power factor. These same businesses would tend to have a computer room or multiple computer rooms for their IT needs. These computer rooms are major sources for harmonics and as a result in building such as these, resonance is most likely to occur than in a regular office building.

Resonance in power distribution systems occurs when inductance reactance is equal to the capacitive reactance at a specific frequency. In power systems, this tends to occur for example when the capacitive reactance from the P.F correction capacitors is equal to the system inductance.

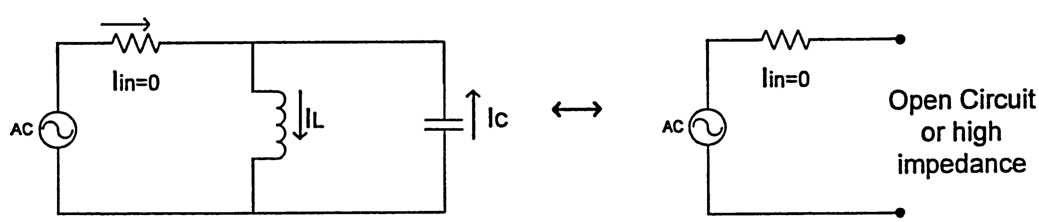
*Series resonance:*

At the resonance frequency, the voltage across C and L are equal in magnitude. Since these voltages are 180° out of phase with each other, they cancel out causing zero voltage across the LC combination. The circuit looks like a short during a series resonance.




*Parallel Resonance:*

Just as in the series resonance, the parallel resonance takes place when the inductance reactance $X_L$ is equal to the capacitive reactance at a specific frequency. This causes the branch currents $I_C$ and $I_L$ to be equal in magnitude. Since they are 180° out of phase with each other, they cancel out causing the circuit to look like a high impedance.




The frequency at which parallel or series resonance occur is $f_r = \frac{1}{2\pi\sqrt{LC}}$ derived from

$$X_L = X_C \rightarrow 2\pi f_r L = \frac{1}{2\pi f_r C} \rightarrow f_r = \frac{1}{2\pi\sqrt{LC}}$$

In a system rich of harmonics, there are many frequencies at which resonance could occur, and therefore the likelihood of resonance occurring increases dramatically. Harmonic current encountering high harmonic impedance in a parallel resonance situation will result in a very high voltage at that particular harmonic. Series resonance occurs in power distribution systems when capacitors are located near the end of feeder branches. The capacitor acts as a low impedance to a particular harmonic current, almost like a tuned filter. High capacitor current can flow for relatively small harmonic voltage causing nuisance blown fuses conditions and quick degradation of capacitors.

### 4.3.1 Power Factor Correction Capacitors and Harmonic Resonance

Capacitor banks are widely used in industrial power distribution system to supply reactive power to improve the system power factor. This is typically achieved by switching the capacitor with the motor load to compensate for the motor's low power factor.

In the past, these capacitor banks were indiscriminately applied in the power system without any serious adverse affects. However, in the last decade, with the increase use of variable frequency drives, switch mode power supplies and other non linear loads, engineers had to consider more seriously the effect of harmonics when integrating capacitor bank into the power system.

Resonance as discussed in previous section occurs at $f_r = \dfrac{1}{2\pi\sqrt{LC}} = \dfrac{\omega_0}{2\pi\sqrt{X_L / X_C}}$

In a power distribution system

$X_L$ can be replaced with $X_{lpu}$ which is the system per unit inductance reactance and $X_C$ with $X_{Cpu}$ which is the system per unit capacitance reactance. $X_{lpu}$ and $X_{Cpu}$ are defined as follow:

$$X_{lpu} = \frac{1}{SCMVA_{PU}} \text{ and } X_{cpu} = \frac{1}{CAPMVA_{PU}} \text{ [3]}$$

Where

$SCMVA_{PU}$ is the short circuit MVA rating

$CAPMVA_{PU}$ is the capacitor MVA rating

Rewriting $f_r$ in term of $SCMVA_{PU}$ and $CAPMVA_{PU}$ we have:

$$f_r = f_0\sqrt{\frac{SCMVA_{PU}}{CAPMVA_{PU}}} \text{ or } \frac{f_r}{f_0} = \sqrt{\frac{SCMVA_{PU}}{CAPMVA_{PU}}} = K$$

Where $K$ is the Harmonic order at which resonance will occur.

For example a power system with system impedance of 500MVA and a capacitor bank of 4MVA will cause parallel resonance at $K=\sqrt{\frac{500}{4}}$ =11.8 or the 11th harmonic.

#### 4.3.1.1 Simulations With Matlab Simulink

Using Matlab Simulink, we developed the following circuit models to further illustrate how resonance would occur when power factor correction are applied in a power system with harmonic presence.

The first circuit shown in Figure 32 shows a simplified single phase power system feeding a 4KVA load with a 0.61 power factor. The measured voltage and current supplied to the load are shown in Figure 33. We see how the current lags the voltage before power factor correction is applied.

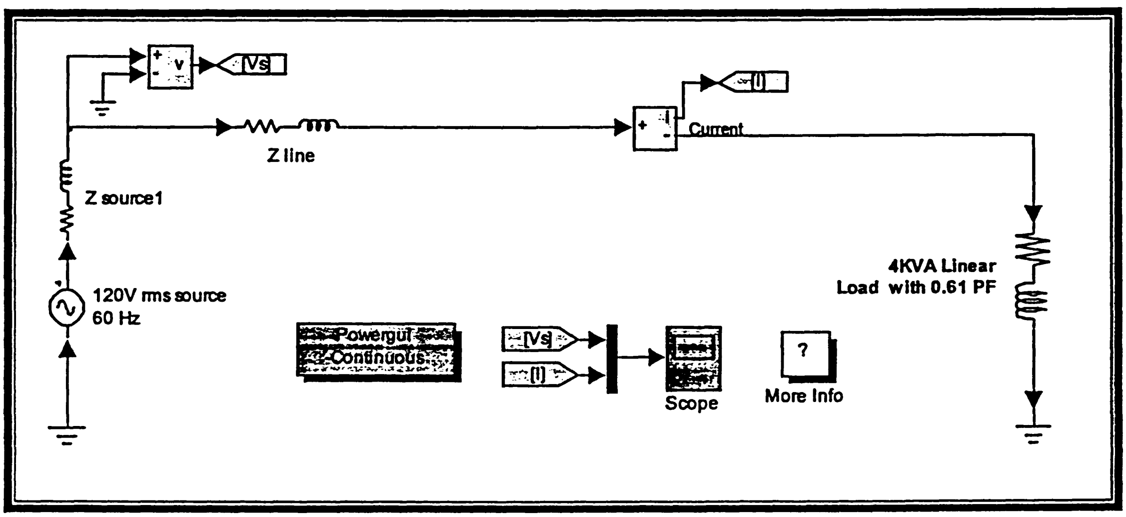



Figure 32- Matlab Simulink Model of a Simplified Single Phase Power System Feeding a 4KVA Load with a 0.61 Power Factor

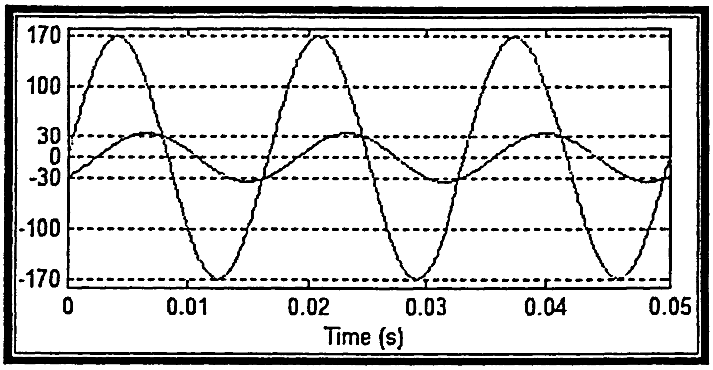



Figure 33- Supply Voltage and Current Measured in the Circuit of Figure 32 before P.F Correction *(voltage shown in red)*

The next circuit shown in Figure 34 is the same circuit of Figure 32 but with a power factor correction capacitor added. The waveforms of the voltage and current supplied to the load are shown in the Figure 35. We see how the current and voltage are now in phase. However, with the capacitor bank added to the system we see that resonance in this case would occur at a frequency of 300Hz as indicated in the impedance to frequency graph (Figure 36).

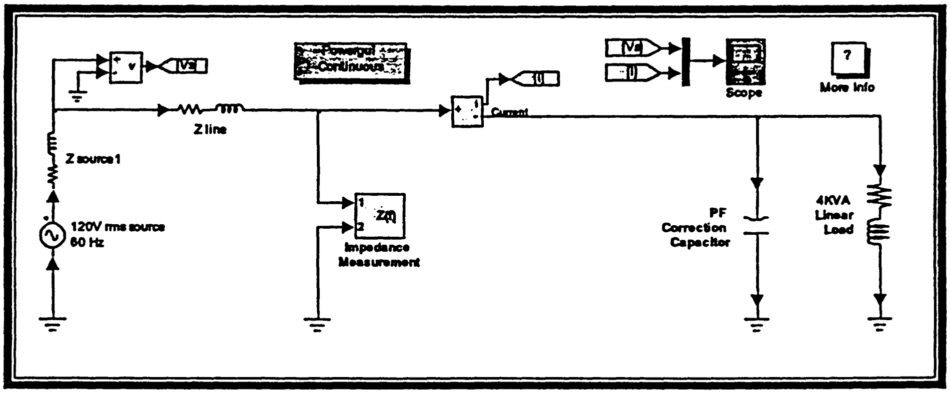



Figure 34- Circuit Model of Figure 32 with Power Factor Correction Capacitor Added

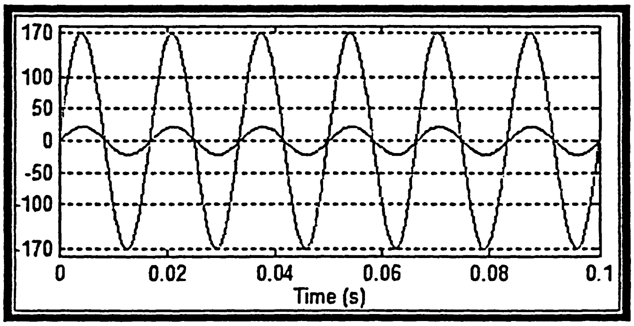



Figure 35 - Voltage and Current Measured at the Circuit of Figure 34 after P.F Correction Capacitor is applied

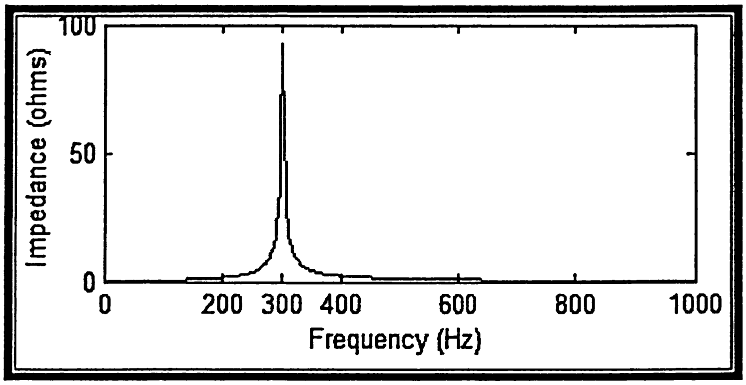



Figure 36- Impedance to Frequency Graph of the Circuit of Figure 34

Finally, to see the impact of a 5th harmonic presence in the system, we added a current source with a frequency of 300Hz to the circuit of Figure 34 to represent a 5th harmonic current as shown in Figure 37. The measured voltage and current supplied to the load are shown in Figure 38. We can clearly see that resonance has occurred because of the fifth harmonic current.

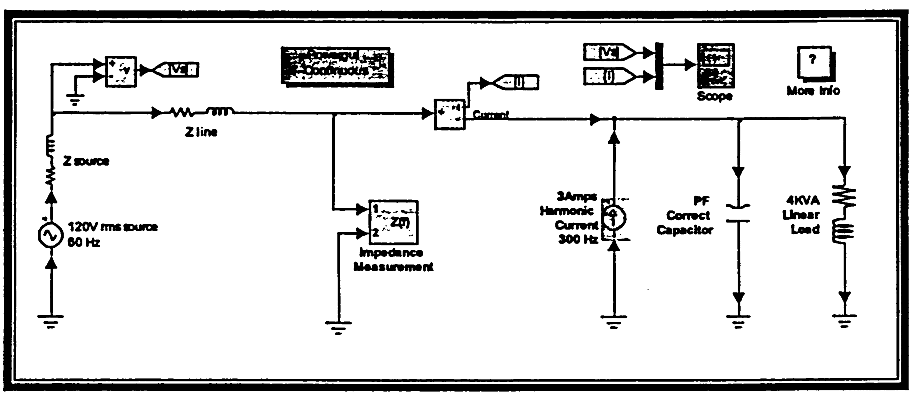



Figure 37- Circuit Model in Figure 34 with a Fifth Harmonic Current Added to the System

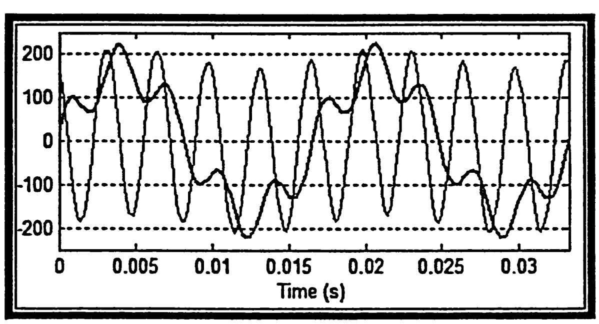



Figure 38- The Voltage and Current Measured at the Circuit of Figure 37 after the Fifth Harmonic Current is added

## 4.4 Effects of Harmonics on Induction Motors

Harmonics affect induction motors in two different ways. First they cause excessive heating losses in the same way as in the transformer; in the stator winding, rotor circuit, the stator and rotor iron losses and leakage fields. Second, they generate losses from harmonic generated fields.

In a balanced power system, harmonics manifest themselves in one of three types as shown in table 4.2: Positive, negative and zero sequence. The fundamental, 4th, 7th harmonic, etc. are referred to as the positive sequence harmonics. 2nd, 5th, 8th harmonic, etc. are referred to as the negative sequence. 3rd, 6th, 9th, etc. are referred to as the zero sequence. Negative sequence harmonics produce rotating field in the opposite direction as the 60Hz resulting in a negative torque. In a similar way, positive sequence harmonics produce rotating field in the same direction as the 60hz adding to the torque. Positive and negative sequences will result in torque pulsation or vibration which overtime could cause damage to the motor. High level of negative sequence harmonics mainly the 5th harmonic can lead to high current flowing in the stator. The increased current is generated in order to maintain rated torque and counter the negative torque caused by the 5th harmonic. This high current would tend to cause the overload protection for the motor to operate dropping the load.

| Harmonic Order | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sequence | + | - | 0 | + | - | 0 | + | - | 0 | + | - | 0 |

Table 4.2- Harmonic Orders and their Sequences

## 4.5 Effects of Harmonics on Power Distribution Protection Devices

The type of protection devices that do not measure true rms current, and which operation is governed by the voltage/current peak or zero voltage, are greatly affected by harmonics and may not operate properly in their presence. Harmonics in power distribution systems can often lead to nuisance tripping or no tripping when it is required. Ground fault relays and ground fault interrupting (GFI) circuit breakers which rely on the magnetic field summation between the phases and the neutral to detect a ground fault may operate unnecessarily due to 3rd harmonic adding up in the neutral.

In other situations where the protection device relies in its operation on sensing the average current and not measuring the true rms value, the current in the circuit may appear lower than what it actually is, and the protection device may not open when it is supposed to, allowing the circuit to remain overloaded resulting in a hazardous situation. To illustrate this, we need to look at two important ratios used in current measurement:

$$Crest\,factor = \frac{PeakValue}{RmsValue}$$

$$Form\,factor = \frac{RmsValue}{MeanValue}$$

For a pure sine wave (Figure 39)

The Crest Factor = 1.414

The Form factor = 1.111

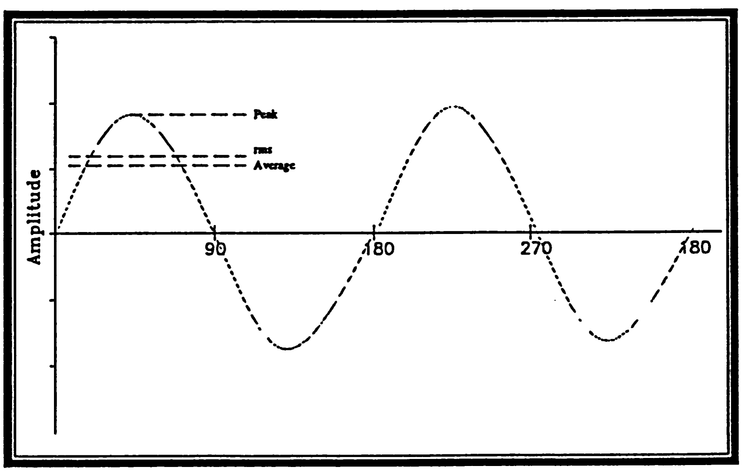



Figure 39- Linear Load Current Waveform

In a pure Sine wave as shown in Figure 39, it is OK to obtain the *RMS* by taking the mean value and multiply it by the form factor 1.111, where the mean value in this case is equal to

$2\times\left(\frac{Peak}{\pi}\int_0^{\pi}(\sin t)dt\right)$=0.636*Peak*, making the *RMS* value = (0.636*1.111)*Peak*

=*0.707Peak*. This turns out to be the same as using the crest factor to obtain the RMS value where the *RMS* is equal to $\frac{PeakValue}{CrestFactor}=\frac{PeakValue}{1.414}$=*0.707Peak*. A meter using this technique to get the RMS is known as mean reading RMS calibrated meter. This meter when used to measure the RMS in a nonlinear load sine wave similar to the one shown in Figure 40, will indicate a value much lower than the actual value. To get the true value the meter must take the square of the instantaneous value of the input, take the average over time then display the square root of the average. This method will provide a more accurate measurement of the current regardless of the shape of the waveform. For this reason, this meter is referred to as true RMS meter.

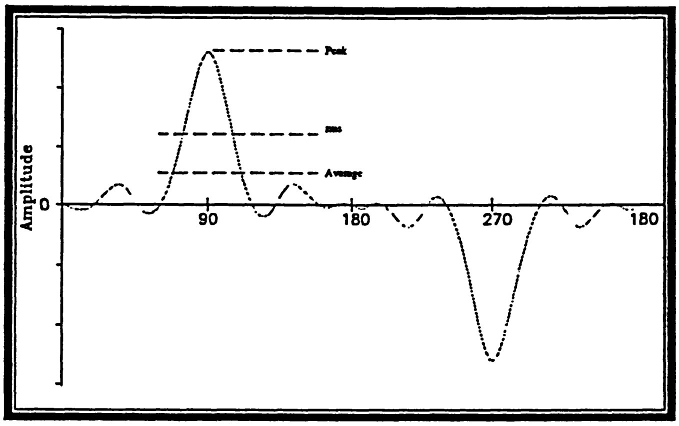



Figure 40- Non Linear Load Current Waveform

## 4.6 Back Up Generators in Harmonic Rich Power Distribution System

A back up generator system is a vital component in 24x7 facilities such as data centers, computer rooms, emergency health care facilities, emergency response facilities, some biotech industries and many other mission critical facilities. The need for back up generators has seen a sharp increase in the last decade which was triggered in most part by the need for a continuous more reliable power flow. Furthermore, the recent high demand for power has led to the utility grid becoming overloaded and operating at near capacity during certain periods of the year resulting in power outages occurring more frequently.

There is a popular sentiment nowadays among most 24x7 facility managements that they can not rely on the power utilities to guarantee continuous power flow with minimum interruptions. The consensus is that power outages will become more frequent and will be lasting longer in the years to come.

Back up generators in an environment rich with harmonic generating equipment- which is the case in most of 24x7 facilities- may introduce new problems. These problems are further amplified when an uninterruptible power system (UPS) is introduced in the system to ride through a power outage until the generator starts and ready to pick up the load as shown in Figure 41.

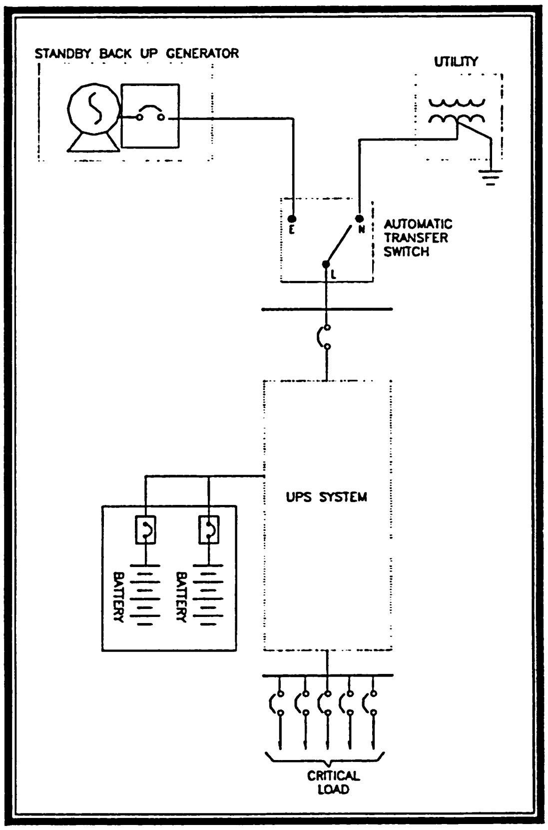



Figure 41- Partial Single Line Diagram of a Distribution System with UPS and Back up Generator System

Unlike the utility, the generator is a high impedance source (between 10 to 15% versus 3 to 6% for a transformer). Since the level of distortion is a direct result of harmonic current interacting with the source impedance, it becomes very clear that a high level presence of harmonics in a power distribution system will cause three or more times higher voltage distortion on a generator back up system than it would on utility transformer. Furthermore, the distortion increases the rms value of the output voltage resulting in the disturbance of the generator regulation which is based on the rms value of the sinusoidal voltage.

In a system similar to the one shown in Figure 41 which has a UPS and a back up generator system in the same power system, voltage drop due to current harmonics on generator's output impedance may introduce 15-20% THD voltage distortions on generator's output terminals, decrease the rectified DC voltage and increase converter's output distortions [10]. Moreover, harmonic currents at the input of the UPS rectifier decrease the power factor seen by the generator resulting in an increase in the generator's losses and limiting its ability to supply full power.

What has been occurring in many of these 24x7 facilities- where the power system includes a generator and a UPS system- is that when a power outage takes place and the stand by generator is called upon to supply power to the load through the UPS, the distorted voltage from the output of the generator, which is caused by harmonics reflected from the UPS and other non linear loads, is seen by the UPS as unacceptable voltage. This causes the UPS to switch to its batteries thereby isolating the UPS rectifier and the load from the generator. As soon as this happens, the voltage and frequency on the generator becomes stable again (because it is isolated from the load). The UPS switches back again to the generator, but as soon as it does so, the same thing happens all over again in the same sequence and continue to happen until the batteries are depleted and the UPS shuts off. This problem is common especially when the UPS system technology used is one of these two types:

*Type A -. Offline UPS*: As shown in Figure 42 [11], the critical load is fed directly from the utility. Only when the utility fails or experiences fluctuations that the inverter is used to convert the DC power from the battery to AC power to support the load, otherwise the inverter remains on a standby mode.

*Type B -. Line interactive UPS:* As shown in Figure 43 [11], this type of UPS system uses similar topology as the offline type, except that a transformer or an inductor is installed in series between the power source and the load. The transformer/inductor, through "buck and boost circuitry allows the inverter to provide limited power conditioning to the load. As the input voltage changes from the incoming power source, the tap-changing transformer can modify the output voltage to the desired level. The tap transformer compensates for power surges and sags of 20% to 30% of normal incoming voltage level without requiring the use of the batteries to regulate voltage providing significant reduction in battery use [12].

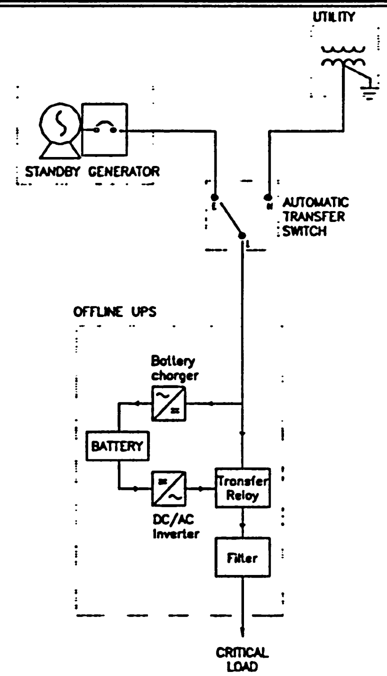



Figure 42. Typical Block Diagram for an Offline Type UPS Operating in a Power Distribution System with a Standby Generator

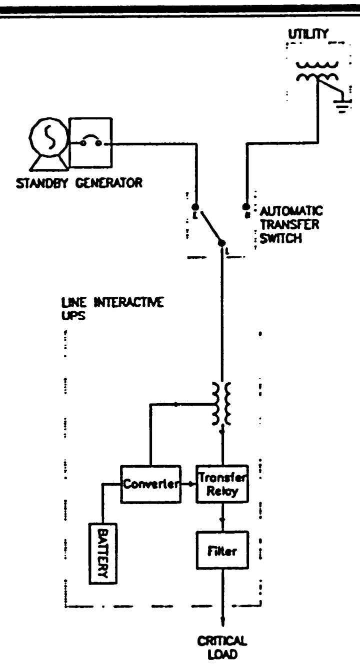



Figure 43. Typical Block Diagram for a Line Interactive Type UPS Operating in a Power Distribution System with a Standby Generator

The latest UPS system which uses double conversion technology, where the input AC voltage is converted to DC then from DC back to AC, provides a limited solution to the problem because the output inverter takes the DC power and produces regulated AC power to support the load unaffected by variations in the input side. If the input voltage and frequency fluctuates, the UPS would not care since the rectifier is only making DC power to feed the DC bus.

However in a UPS system with a bypass (Figure 44) and where the UPS must synchronize to the bypass at all time to allow for uninterruptible transfer to the bypass for maintenance on the UPS or during momentary overloads, in that situation, variations in the input voltage and frequency will cause the UPS not to be able synchronize to the bypass and as a result any manual or automatic transfer to the system bypass will be prohibited in order to protect the

UPS and the critical load from an out of phase transfer. The UPS then goes into what is called a free run.

Not being able to synchronize to the system bypass puts the UPS system at risk during a momentary over voltage or short circuit event.

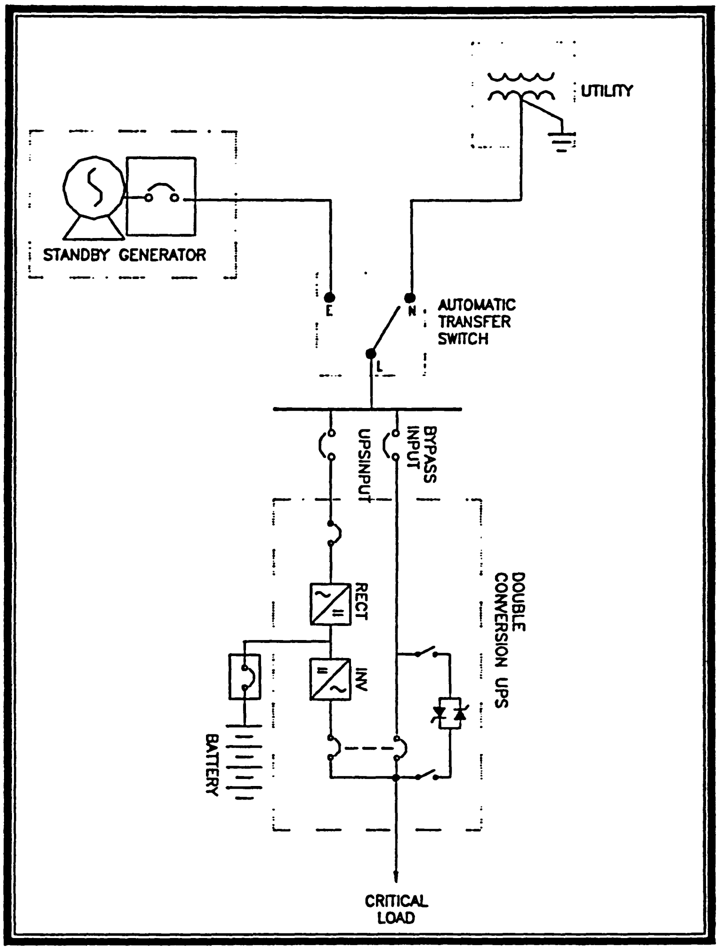



Figure 44- Typical Block Diagram for a Double Conversion Type UPS with Bypass Operating in a Power Distribution System with a Standby Generator

To deal with this issue of UPS operating with the generator, consultant engineers have been specifying oversized generator to compensate for high harmonics levels and low power factor. The ratio that is commonly used is a 2 to 1 ratio meaning that if the UPS is 100KVA, the generator will be sized at 200KVA.

# CHAPTER 5

# 5. SOLUTIONS TO HARMONICS IN POWER DISTRIBUTION SYSTEMS

The production of harmonic currents by non linear devices is essential to their normal operation. Therefore nothing can be done to stop them form being generated. However, there are many ways by which these harmonic currents can be prevented from entering the rest of the power system. This is achieved by controlling their flow within defined and smaller circuit loops. There is no single best solution available. Instead different solutions are available that have different effectiveness depending on the type of non linear loads present in the power system, the level of harmonic distortion and which harmonic orders are the dominants.

This chapter provides an analysis of some the different measures commonly used to control and mitigate harmonics with some insight on their effectiveness and drawbacks.

## 5.1 Basic Solutions Using Simple Design Practices in Power Distribution Systems.

There are some simple design guide lines that can be followed during the design process of a single line diagram of a new power distribution system. These design guidelines if adopted will reduce the effect of harmonics on the power distribution system without incurring the high cost usually associated with the implementation of special harmonic mitigating equipment.

One solution is to separate the linear loads from the non linear loads, and feed each from a separate Bus (Figure 45). The non linear loads should be installed downstream the linear loads and as far as possible from the source to reduce the voltage distortion at the source, while the linear loads should be installed as close to the source as possible.

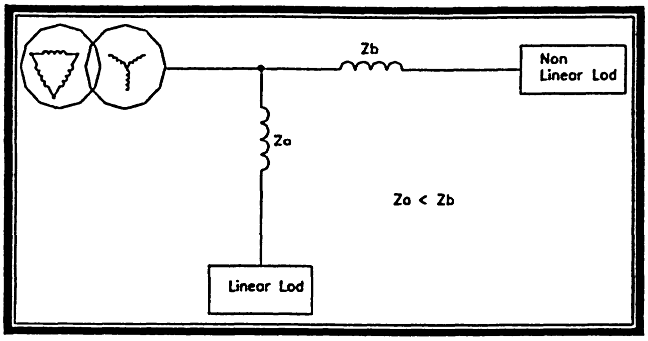



Figure 45- Non-linear Loads Installed upstream Linear Load and Close to the Source

Further improvements can be achieved by the installation of isolation transformers upstream the linear and nonlinear load (Figure 46). This will create a new separately derived system with a new ground reference. It would also result in the automatic elimination of certain low order harmonics.

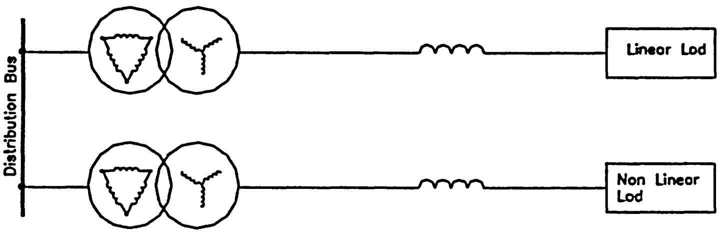



Figure 46 - Supplying Nonlinear loads and Linear Loads Through Separate Transformer

### 5.1.1 Simulations with Matlab Simulink

Using Matlab Simulink, we developed the following circuit models to show how some simple design practices in a power distribution system could reduce the impact of harmonics.
The first circuit model shown in Figure 47, shows a simplified distribution system where both the linear and non linear load are fed from the same panel downstream of the supply transformer. The current and voltage measured at the transformer output, at the linear and non linear load, and their harmonic profiles are shown in Figure 48. We see that the same voltage distortion seen at the nonlinear load is seen at the linear load causing harmonic current to flow in the linear load as well.

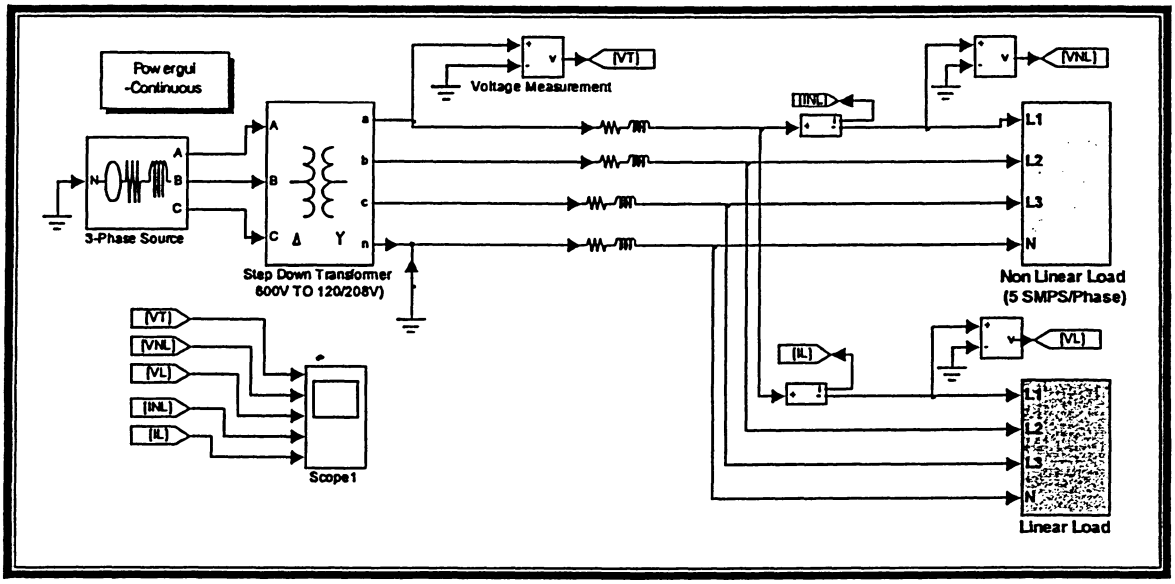
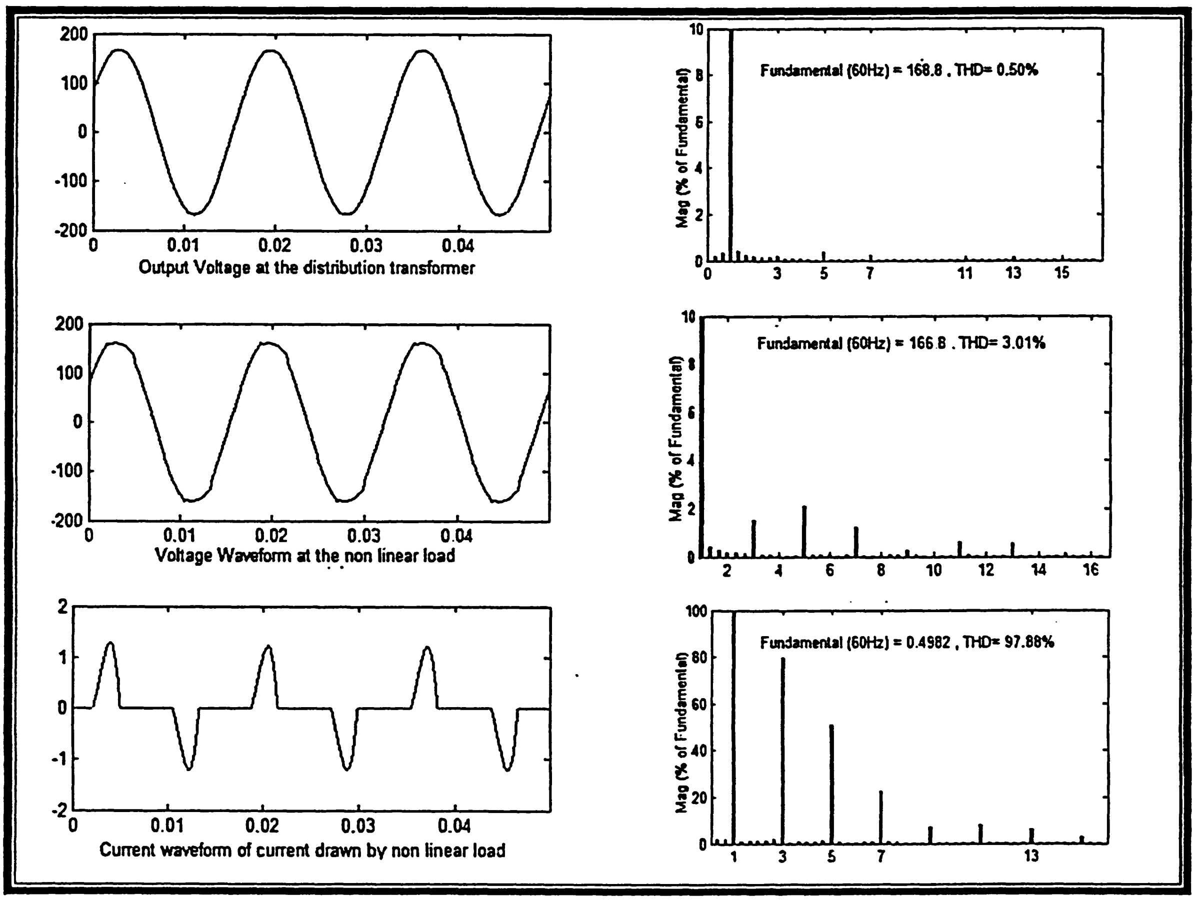



Figure 47- Matlab Simulink Model of a Simplified Distribution System where the Linear Loads and Non Linear Loads are Fed From the Same Point Downstream the Supply Transformer



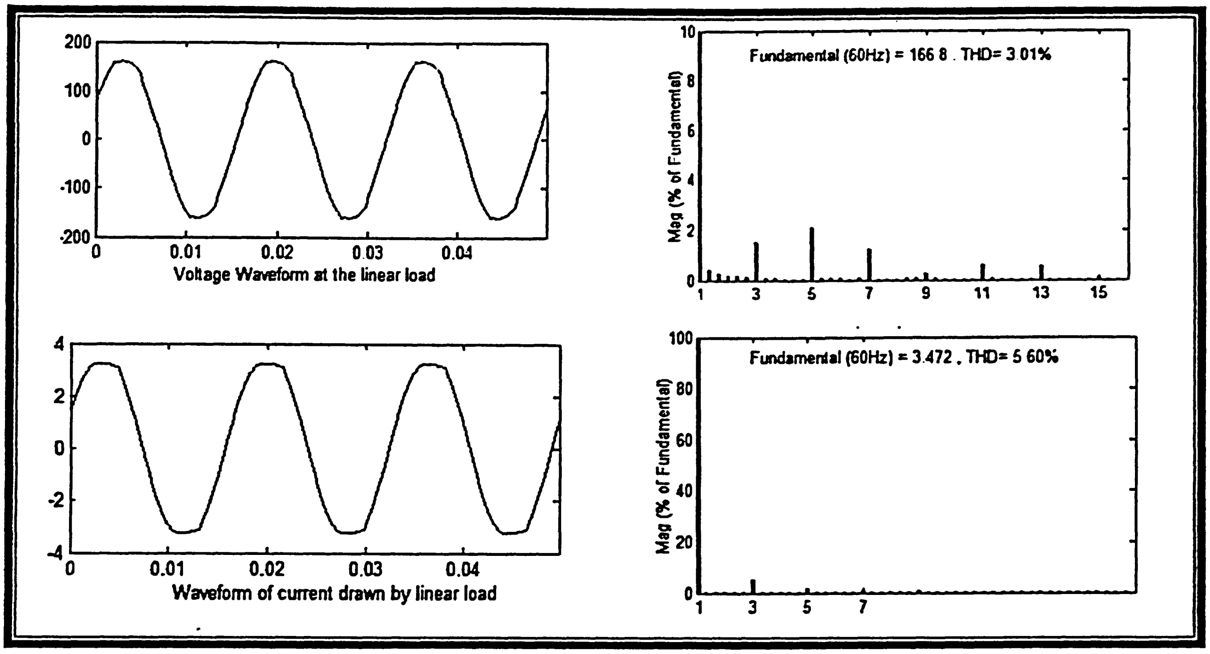



Figure 48- Waveforms of the Voltages and Currents Measured at the Circuit of Figure 47.

The next circuit shown in Figure 49 shows the same circuit of Figure 47 but with the linear load moved upstream of the non linear load and close to the supply transformer. The current and voltage measured at the transformer output and at the linear and non linear load with their harmonic profiles are shown in Figure 50. We see that the voltage distortion at the non linear load has dropped from 3% to less than 0.5%. This is a good improvement that did not require adding any costly equipment to the power distribution system.

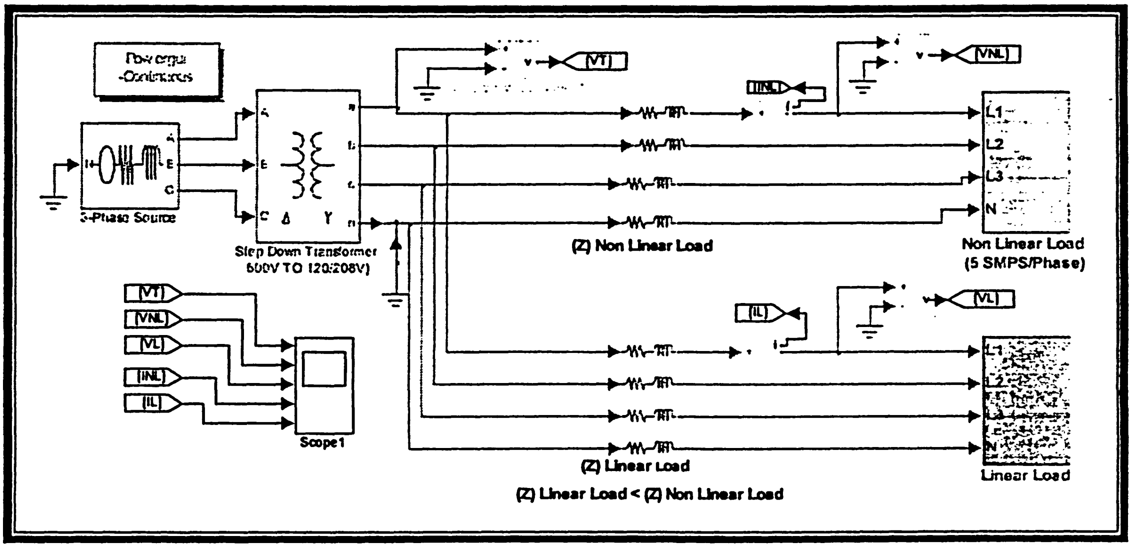



Figure 49- Same Circuit Model as in Figure 47 But with the Linear Load Moved Upstream the Non Linear Load.

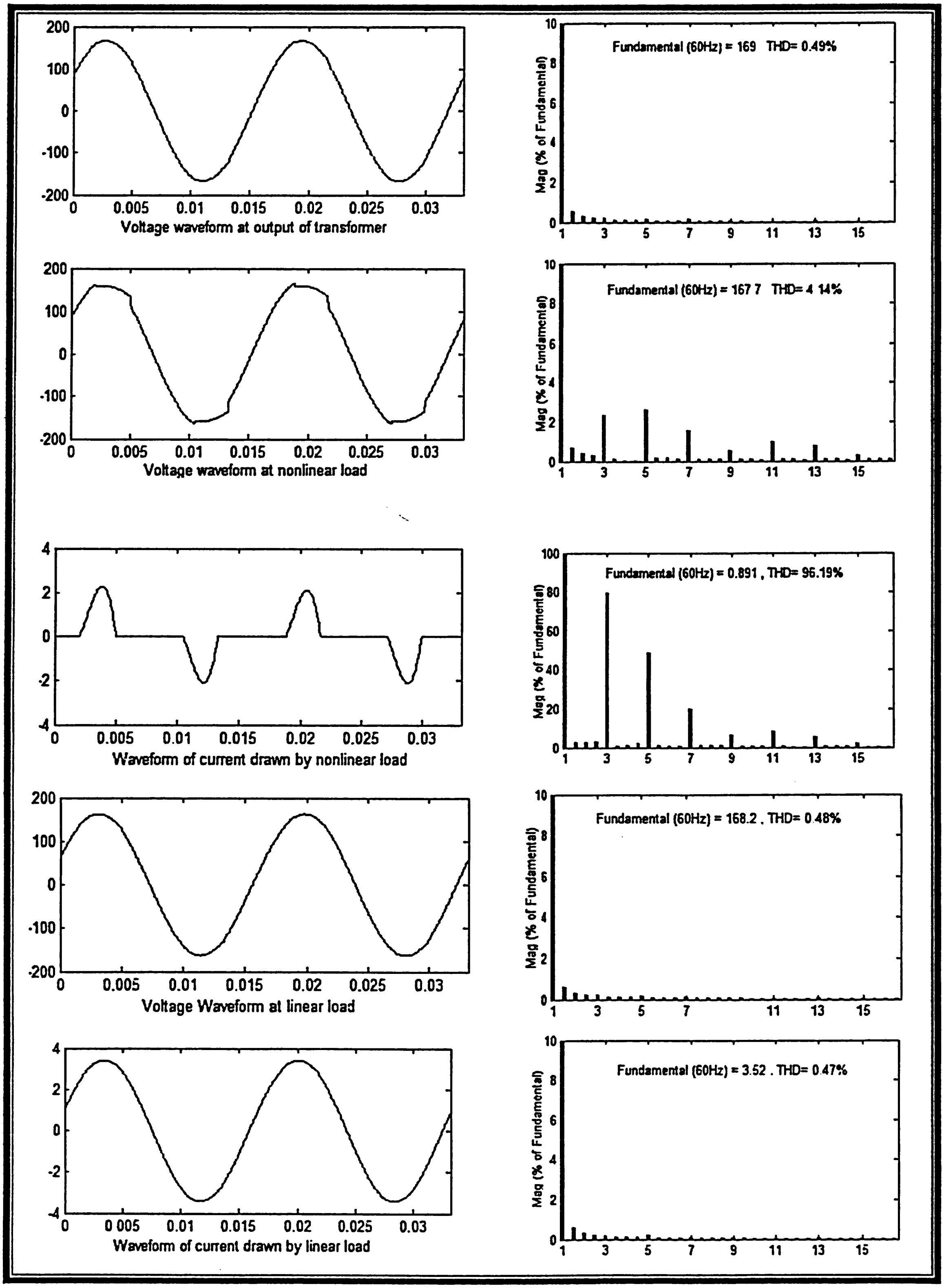



Figure 50 - Waveforms of the Voltages and Currents Measured at the Circuit of Figure 49

## 5.2 K-rated Transformers and Double Sizing the Neutral

One of the simplest methods to cope with harmonics, which is very popular among power distribution engineers, is the use of delta-wye connected transformers. This is because zero sequence triplen harmonics gets trapped in the delta primary of a delta-wye transformer.

In the following simulink circuit model (Figure 51), we added a delta/wye isolation transformer between the non linear load (multiple single phase SMPSs) and the power source to show the transformer's effect on current distortion. After running the simulation, we obtained the waveforms in Figure 52. The first waveform is the load current measured at the secondary of the transformer. This is a typical current waveform of a SMPS which has high level of third harmonic current as indicated in the harmonic profile. The second waveform is the load current measured at the primary of the transformer. The harmonic profile of this current shows the elimination of the third harmonic current as expected because of the delta winding in the transformer primary.

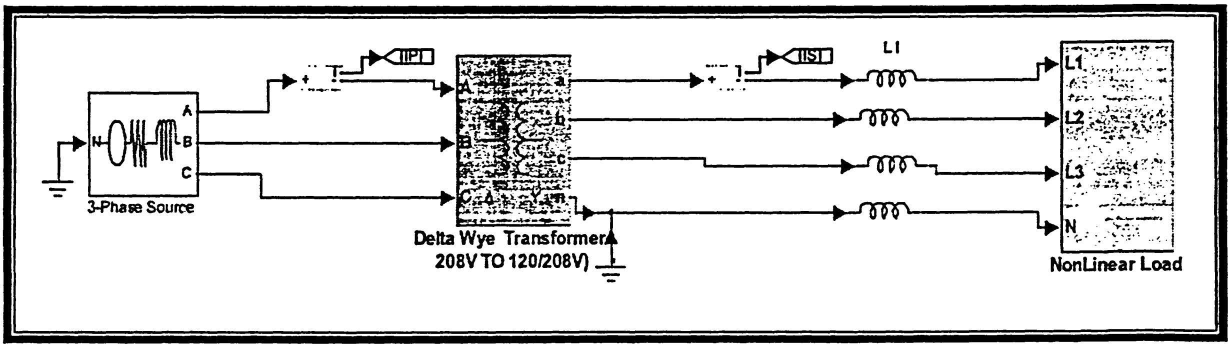
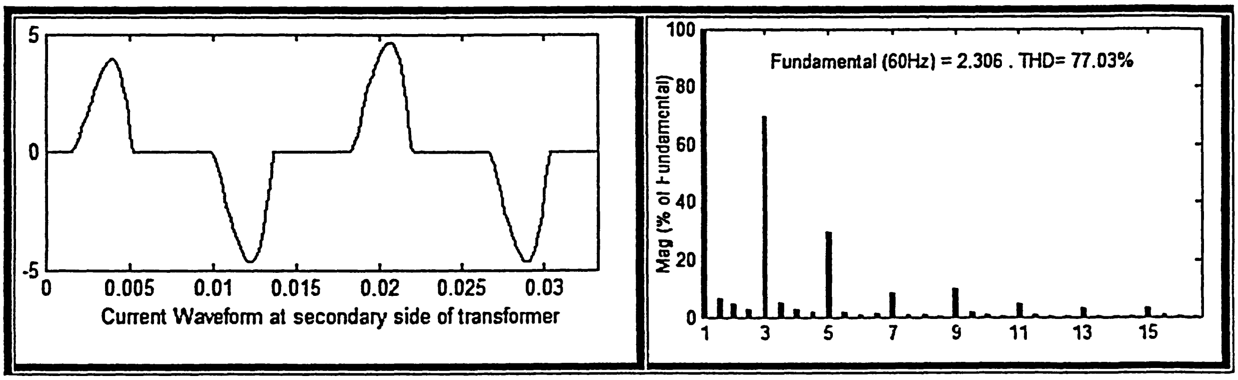



Figure 51- Matlab Simulink Model of a Simplified Distribution System Showing a Delta/Wye Transformer between the Non Linear Load and the Power Source



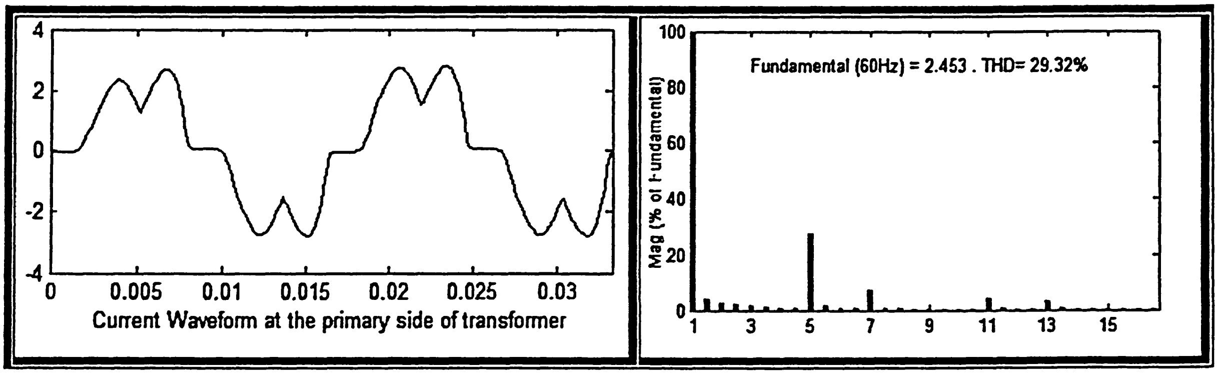



Figure 52- Waveform of the Current Measured at the Primary and Secondary of the Transformer in the Circuit of Figure 51 and their Harmonic Profiles.

However, as discussed in chapter 4, harmonic currents flowing in transformers will result in excessive losses due to eddy current. These losses will cause the transformer to overheat and possibly fail. To cope with the issue of overheating and prevent the transformer from failing when operating under heavy non linear loads, the electrical industry introduced a special type transformers specifically designed with extra steel in their cores and copper in their windings to absorb and tolerate the additional excess heating from harmonic currents. These special type transformers are known as K-factor rated transformers.

K factor rated transformers have the following features [13]:

- They have Reduced core flux to compensate for harmonic voltage distortion
- They employ an electromagnetic shield between the primary and secondary winding of each coil, thus protecting sensitive equipment from some types of common-mode electrical noise and transients generated on the line side of the transformer.
- They provide a neutral twice the size of a phase conductors, to account for increased currents due to the flow of triplen harmonics.
- Windings are designed with several smaller sizes parallel conductors, therefore reducing skin effect at higher frequency harmonics.
- They use insulated and transposed conductors resulting in reduced losses.

The K factor which was devised by the underwriters Laboratories in the U.S calculates the factor increase in the eddy current loss in terms of the existing harmonic current amplitudes and is defined as [14]:

$$K = \sum_{h=2}^{h=\max} h^2 I_h^2$$

Where:

$h$ = harmonic order

$I_h$ = the fraction of total rms load current at harmonic number h

The K factor is an indication of how much higher is the eddy current losses in the transformer from the value at the fundamental frequency with no harmonic currents.

The following table provides and example for calculating the K factor [14].

| **Harmonic Order** | $\frac{I_k}{I_1}$ | $\left(\frac{I_k}{I_1}\right)^2$ | $\frac{I_k}{I}$ | $\left(\frac{I_k}{I}\right)^2$ | $\left(\frac{I_k}{I}\right)^2 \times h^2$ |
|---|---|---|---|---|---|
| 1 | 1 | 1 | 0.9192 | 0.8450 | 0.8450 |
| 3 | 0.34 | 0.1156 | 0.3125 | 0.0977 | 0.8791 |
| 5 | 0.180 | 0.0324 | 0.1655 | 0.0274 | 0.6844 |
| 7 | 0.125 | 0.0156 | 0.1149 | 0.0132 | 0.6469 |
| 11 | 0.081 | 0.0066 | 0.0745 | 0.0055 | 0.6708 |
| 13 | 0.075 | 0.0056 | 0.0689 | 0.0048 | 0.8033 |
| 17 | 0.052 | 0.0027 | 0.0478 | 0.0023 | 0.6603 |
| 19 | 0.046 | 0.0021 | 0.0423 | 0.0018 | 0.6455 |
| 23 | 0.039 | 0.0015 | 0.0359 | 0.0013 | 0.6799 |
| 25 | 0.036 | 0.0013 | 0.0331 | 0.0011 | 0.6844 |
| | Sum = | 1.1834 | | | **7.1997** |
| | ***Total (rms) I=*** | **1.0879** | | | |
| | | | | **K-factor =** | **7.1997** |

## 5.2.1 Limitations with K-rated Transformers

K rated transformers, to a certain degree, provide a solution to the problem of harmonics by safely dissipating damaging harmonic currents as heat and by being able to operate in a harmonic rich environment without sustaining damages over extended periods of time.

However, this solution only accommodates the problem since harmonic currents remain present in the system causing voltage distortion problems, poor power factor, energy losses and system malfunctions. Voltage distortion may get even worse as some users will tend to feel more comfortable about applying more non linear loads to a K rated transformer without considering the effect on the rest of the power system. Furthermore, one of the characteristic of a K rated transformer that is rarely taken into consideration, when it replaces a similar size standard transformer, is its lower impedance compared to a standard transformer. As a result, when a standard transformer is replaced with a Krated transformer, the available fault current will increase. Therefore, care must be taken to insure that the fault current interrupting rating of the panel and over-current devices downstream the K-rated transformer is not exceeded.

### 5.2.2 Limitations with Double Sizing the Neutral

Double sizing the neutral will address the safety concern resulting from overloading an unprotected wire, but as with the K rated transformer, this is also an accommodating solution. Harmonics will remain present in the system causing problems.

## 5.3 Solution to Resonance Through Detuning

Power factor correction capacitors can have adverse affects on power systems rich with harmonics. This was discussed in detail in chapter 4, section 4.3. The reactance of the capacitance decreases with the increase of frequency ($X_C = \frac{1}{2\pi fC}$). This characteristic can causes the rating of the capacitor to be exceeded if higher frequencies harmonics exist in the system. It also increases the likelihood of resonance occurring at one of these harmonic frequencies. To correct this situation, the power factor correction capacitors are de-tuned. Detuning is achieved by connecting a reactor in series with the PFC capacitor bank. This combination capacitor/inductor behaves as a capacitor at the fundamental frequency with controlled behavior for harmonic frequencies.

The reactive power rating of the detuning reactor is usually 5%, 7% or 11% of the reactive power of the compensation capacitor [15]. This is referred to as the "detuning factor". If for example a 5% de-tuning factor is applied to a PFC capacitor bank, it will result in a $\frac{5}{100}$ %

voltage drops across $L$ and $\frac{105}{100}$% drop across $C$, subtracting to 100% overall. As the frequency increases, the voltage drop across $L$ increases while the voltage drop across $C$ drops and at a specific frequency they will become equal resulting in a resonance state. As the frequency continue to increase the voltage drop across $L$ continue to increases while the voltage drop across $C$ continue to drop and at $f_n = \frac{100}{5} f_1 = 20 \times 60 = 1200Hz$ the starting ratio would be reversed. The resonant frequency therefore lies in the middle between 60Hz and 1200Hz. This frequency can be found as $f_r = \sqrt{\frac{100}{5}} f_1 = 268Hz$ [15]. For a 7% detuning factor, the resulting resonance frequency is $f_r = \sqrt{\frac{100}{7}} f_1 = 226Hz$. We notice that both of these frequencies are not typical harmonic frequencies in power systems. Therefore the de-tuning factor would allow the PFC capacitor to provide for the desired compensation without being affected by the system harmonics.

There are cases when de-tuning can be designed in such a way to provide filtering while at the same time allowing for compensation. For example an 11% de-tuning factor applied to a PFC capacitor will result in resonance at the frequency:

$$f_r = \sqrt{\frac{100}{11}} f_1 = 3 \times 60 = 120Hz.$$

In this situation the de-tuned PFC capacitor becomes a passive filter for the 3$^{rd}$ harmonic.

### 5.3.1 Simulations With Matlab Simulink

In the following Simulink circuit model (Figure 53), we used the same circuit of Figure 34 in chapter 4 which resonated with the 5$^{th}$ harmonic current, and we added a 5% detuning reactor to the power factor correction capacitor. The resulting waveforms of the supply voltage and current are shown in Figure 54. We see that adding the detuning reactor did not have a negative effect on the power factor correction of the capacitor. However, looking at the impedance versus frequency graph shown in Figure 55, we see that resonance would now occur at the 267Hz frequency which is not a typical harmonic frequency.

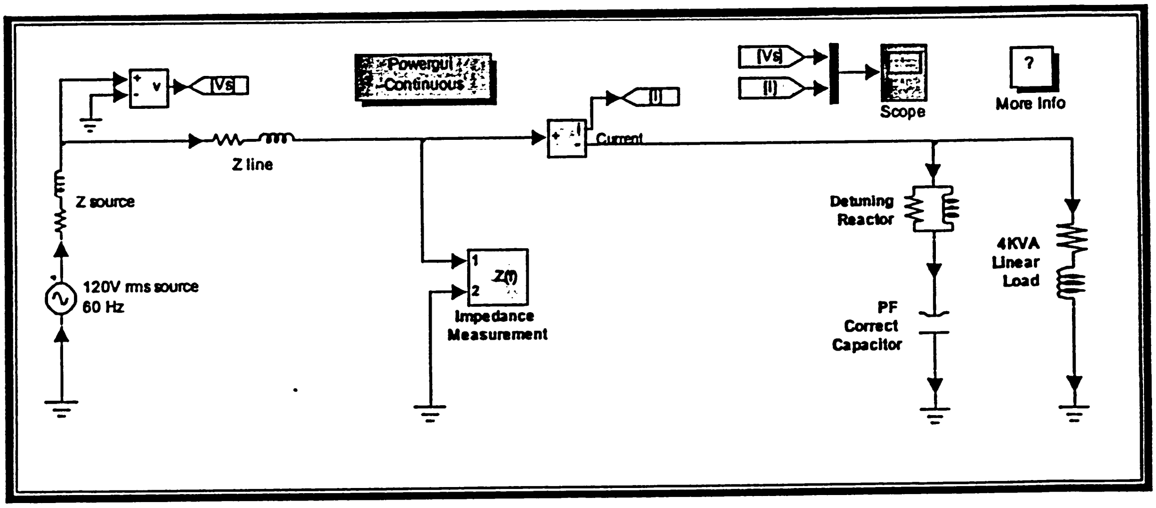



Figure 53- The Same Circuit of Figure 34 but with a Detuning Reactor added to the Power Factor Correction Capacitor

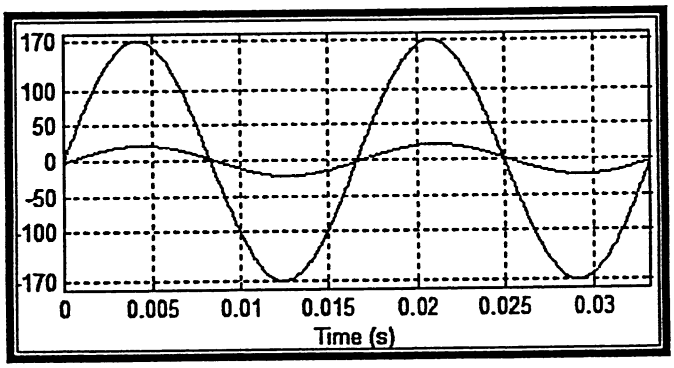



Figure 54- The Supply Voltage and Current in the Circuit of Figure53- with the Detuning Reactor

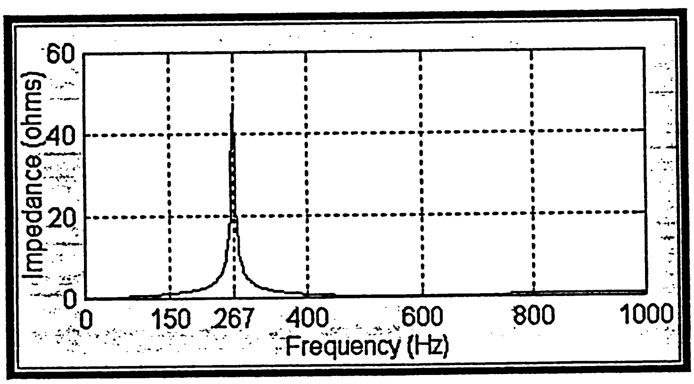



Figure 55 - Impedance to Frequency the Graph of Circuit in Figure53

To put the circuit to test, we added a current source with a frequency of 300Hz as shown in Figure56 to represent a 5[th] current harmonic. The measured voltage and current supplied to the load are shown in Figure57. For comparison, we show the measured voltage and current supplied to the load before the detuning reactor was added (Figure58).

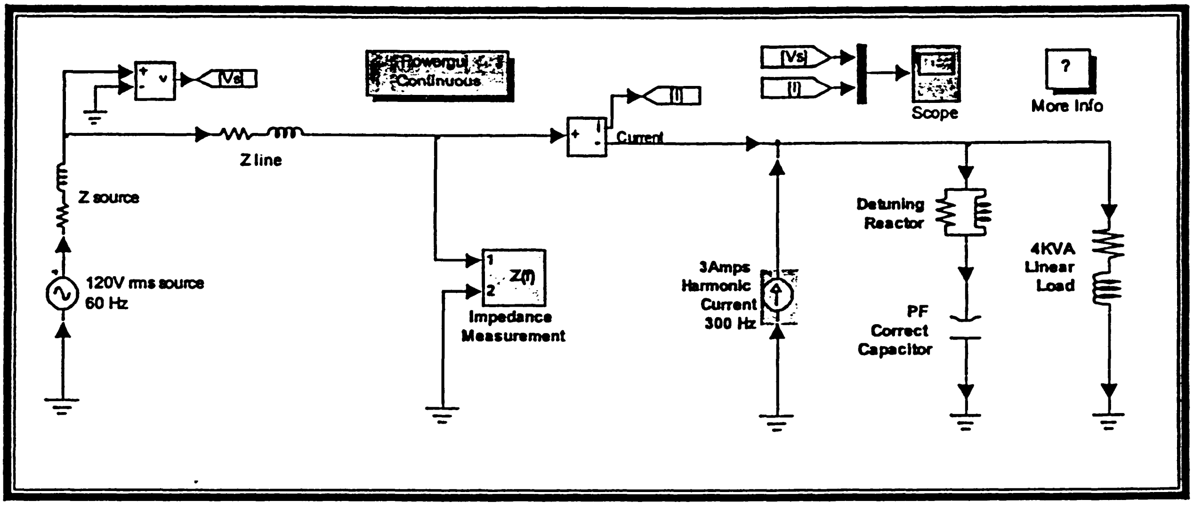



Figure56. Circuit Model of Figure 55 with a Fifth Harmonic Current Added to the System

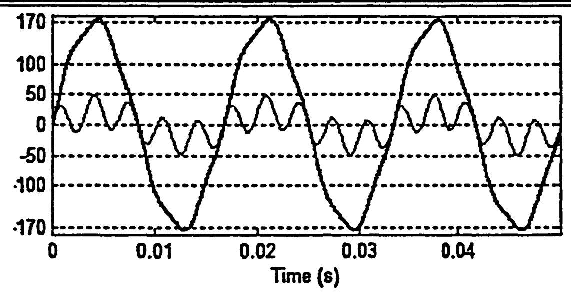



Figure 57- Supply Voltage and Current in the Circuit of Figure 56 with Detuning Factor.

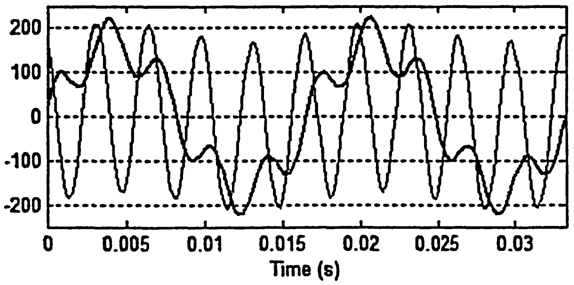



Figure 58- Supply Voltage and Current Without Detuning Factor.

## 5.4 The Insulated Gate Bipolar Transistor IGBT

The introduction of the insulated bipolar transistor (IGBT) has been one of the greatest innovations in high power switching devices. IGBTs have been replacing silicon controlled rectifier (SCR), which until recently were the switching devices used in most large KVA UPS systems and motor drives. An IGBT combines the power gain of the silicon control rectifier (SCR) with the switching characteristic of the solid state transistor [16]. But what made IGBTs very popular is their ability to eliminate harmonic problems that are associated with SCRs.

The IGBT has a very low resistance between the collector and the emitter. Figure 59 shows the structure of an IGBT [16]. The IGBT is constructed by joining two bipolar transistors. This configuration makes the channel current flowing to the substrate the same current flowing to the base of bipolar transistor. The combined bipolar transistors with the MOSFET allow the IGBT to control up to 1500volt and 100 ampere giving the IGBT high power gain [16]. IGBTs are now being used in both the rectifier and the inverter in UPS systems and motor drives (Figure 60) [16].

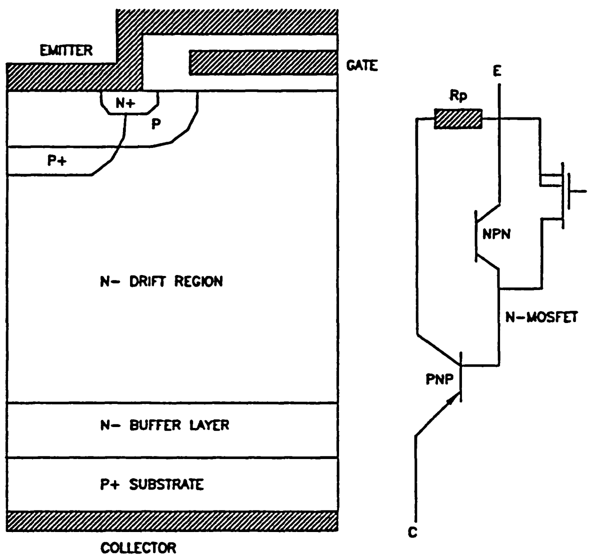



Figure 59- IGBT Structure

Silicon controlled rectifier (SCR) can not be turned off once gated unless forced to go to zero current. IGBT on the other hand can be turned off by removing the gate signal. This, combined with high speed switching of the IGBT allow for greater controls through pulse width modulation (PWM) resulting in much lower harmonics being generated. This active modulation of the IGBT helps maintain the power factor close to unity.

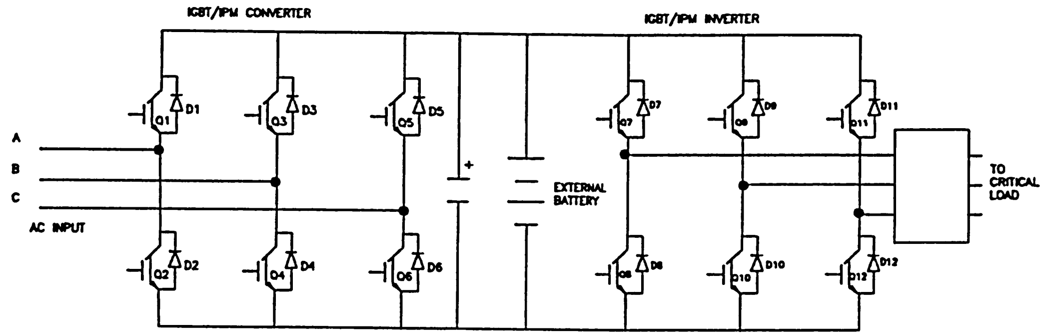



Figure 60- UPS Converter Topology Using IGBTs

The following are some published typical input harmonics in UPS systems using IGBTs [16]:

4 percent at 100 percent load.

5 percent at 75 percent load.

7 percent at 50 percent load.

As was discussed in chapter4 section 4.6, harmonic reflected from a UPS system can create problems for a back up generator because of the generator high impedance, and in order for a generator to operate properly with a UPS, it was becoming a good design practice to oversize the generator to accommodate harmonics. The use of IGBTs in the latest UPS technology has solved this problem allowing nearly 1 to 1 relationship between the generator and the UPS KVA.

## 5.5 Harmonic Mitigation Transformers

Harmonic mitigating transformers are special form of three phase transformers where the windings are specially configured that a phase shift is created between the primary and the secondary line to line voltages.

Through the control and manipulation of the phase angle, harmonic mitigation is then achieved through sine wave recombination. Combining sine waves is accomplished two ways [17]:

- By using the inherent phase angle displacement of the electrical wave shapes within the transformer which are then combined at the nodes or connection points of the windings within the transformer or
- By combining the sine waves at the common bus feeding two transformers of different phase shift.

### 5.5.1 Harmonic Mitigation Transformers for Single Phase Non Linear Loads

The most popular harmonic mitigating transformer for single phase non linear loads is the Delta-Zigazg or Wye-Zigzag transformer. Figure 61 shows the wiring diagram of a 30 deg pahse shift wye to zigzag harmonic mitigation transformer [18]. The zig-zag winding is a design that places half of the secondary turns of each phase on one leg of the three phase transformer core and the other half of the secondary turns on an adjacent phase. This technique causes cancellation of the magnetic flux established by triplen harmonic currents, so little or none is induced in the primary windings. This particular Zigzag transformer is very popular for single phase electronic loads which produce high level of "triplen" harmonics with the third harmonic being the dominant.

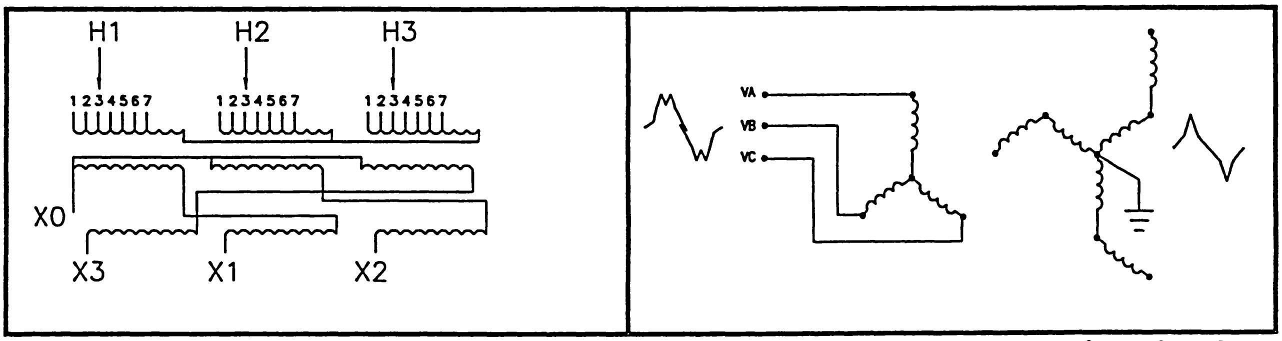



Figure 61- 30deg Phase Shift Wye to ZigZag HMT Used for Single Phase Non Linear Loads

To further attenuate some of the remaining harmonics, particularly the 5$^{th}$, 7$^{th}$, 17$^{th}$ and 19$^{th}$, the single phase nonlinear load can be split equally between two distribution panels where each panel is fed by a separate HMT, one of the HMTs could be a delta-zig-zag which has 0°

phase shift while the second can be either a delta-wye or a wye-zigzag which both have 30°
phase shift (Figure 62).

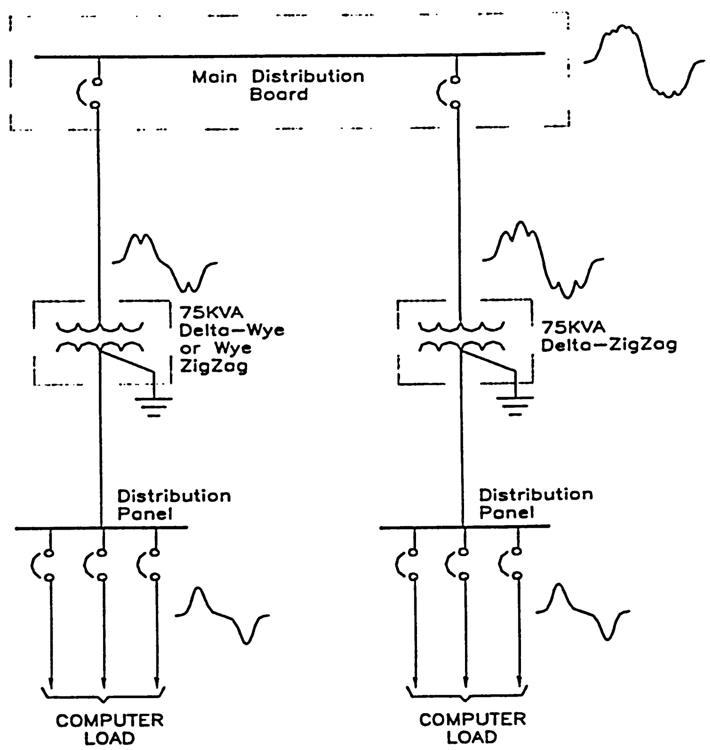



Figure 62- Further Harmonic Cancellation by Splitting the Single Phase Load Between Two HMTs.

5.5.1.1.<u>Simulations With Matlab Simulink</u>

In the following simulink circuit model, we added a zigzg wye isolation transformer between a non linear load rich in third harmonic (multiple single phase SMPSs) and the power source to see the transformer's effect on the elimination of triplen harmonic currents. After running the simulation we obtained the waveforms shown in Figure 64. The first waveform is the load current measured at the secondary of the transformer. This is a typical current waveform of a SMPS which has high level of third harmonic current as indicated in the harmonic profile. The second waveform is the load current measured at the primary of the transformer. The harmonic profile of this current shows the elimination of the triplen harmonic currents as expected due to the zigzag transformer.

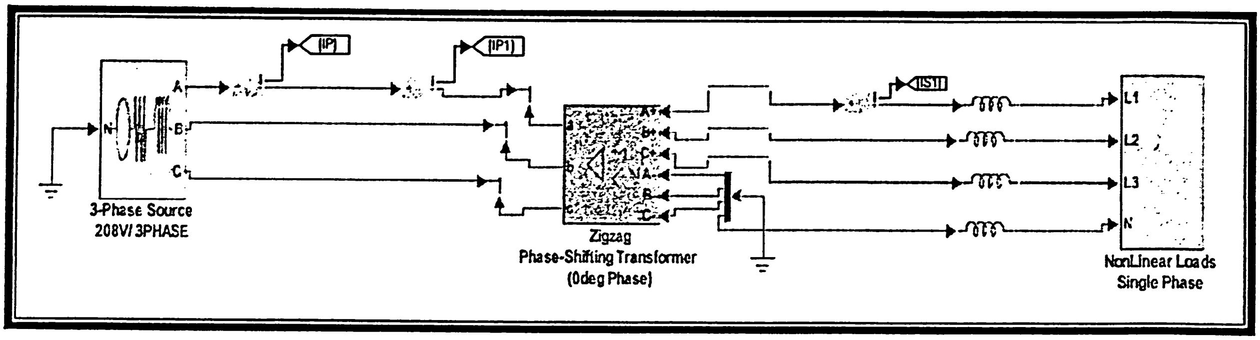



Figure63- Matlab Simulink Model of a Simplified Distribution System Showing a Delta/Wye Transformer Between the non Linear Load and the Power Source

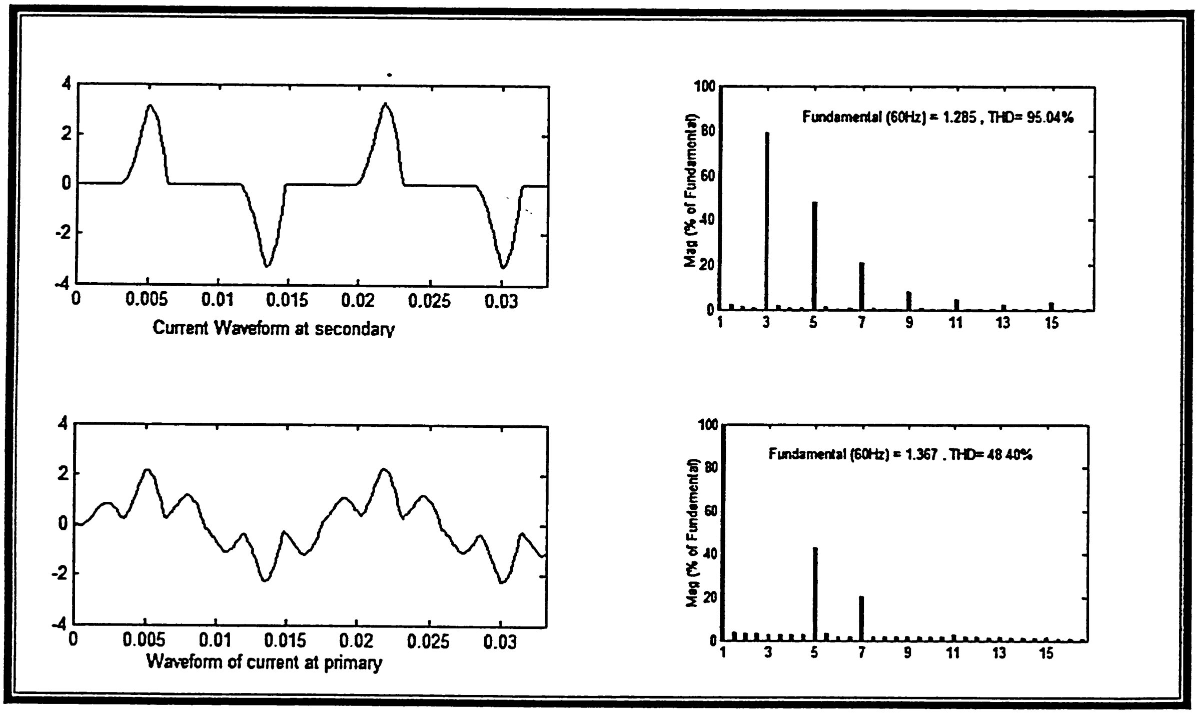



Figure 64 - Waveform of the Current Measured at the Primary and Secondary of the Transformer in the Circuit of Figure 63, and their Harmonic Profiles.

To simulate the power system of Figure 62, we built the circuit model shown in Figure 65. The resulting currents waveforms and their harmonic profiles are shown in Figure 66. The first and second waveforms show the load currents at the secondary of each of the two transformers. This is a typical current waveform of a SMPS which has high level of third harmonic current as indicated in the harmonic profile. The second and third waveforms are of the load currents measured at the primary of each of the two transformers. The harmonic profile of the waveforms shows the elimination of the triplen harmonic currents as expected because the zigzag transformers. The last waveform is of the current at the common bus feeding both transformers. The harmonic profile shows the further attenuation of the 5<sup>th</sup> and 7<sup>th</sup> harmonics which brings the THD to bellow 6%.

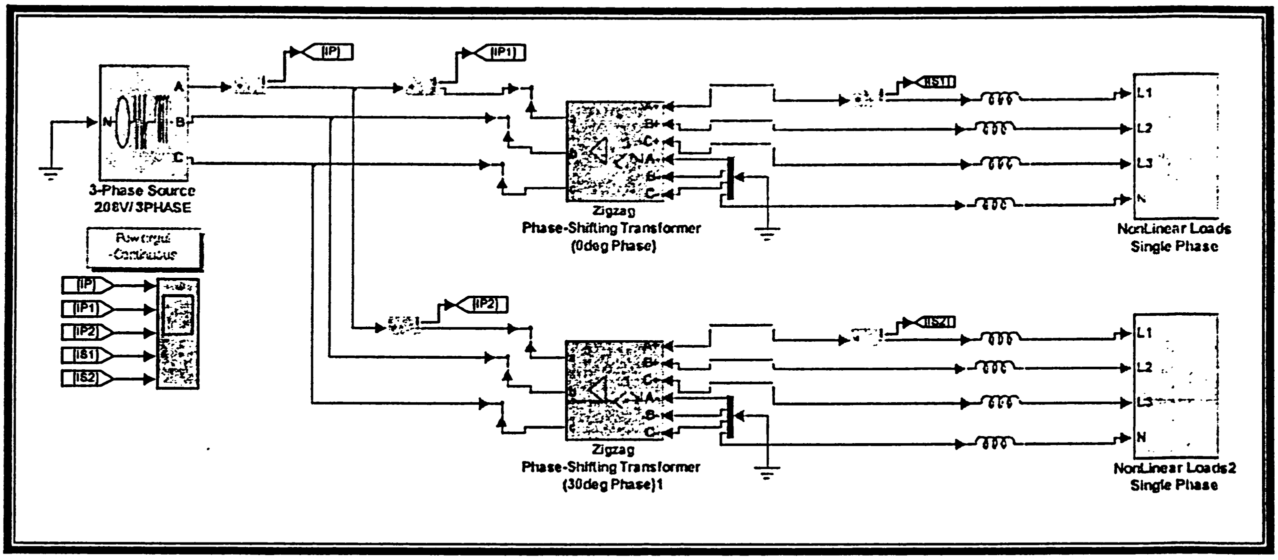
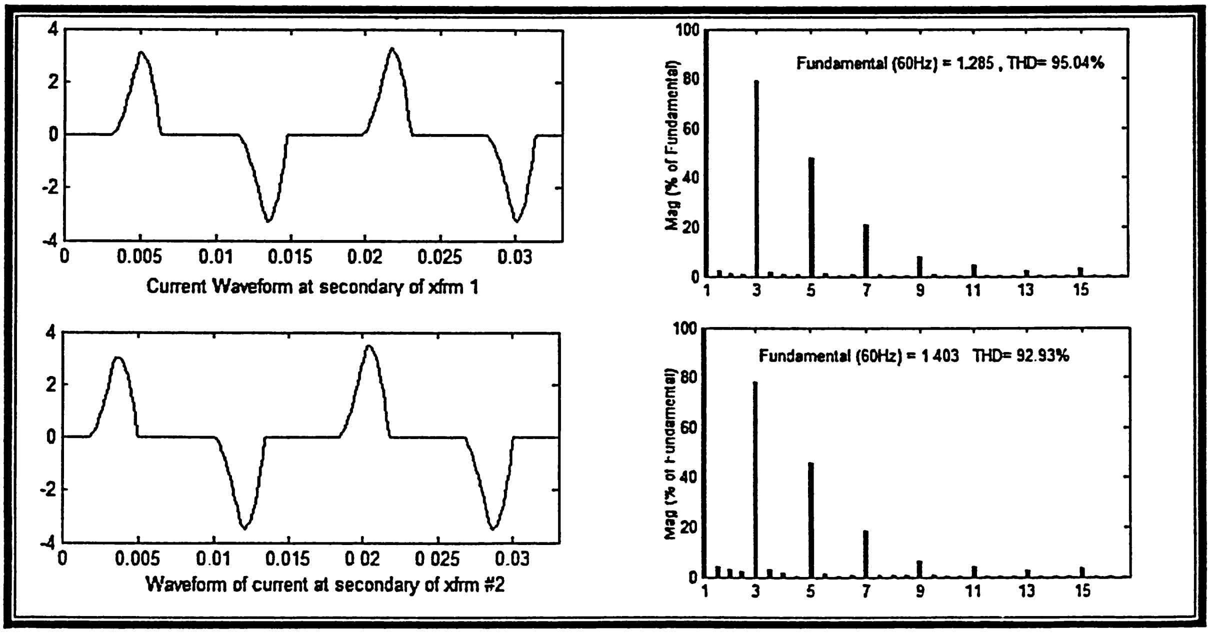



Figure 65- Matlab Simulink Model of the Distribution System Shown of Figure 62



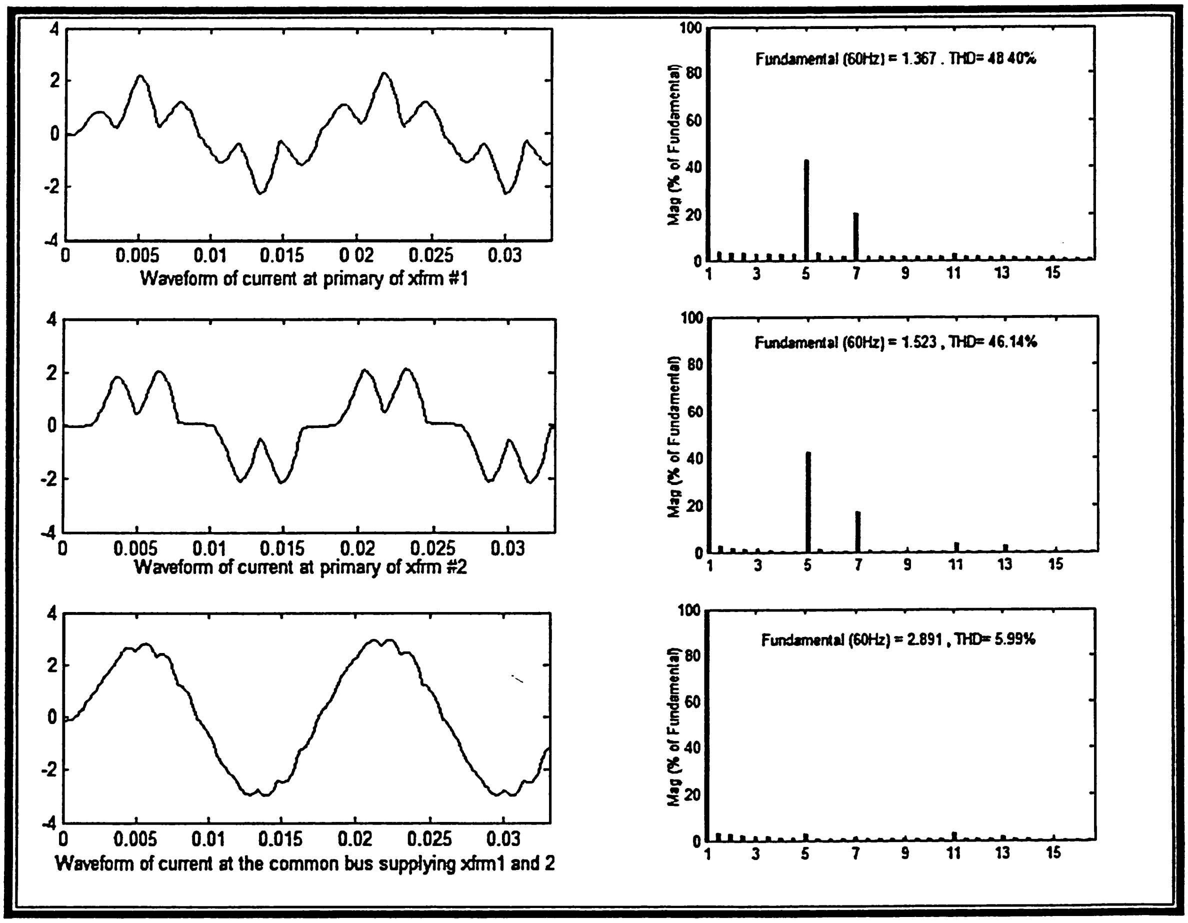



Figure 66. Waveforms and Harmonic Profiles of the Current Measured at Different Points in the System Shown in Figure 65

## 5.5.2 Harmonic Mitigation Transformers for Three Phase Non Linear Loads

In three-phase non linear loads, triplen harmonics are not generated instead the dominant harmonic currents are the 5th, 7th, $11^{th}$, etc. For these non-triplen harmonics, HMTs used are either dual secondary windings or pairs of transformers. In either design, the two secondaries are electrically phase-shifted relative to each other. The degree of relative phase shift is selected such that the targeted harmonic currents from one secondary are close to or exactly 180 degrees out of phase with the targeted harmonic currents from the other secondary, and thus they cancel each other in the primary.

One example of such transformer is the one shown in Figure 67. In this particular configuration, the primary winding is just a typical WYE connection. However, the secondary winding is made up of two sets of coils. One set is connected in a delta configuration, then in series with the second set. The secondary windings are connected such that a small voltage component is injected to the phase voltage to create a phase shifted output voltage without any appreciable change in magnitude.

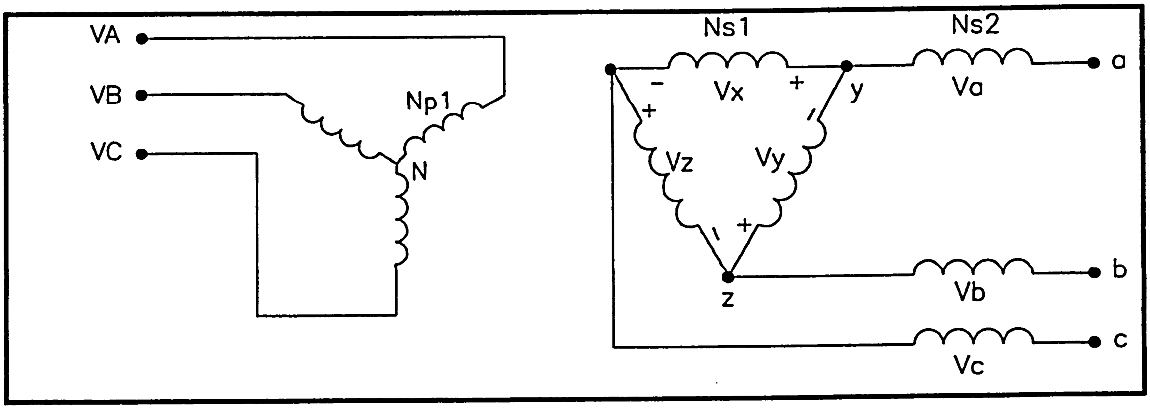


Figure 67- Delta to Delta/Wye phase Shifting Transformer Connection Diagram

The small voltage component can be changed by manipulating the transformer's turn ratio in two different ways [7]:

- At the secondary winding between the delta connected coil and the one connected in series to it or,
- Between the primary and the secondary windings.

This is illustrated by looking at triangle ($V_{by}, V_a, V_{ab}$) in the phasor diagram of Figure 68 and using the sine law on $V_a$ and $V_{by}$ from which the following is obtained [7]:

$$\frac{\overrightarrow{V_a}}{\sin(30-\theta)} = \frac{\overrightarrow{V_{by}}}{\sin(30+\theta)} = \frac{\overrightarrow{V_{ax}}}{\sin(30+\theta)} \quad (1)$$

From which we get:

$$\frac{\overrightarrow{V_a}}{\overrightarrow{V_{ax}}} = \frac{\sin(30-\theta)}{\sin(30+\theta)} = \frac{N_{S2}}{N_{S2+}N_{S1}} \quad (2)$$

As we can see from equation (2), the phase angle $\theta$ can be changed by manipulating the turn ratio on the secondary side.

Similarly by using $V_{ab}$ instead of $V_a$ in equation (1) the following is obtained [7]:

$$\frac{\overrightarrow{V_{ab}}}{\sin(120)} = \frac{\overrightarrow{V_{by}}}{\sin(30+\theta)} = \frac{\overrightarrow{V_{ax}}}{\sin(30+\theta)}$$

From which we get:

$$\frac{\overrightarrow{V_{ab}}}{\overrightarrow{V_{ax}}} = \frac{\sin(120)}{\sin(30+\theta)} = \frac{N_{P1}}{N_{S2+}N_{S1}}$$

We note from the phasor diagram that with this particular transformer, the phase shift angle on the secondary line to line voltage is a positive angle that changes from $0^\circ$ when $N_{S1}$ is zero (WYE connection), to $30^\circ$ when $N_{S2}$ is zero (Delta connection).

A lagging phase shift angle changing from $0^\circ$ to $-30^\circ$ on the secondary line to line voltage is obtained with the same type transformer by changing the phase rotation on the delta connected coil.

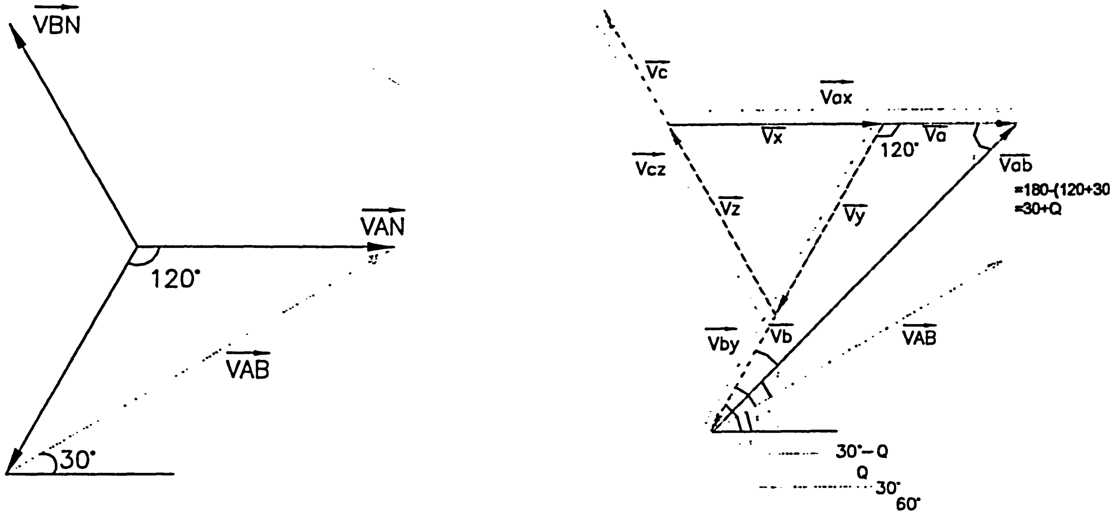



Figure 68- Delta to Delta/Wye Phase Shifting Transformer Phasor Diagram [7]

### 5.5.3 How are harmonics canceled through phase shifting transformers:

Let's consider the delta to delta/wye phase shifting transformer shown in Figure 69. This type transformer is typically used for a 12 pulse rectifier but it can also be used in a power distribution system where the non linear load is split equally between the two secondary transformers in order to eliminate certain low order harmonics as discussed in section 5.1.

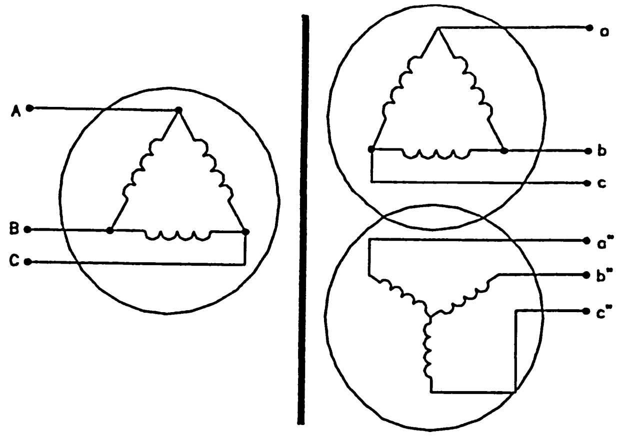
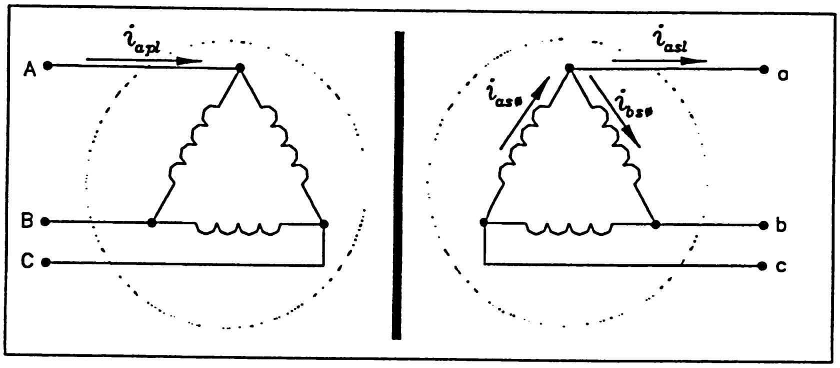



Figure 69- Delta to Delta/Wye Phase Shifting Transformer Connection Diagram

If we assume a balanced system and consider first the delta connected secondary as shown in the figure bellow.




The secondary current is expressed as:

$$i_{as(L)} = i_{as(\phi)} - i_{bs(\phi)}$$

Where

$i_{as(L)}$ is the line current on secondary delta transformer

$i_{as(\phi)}$ is the phase current on phase 'a' of the secondary delta transformer which can be expressed as:

$$i_{as(\phi)} = \sum_{n=1,5,7,11}^{\infty} \dot{i}_{a\phi_n} \angle 0$$

$i_{bs(\phi)}$ is the phase current on phase 'b' of the secondary delta transformer which can be expressed as:

$$i_{bs(\phi)} = \sum_{n=1,5,7,11}^{\infty} \dot{i}_{b\phi_n} \angle n(-120)$$

$i_{as(L)}$ is therefore equal to $\sum_{n=1,5,7,11}^{\infty} \dot{i}_{a\phi_n} \angle 0 - \sum_{n=1,5,7,11}^{\infty} \dot{i}_{b\phi_n} \angle n(-120)$

And for:

$$n=1,\ i_{as(L)} = (\dot{i}_{a\phi_1} \angle 0 - \dot{i}_{b\phi_1} \angle -120) = \vec{I} \angle 30$$

$$n=5,\ i_{as(L)} = (\dot{i}_{a\phi_5} \angle 0 - \dot{i}_{b\phi_5} \angle 5(-120)) = \vec{I} \angle -30$$

$$n=7,\ i_{as(L)} = (\dot{i}_{a\phi_7} \angle 0 - \dot{i}_{b\phi_7} \angle 7(-120)) = \vec{I} \angle 30$$

$$n=11,\ i_{as(L)} = (\dot{i}_{a\phi_{11}} \angle 0 - \dot{i}_{b\phi_{11}} \angle 11(-120)) = \vec{I} \angle -30$$

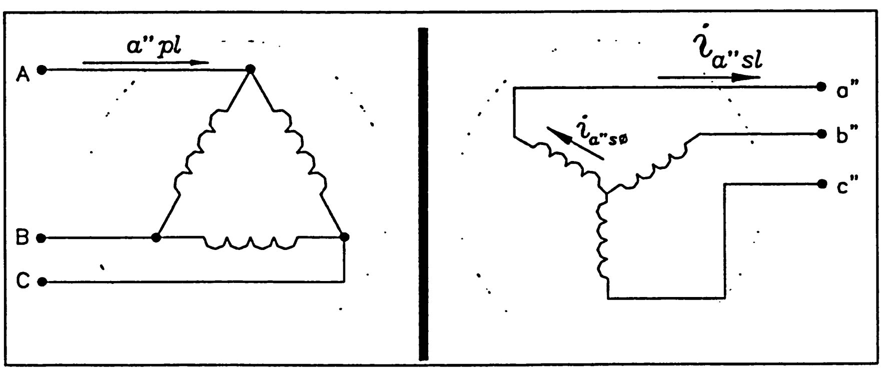
We notice a pattern here which is:

$$i_{as(L)} = \sum_{n=1,7,13}^{\infty} \vec{I_n} \angle (+30) + \sum_{n=5,11,17}^{\infty} \vec{I_n} \angle (-30)$$

Since this is a delta to delta transformation there is zero phase shift between the primary and the secondary. The secondary current referred to the primary is therefore:

$$i_{ap(L)} = \frac{1}{2} \left( \sum_{n=1,7,13}^{\infty} \vec{I_n} \angle (+30) + \sum_{n=5,11,17}^{\infty} \vec{I_n} \angle (-30) \right)$$

Let's now consider the Wye connected secondary as shown in the figure bellow.



$$i_{a's(L)} = i_{a's(\phi)} = \sum_{n=5,7,11,13,..}^{\infty} \vec{I_n} \angle 0$$

Where

$i_{a's(L)}$ is the line current on secondary wye transfomer

$i_{a's(\phi)}$ is the phase current on phase 'a' of the secondary wye transformer.

Since this is a delta to wye transformation, there is 30° phase shift between the primary and the secondary. The secondary current referred to the primary is therefore:

$$i_{a'p(L)} = \frac{1}{2} \sum_{n=5,7,11,13,..}^{\infty} \vec{I_n} \angle n30$$

And for:

$$n=1,\ i_{a'p(L)} = \frac{1}{2} \vec{I_1} \angle 30$$

$$n=5,\ i_{a'p(L)} = \frac{1}{2} \vec{I_5} \angle 5(30) = \frac{1}{2} \vec{I_5} \angle 150 = -\frac{1}{2} \vec{I_5} \angle -30$$

$$n=7,\ i_{a'p(L)} = \frac{1}{2} \vec{I_7} \angle 7(30) = \frac{1}{2} \vec{I_7} \angle 210 = -\frac{1}{2} \vec{I_7} \angle 30$$

$$n=11,\ i_{a'p(L)} = \frac{1}{2} \vec{I_{11}} \angle 11(30) = \frac{1}{2} \vec{I_{11}} \angle 330 = \frac{1}{2} \vec{I_{11}} \angle -30$$

$$n=13,\ i_{a'p(L)} = \frac{1}{2} \vec{I_{13}} \angle 13(30) = \frac{1}{2} \vec{I_{13}} \angle 210 = \frac{1}{2} \vec{I_{13}} \angle 30$$

The total primary current is therefore equal to:

$$i_{ap(Total)} = i_{ap(L)} + i_{a'p(L)}$$

$$= \frac{1}{2} \vec{I_1} \angle 30 + \frac{1}{2} \vec{I_1} \angle 30 + \frac{1}{2} \vec{I_5} \angle -30 - \frac{1}{2} \vec{I_5} \angle -30 + \frac{1}{2} \vec{I_7} \angle 30 - \frac{1}{2} \vec{I_7} \angle 30 + \frac{1}{2} \vec{I_{11}} \angle -30 + \frac{1}{2} \vec{I_{11}} \angle -30 + \frac{1}{2} \vec{I_{13}} \angle 30 + \frac{1}{2} \vec{I_{13}} \angle 30$$

Other phase shifting angles are achieved using a delta connection on the primary windings with the same two different configurations on the secondary winding. The equations for the different phase angles are derived in the same fashion as was done in the case of the WYE connected primary. Reference [7] addresses all the different cases in more details.

5.5.4 Limitations and Concerns with Harmonic Mitigating Transformers

One very important characteristic of a deta-or wye zigzag connected transformer, which is rarely taken into account by power distribution engineers when they specify these type of transformers, is that in a delta or wye-zigzag transformer, the line to neutral impedance is somewhere between 75% and 85% of the positive/negative sequence impedance. This low impedance will result in higher available fault current during a line to neutral or line to ground fault. This could result in an unsafe situation especially when this type transformer is integrated in an existing power distribution system where the interrupting current rating on a panelboard or protection device downstream may not meet the new available fault current.

It should also be noted that the harmonic currents which are not produced in the transformer primary continue to circulate in the secondary side generating losses in the transformer. These harmonic currents continue to flow in the distribution feeders on the secondary side as well, and as result, double sizing the neutral, in the case of single phase loads, will be still required.

The extra weight of the HMTs and the additional floor space required for their installation can in some cases create issues.

## 5.6 Multiple pulse Rectifiers

To reduce the line current harmonic distortion in the three phase rectifier, a six pulse rectifier is sometimes replaced with a multipulse rectifier. The multipulse rectifier can be configured as 12, 18 or 24 pulse rectifier by connecting in parallel multiple six pulse rectifiers and using phase shifting transformers to feed the same DC bus. This gives a smoother current waveform than in the single six-pulse bridge. Figure70 shows a typical circuit diagram for a twelve pulse rectifier.

The line current in a 12 pulse rectifier is described by the following equation [7]:

$$I_a = 2(\frac{2\sqrt{3}}{\pi})I_d \left( \cos(\omega t) - \frac{1}{11}\cos(11\omega t) + \frac{1}{13}\cos(13\omega t) - \frac{1}{23}\cos(23\omega t) + \frac{1}{25}\cos(25\omega t)... \right)$$

We notice the absence of the $5^{th}$ and $7^{th}$ harmonics which are present in the 6 pulse rectifier. The twelve pulse bridge only contains harmonics of the order of n=12k +/- 1 where k is an integer. The harmonics of orders 12k+1 are of positive sequence and the ones of orders 12k-1 are of negative sequence. The disappearance of the 5th and 7th harmonic is attributed to the use of the wye to wye/delta transformer where the 30°phase shift causes them to cancel out on the primary. This harmonic cancellation was explained in more detail in the harmonic mitigation transformers section.

Higher than a 12 pulse rectifier is achieved through the addition of more appropriately phase shifted transformer connected in parallel and with the appropriate transformer ratio. For instance the 18 pulse is achieved through three transformers with 20° phase shift which results in the elimination of the 11th and 13th harmonics further improving the THD. The 24 pulse is achieved through four transformers with 15° phase shifts resulting in the elimination of the 17th and 19th harmonics. Higher than 24 pulse rectifier is achievable through additional transformers. However, this is not practical in real applications from a cost/benefit standpoint. The typical distortion improvement to bellow 4.5% rarely pays for the additional cost.

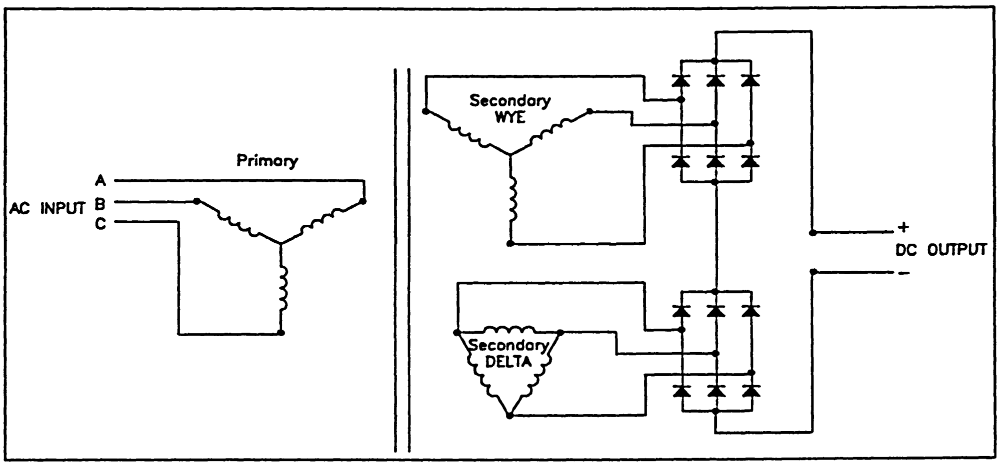



Figure 70- Circuit Diagram for a 12 Pulse Rectifier

### 5.6.1 Simulations With Matlab Simulink

To simulate the power system of figure 70, we built the circuit model shown in Figure71 using Matlab Simulink. The resulting currents waveforms and their harmonic profiles are shown in Figure72. The first and second waveforms are the currents at the wye and detla secondaries of the transformer drawn by the six pulse rectifiers. We can see the 30deg phase shift between the two waveforms. The currents are rich in non triplen harmonics as indicated in the harmonic profile and as was discussed in chapter 2. The last waveform is of the load current measured at the primary of the transformer. The harmonic profile shows the elimination of the 5th and 7th harmonics.

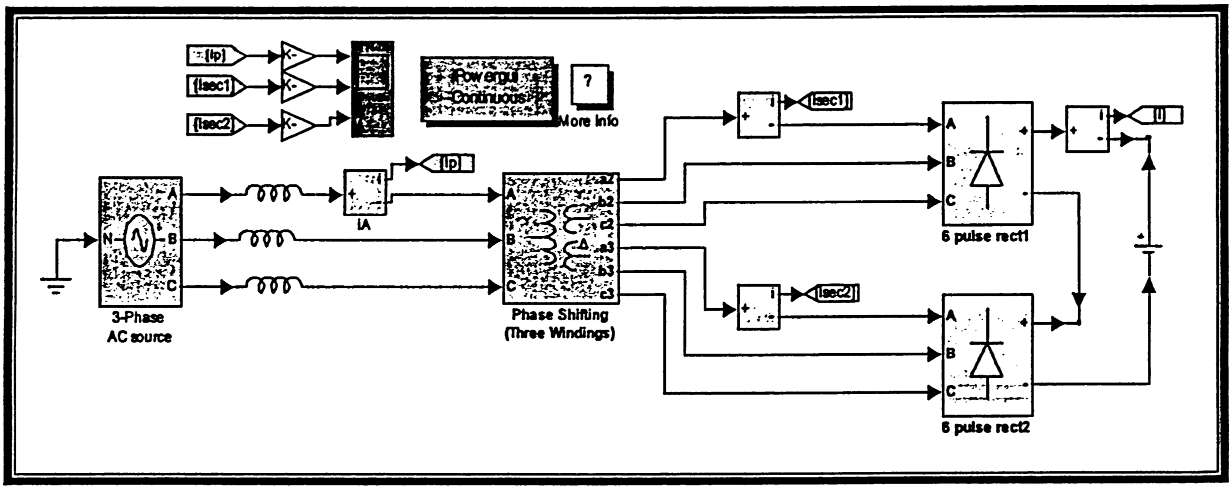
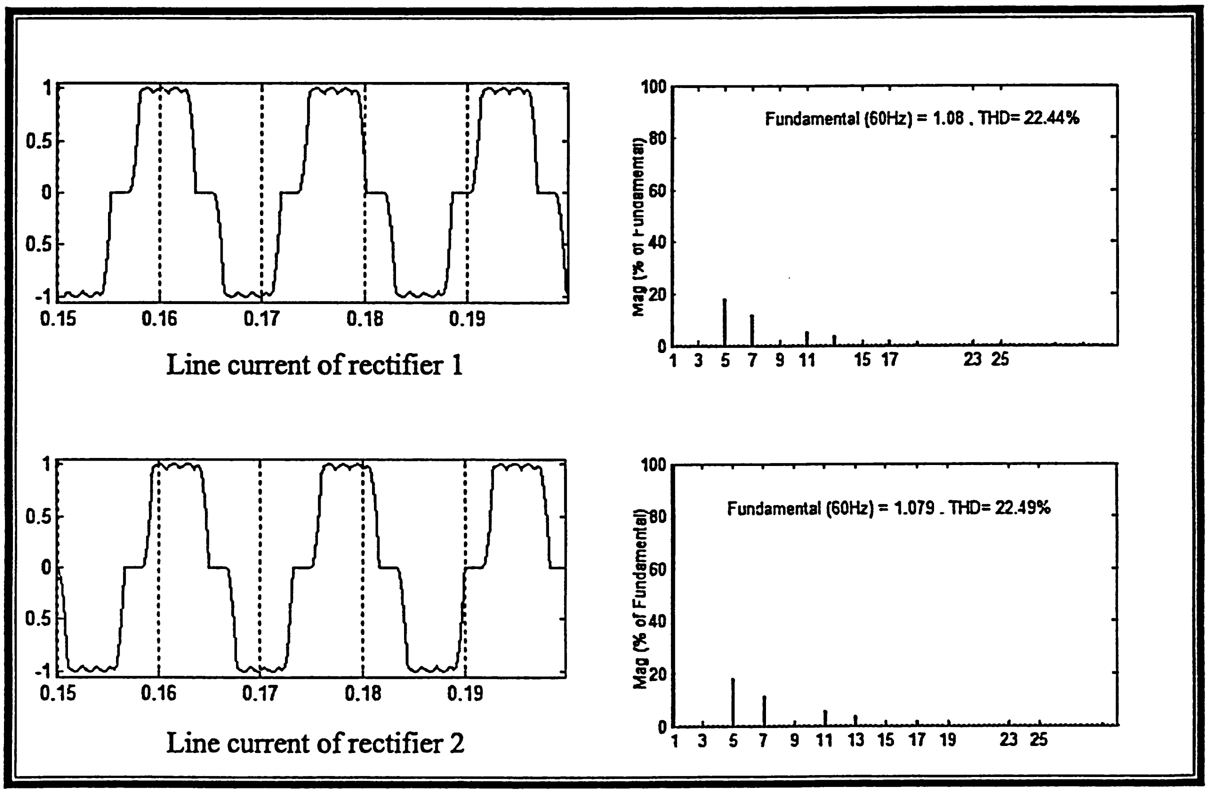



Figure 71- Matlab Simulink Model of the Distribution System Shown in Figure 70



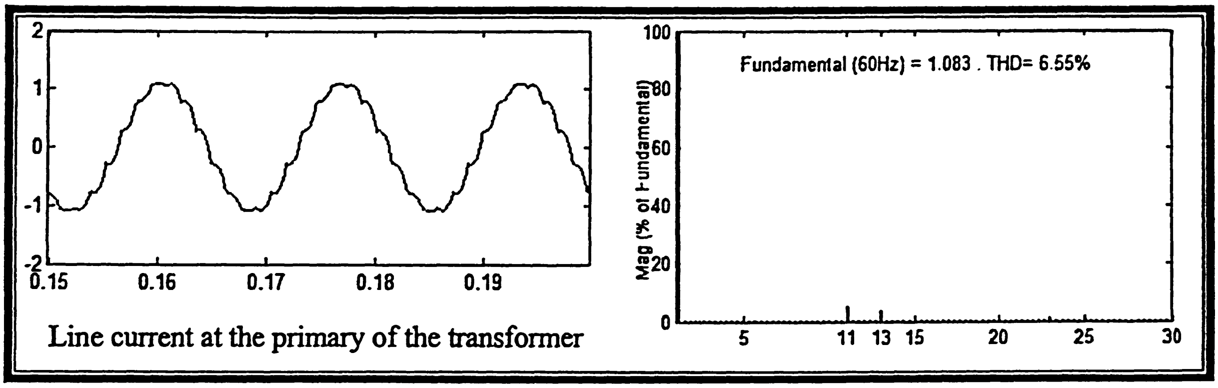



Figure 72- Waveform of the Current Measured at the Primary and Secondary of the Transformer in the Circuit of Figure71 and their Harmonic Profiles.

### 5.6.2 Drawbacks in multipulse rectifiers

The major drawback in a multipulse rectifier is the introduction of more equipment (transformers and additional 6 pulse rectifiers). The additional equipment not only increases the cost of the system but also increases its overall foot print and weight, and the system will require more cooling which further require additional equipment and space for these equipment. Most important, more components in the system result in lower meantime between failures (MTBF) and increase the likelihood of failures in the system.

It should be noted that the current harmonics which cancel out in the transformer primary of a multipulse rectifier continue to circulate in the secondaries and as a result will still generate losses in the transformer.

Another drawback of mulipulse rectifiers is the degradation of total harmonic distortion as the load is reduced. Most variable frequency drives and UPS systems operate bellow rated full load in real application and as a result the actual line current THD is twice or higher than what the system manufacturer guarantees. This can be clearly seen from the results obtained from a simulation using matlab simulink. During the simulation, we loaded the 12pulse rectifier at 100% then at 10% rated load. Figure 73a and 73b show the waveform of the line current and its harmonic profile at **100%** loading. Figure 73c and 73d show the waveform of the line current and its harmonic profile at **10%** loading. The THD in the line current during the 100% loading was around 6%. When the load changed to 10%, the THD increased to around 16%.

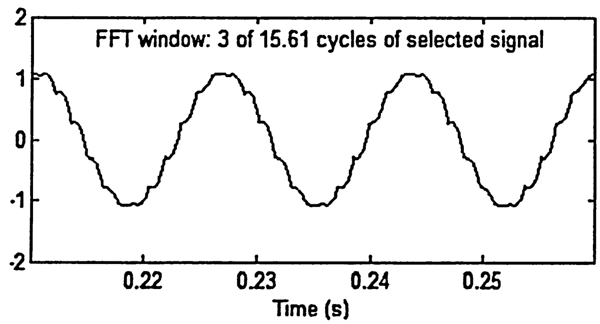



Figure 73a. Waveform of the Line Current in the Primary Side of the Transformer Feeding a 12 Pulse Rectifier at 100% loading.

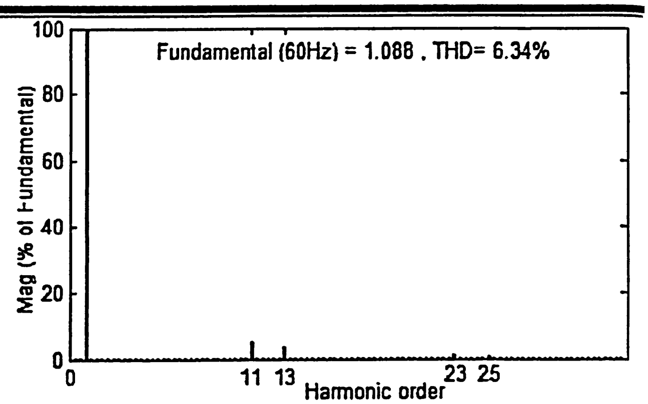



Figure 73b. Harmonic Spectrum of the Waveform Shown in Figure 73a.

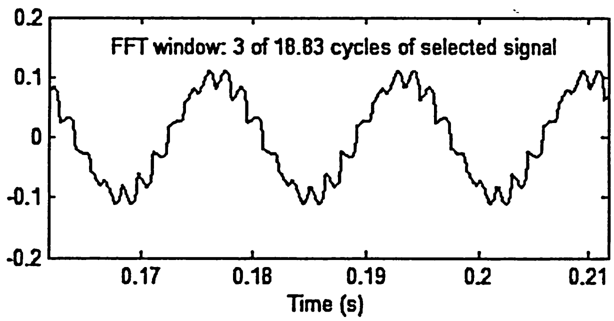



Figure 73c. Waveform of the Line Current of the Primary Side of the Transformer Feeding a 12 Pulse Rectifier at 10% loading.

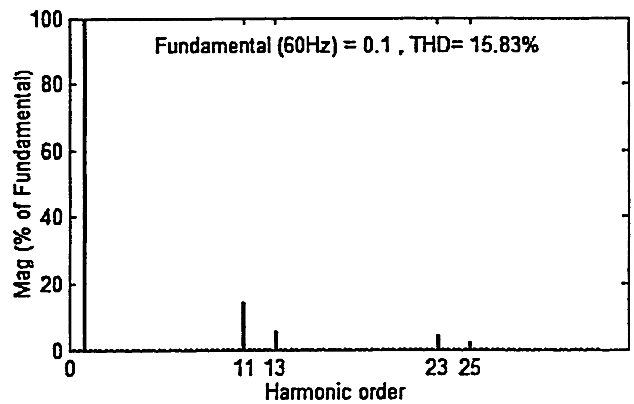



Figure 73d. Harmonic Spectrum of the Waveform Shown in Figure 73c.

## 5.7 Passive Filters

A passive filter works on the principle of resonance to absorb specific current harmonics. The passive filter is nothing but an LC circuit tuned to the frequency order to be filtered out. The filter is typically installed in parallel with the non-linear load providing a short circuit path for the harmonic, thereby blocking it from flowing back to the voltage source and through the power distribution system upstream (Figure 74). Multiple parallel connected branches of filters are sometimes used when several dominant harmonic orders are to be filtered out.

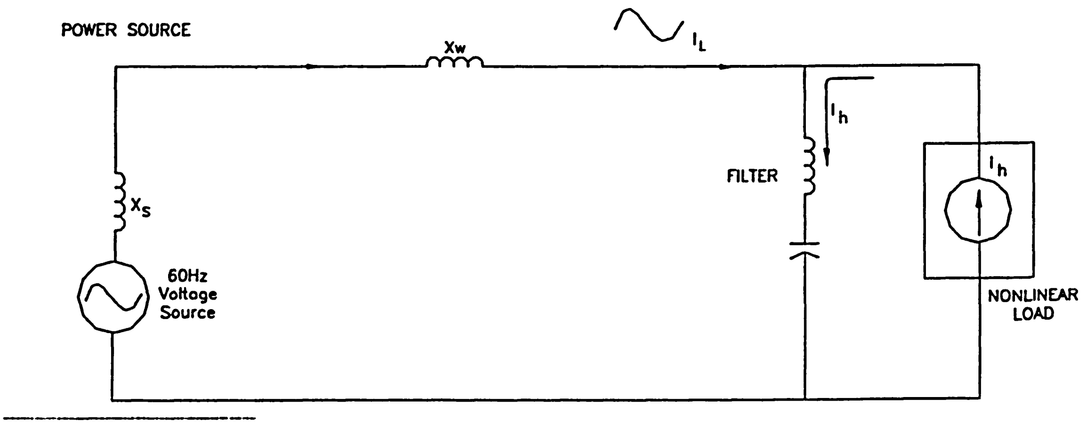



Figure 74- Typical Harmonic Trap Filter Configuration

The three most popular harmonic passive filters are the series tuned filter, the double band pass filter and the damped filter shown in Figure 75 [12].

The series tuned filter consists of a series combination of a capacitor and a reactor and is tuned to a low harmonic frequency.

The double band pass filter consists of a series combination of a main capacitor, a main reactor and a tuning component consisting of a tuning capacitor and a tuning reactor connected in parallel. This type filter provides low impedance for two tuned frequencies.

The damped filter consists of a capacitor in series with a parallel combination of a rector and a resistor. This configuration provides low impedance for a wide range of frequencies and is generally used to eliminate high order harmonics.

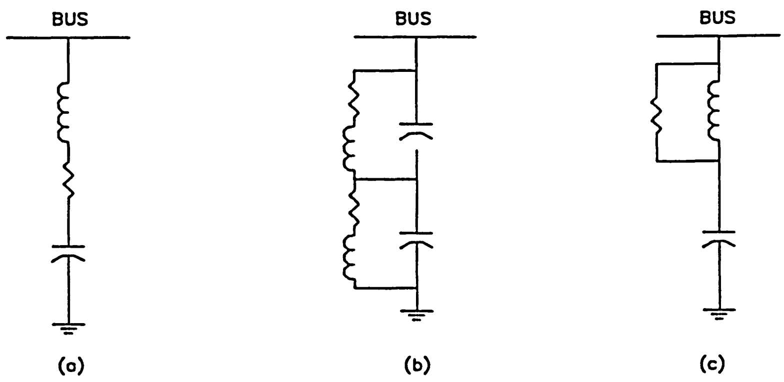



Figure 75- Typical Harmonic Filters: *(a) Series tuned (b) Double band pass (c) Damped*

### 5.7.1 Simulations with Matlab Simulink

To further illustrate how passive filters eliminate harmonics and improve current distortion, we built a simplified single phase distribution system using Matlab Simulink as shown in Figure 76. The system shows a 5th dominant harmonic current flowing back to the source modeled by a current source. The supply voltage and current waveforms before the application of a passive filter are shown in Figure 77.

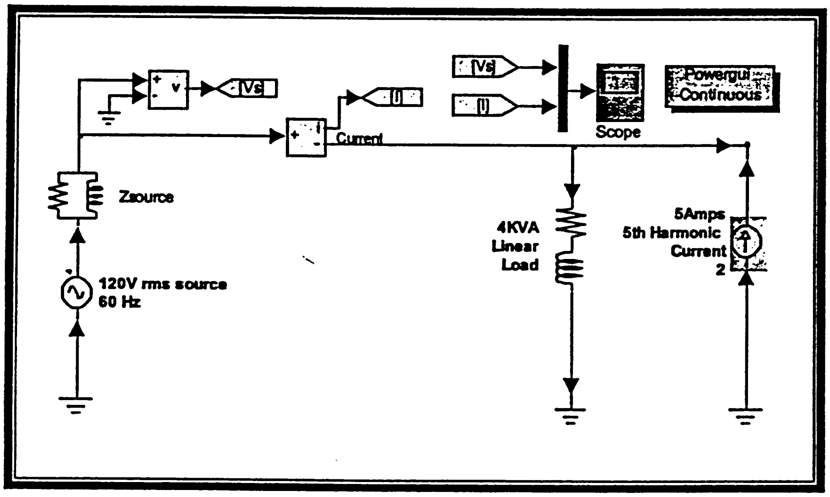



Figure 76- Simulink Model of a Simplified Single Phase Distribution System with a 5th Harmonic Current Flowing in the System.

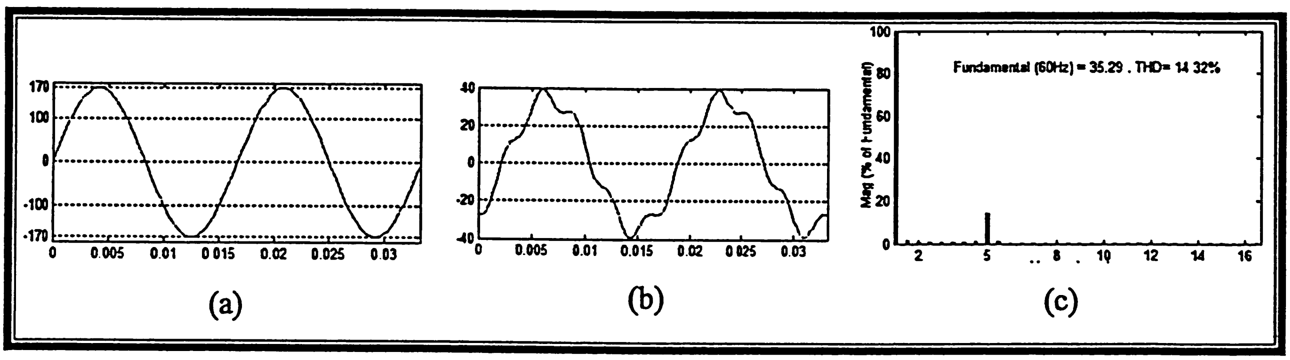



Figure 77- Simulation Results from Circuit Model of Figure 76: *a) Supply Voltage, b) Line Current, c) Line Current Harmonic Spectrum.*

In the next model shown in Figure 78, we added a 5th harmonic passive filter to the system of Figure 76. The supply voltage and current waveforms after the application of a passive filter are shown in Figure 79. We can see the effectiveness of the application of a passive filter when the goal is to eliminate a predetermined dominant harmonic current.

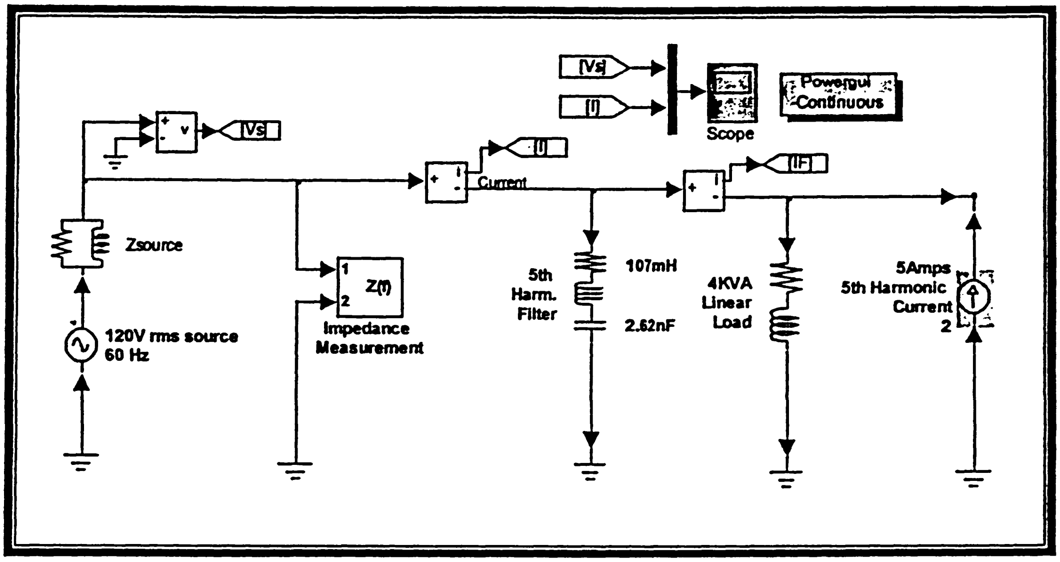



Figure 78- Circuit Model of Figure 76 with a 5$^{th}$ Harmonic Passive Filter

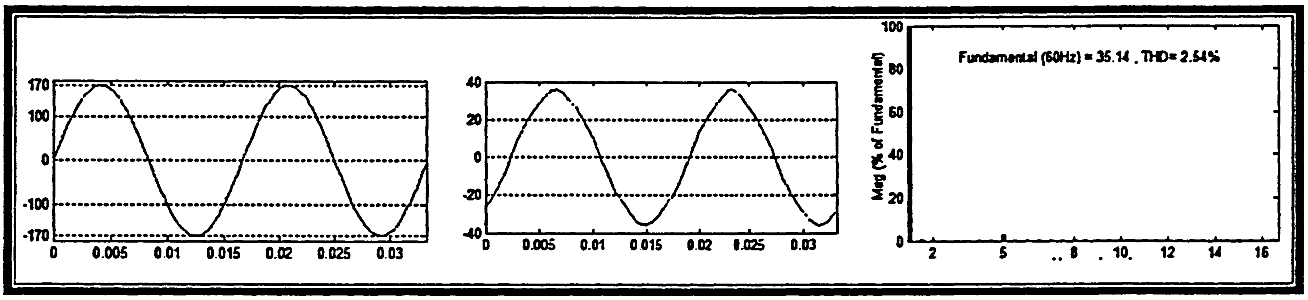



Figure 79- Simulation Results From Circuit Model of Figure 78: *a) Supply Voltage, b) line Current, c) Line Current Harmonic Spectrum.*

## 5.7.2 Drawbacks from Passive Filters

Passive filters are the ideal solution when there is a predominant known harmonic such as the case with 3$^{rd}$ harmonic in PC type loads, and where the load does not vary significantly. They are also much cheaper that active filters. However, they can have major drawbacks when the harmonic characteristics changes in the load they were designed to operate in. The passive filter in these cases will draw leading power factor current from the transformer, leading to overheating. They can also provide undesirable excitation for a back up generator, when one exists, leading to unstable operation in the ways outlined in chapter 4 in the generator section.

It is important to point out that when a passive filter is applied to absorb a specific harmonic current, that harmonic current just because it does not flow back to the source, it does not mean it disappeared. The harmonic current still flows around the installation between the nonlinear load and the passive filter but through a smaller loop circuit. This new loop circuit will naturally have much lower line impedance which means a higher level current will now be flowing through this circuit. As a result some of the precautions to cope with the flow of harmonics will still have to be taken such as double sizing the neutral or de-rating of the transformer if the filter is installer upstream of it.

Other problems that can arise from passive filters, is during de-centralization. Two filters with the same rated resonance frequency when operating under different conditions will have their actual resonance frequency slightly changed from the rated one [19]. This slight change in resonance frequency could cause one of the two filters to appear capacitive while the other inductive creating a rejection circuit. It could also causes more harmonic current to flow on one filter more than the other causing one of them to become overloaded. Moreover, a passive filter is always on the alert and waiting for the harmonic it is tuned to. Its performance is not dependant on a specific part of the load in the power distribution system. Instead it will be exposed to the harmonic it is tuned to that is present anywhere in the whole power system. Therefore, it should be properly sized and protected.

## 5.8 Active Filters

Active filters are probably the most effective solution to harmonics in power distribution systems. Installed in parallel with the non linear load, active filters compensate the harmonics generated by nonlinear loads by generating the same harmonic components in the opposite phase. They continuously monitor the harmonic currents drawn by the load then inject the same harmonic to the load with the appropriate phase. They are more dynamic than passive filters and have the capability to correct a wide range of harmonics.

### 5.8.1 Active Filters with Magnetic Compensator

Early type active filters utilized magnetic compensators to eliminate harmonics. The system block diagram is shown in Figure 80[3]. The filter worked as follow: A current transformer is used to capture the load current. The current at the fundamental frequency is then eliminated through a series resonant circuit tuned at the fundamental frequency. The remaining currents are therefore all harmonics. The remaining harmonics are then amplified through a linear amplifier and get fed back to the supply transformer through a tertiary winding transformer.

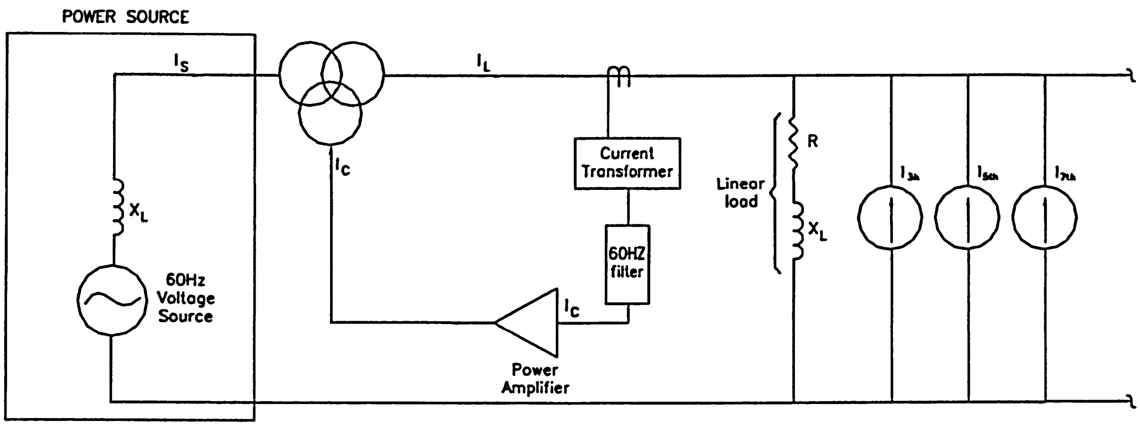



Figure 80- An Active Filter with Magnetic Compensator

## 5.8.2 Active Filters with Active Compensation

With the introduction of signal processing, newer more effective active filters were introduced. In these advanced type active filters, a sample harmonic current content is transmitted to a signal processing unit which synthesizes a sinusoidal wave in phase with fundamental component of the load current [3]. The synthesized sinusoidal current is then subtracted from the signal representing the load current and the remaining would be the required compensating current. This signal current which contains all harmonics except the 60Hz is then fed to an amplifier then combined with the load current through and inductor. The system block diagram is shown in Figure 81[3].

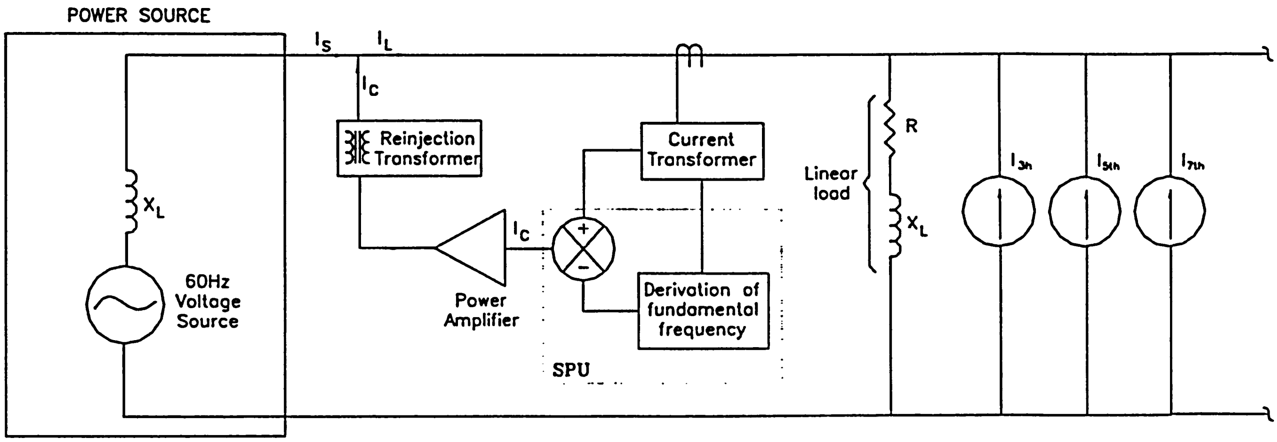



Figure 81- An Active Filter Using Active Compensation

Unlike the early type active filters, these latest ones are not limited to one specific fundamental frequency and can be effective with different fundamental source frequencies. They can also provide power factor correction. Most active filters use as their power circuit either a voltage-source pulsewidth-modulated (PWM) converter equipped with a dc capacitor or a current-source PWM converter equipped with a dc inductor [18].

Unlike passive filter, the active harmonic filter does not cause leading power factor under no-load conditions. When the load generating harmonics is off, and no compensating harmonic current is needed, it will automatically reduce its output to zero.

### 5.8.3 Hybrid active filter

To combine the benefits of the passive filter with those of the active filter, a hybrid active filter combining the two can be utilized. The hybrid filter would consist of a series connected active filter and a passive filter consisting of two or more single tuned filters to the lower order dominant harmonics such as the $5^{th}$ and 7th. The introduction of the passive filter into the active filter allows a significant reduction in the rating of the active filer.

### 5.8.4 Active Filters Disadvantages

Active filters have few disadvantages, the first one being the high cost associated with their implementation. They are probably the most expensive solution for harmonics. Secondly, active filters must be re-sized and "upgraded" each time more loads are added to the system, and because they draw power from the same electrical system they are protecting, they require special precautionary measures in their integration into the power system. Some of these measures are double sizing of the neutral, special fuses and circuit breakers. Thirdly, because active filters have more electronic components in them they are inherently more susceptible to failures than passive filters. Finally, because an active filter is continuously monitoring the load generating harmonics, it will not provide any protection against harmonics generated by the source from other non linear loads.

# CHAPTER 6

# CONCLUSIONS

There are many specific areas in the issue of harmonics that can be tackled separately and analyzed in a much deeper level. The effort made in this report was to provide a broad analysis on harmonics in commercial power systems, how they are generated, their effects and the different solution used to deal with them. The intent is to provide an educational tool on harmonics in commercial power systems that can be used by power distribution consulting engineers to assist them in making good evaluation of a new or an existing system, thereby allowing them to propose the proper solution for different situations.

There is no doubt that harmonics in commercial power distribution systems will become an issue that will require serious attention in the future as commercial buildings become heavily loaded with non linear loads. Harmonic currents can clearly cause more problems in power systems than reactive power as was outlined in chapter 4, so it is reasonable to expect that the utilities will eventually start penalizing for voltage distortion caused by harmonic as they normally do with fundamental reactive power.

It is fairly simple to address harmonic problems in large power plans or specialized industrial buildings where the nonlinear loads are isolated and the system operation is well defined with predictable results. The situation is more complicated when it comes to power distribution systems in regular commercial buildings. Different players can impact the system with no clear guidelines or standards that sets the rules and responsibilities, and the location and operating characteristic of the dispersed load are not well defined.

Dealing with harmonics should not be limited to having manufacturer comply with IEEE recommendations. Consulting engineers designing power distribution systems should play a leading role in reducing the level of harmonics. They should specify and recommend the proper equipment to the customer, and if the initial cost of these equipments is not well perceived by the customer, then it becomes the engineer's responsibility to lay down the long term savings and benefits. Consulting engineers should also follow some of the simple design guidelines as outlined in chapter 5.

Facilities managers or buildings operators can play a critical role as well. They have the power to enforce guidelines and standards, and they often do with contractors and engineers during the implementation of new systems or the modification of existing ones in the buildings they are responsible for. Most facility managers, however, are not well educated in the issues of power harmonics. As a result, they rarely bring the issue for discussion during the engineering phases of a project. Facility managers should be made aware of the impact high harmonic levels could have on equipment life and proper operation so that they can properly monitor their power system and take remedial action before unexpected failures takes place.

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