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Regulation of Power Quality

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by

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Abstract

The quality of electric energy delivered to consumers is adversely affected by nonlinear loads that inject current harmonics into a power network. The current trend of growing power quality disturbances, which lead to premature equipment failure, presents an increasing monetary burden to society. This project draws a unique analogy between electrical power disturbances and vehicle emissions, providing the necessary leverage for governmental participation in solving power quality issues. Recommended solutions address the technical, financial, and legal aspects of the subject.

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1 Introduction

The past century has seen a surge of technological breakthroughs, among which electricity is arguably the most remarkable and valuable.

Electric energy is a major facet of modern life. As a practical advancement, electricity is utilized in various fields, such as communications, industry, and household service. The use of electrical energy enables people to communicate through devices such as cell phones, conventional telephones, and amateur radio, just to name a few. Electrical energy is widely employed in numerous industrial applications, where transformers and electrical motors play the role of industry's workhorse. In this day and age, electrical appliances, ranging from TVs, DVDs, and stereos, to air conditioners, and refrigerators, have become household necessities. An ever-increasing number of devices and instruments, such as computers, coffeemakers, toasters, and hair dryers, could not function without the use of electrical energy. There is no doubt that the use of electricity is a major factor in our economic progress and has greatly eased our lives, however, we must ask at what cost?

Skeptical analysts have raised questions about negative impacts associated with the generation and use of electrical energy. A great deal of research has been conducted on health problems that may be caused by electromagnetic radiation, especially for people living close to high voltage power lines[1]. Others have informed us of negative environmental effects induced by the generation of electricity, whether it affects wildlife or increases the emission of greenhouse gases[2]. While the above issues are beyond the scope of this project, our intent is to draw upon the attention and imagination of interested readers, and sprout an interest in

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[1] http://www.mcw.edu/gcrc/cop/powerlines-cancer-FAQ/QandA.html#12

[2] http://www.iaea.or.at/worldatom/Press/Statements/FormerDG/dgsp1995n10.html

discussing possible solutions for problems associated with the generation, transmission and use of electrical energy. A common belief is that inadvertent drawbacks occur with any innovation; however measures can be taken to minimize and, as current technology provides, alleviate any negative effects introduced by such advancements.

More recently, the engineering community has focused on power quality issues and their relationship to the consumption and regulation of electric energy. Power disturbances reduce the lifespan of equipment plugged in the AC grid, causing significant economical damage. Our team was commissioned to investigate the technical, economical and legal effects of power quality issues.

1.1 Project Statement

The goal of our project is to examine electric power quality, relate the technological aspects of power quality problems with social issues, and provide technical, financial, and legal solutions to such problems. To ease the understanding of technically advanced subjects, one needs to provide an apprehension bridge, built on comparisons to simpler topics.

1.2 Report Summary

In this report we present the necessary material for understanding our project and substantiate recommendations that we make. We detail the relevant background for understanding electric power quality and power disturbances, and then present the detailed goals of our assignment. As part of our methodology we verify power quality problems via measurement data, and summarize their financial burden on our economy. A retrospective of vehicle pollution control enables the reader to recognize the government as an essential contributor to the improvement of power quality. In order to explore methods that mitigate effects of power disturbances, one needs to take into account the many social, economical, legal, and technical aspects of the issue. The project addresses these concerns along with the pros and cons of various solution schemes.

2 Background

2.1 Electrical Energy as a Product

The primary reason that electrical energy is of perennial importance in our lives is the ease of its transportation and conversion. As a product, electric energy provides the means for electrical customers to fulfill disparate needs or carry out sundry services. It is generated in various ways and delivered through the electric grid to end-users, who convert it easily into the forms of energy they require, such as thermal (by use of ovens), mechanical (using motors), or luminous (as in fluorescent lights). Unfortunately, during the conversion processes waste by-products are generated. Such by-products often are waste heat, acoustic noise, and electromagnetic (EM) pollution, the topic of this study.

The consumption of electric energy has a unique peculiarity, in that the way one customer converts and uses electricity affects the energy conversion that takes place in other customers' equipment. For example, if one customer uses "too much" power, the resulting brownout (low voltage level) will affect others as well. One observes that during the starting period of a "large" motor, the surging current required by the motor can cause a voltage reduction and flickering lights for many others. It is also common to observe that turning on a "large" appliance, such as an air conditioner or refrigerator, can cause the light bulbs to dim momentarily. These examples are a demonstration of electrical power quality's dependence on the power network topology and interactions, and while we would like to think that our power consumption is independent of our neighbors', it is often not the case. Many questions naturally arise: what constitutes Electrical Power Quality? What are the conditions and disturbances that affect Electrical Power Quality and electric energy consumption?

In order to answer these questions, we need to develop the necessary background to understand the Power Quality issue. The source of Power Quality problems, such as the ones mentioned above, is not always easy to ascertain. The unacceptable quality of power may be a utility responsibility, or it may be self-generated by an electrical consumer. To avoid disturbances related to the consumption of electrical power, both utility and consumers need to identify problems and work towards establishing fair solutions.

2.2 Electrical Power Quality

When electrical energy is generated, it is distributed to end-users in the form of a 60Hz sinusoidal voltage waveform (Figure 2.2.1). To the electrical generator, different consumers simply represent different electrical *loads* of unique topologies, whether being a motor, a furnace or an oven. The generator-load network is the embodiment of a supply and demand structure, where consumers' demands define the workload of the electrical generator. On the other hand, the available *energy supply* is defined by the *total amount of work* that the generator does to keep its customers happy.

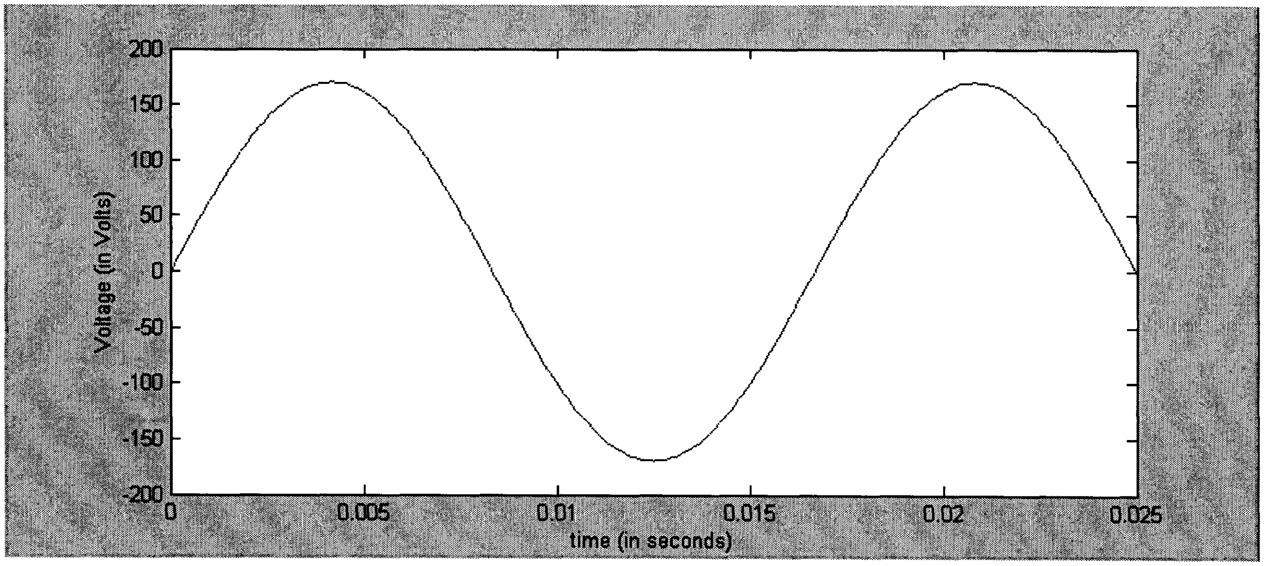


Figure 2.2.1 *Ideal 60Hz, 120 volts (RMS) sinusoidal voltage waveform*

The quality of the electrical energy supply is closely tied to customer needs. The consumer expects a certain degree of reliability that can be cast in the following terms (1):

1) The supply of electric energy must be uninterrupted.

2) The supplied voltage must alternate at a constant frequency (60Hz in the U.S.) and have a sinusoidal shape (Figure 2.2.1). The magnitude of the voltage must comply with the limits recommended by the equipment manufacturer.

3) A perfect symmetry must exist in three-phase systems: the three voltages must be identical sinusoids shifted 120° with respect to each other (Figure 2.2.2).

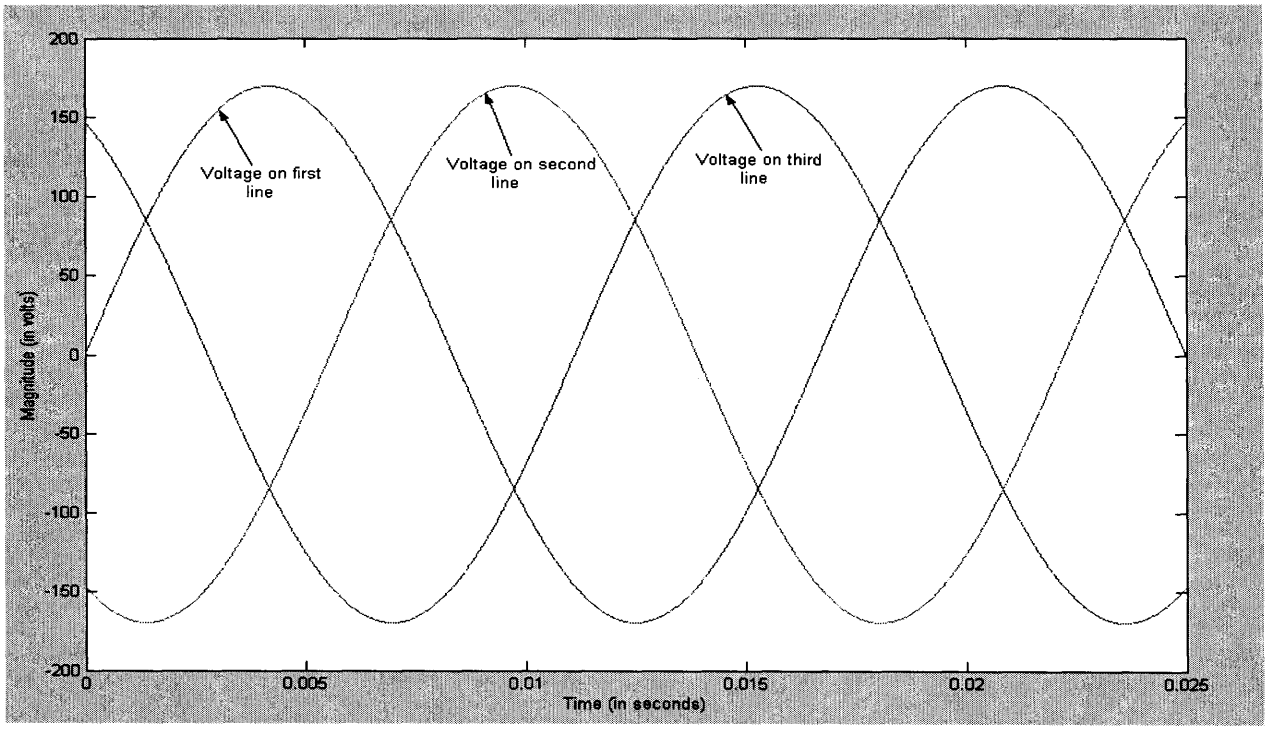


Figure 2.2.2 *Ideal 60Hz, 120 volts (RMS), three phase, sinusoidal voltage waveform*

Aberrations from the above conditions determine Electric Power Quality, which is defined as "the degree to which both the utilization and delivery of electric power affect the performance of electric equipment" (2). The term *power quality* can be better understood if electric energy is perceived as a product or a service. Power quality can then be "properly conceived as the quality of the product, which is electric energy" (1).

It is rather inconvenient to quantify electric energy; therefore, engineers employ a more manageable quantity: electrical power. Power can be properly conceived as the generation rate, or flow rate, of energy. Power is related to voltage and current in such a way that it equals the product of RMS (root mean square) voltage and RMS current (Appendix A). For example, the power consumed by a load is the product of RMS voltage across the load and the RMS current flowing through it. The voltage across all consumer loads is of fairly constant value: in the U.S. (single phase systems) the RMS value is approximately 120 volts. On the other hand, the amount of current delivered varies greatly from one load to another. The current amount can be used to assess the amount of power consumed; current is also seen as the mechanism that sustains the electrical power flow.

Within an electrical system, the power provided by the generator must be greater than the total power demanded by all loads, since we have to account for unwanted power losses. These losses are inherited with the transmission and distribution of the electrical energy. Copper or aluminum wires are usually the main transporters of electrical energy; these materials are good conductors of electricity. In general, a good conductor is seen as a material that presents minimal resistance to the flow of current in it. Good conducting materials include gold, copper, and aluminum. When current flows through a wire, an associated voltage drop occurs (Appendix A); this drop, although small, occurs even in good conductors. From power plants to feeders, voltage drops occur across conductors, cables and transformer windings. These drops constitute unwanted power losses associated with the transmission of electrical energy.

In order to minimize transmission losses, voltage is transported at higher levels (around 100 thousand volts) than it is generated or consumed. This is accomplished via a transformer; ideally (disregarding power losses) the power going into a transformer equals the power coming out of it. Therefore, when converting to a higher voltage, the amount of current (out of transformer) is reduced. A current minimization during transmission yields smaller voltage drops across conductors, or power line cables, minimizing unwanted power losses thereof.

It is in the utilities' best interest to distribute power to all consumers at the highest possible efficiency. Although no practical system is 100% efficient, the duty of a power engineer is to minimize any and all power losses; to us, as consumers, minimizing unwanted losses yields cost and waste reduction. For example, a power engineer would choose better conductors to minimize power losses during transmission. However, better conductors are usually more expensive; hence, the engineer is faced with a dilemma, and deciding the best tradeoff is not quite so apparent. As illustrated by this simple example, in the study of power systems' efficiency, many conditions, issues and variables have to be taken into account. Based on such conditions and variables, an engineer can characterize power systems' efficiency and find methods of maximizing it.

One of these variables is the power factor (PF), which represents an important dynamic of the electrical energy's flow. It can be seen as a figure of merit for the electrical system, and is commonly used to model and characterize power systems' efficiency. The power factor is the ratio of actual power to the apparent power (Appendix A). Through research and mathematical manipulation the power factor can be expressed as the cosine of the angle between the voltage and current sinusoidal waveforms (Figure 2.2.3).

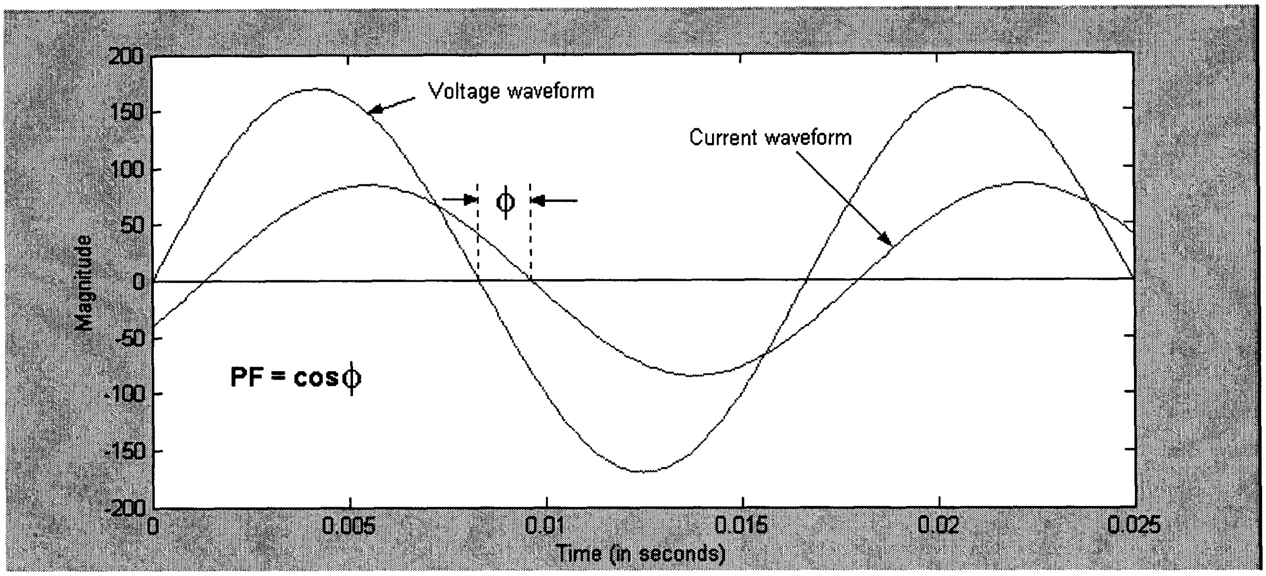


Figure 2.2.3 Out of phase voltage and current waveforms

This result has a meaningful importance: it points out a way of maximizing the efficiency of power usage. When voltage and current are in phase ($\phi = 0$), the consumption of electrical power is 100% productive (Figure 2.2.4). In that case, a unity power factor (PF =1) would be indicative of maximum power usage efficiency. As the current either lags or leads the voltage (equivalent to $\phi \neq 0$), power consumption will be less efficient.

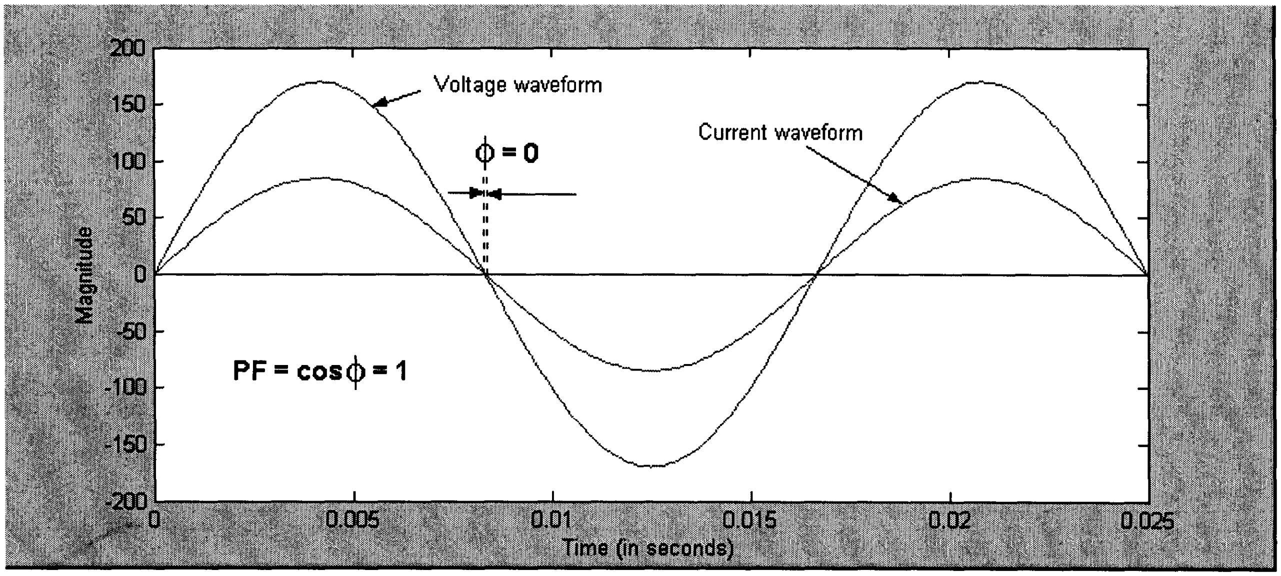


Figure 2.2.4 In phase voltage and current waveforms (PF =1)

Utilities prefer that end-users' loads function close to unity PF (100% efficiency), since it minimizes losses and maximizes system's power usage efficiency. Since the efficiency of the system is closely tied to cost, utility companies have instituted a tariff system that encourages consumers to have a PF greater or equal to 0.9. However, the power factor can change due to load characteristics. To counteract this change it is a common practice to install capacitor banks near a load; these are often known as power correction capacitors for apparent reasons.

A rising concern with mounting capacitor banks is the possibility of system resonance. System resonance occurs when unpredicted factors and conditions, such as harmonic frequencies, become significant. In order to understand this effect, the necessary background is developed in the proceeding section; important concepts, such as single frequency AC, and harmonic frequencies are also introduced.

2.3 Origin of Harmonics

There is a common belief that the 60Hz frequency, under which our AC system operates, was chosen to be the optimum value for a time-varying sinusoidal voltage (as seen in Figure 1.1). The frequency needs to be high enough to fool the human eye. For instance, if the frequency was chosen to be significantly lower, say 20Hz, the human eye could detect the light bulb turning on and off at that rate: not a pleasant sight! At the same time, choosing a "much" higher frequency would prove to be shortsighted, resulting in higher transmission losses and radiation health risks. Nevertheless, the 60Hz frequency may not be the best choice, but it's pretty close to being one. The more important fact is the existence of a single frequency, 60Hz, often named the fundamental.

When additional "foreign" frequencies enter the power grid, electric power becomes polluted, hence, the name: electromagnetic pollution. The majority of these "foreign" frequencies is an integer multiple of the fundamental (60Hz); these frequencies are entitled harmonics. For example, 120Hz would be called the second harmonic; the 180Hz is named the third harmonic and so on. Once harmonic frequencies couple with the fundamental, the waveform becomes distorted; hence, the name harmonic distortion.

To help understand the phenomenon of harmonic distortion, let us compare it to chemical pollution of a lake. An ideal power grid would only accommodate a 60Hz sinusoidal voltage and current waveforms, comparable to a "clean" lake with its main chemical compound: water. Chemical pollutants deposited in the lake are equivalent to harmonic frequencies present in the power grid. As the number and quantity of pollutants increases, so does the damage that they cause on our environment; consequently, more money must be spent to neutralize the negative effects. Similarly, as the number and "magnitude" of harmonic frequencies increases, more equipment gets destroyed and the efficiency of our electric grid is reduced.

Certain electrical loads, categorized as nonlinear loads, generate most of the harmonic content. Nonlinear loads play the role of polluting plants: they inject harmonic frequencies in the current spectrum. The spectrum of a physical entity simply provides the frequency content of that entity. Frequency components of voltage or current are similar to the chemical composition of a material. For example, an ideal 60Hz AC current would have a component only at (or very close to) 60 Hz and nowhere else (Figure 2.3.1).

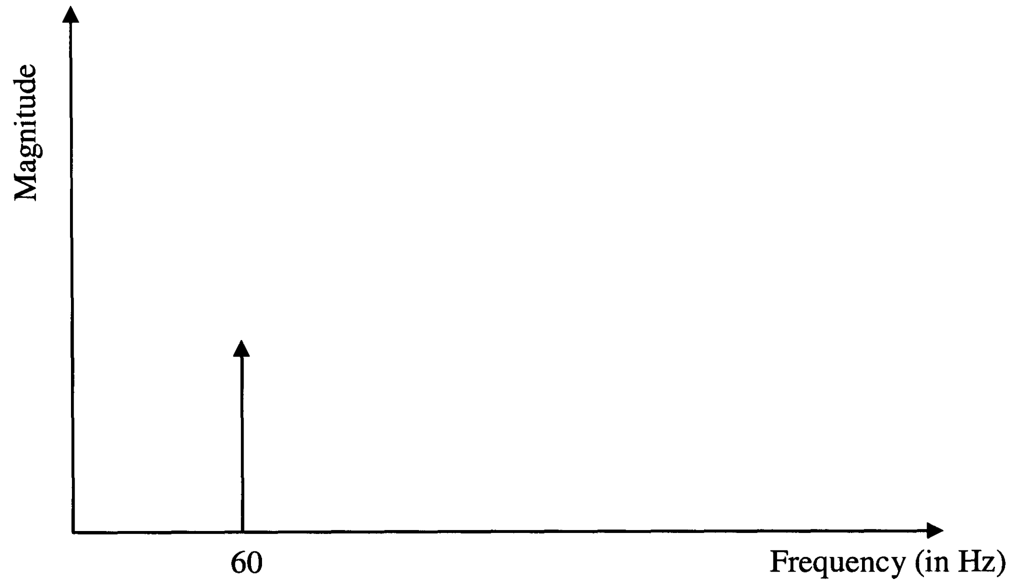


Figure 2.3.1 *The frequency spectrum of an ideal sinusoid*

Conversely, a polluted current can have numerous harmonics, depending on the degree of pollution (Figure 2.3.2).

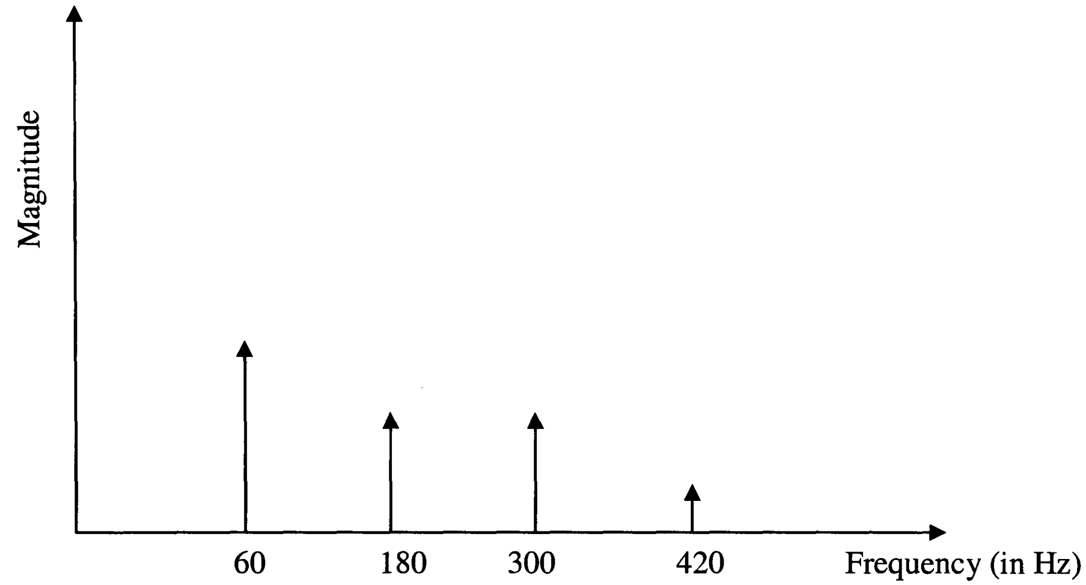


Figure 2.3.2 *The frequency spectrum of a polluted sinusoid*

Nonlinear loads can be modeled as sources of harmonic current; these currents created at one customer's equipment can travel towards the generator. Due to complex power system topology, certain harmonic currents will cancel each other, or get absorbed by the system; however, the majority of them will find their way back in the power network, and distort the current being supplied to other consumers (Figure 2.3.2).

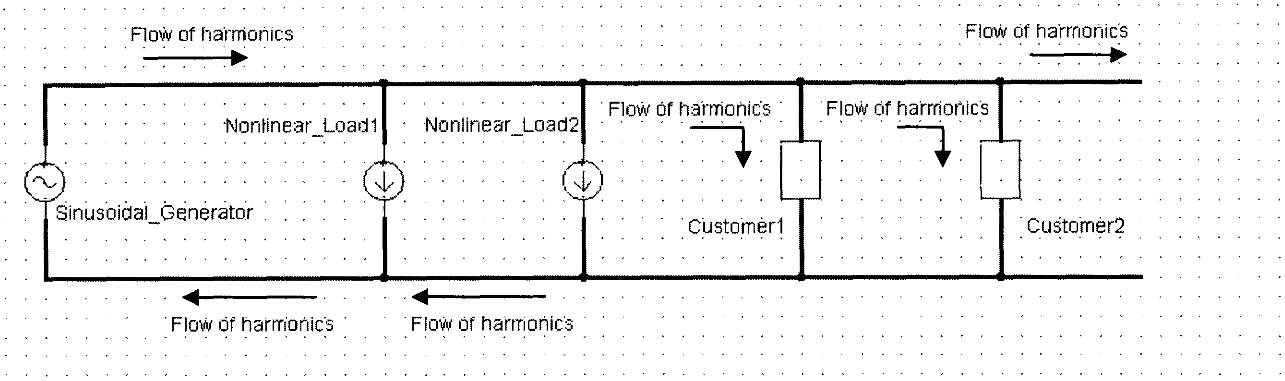


Figure 2.3.2 Flow of Harmonic currents in a power grid

Due to system's impedance, such as conductors, power line cables, some current distortion translates into voltage distortion (by virtue of Ohm's law: Appendix A). Although, interrelated to a large degree, current and voltage distortion have distinct effects (see effects of Harmonic Distortion). The presence of harmonic currents causes voltage distortion; however, it is the latter that is the more financially burdensome and causes most of the equipment damage. Total Harmonic Distortion (THD) represents the amount of voltage distortion (Appendix A). It is a relative measure of how much the harmonic components influence the voltage RMS value. Whereas power factor (PF) was a measure of power quality, total harmonic distortion is a figure of merit for voltage.

Depending on the power network topology, anticipated electricity, 120 volts RMS 60 Hz waveform can be somewhat different from what the outlet delivers. The alternating voltage produced by electric generators adheres to a sinusoidal waveform with fundamental frequency of 60Hz, but that is not necessarily what the consumer receives. Harmonic distortion causes an everyday deviation from the ideal voltage, and is mainly produced by nonlinear loads. More correctly, harmonic distortion is a by-product of the way nonlinear loads process electric energy. The next section discusses the types of nonlinear loads, and presents harmonic research data.

2.4 Nonlinear Loads

Before examining nonlinear loads and their behavior, let us briefly describe what linear loads are. For instance, a resistor is named a linear device, because the voltage across it is directly proportional to the current flowing through it. The proportionality constant is the impedance of the element (in case of a resistor: resistance). When a proportional relationship between voltage and current no longer exists, the component is called nonlinear. Frequency dependence does not imply non-linearity, since at any fixed frequency the impedance is linear (Appendix A). Hence, inductors and capacitors are considered linear elements. Power line cables are linear elements as well. On the other hand, we can group the nonlinear devices of a power grid into three major classes (24):

1. Ferromagnetic (transformer magnetizing)
2. Arcing (arc furnaces, arc lightning) devices
3. Electronic power converters.

These nonlinear elements are mostly present in loads or in specialized switching equipment.

Ferromagnetic devices have a coil wound around an iron core (or magnet), and are in use mainly in transformers or motors. The elements of this class can be modeled as comprising of a series, and, magnetizing impedance. The magnetizing impedance is the *only nonlinear part* of the circuitry, and can be accounted for injecting harmonic components into the AC current spectrum. A summary of current harmonic contents, generated by the magnetizing impedance, can be seen in Table 2.4.1 (24).

Harmonic	Harmonic Magnitude (vs. fundamental)
3	50%
5	20%
7	5%
9	2.6%

Table 2.4.1 *Current harmonic spectrum of a ferromagnetic load*

Thankfully, the current flowing in the *magnetizing part* of the circuit is only about 0.5-1 percent of the overall current; hence, it is important to note that the harmonic magnitudes presented in table 2.4.1 are compared to the 60 Hz current flowing *only in the magnetizing part* of the circuit. Furthermore, delta windings reduce the triplen (3-rd, 9-th, and so on) harmonics. This means that the surviving 5 and 7-th harmonics are very small compared to the overall 60 Hz current. However, their power significance can accumulate as more transformers or motors are present in the grid.

The power network contains several arcing devices such as arc furnaces, mercury vapor lighting and fluorescent lights. These devices have a common basic principle: current is rushed through an air gap causing an electric spark through the gap. In arcing furnaces the temperature increases tremendously: high enough to melt scrap metals. A typical harmonic spectrum of the current flowing through arcing devices is shown in Table 2.4.2 (24).

Harmonic	Harmonic Magnitude (vs. fundamental)
3	15%
5	4%
7	1.5%
9	1.0%

Table 2.4.2 *Current harmonic spectrum of an arc furnace*

In balanced three phase systems, where arc furnaces operate, the triplen harmonics are severely reduced. On the other hand, the 5-th and 7-th order harmonics can find their way back into the power grid. Occasionally, even harmonics (such as 2-nd, 4-th, 6-th ...), caused by erratic arcing during scrap meltdown, can be detected in the current spectrum. As it is the case with ferromagnetic loads, the surviving harmonics' magnitude seems small and harmless; however, considering the number of nonlinear loads present in the system, the aggregate effect can be nothing short of destructive.

The last category of nonlinear loads is a growing concern to power system engineers, and it should be for everyone, because of the increasing number of different electronic appliances present in today's households. In general it is hard to group all electronic converters in one class, due to different characteristics they display. Some examples include: the full wave rectifier, pulse inverters, switched power supplies and so on. Typical current harmonic levels for a line-commutated inverter are shown in Table 2.4.3 (24).

Harmonic	Harmonic Magnitude (vs. fundamental)
3	16.4%
5	5.2%
7	2.9%
9	2.0%
11	1.5%

Table 2.4.3 *Current harmonic spectrum of a line-commutated inverter*

Apart from harmonic distortion, the power network experiences other disturbances as well. Some major disturbances, which affect Power Quality, are summarized in the following paragraphs.

2.5 Power Disturbances

1) Distortion

Non-linear loads present in a power grid, such as ferromagnetic devices, arcing devices, and electronic power converters, inject current harmonics into the system. Depending on the system's impedance, current harmonics can translate into voltage harmonics; therefore, creating harmonic distortion. IEEE Standard 519-1992 contains a thorough discussion on harmonic distortion and the suggested limits on voltage distortion. Voltage harmonics can create problems for any equipment plugged in the AC power line. Problems vary from motor and transformer overheating, capacitor damage, telephone interference, malfunctioning of electronic controls. These effects are further explored in the latter section, titled "Effects of EM Pollution".

2) Imbalance

Voltage imbalance manifests itself as the presence of noninteger harmonics, also known as subharmonics, in the voltage waveform. Subharmonics are frequencies unrelated to the 60Hz (i.e. 132Hz is a subharmonic).

Voltage imbalance is caused by:

a) Unbalanced transformer connections (e.g. open-wye, open-delta).

b) Transformer banks with unmatched impedances.

c) Load unbalance applied to balanced and unbalanced transformer banks.

3) Transients

Most users are aware of the danger of power transients. These are extremely short-lived surges in voltage, but the increase can be in the thousands of volts. Lightning strikes are perhaps the most common source, and without sufficient protection, most people understand that the extra voltage can find its way into sensitive components and damage or destroy them.

Even without considering lightning, other devices within the same electric grid can cause voltage spikes and surges. The voltage increase caused by this change in the load current is not usually as great as with a lightning-induced transient, but it can be damaging nonetheless.

Transients are classified as impulsive or oscillatory. Impulsive transients also know as voltage spikes or switching surges, are usually caused by lightning, capacitor switching, or system faults. They are characterized by a sudden, extremely fast, rise and drop in voltage, reaching a high peak in voltage amplitude. Oscillatory transients last longer than impulsive transients, due to oscillations or ringing. They can be characterized as sudden changes in voltage where oscillations can last several microseconds. These transients are most likely the response of the system to an impulsive transient.

4) Sags

Voltage sags are short-term drops in voltage, of perhaps a few cycles in duration. The voltage decrease is on the order of more than 10% and less than 90%. A typical cause of voltage sags is the start time of a large motor. The large starting current causes the voltage to drop and the lights to dim.

Voltage swells, on the other hand, are short-term increases in voltage of a few cycles duration. The voltage increase is again on the order of more than 10% and less than 80%. Ground faults or energizing capacitor banks usually cause voltage swells.

5) Flicker

The light intensity of a light bulb changes when subjected to a voltage sag or swell; during a voltage swell the light bulb will become brighter, whereas during a voltage sag the light bulb will dim. Flicker is the perceptible change in the light brightness during a voltage sag or swell. Appreciable voltage disturbances can cause significantly apparent changes in bulb's luminosity. Flicker can become an annoying occurrence especially under recurring voltage aberrations.

From all the above voltage aberrations, harmonic distortion requires detailed attention, since it can be a source of confusion to people that are not familiar with the problem. It also requires governmental oversight to counteract the adverse effects of nonlinear loads on the quality of the energy supplied to all customers.

2.6 Effects of Harmonic Distortion

Among its major problems, harmonic distortion overheats and destroys electrical motors and transformers, causes capacitor failures and instrument errors. By and large, harmonic distortion can damage any electrical equipment plugged in an AC power line, reducing their operating lifespan and increasing repair costs. Overall, the effects can be categorized in

1) Financial burdens
2) Socio-ethical violations
3) Grievance issues.

The topic of harmonic distortion has been thoroughly investigated; numerous studies have been conducted and abundant technical papers have been written on this subject. Hence, it is not necessary to dwell on the technical details; rather, taking advantage of existing literature we summarize harmonic effects in the following paragraphs.

2.6.1 Impact on transformers

The adverse effect of harmonic distortion on transformers is closely tied to a phenomenon known as the "skin effect". Simply stated, the skin effect is a result of the increase in frequency of the current flowing in a conductor. At DC, the entire cross section of the conductor is utilized for current flow; however, as frequency increases more of the current tends to flow in the outer perimeter (hence the word skin) of the conductor. Clearly, the skin effect is not an issue at low frequencies (like 60Hz); however, it becomes more significant as frequency increases. The effect can be seen as an increase of resistance, hence, augmentation of thermal losses, at higher frequencies (like harmonics). These losses are also known as stray losses or "winding eddy-current losses". Stray losses increase the temperature of transformers' insulator, which causes overheating and eventual breakdown.

2.6.2 Impact on motors

A major impact of voltage and current harmonic distortion is overheating due to increased thermal losses in iron cores and copper windings at harmonic and subharmonic frequencies. As a result, the motor's efficiency decreases, along with its useful lifetime. The overall cost of motor loss life due to harmonic pollution and imbalance, in U.S. today, is estimated to be in the range of 1 to 2 billion dollars per year (9).

Thermal losses in electric motors depend on the frequency spectrum of the applied voltage waveform. When voltage harmonic components are present, additional eddy-current losses occur in motors' windings. The added rise in temperature is adiabatic; hot spots develop mainly near stator windings due to the skin effect. Therefore the stator insulation experiences thermal aging, which results in reduction of motor's life.

A greater concern is the flow of harmonic currents in the rotor. The basic principle of an electric motor lies in Faraday's law: the alternating voltage in the stator induces an alternating current in the rotor. Permanent magnets, in the stator, exert a magnetomotive force (Lorenz' force) on the rotor, causing it to rotate. Problems occur when different frequencies compete with each other, i.e. cause the rotor to rotate in opposite directions. Studies have shown that different odd harmonics, such as the fifth and the seventh, couple in the rotor and cause torques that oppose the torque from the fundamental 60Hz (3). This conflict imposes unwanted mechanical stresses on bearings, couplings, or, gears; consequently, leading to metal fatigue and fracture. In addition, current harmonics in the rotor cause a pulsating torque behavior, cogging (refusal to start smoothly), as well as higher audible noise.

2.6.3 Impact on capacitor banks

The effect of harmonic distortion on capacitors is a display of resonance. Resonance is a familiar phenomenon to all engineering practices. Bridges have fallen under the regular pacing of the march of a group of soldiers. The same bridge could support thousand times the weight of the group. The march caused the bridge to vibrate very close to its natural frequency, hence causing amplification of the thumps to the point of destruction. Civil engineers will design bridges to have natural frequencies very different to what any well-paced group, or the wind through its structure, can achieve. The fact is that every system has a so-called self-resonant or natural frequency, and a small perturbation near that frequency can grow into greatly amplified vibrations. This results in damage or complete destruction of components in the system.

Electrical systems, too, can exhibit resonance. If an inductor-capacitor series or parallel configuration is excited near its natural frequency, resonance occurs. This becomes an issue with capacitor banks, which are connected in parallel to the load (also known as shunt capacitors) for the purpose of power correction. Good engineering practice teaches us to make sure that the system we design will not operate near the natural frequency of such system. For example, experience has taught power engineers to design systems that have a natural frequency much different than the fundamental 60Hz (where the system operates). However, with a multitude of harmonics, who can account for all the unforeseen frequencies?

Parallel resonance causes most of its damage to shunt capacitors. The effect becomes worrisome with the presence of different voltage harmonics in the power network. Two conditions must be met for resonance to occur in a parallel inductance-capacitance combination of a power system:

1) The natural frequency of the L-C parallel circuit must be very close to an harmonic frequency
2) Enough excitation must be provided at the natural frequency.

When both criteria are met, the voltage across the capacitor gets high enough to cause the dielectric material between the plates to break down.

In addition, the load is also susceptible to breakdown due to parallel resonance. Systems that have a low series-load resistance are more likely to suffer the parallel resonance effects, as are transformers and electromagnetic motors. The series-load resistance acts as a dampening factor; it provides a mechanism for controlling the amplitude of resulting excitations. Parallel resonance can still occur, however, the magnitude of resonance effects is greatly reduced.

2.6.4 Interference

Series resonance is usually less likely to occur, although it still needs to be taken into consideration. There is no amplification of the injected current, but the flow of harmonics can take place in unwanted portions of a power system. Series resonance results in a surge current that can cause electromagnetic interference (EMI) in nearby communication lines.

Power correction capacitor banks can change the flow of current harmonics in a power system. Since the reactance of a capacitor decreases with frequency, a capacitor will sink harmonic currents. During a series resonance the surging harmonic current is a concern because of two major effects:

1) It can create a large magnetic field that can affect communications in unshielded nearby telephone lines, or
2) It can increase heating and dielectric stresses, and as a result, shorten capacitor life.

2.6.5 Instrumentation errors

Power electronics, energy meters are susceptible to misoperation under voltage distortion conditions. Several electronic devices depend on accurate voltage zero-crossing to implement control functionality, such as turning the power to a load on and off. Multiple crossings, caused by harmonic distortion, can disrupt normal operation of electronic devices. Ubiquitous devices that depend on the accuracy of their power supply include digital timers, programmable controllers, medical devices, and, silicon rectifier circuits (SRCs). High levels of voltage distortion result in erratic operation, malfunctioning, electromagnetic interference, and rarely, but possible, device damage.

Measurement errors add to the list of effects attributed to voltage distortion. Disk-type induction meters are amongst instruments prone to displaying erroneous data. These types of energy meters are designed to operate with sinusoidal voltages, but in the presence of harmonics, the disk can either speed up or slow down. Studies show that negative and positive errors are possible, so, next time we look at our watthour meter, we will be wondering whether it registered less or more energy than we consumed.

2.6.6 Relay malfunctioning

Voltage or current distortion can cause protective relay units to operate improperly or not operate when required. Due to the assorted variety of present protective relays, it is hard to generalize the response of a relay unit; needless to mention that relays from the same manufacturer can often respond differently under same fault conditions.

Electromechanical relay units are the ones mostly susceptible to harmonic distortion, because they operate based on a design that utilizes electromotive force acting on an armature, or, a torque applied on a disc. The electromotive force, or torque, can either be reinforced or diminished in the presence of harmonics, causing misoperation of the relay unit. The issue becomes a recurring theme when higher harmonics carry sufficient power to cause the relay to trip. For example, plunger or clapper relays can experience nuisance tripping due to high frequency harmonics; induction disc overcurrent and phase balance relay units can falsely trip under current polluted conditions.

In contrast to electromechanical relays, digital relays are essentially immune to harmonic issues. Digital relays employ a filtering scheme to reject any unwanted frequencies from the current/voltage waveforms; furthermore the current/voltage inputs are sampled and the resulting data is fed to a local microprocessor. Since the presence of harmonics is anticipated, the microprocessor can be used to accommodate for harmonic pollution.

3 Project Statement

This section describes our detailed project goals. These goals helped to specify from the outset a measure of assessing our results.

3.1 Project Goals

There is a trend of growing power quality problems, and the future holds more trouble if steps aren't taken to ameliorate the current trends. Our team was commissioned to closely investigate the issue of harmonic distortion through literature research and measurement data. The research is then to be extended to all power disturbances and power quality issues. Our goal is to relate power quality problems to socio-economical issues.

Goals:

1. Investigate current trends in electric power quality and power disturbances.
2. Investigate sources and effects of harmonic distortion.
3. Provide a tool that facilitates the understanding of technically advanced subjects.
4. Relate electric power disturbances to socio-economical issues.
5. Provide tentative solutions to power quality problems by taking into account technical, economical, and legal issues.
6. Avoid "reinventing the wheel" in order to concentrate on what has not been done.

4 Methodology

In working towards satisfying the specific goals of our project, it was first necessary to provide measurement data that verifies the presence of harmonic distortion. We initially collaborated with our WPI advisor and co-advisor to attain the necessary equipment for making such measurements. This information is presented to the reader in a graphical format.

As a major part of this project, it is incumbent on us relating the technological aspects of our study to social issues. This relationship demonstrates the bond between technology and society, as well as the role of technology in society's decision-making. Power quality problems are not just technical; rather they carry financial and legal concerns. As part of our study, we present the economical burden of power disturbances, such as harmonic distortion, and outages. These financial figures provide a bridge between power quality problems and socio-economical issues.

Presenting and verifying problems related with the consumption of electrical power is one side of the issue; another would deal with ways of properly mitigating them.

In order to recommend solutions to power quality problems, we consulted with our advisors to explore the possibility of comparing harmonic distortion to air/water pollution. From this comparison we raise the following question: to what degree is government intervention appropriate for regulating harmonic distortion and other power quality problems?

4.1 Test Measurements

Harmonic pollution is invisible to the human eye, but fairly easy to detect via a device called frequency spectrum analyzer. The device can provide a picture of the frequency content for voltage or current. Utilizing such device, our team conducted several tests to measure both current and voltage harmonic levels, present in WPI's computer labs. The following graphs summarize our findings.

The devices under test encompassed different computers, such as desktops, and Sun machines. For each computer we monitored the current waveforms on the "hot", and "neutral" wires, as well as the voltage between the "hot" and "ground". In the below graphs we present the time waveform and the frequency content of measured quantities.

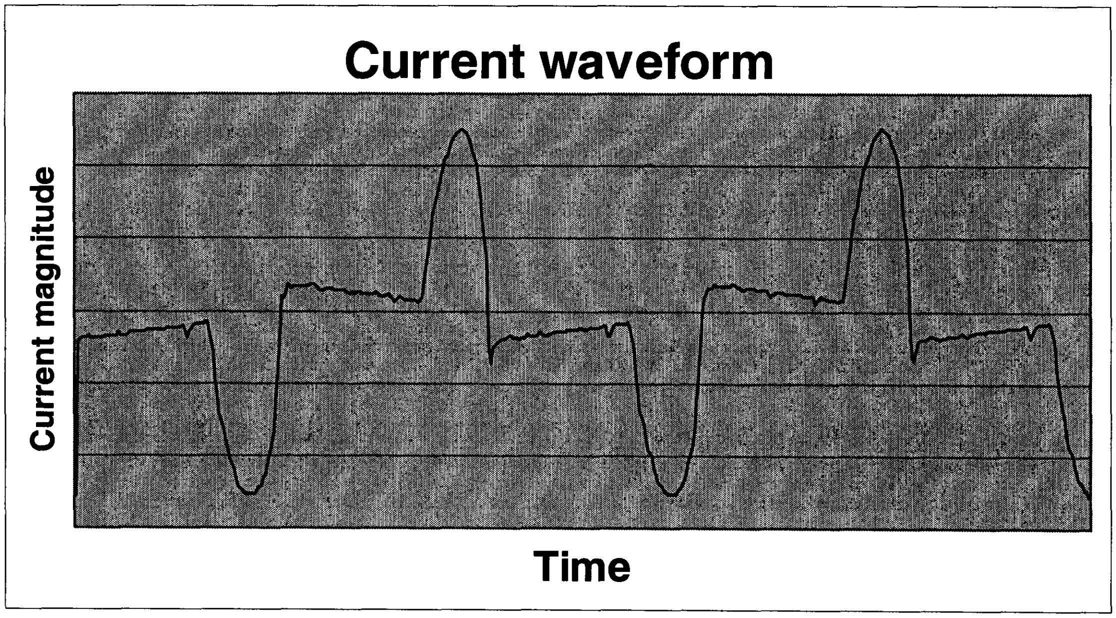


Figure 4.1.1 *Current waveform in the "hot" wire of a personal desktop*

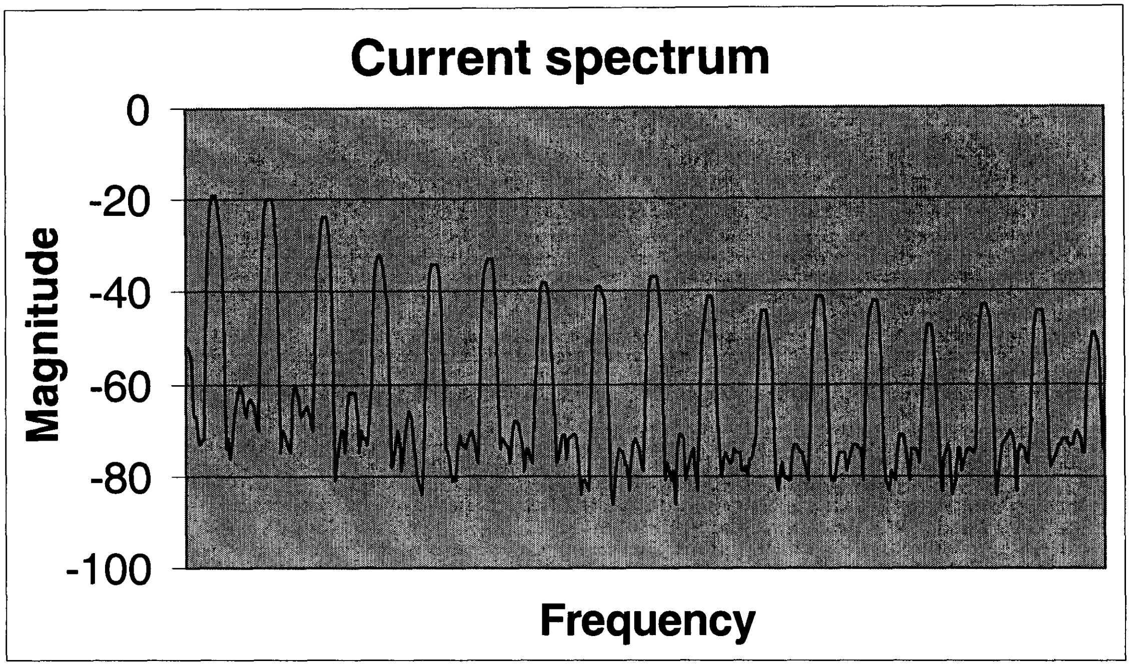


Figure 4.1.2 *Frequency content of the current in the "hot" wire of a personal desktop*

As it can be seen from the time domain analysis, the current waveform is highly non-sinusoidal. The frequency content confirms such behavior, with all peaks occurring at odd harmonics only. The first peak occurs at 60 Hz (fundamental), the second at 180 Hz (third harmonic), and so on. We were unable to show the frequency axis values, to preserve space and the integrity of the display; this can be said for all waveforms presented below. In addition, the magnitudes in the vertical axis are expressed in decibel (dB), which is a relative measurement unit (Appendix C).

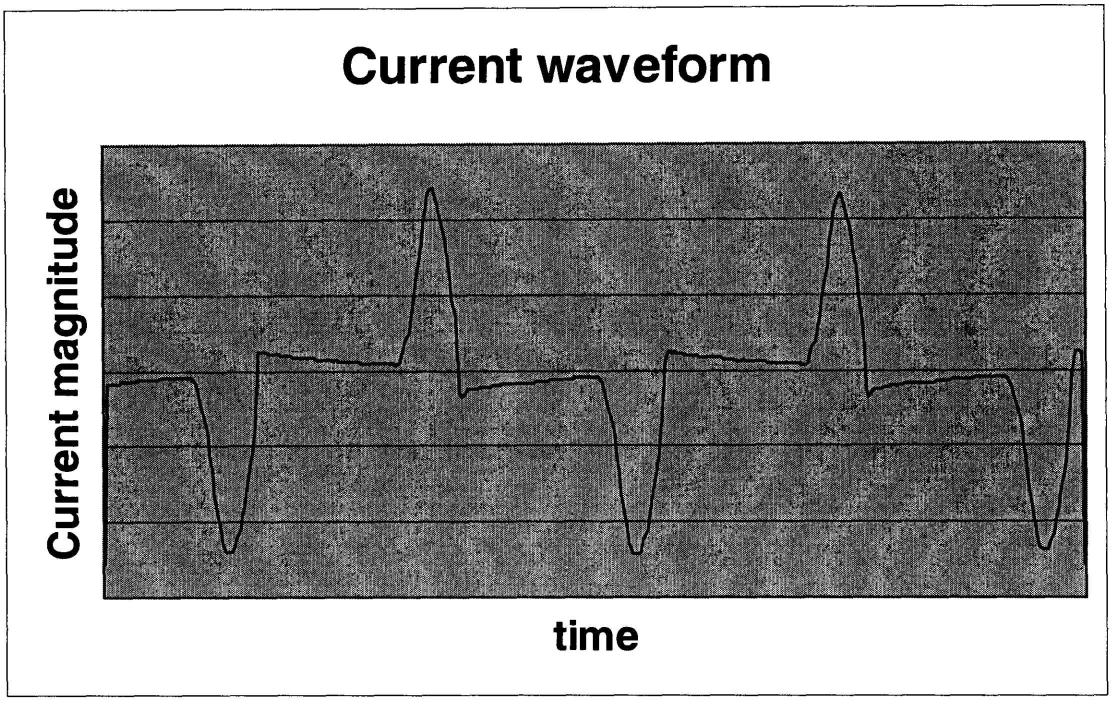


Figure 4.1.3 *Current waveform in the "neutral" wire of a personal desktop*

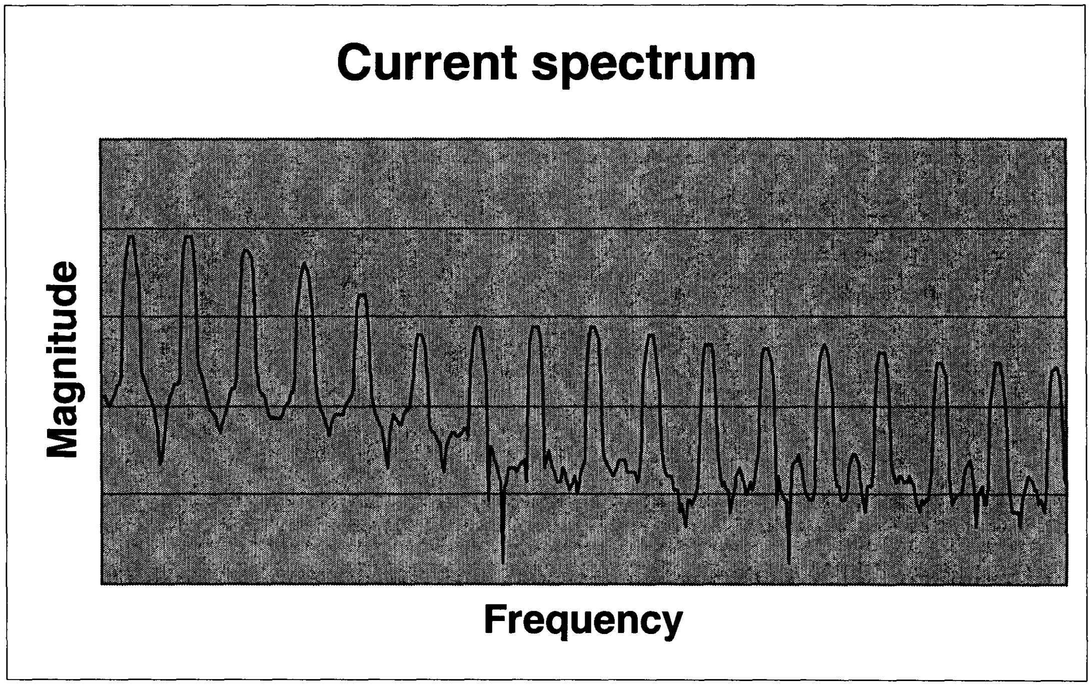


Figure 4.1.4 *Frequency content of the current in the "neutral" wire of a personal desktop*

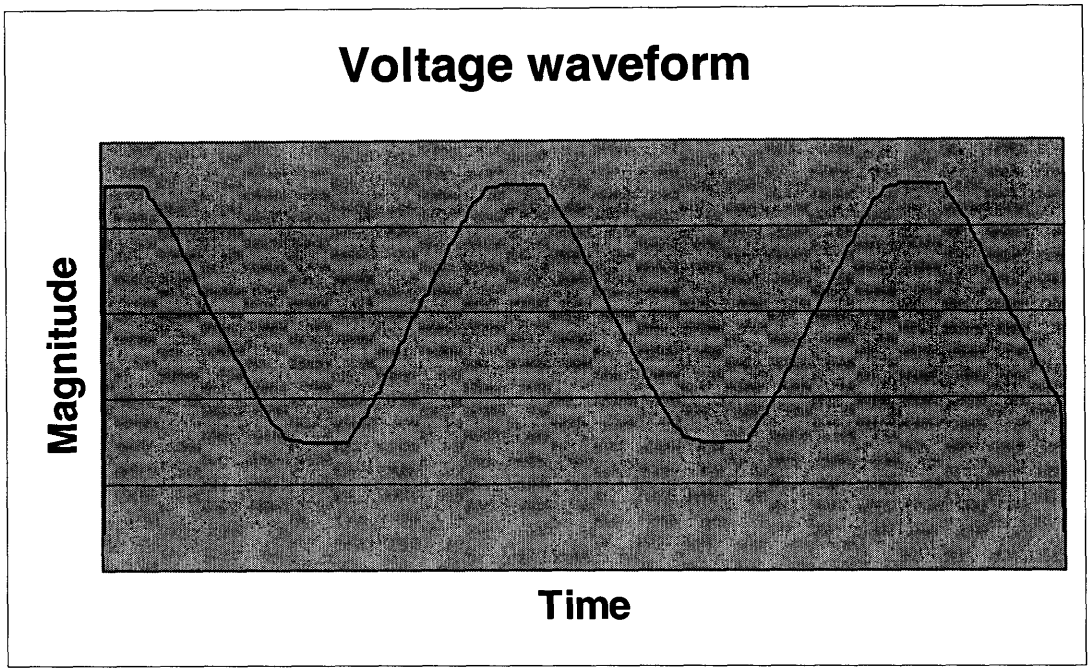


Figure 4.1.5 *Voltage waveform of a personal desktop*

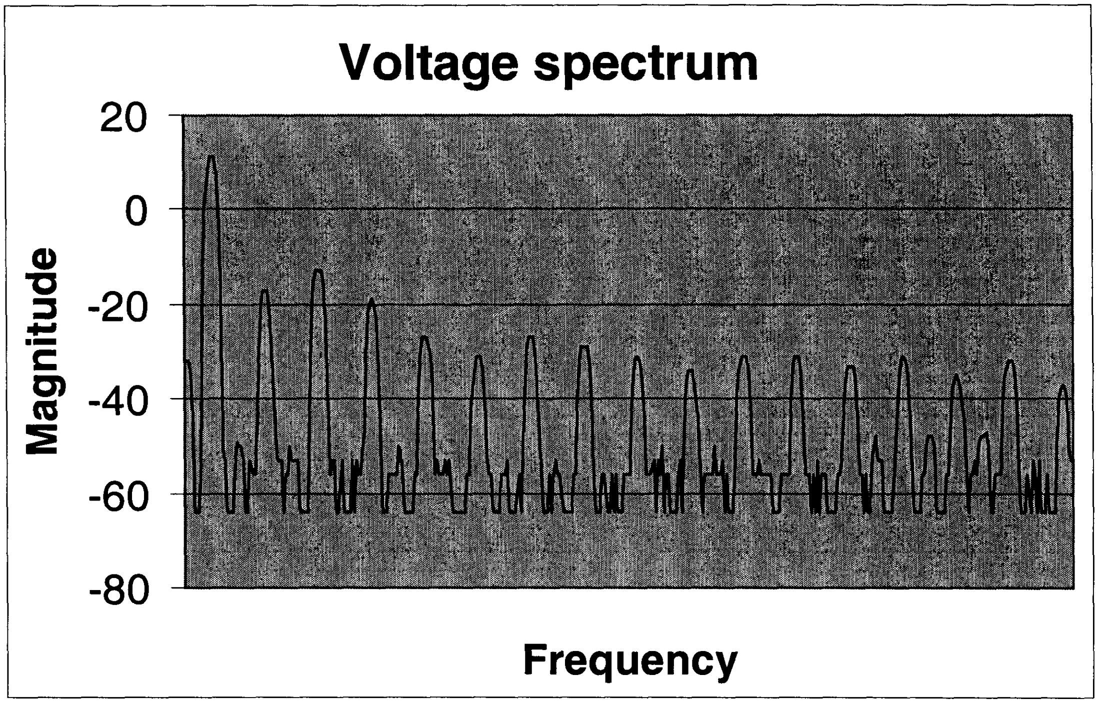


Figure 4.1.6 *Frequency content of the voltage of a personal desktop*

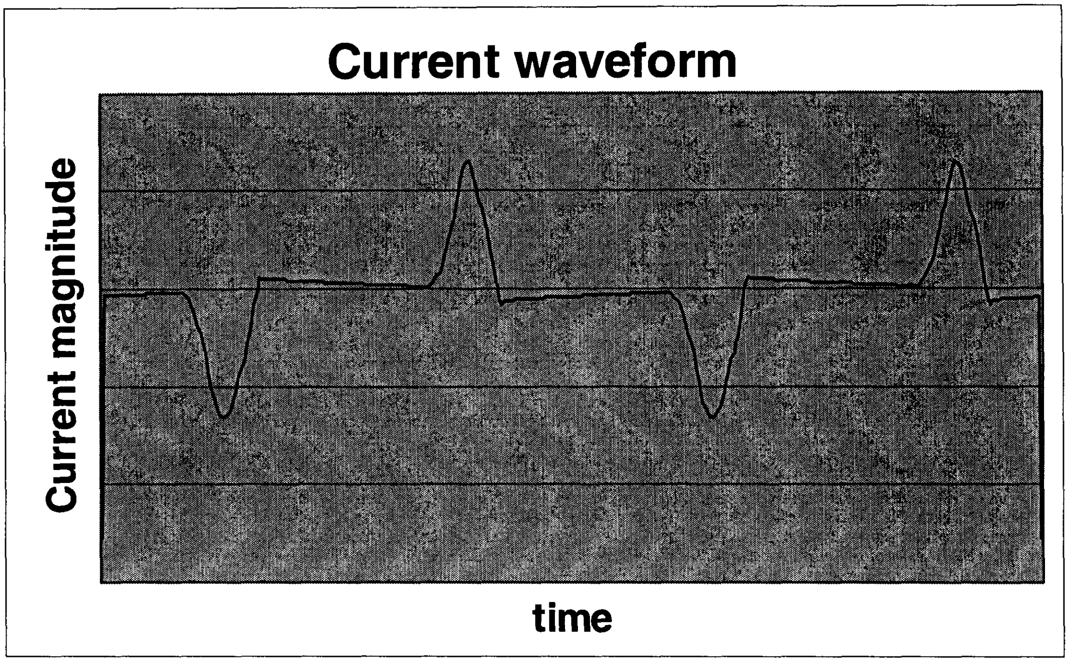


Figure 4.1.7 *Current waveform in the "hot" wire of a Sun machine*

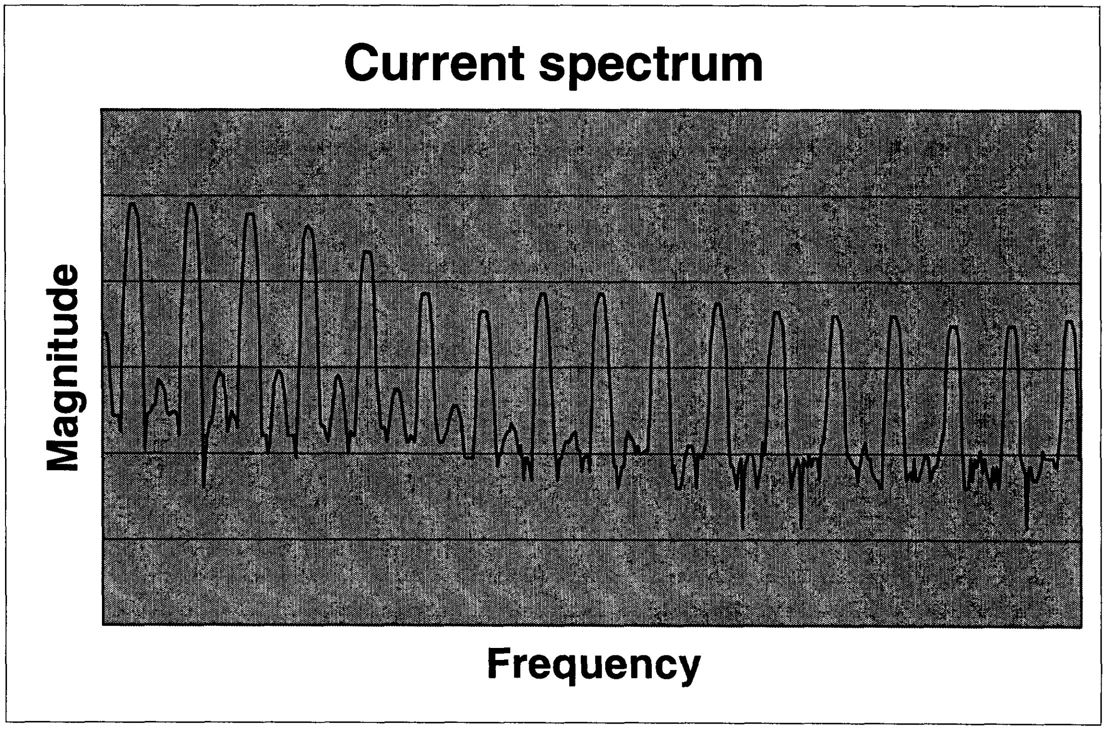


Figure 4.1.8 *Frequency content of the current in the "hot" wire of a Sun machine*

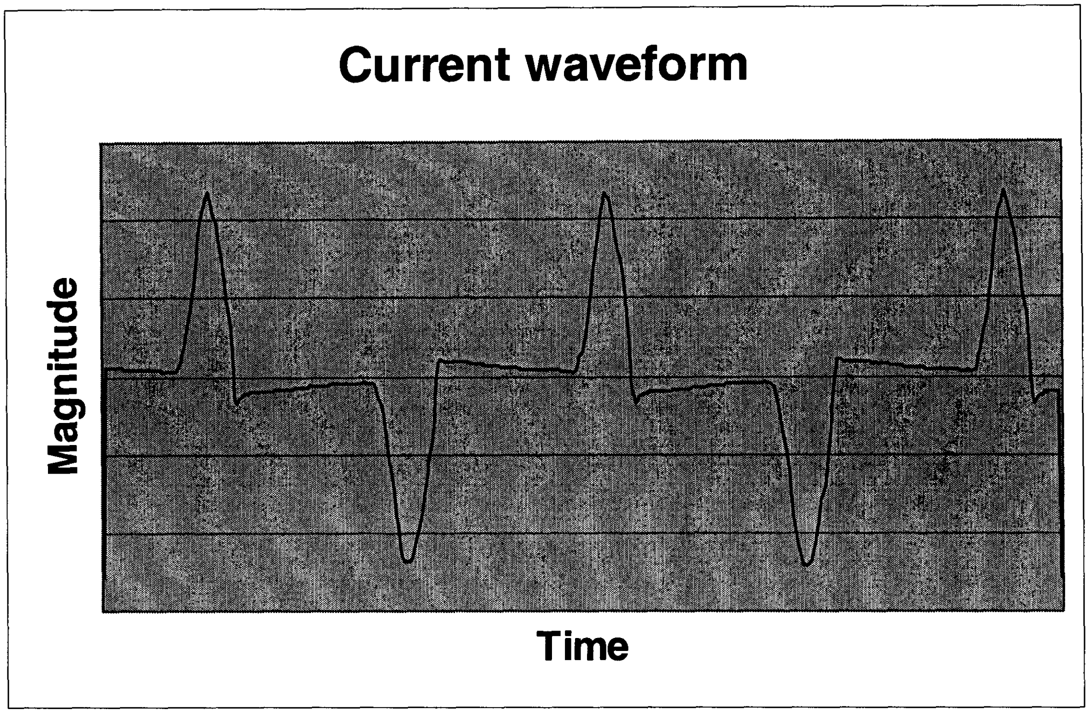


Figure 4.1.9 *Current waveform in the "neutral" wire of a Sun machine*

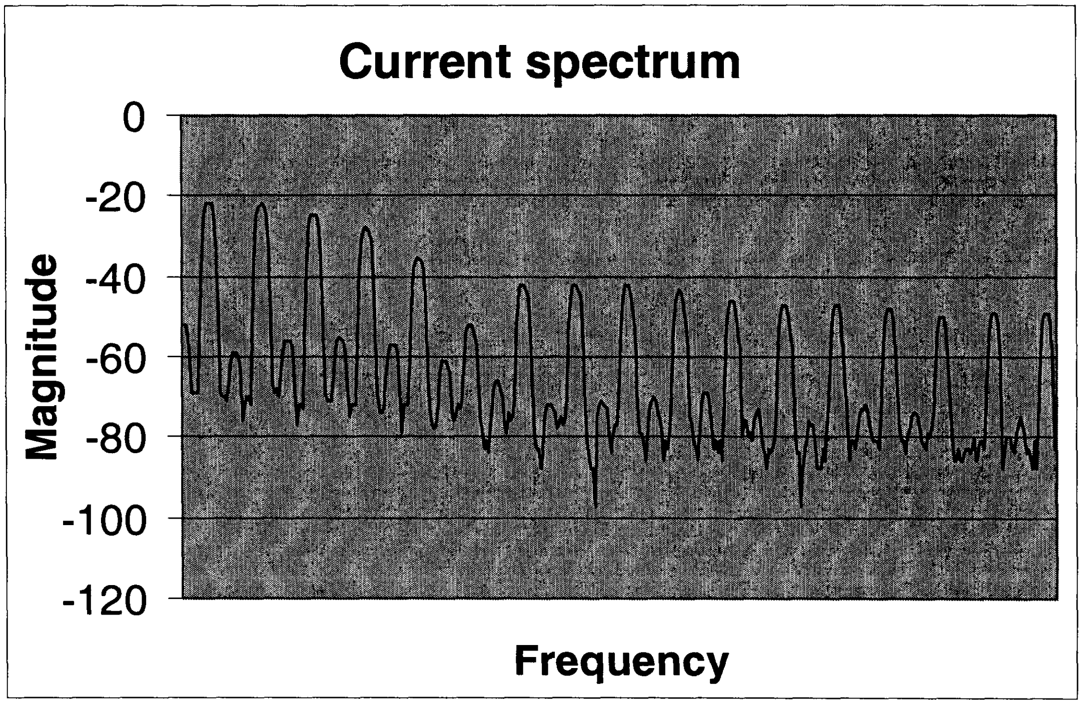


Figure 4.1.10 *Frequency content of the current in the "neutral" wire of a Sun machine*

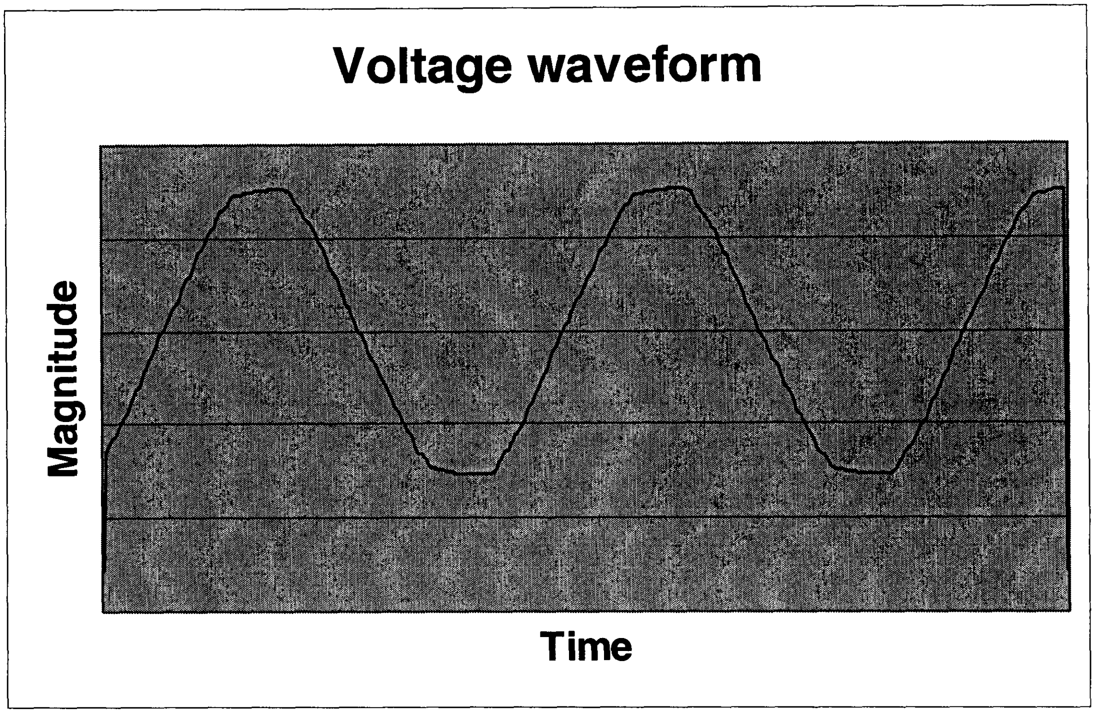


Figure 4.1.11 *Voltage waveform of a Sun machine*

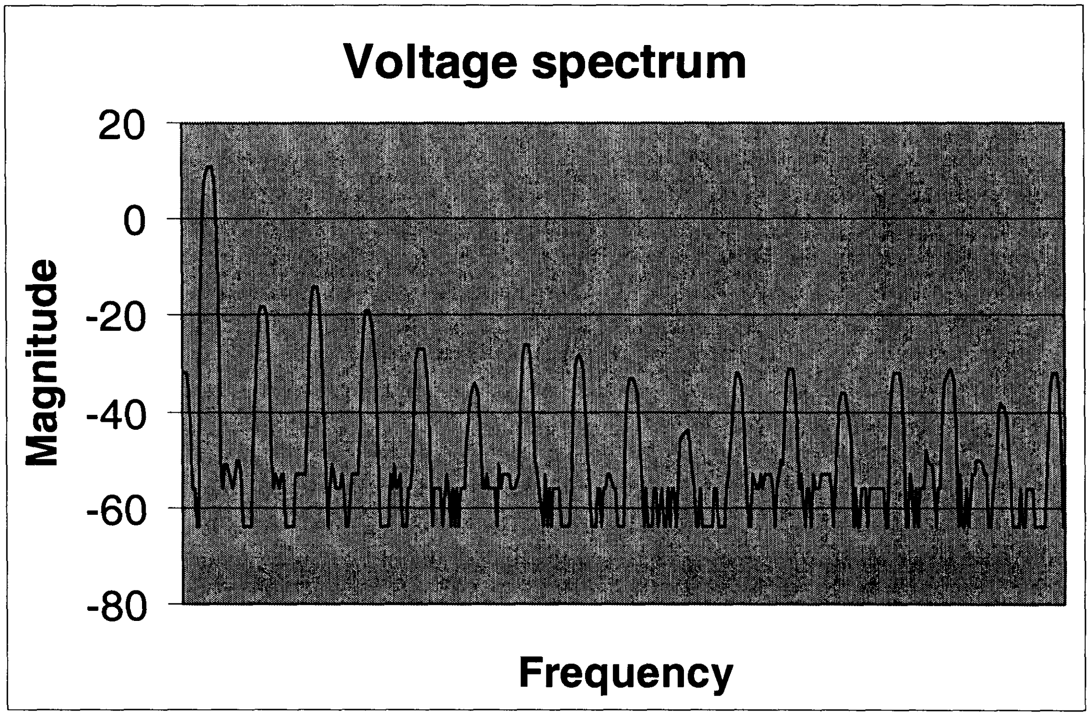


Figure 4.1.12 *Frequency content of the voltage of a Sun machine*

Other measurement techniques employ more involved engineering methods. One approach utilizes the magnetic field produced by harmonic currents in three-phase systems (5). These methods are beyond the scope of our project, as our focus will be on the economic impact of power disturbances.

4.2 Power Quality and Economics

In the past 15 years, there has been an increasing awareness of electric Power Quality issues. In 1991, Business Week magazine reported that spikes, sags and outages cost the nation $26 billion in downtime (10). More recently, an Electric Power Research Institute (EPRI) study put that figure at above 119 billion for just the power-sensitive portion of the economy and without counting the cost of rolling blackouts (10). The study identified three sectors that are mostly susceptible to power disturbances: the digital economy, continuous process manufacturing, and fabrications and essential services. These sectors account for approximately 40 percent of U.S. gross domestic product, while only encompassing roughly 17 percent of U.S. businesses.

"The study concluded that digital economy and industrial firms lost $45.7 billion annually to outages and an-other $6.7 billion to power quality disturbances. Also reported was that across all business sectors, and not just these power sensitive ones, the U.S. economy is losing between $129 and $188 billion a year to outages and power quality phenomena ..." (10)

According to the study the states that suffer the most from energy disruptions and disturbances were California, with losses ranging from $13.2 billion to $20.4 billion without rolling blackouts; Texas, $8.3 billion to $13.2 billion; and New York, $8 billion to $12.6 billion.

"The report extrapolated data from 985 representative establishments to reflect the costs of approximately 2 million industrial and digital economy companies. For each company an individual who was knowledgeable about the effects of power disturbances and the facilities energy consumption completed the survey. The respondents were presented with a set of outage scenarios and asked to estimate the costs for several categories." (10)

While these monetary figures sound alarming, they are more conceivable if one is to consider the cost of lost production, lost time, production of scrap, lost sales, delivery delays, and damaged production equipment. More importantly, the findings of the report underscore the economy's burgeoning reliance on power quality and reliability.

Power quality issues have gotten a lot of press lately, especially with the rolling blackouts in California during the summer of 2001. Due to a poorly implemented power strategy a current legal struggle involves the contract that was implemented during the peak of last summer's troubles (16).

Governor Gray Davis' administration signed $43 billion worth of electricity contracts with 18 energy suppliers for power over the next 10 years (12). The contracts aimed at lowering the amount of power the state had to buy in daily markets, where prices have soared. Such contract however, received large scale criticism, and public disapproval (13). In closed-door settlement talks, California officials demanded that energy companies forgo $8.9 billion in bills for electricity that the state argues was overpriced. However, the decision to refund the state in the form of cheaper long-term contracts was later delayed by federal regulators (15). From this we learn that changing regulations at times of crisis often brings about worse future troubles. If the proper carrots and sticks are presented with care so that they are both possible and reasonable, such crises can be avoided.

A case in point is the great progress that was made in automobile emission control. Emission control was a case in which the manufacturers were initially very much against the antipollution standards, because installing catalytic converters increased the cost of production. As a result, manufacturers were worried that their cars would be more expensive than their competitors'; hence, they would not be able to sell them. At that time, the government intervened and imposed minimum emission standards for all vehicle manufacturers; these regulations put the health of millions before personal profits. Car manufacturers adopted the rules with great gusto, once they saw the advantages in advertising and marketing cleaner-running cars over their competition.

We argue in this section against those that say government has no role, by showing first of all that government has achieved results that would not have been possible without their intercession in the past, such as was the case with automotive pollution controls, and secondly by arguing that in the case of power quality issues the government can again achieve results that would be difficult, if not impossible, without it, at least before the crisis impinges itself to a greater degree on the public consciousness.

4.3 Retrospective on Laws Governing Car Emissions

(or a case study of how and why the government sometimes does the right thing)

4.3.1 The Air Quality Act of 1967

The Air Quality Act of 1967 authorized the Secretary of Health, Education and Welfare (who then had chief responsibility for federal environmental protection programs) to designate so-called air quality regions throughout the country; the states were given primary responsibility for adopting and enforcing pollution control standards within those regions.

Some of those involved in the enactment of the 1967 statue had significant doubts as to the viability of the regional approach to air pollution control; after all, air contamination does not stop as neatly defined regional boundaries. Nevertheless, Congress as a whole and the American industry were not yet convinced of the need for a national strategy for pollution control; therefore, as a first step, the 1967 statute's regional approach became the law of the land.

The approach was a notable failure. By 1970, fewer than three dozen air quality regions had been designated, as compared to an anticipated number in excess of 100. Moreover, not a single state had developed a full pollution control program.

This unsatisfactory record, coupled with the public pressures created by the Earth Day movement (see below), provided the necessary impetus to convince Congress that national air quality standards were the only practical way to rectify the United Sates' air pollution problems. Similarly, the record of inaction under the 1967 law led Congress to impose statutory deadlines for compliance with the emissions standards authorized under the 1970 statute, in hope that those deadlines would spur action.

4.3.2 The clean Air Act of 1970/1977

Just as important as its deadlines and innovative nationwide standard-setting approach was to raise the consciousness of the American public and American business regarding the importance of pollution control. In enacting the 1970 statute, Congress figured that a central element in any successful approach to air pollution control (and, indeed, environmental protection generally) would have to be a change in attitude about the value of environmental protection.

4.3.3 Public hearings on Automobile Pollution Control

In April 1970, William D. Ruckelshaus, Administrator of the Environmental Protection Agency (EPA), asked domestic and foreign automobile manufacturers to show they are making every effort to meet automobile and pollution control requirements of the 1970 amendments to the Clean Air Act. He said the information they submit would be examined in public hearings beginning May 4, 1971. Ruckelshaus, in letters to the companies, requested each of the auto manufacturers to appear at the hearing and to tell about their efforts to develop systems to reduce automobile emissions. Data obtained from the companies will be used in EPA's report to Congress on progress in meeting emission standards. The report is required under amendments to the Clean Air Act, which President Nixon signed on December 31, 1970.

The Act directs the Administrator of EPA to prescribe standards to reduce emissions of carbon monoxide and hydrocarbons by 90 percent from 1970 model levels in the 1975 model autos. Nitrogen oxides standards, reduced 90 percent from 1971-model levels, were to take effect in the 1976 model year. Ruckelshaus asked the companies to provide the following information by April 2, 1971:

A description of the basic techniques being explored to meet emission standards; an indication of the current stage in development and testing; each firm's assessment of prospects for perfecting each technique to the point at which it could be used on production line vehicles; a description of major problems which remained on perfecting techniques' and identification of all other companies participating in developing and testing each technique.

Further information requested by Ruckelshaus included a summary of the resources, in dollars and professional-technical man-years, each company has applied during calendar year 1970 and expected to apply during calendar year 1971, or equivalent company fiscal years, in developing and testing each technique. The EPA Administrator notified that each company should submit a prepared statement for the May 4 hearing, and other supporting material by April 16, 1971.

List of firms receiving the Ruckelshaus letter:

American Motors Corporation; Chrysler Corporation; Ford Motor Company; General Motor Corporation; International Harvester Company; Alfa Romeo, Ins.; Bayerische Motoren Werke AG; Lotus Cars Limited; British Leyland Motors, Inc.; Citroen Cars Corporation; Lincoln-Mercury Division ((European Ford); Fuji Heavy Industries, Ltd.; Fiat S.p.A.; Automobili

Ferrucio Lamborghini; Morgan Motor Company, Ltd.; American Honda Moor Company, Inc.; Mitsubishi Motors Corporation; Nissan Motor Corporation in U.S.A.; Peugeot, Inc.; Renault, Inc.; Rolls-Royce, Inc.; Saab-Scania of America; Volvo, Inc.; Toyota Motor Company, Ltd.; Officine Alfieri Maserati S.p.A.; Volkswagen of America, Inc.; Mercedes-Benz of North America, Inc.; Toyo Kogyo Company, Ltd.

4.4 Effect of Public Consciousness

4.4.1 Earth Day 1970

When President Nixon and his staff walked into the White House on January 20, 1969, they were totally unprepared for the tidal wave of public opinion in favor of cleaning the nation's environment that was about to engulf them. During the 1968 presidential campaign, neither the Nixon nor Humphrey campaign gave more than lip service to environmental issues. Rather, their thoughts focused on such issues as Vietnam, prosperity, the rising crime rate, and inflation. If the candidates showed little interest, so did the national press corps.

Yet only 17 months after the election, on April 22, 1970, the country celebrated Earth Day, with a national outpouring of concern for cleaning up the environment. Politicians of both parties jumped on the issue. So many politicians were on the stump on Earth Day that Congress was forced to close down. The oratory, one of the wire services observed, was "as thick as smog at rush hour."

A comparison of White House polls (done by Opinion Research of Princeton, New Jersey) taken in May 1969, and just two year later in May 1971, showed that concern for the environment had leaped to the forefront of our national psyche. In May 1971, fully a quarter of the public thought that protecting the environment was important, yet only 1 percent had thought so just two years earlier. In the Gallup polls, public concern over air and water pollution jumped from tenth place in the summer of 1969 to fifth place in the summer of 1970, and was perceived as more important than "race, "crime", and "teenage" problems, but not as important as the perennial poll leaders, "peace" and the "pocketbook" issues. Why, after it was so long delayed, was the environmentalist awakening so much more advanced in the United States than in other countries? What motivated millions to so much activity so long after publication of Rachel Carson's Silent Spring in 1962? Many factors seem to have been involved.

First, the environmental movement probably bloomed at the time it did mainly because of affluence. Americans have long been relatively much better off than the people of other nations, but nothing in all history compares even remotely to the prosperity we have enjoyed since the end of the Word War II, and which became visibly evident by the mid fifties. An affluent economy yields things like the 40-hour week, three-day weekends, the two-week paid vacation, plus every kind of labor-saving gadget imaginable to shorten the hours that used to be devoted to household chores. The combination of spare money and spare time created an ambiance for the growth of causes that absorb both money and time.

Another product of affluence has been the emergence of an "activist" upper middle class-college-educated, affluent, concerned, and youthful for its financial circumstances. The nation has never had anything like this "mass elite" before. Sophisticated, resourceful, politically potent, and dedicated to change, to "involvement", it formed the backbone of the environmentalist movement in the United States. Other factors included the rise of television and the opportunities it provides for advocacy journalism.

Also, science contributed another dimension to the national agitation. To the obvious signs of pollution that people could see, feel, and smell, science added a panoply of invisible threats: radiation, heavy metal poisons, chlorinated hydrocarbons in the water, acidic radicals in the atmosphere, all potentially more insidious, more pervasive, and more dangerous than the familiar nuisances. This could happen only in a country able to support a large, advanced scientific community with an immense laboratory infrastructure, marvelously sensitive instruments, intensive funding, computers, data banks, and vast interchanges of information able to isolate and the progress through the ecosystem of elements and compounds at concentrations measured on parts per billion, and to establish their effects upon living organisms in the biosphere.

The press served its function, transporting the latest scientific findings to the public, which reacted with fear and misgivings. These in turn were relayed by the press back to the scientific community, which was stimulated by public concern to intensify its investigations, leading to more discoveries of new perils, and so on. This in itself provided a climate in which support for environmentally related causes could be elicited.

The feverish pitch of Earth Day 1970 passed, but the environmental movement did not go away. Instead, the drive for a cleaner environment became part of our national ethic. Now it is taken for granted, the best possible testimonial that progress is being made. Our nation's thinking has changed. Endorsing growth without regard to the quality of that growth seems forever behind us. The failure of the economy to take into full account the social costs of environmental pollution is being rectified. Not only are environmental considerations now factored into federal government decision – making but over and over again Americans pay for low-polluting or pollution-free products like low-sulfur heating oil, unleaded gasoline, and coal from fully reclaimed strip mines, for automobile emission controls, for electricity from cleaner fuels, and for more parklands and wildlife refuges. More fundamentally, we are beginning to understand that the environment is an independent whole of which man is only a part.

But in the early 1970s it was clear that the executive branch could not respond to public demand to clean up the environment without first creating an organization to do the job. At cabinet meetings, HEW Secretary Bob Finch, responsible for air pollution controls, and Transportation Secretary John Volpe, argued over which department should take the lead in developing a research program for unconventional low-polluting automobiles. Maurice Stans at Commerce was wary of tighter pollution controls and what effect this might have on corporate profits. Paul McCracken, Chairman of the Presidents' Council of economic Advisors worried that we would be uncompetitive in international markets if our product prices reflected the pollution abatement standards that were more stringent than those of other countries. There was hardly a Cabinet officer who did not have a stake in the environment issue. Even the Postmaster General joined the debate, offering to use postal cars to test an experimental fleet of low-pollution cars.

The Cabinet meeting left President Nixon dissatisfied. There was no overall strategy, too many unanswered questions. Should enforcement be done by regulation, or by user fees, or a combination of both? What were the overall costs to industry and the consumer in terms of both the increased price products for various pollution abatement schedules under varying standards and regulations? Finally, what would the various clean-up scenarios do to the federal budget? Nixon clearly needed a "pollution czar" and one agency to look for the answers.

First, Nixon discarded the option of a Department of Environment and Natural Resources as well as other reorganization plans. In July 1970 he submitted to Congress the Environmental Protection Agency plan; the new agency came into being on December 2, 1970. Bill Ruckelshaus to run the new agency was a "bull's eye".

Now, years later, the accomplishments of the Nixon years are plain to see: new clean air, water, solid waste, and pesticide laws, coastal zone management planning seed money, new national parks, including the great urban parks in New York City and San Francisco harbors. In addition, Nixon order federal agencies to shed spare federal acreage that would be converted into parks and recreation areas, especially in urban areas. More than 82,000 acres in all 50 states were converted into 642 parks, the majority of them in or very close to cities, really bringing parks to the people.

What Nixon – and subsequent presidents – could not accomplish is to address in a rational was the cost of pollution abatement control: how fast should the national clean up and at what cost? In the early 1970s, our polls clearly showed the public demanded a cleaner environment, but data on the public's willingness to pay was ambivalent. Our initial Opinion Research polls showed that about three fourths of the public supported more government spending for air and water pollution abatement programs, that support existed in all population groups, and that it was particularly high among the young. But this did no mean that taxpayers had committed themselves to spending their own money to improve the quality of the environment. Spending for government programs never seems to equate in the public's mind with spending their own money. Opinion Research reported that in May 1971, three-fourths of the public would pay small price increases for pollution control, but six put of 10 opposed large increases for that purpose.

A Harris poll in October 1971 indicates that 78 percent of the public would be willing to pay (how much was not specified) to have air and water pollution cleaned up, and 48 percent would accept an 10-percent reduction in jobs for a cleaner environment. Poll editor Hazel Erskine indicated that individuals were not "personally anxious" to foot the bill for correcting pollution damage, although willingness to pay for pollution control was growing.

Congress received even stronger messages. Twenty-two congressmen, in a survey of 300,000 Americans in varying kinds of congressional districts, asked constituents if they were willing to pay for more pollution control. Respondents in all but three districts answered affirmatively. Representative Gerald Ford asked his Michigan constituents, "Should the federal government expand efforts to control air and water pollution even if it costs you more in taxes and prices"? The answer: 68.33 percent yes, 27.5 percent no. Congress, fanned by the political hurricane of the environmental movement, enacted deadlines that could never be met, like the 1977 deadline for secondary treatment of municipal waste, and an $18 billion appropriation over the three-year life of the law, which could not even be dispensed under the law's cumbersome grant system. Similarly, Congress legislated technology that did not exist by setting emission standards for automobiles that could not be met and later were postponed. The missed 1987 year-end ozone deadline is another glaring example of Congress; tendency to legislate non-existent technology.

Today Americans spend about $100 billion annually for environmental improvements. Today we have scientific capability and sophisticated cost-benefit analysis to steer a course toward a cleaner environment. The question is, will our elected officials and executive branch regulators read the signs of future problems before they become large enough to slow down our economy?

4.4.2 Ralf Nader – Hero?

By the second summers of their existence, 200 "Nader's Raiders" were selected from among 30000 applicants. I think one-third of Harvard Law School applied, Harrison Swellford, then the director of the Center, told a reporter. The task forces were charged with investigating corruption and incompetence at the Interstate Commerce Commission, the now-defunct agency which regulated trucking and railroad rates (The Interstate Commerce Omission, by Robert C. Fellmeth, 1970); documenting the health hazards of air pollution made worse by irresponsible businesses and complicit politicians (Vanishing Air, by John Esposito, 1970).

What made the early Nader investigations so riveting and newsworthy was the limited nature of mainstream American journalism at the time. Investigative journalism was hardly practiced at most daily newspapers, and few legislators cared to look very closely at the performance of federal agencies from the perspective of the average citizen. By naming names and providing meticulous documentation, the Nader study groups made for hot copy. The spectacle of greenhorn students exposing one instance after another of government foot-dragging, special-interest collusion, corporate malfeasance and outright corruption, made the reports all the more compelling. In light of future revelations of environmental pollution and government scandal in the Nixon and Reagan administrations, Nader reflected in 1989 that the early reports were actually “quite understated”.

The genius of the early Nader reports was to expose the blatant disparity between obvious public wants (clean air, safe workplaces, honest competition, quality goods and services) and the failures of the marketplace, as constituted, to meet those wants. Nader and his associates went a step beyond documenting this disparity, however. They waged aggressive follow-up lobbying, litigation, citizen organizing and publicity to force the government to reform a seriously flawed marketplace. As Edward B. Rust, then-president of the US. Chamber of Commerce once admitted: “The whole point of Nader -- so obvious that it is often overlooked -- is his single-minded dedication to making the free enterprise system work as it is supposed to -- to make marketplace realities of the very virtues that businessmen ascribe to the system”.

4.5 Regulation of Power Quality

The retrospective of vehicle pollution control provides the necessary leverage for an argument that supports government participation in mitigating power quality issues. Government involvement was necessary to legislate and implement emission control standards;

without government's arbitration such standards would unlikely emerge into reality. Power disturbances, especially harmonic distortion, exhibit a similarity to air/water pollution, in the sense that one's wrongdoing affects other consumers in the grid. While power disturbances do not affect the air we breathe or the water we drink, they violate consumer rights: the expectations of the electric consumer are not met due to poor power quality.

In terms of legislation, power quality issues are where air/water pollution standards stood in the late 60's. IEEE Std. 519-1992 outlines standards and methods of mitigating harmonic distortion; however, these standards are not set rules that one has to follow. The source and effects of disturbances are well known, yet the lack of ratification violates consumer rights. Clearly, the need for enactment recognizes the government as a crucial player in mitigating power disturbances. Several issues remain unclear however. To what degree should the government be involved? Moreover, which other parties are involved with power quality issues? What concerns should be addressed when mitigating power disturbances?

Next section details the answers.

5 Recommendations

This section of the report details our recommendations for mitigation of harmonic distortion and other power quality problems.

Before recommending a solution, the team initially identifies aspects of power quality issues: what needs to be addressed before a solution is implemented. Secondly, we look at the parties involved and recommend the degree of their participation. At last, a look into the future predicts more troubles if appropriate steps are not taken to deal with the current trends of power quality.

5.1 What Should Be Taken Into Account

Mitigating power quality problems is not an easy task, even when causes of disturbance have been determined. A solution needs to primarily address the following aspects:

1) Technical
2) Financial
3) Legal

5.1.1 Technical Aspects

Power disturbances, including harmonic distortion, have been thoroughly studied and technical solutions are readily available. (28)

The two main methods used for reducing harmonic distortion are (Appendix B):

a) Series filters
b) Shunt or parallel filters

For each approach two main configurations are used: passive, or active. The first configuration incorporates only passive components such as resistors, inductors, and capacitors. An active filter, on the other hand, is distinguished by the use of active devices, such as transistors or amplifiers, but it can include any passive component as well.

Passive filters are the most widely used, since they provide a cost effective solution. They utilize an inductor and capacitor connected in series, which resonates at or near the frequency of a dominant harmonic component. In this case, the resonance effect is used to one's advantage, acting as a tool to diminish a certain harmonic component. In addition, parallel filters also provide the means for improving the power factor to a certain extent. Several disadvantages exist from the use of passive filters:

a) They can sink harmonic currents from all nonlinear loads present in the power network. Such an effect tends to overload the filter, reducing its useful lifetime, or causing breakdown if sufficient current flows through it.

b) Passive filters tend to be bulky, so they can present size problems.

c) A passive filter can only be tuned to filter out a certain harmonic. In order to reduce all harmonics, a passive design needs to incorporate several filters.

Active filters can be designed in such a way that these shortcomings are surmounted. However, while active filters provide a better technical solution, they are more expensive than their passive counterparts.

Mitigation equipment is available for dealing with other disturbances as well. Table 5.1.1 provides a summary of equipment used for dealing with power disturbances, and the relative cost (1).

Disturbance	Surge Suppressor	Filter	Isolation Xformer	Voltage Regulator	Motor-Generator	Dual Feeder	UPS	UPS and Engine-Generator
Surge	V				V		V	V
Sag/swell				V	V		V	V
Interruption						V	V	V
Harmonics		V		V			V	V
Noise		V	V		V		V	V
Relative Cost %	<1	1-30	5	35	45	25-50	60	100

Table 5.1.1 *Mitigation equipment for power disturbances*

5.1.2 Financial Aspects

While technical issues can present a tough challenge, it is the financial issues, which become a major source of conflict and disparity. Financial disagreements originate with the popular question: who pays? The difficulty of cost allocation is augmented from the fact that there is a multitude of loads causing disturbances, and the corresponding consumer is not likely to accept responsibility.

Consider again the example of the chemical pollution of a lake. Two existing chemical plants, A and B, dump into the water respectively X and Y quantities of the same pollutant. Typically, the monetary damage is proportional to the square of the quantity. This damage represents the cost required to neutralize the pollution effects. The following diagram illustrates this:

Power plant A dumps X kg of certain pollutant

Power plant B dumps Y kg of same pollutant

Total damage = $(X+Y)^2 = X^2 + Y^2 + 2 \cdot X \cdot Y$ dollars

The majority of disagreement originates from the cross-product: 2XY. The task of damage allocation becomes arduous as the number of polluting plants increases. If a new power plant C is added to the topology, the aggregate damage becomes:

Power plant A dumps X kg of certain pollutant

Power plant B dumps Y kg of same pollutant

Power plant C dumps Z kg of same pollutant

Total damage = $(X+Y+Z)^2 = X^2 + Y^2 + Z^2 + 2 \cdot X \cdot Y + 2 \cdot X \cdot Z + 2 \cdot Y \cdot Z$ dollars

Therefore, existing plants A and B will now have to pay more than what they used to when C was not there. The complexity becomes obvious as more polluting plants appear, more chemicals are added, and if instead of a square law, the damage is proportional to the cube, the fourth, or even a higher power of the pollutants' mass.

This simple example illustrates the difficulty of damage allocation associated with chemical pollution. The same argument can be extended to other types of pollution, such as harmonic distortion. In that case, nonlinear loads play the role of polluting plants, and harmonic frequencies are the pollutants. With a multitude of nonlinear loads and harmonics, the problem of properly dividing the cost among consumers becomes improbable. The addition of other power disturbances makes the task of cost distribution nearly impossible.

The tedious task of damage allocation can be alleviated if power disturbances, such as harmonic distortion, are eliminated firsthand. This entails selling equipment that does not pollute the power grid or cause other disturbances. For example, to mitigate harmonic distortion effects, nonlinear equipment can have filters built in them; these filters reduce the very harmonics the equipment produces. While this serves the purpose of maintaining a pollution-free power grid, it will increase the cost of production.

5.1.3 Legal Aspects

The idea of installing mitigation equipment along with the device being marketed follows the same path as to what was done with emission control in the 70's. Car manufacturers opposed the idea of installing catalytic converters, because it raised the price of cars. By the same token, electronic equipment manufacturers will initially resist similar ideas since it raises the cost of manufactured goods; their intent is to sell a product at the lowest possible cost. However, if the drive for profit adversely affects other consumers, something needs to be done to establish fairness in the marketplace. Such fairness can be obtained by enacting laws that demand all manufacturers to meet certain standards.

Several issues need to be addressed:

1) Benefits of regulations versus cost. What are some of the drawbacks associated with solution schemes? If laws that regulate harmonics result in large revenue reductions, then the standards should be tailored to economy's welfare.
2) Who should be entrusted with the supervision of electric power quality? Furthermore, should the society rely only on one information channel?
3) What are some steps that need to be taken to assure impartiality?

It would be easy to blame power companies and utilities for power quality problems; after all they are the ones supplying the power, hence they should be responsible for maintaining a "pollutant free" power grid. This theory disregards, of course, the fact that each consumer that inserts a plug in an AC outlet can adversely affect the quality and efficiency of the power grid. Keeping harmonic distortion out of the power lines is in the best interest of not only utilities, but consumers as well. Therefore, legal matters pertain not only to distributors, rather to all parties involved with the quality of electric energy.

5.2 Parties Involved

While the government is an important factor in influencing a change, there are also other parties involved with the issue. There is the distributor/utility, equipment manufacturers, and the electric consumer.

5.2.1 Utility Side Mitigations

Arguably the most important power quality related task of electric distributors is the evaluation of power system efficiency and power quality. This will entail the duty of collecting and keeping track of power quality data. For this purpose, utilities can install measuring points in strategic locations, such as near feeders, problematic consumers, and affected customers.

The evaluation of power quality will help distributors locate consumers that cause power nuisances. For example, if utilities have readily available power quality data, they would be able to evaluate power quality near the feeder with and temporarily without a particular customer connected to the grid. This technique will work especially well with new clients, however could be a major source of conflict with existing clients, especially when taking into account the multitude and variety of electrical customers. In the latter case, power interruption could be unacceptable even for a short period of time, making power quality data collection nearly impossible. In such instance, a common agreed upon time can be used for data collection. In the case of industrial consumers, such time could be a weekend or holiday. To facilitate the laborious task of data collection, measurements can be taken in a whole region at a particular day. These measurements should be repeated at certain time periods, such as yearly, because it is common for consumers to install new equipment in their homes or industrial facilities.

While data collection helps evaluate power quality, it is important to observe particular trends in the power market. This task would entail analyzing the collected data and predicting power quality for the future. Attained data can be used to characterize electric power consumption and evaluate power quality. This information would be helpful in locating those consumers that adversely affect power quality, also known as problematic consumers. In addition, utilities can extrapolate future power quality, based on present tendencies of power consumption. This step would enable the electric distributor to alert of possible power problems, such as outages.

Once collected data has been analyzed, mitigations should begin with the common goal in mind of solving identified problems. As a start, utilities should involve the general public with power quality issues. Public awareness can be achieved through many ways. For example, advertising which type of equipment is or is not conforming, serves the purpose of public awareness. In addition, the following paragraph details some suggestions.

Pamphlets that explain power quality issues and disturbances can be put together and distributed to the electrical consumer. So far, the knowledge about harmonic distortion is confined within interested parties, such as utilities, power engineers, and equipment manufacturers. To the general public, the topic of harmonic distortion may seem mysterious and incongruous, because for the most part the public is unacquainted with the issue. To this unfamiliarity adds the difficulty of explaining such topic: the average man does not deal on daily basis with concepts like frequency spectrum or harmonic content. As it was the case with air/water control movement, an effort must be made to explain in simple terms the phenomena, causes and effects of power disturbances, such as harmonic distortion. For this purpose, comparisons could be useful to gain public sympathy and support. The similarity with the chemical pollution of a lake is valuable and practical: while harmonic distortion doesn't kill any fish, it slowly degrades and kills power grid inhabitants: electrical equipment.

While many consumers may not fully understand the many topics of power quality, they are willing to listen about financial effects. Ultimately power disturbances affect the consumer pocketbook, and put a burden in our economy. Harmonic distortion can then be seen as an economical parasite, which we have to get rid of.

In order to provide a fair solution to power quality problems, the cost of mitigating equipment and labor must be properly divided amongst problematic consumers. For this purpose, the customer needs to be convinced, through collected data, that his equipment is causing power disturbances. This is an important step, because without a common ground no further progress can be made. When exact causes of power disturbances are determined and agreed upon, utilities can propose a variety of solutions to consumers. One solution, involves installing mitigation equipment at each problematic consumer.

Since each technical solution has an accompanied cost, it is up to the consumer to decide which one best fits his needs. Upon his choice, the consumer can let the utilities install mitigation equipment or do it himself. However, if utilities were to install equipment that filters out certain harmonic(s), then the cost of hardware and associated labor must be recovered.

In addition, distributors can institute financial systems that compensate clean power consumption. This system would encourage and get customers involved with minimizing power disturbances. The encouragement can come in the form of lower cost per kilowatt-hour or other monetary benefits. In addition, consumers can benefit from programs such as rebating. For example, when a consumer buys equipment that conforms to harmonic pollution standards he should receive a percentage of the money back. Rebating programs can be established through a combined effort of utilities, government, and equipment manufacturers. Each of these can put aside funds for the purpose of encouraging clean power consumption. Rebating programs are of key importance, especially in the early phase of regulation efforts.

Instituting financial systems should not become a way for distributors to overcharge consumers. The perennial importance of electric power makes it hard for consumers to deprive themselves of its services. Therefore, these financial systems should be closely watched by a dedicated governmental agency or branch of it. Utilities should deliver yearly reports to this agency branch, including steps taken to encourage/rebate conforming customers. These reports should be made available to the general public. Consumers can then compare what their utilities are doing better or worse than other power distributors in the country. The above steps will constitute a system of checks and balances, needed to assure fairness and consider consumer input.

Distributors should initially make a push for establishing laws that govern power disturbances, such as harmonic pollution. In petitioning lawmakers ideas or outlines of solutions should be provided. Petitions should be followed up by aggressive lobbying of state and federal officials.

Once standards have been established, utilities have to supervise the grid and preserve power reliability. Non-conforming customers will need to either meet standards, or be denied electric service.

5.2.2 Consumer Side Mitigations

Power disturbances, such as harmonic distortion, ultimately affect the consumer's pocketbook, but ironically the customer is naïve about the subject and has the least power to influence change. When the customer buys equipment, he is not given any information about the harmonic pollution that the instrument causes, so he cannot differentiate between "good" or "bad" equipment. Even concerned and knowledgeable customers are not given the necessary information to influence a decision. Instruments for harmonic testing are readily available, but quite expensive, therefore, only affordable to large electric consumers, such as industrial plants, factories etc.

The electric consumer is mainly concerned with power interruption. In the case of an industrial customer, a production shutdown causes a large financial loss to the company. Encompassed are apparent losses: lost time, lost production, lost wages, production of scrap, damage to equipment, and inability to meet product deadlines. Large companies, which can ill afford a production shutdown, should implement power backup schemes. These schemes are practical of course if the anticipated damage overshadows the cost of implementation.

Apart from power backup schemes, medium to large industrial consumers have the capability to implement power quality mitigation methods. Such methods can encompass steps from self-monitoring power quality to employment of mitigation equipment, such as filters. A self-analysis of their power consumption serves two purposes:

1) To discover whether, and to what extent their loads cause power disturbances.
2) To provide them with a self-reliance method when it comes to data collection, and not blindly accepting information presented by other interested parties.

In collaboration with utilities, medium to large customers should take the following steps to become involved in solutions of power disturbances:

a) Install current monitoring equipment in their facilities. Such implementation would allow the consumers to verify the degree of power pollution their equipment causes.

b) Research power disturbances and possible solutions to determine the superlative scheme of improving power quality. Since, consumer load' characteristics vary from each other there is no ideal mitigation process; it rather varies from one customer to the other.

c) Voicing their opinion in legal matters. The aim of finding a solution and passing regulations is to address the concerns, and consider the welfare of all implicated parties.

The mentioned steps are not just pertinent to large companies. The common belief of smaller customers being ill equipped to perform the above steps does not hold true. Consumers can be involved, by becoming knowledgeable of power quality related issues and mitigation methods. Furthermore, all consumers can help in establishing laws that protect their equipment; after all, any adult person has their say when they head to the voting booths.

5.2.3 Equipment manufacturer mitigations

Power companies and utilities try very hard to provide a single frequency voltage, since harmonic distortion is a great danger to power generators, and the reduction of efficiency results in less energy to sell. Although AC power sources can be accountable for some harmonic generation, this amount is small compared to what their customers' nonlinear loads produce. The responsibility of this pollution seemingly falls on the shoulders of equipment manufacturers, since their marketed products cause power disturbances.

Although, manufacturers are liable to a certain extent, they are not utterly to blame. The intent of maintaining a harmonic-free power grid is presently overwhelmed by the presence of polluting devices. Consider two scenarios of a discerning manufacturer, who puts to market a product that employs sinusoidal consuming techniques:

a) The passive filter he provides along with the electronic device is overloaded by other nonlinear loads; therefore, the device malfunctions or breaks down.

b) The device is two expensive because the added active filter raised the cost over his competitor; therefore, he is unable to sell the device. After all, manufacturers live in a competitive market and the fraction of a dollar can be the difference between selling and going out of business.

Without standards, and regulations, one or several manufacturers cannot make the difference; furthermore, they might end up hurting their finances without accomplishing anything.

On the other hand, enacting power quality laws is in the best interest of equipment manufacturers, since the inability of equipment to last up to the projected goal hurts their image in the long run. With power quality standards set, equipment manufacturers can adopt them to their advantage; such advantages can come from advertisements of methods that cleanly process electric energy, and equipment that does not pollute the electric environment.

Power quality standards are an inevitable occurrence and a necessity. Manufacturers will need to become primarily involved with legal aspects, if they want their case to be heard from federal legislators.

5.2.4 Government involvement

Government has an inertial attitude towards introducing laws that will affect a change in the economy. Here are a couple of reasons for taking such position:

1) The intent of a free market society is to minimize government participation in regulating and affecting the supply and demand chain.
2) Government regulations tend to change the flow of goods. They can have a negative impact on portions of the economy, while benefiting other interested parties.

However, if rules and regulations are needed for the purpose of obtaining a fair solution, then the government has the right and duty to enact appropriate laws. With the current power quality status, the economy cannot afford a government standing in the sidelines.

Instances, where the government intervention is required, include air/water pollution controls, antitrust laws, custom tariffs etc. For that purpose, government agencies are formed; the EPA oversees air/water pollution levels. The FCC is charged with regulating interstate and international communications by radio, television, wire, satellite and cable. (20)

While forming a separate agency for the purpose of supervising power quality would be excessive, an existing agency should be involved with such issues. The most likely candidate is the FCC. A branch of the FCC can oversee power quality issues, via collection of power quality data. This will provide the government with the necessary tools of evaluating present and predicting future power quality, and not just relaying on information presented by distributors or other interested parties.

Before any solution can be implemented, the branch must conduct a thorough economical study of all types of power disturbances, in order to weigh the benefits versus the cost of ratification. Enactment of laws that regulate power quality issues has to aim at not only eliminating the previously discussed financial burdens, but also accurately predict the introduction of any unforeseen economical burdens. The branch will then be able to weigh the pros and cons of taking action versus staying inert.

This FCC division would initially serve the purpose of reporting to Congress damages caused by power disturbances, and suggest ways of improving the current trends. In guidelines provided to Congress, it must be eminent what are the advantages and disadvantages of ratification. These pros and cons would primarily be of, but not limited to, financial nature. Overall, the branch would be the trusted informer, the right hand of Congress.

The guidelines of the IEEE standard 519-1992 provide a good reference when it comes to technical solutions. While legislators can lean on such standards, they need to decide when to enact appropriate laws, based on the knowledge provided by the power quality dedicated branch. When benefits outweigh the cost, federal legislators should clamp on power disturbances and pass laws that acquire all equipment manufacturers to meet minimum standards. These regulations should put economy's welfare over personal profits.

The dedicated FCC branch would then be involved in exercising power quality laws. This task is primarily twofold:

1) Ensure manufactured equipment meets minimum standards. For instance, harmonic conformance can accompany other electrical data, such as power consumption, in new equipment's energy saver tag.
2) Take part on resolving conflicts between equipment manufacturers and distributors, and supervise solutions implemented between distributor and customer, to assure evenhandedness. Although, recurring power disturbances should be dealt with in a timely fashion, the branch should provide rational demands and deadlines.

In addition, Congress should be informed of the short and long term impact such laws have on the economy. This provides a feedback path, which is necessary in determining which laws have to be later amended.

5.3 A look into the future

The government is already involved in alleviating the effects of power interruptions through programs that offer loans covering energy efficiency improvements paid for by the energy savings, and alternative sources, such as the Million Solar Roofs program. The program's stated goal is the installation of some type of solar technology on the rooftops of one million American businesses and homes by the year 2010 (21). These programs go a long way to improve the availability of energy, but do not tackle the problem of reducing harmonics very well. The Million Solar Roof program may instead worsen the power quality problem with regard to harmonics if controls are not put in place specifying products that do not introduce more harmonics into the system.

The Million Solar Roofs Initiative (MSR) enables businesses and communities to install solar systems on one million rooftops across the United States, and sell electrical energy to distributors. Photovoltaic cells take advantage of Sun's energy to produce DC; however, conversion equipment is needed to transfer it to AC. This conversion equipment aims at producing a voltage compatible to the 60Hz, already present in the AC power grid. Cheap conversion equipment can become a major source of harmonics, since the converted voltage waveform will be highly nonsinusoidal, containing numerous polluting frequencies; such an effect will tend to aggravate power quality problems, thereof. More elaborate conversion schemes yield a very close to sinusoidal voltage; however, the equipment tends to be more expensive. In the case that the society allows cheap conversion equipment to be marketed, a chain of events will follow: power disturbances will increase rapidly, the power environment will deteriorate, more equipment will be destroyed, and as a result the economy will lose more dollars.

In today's industry sophisticated electronics are being rapidly introduced into most production processes. These are often in the form of such power quality-sensitive equipment as these:

1) Computers
2) Electronic Processes Controls
3) Robotics
4) Adjustable speed drives.

The reliability of this type of equipment is much more closely tied to the quality of the power supply, as compared to older or more traditional equipment, which might have had relay controls or electrical contactor controls. With the growing trend of power disturbances and aggravation of power quality issues, this type of equipment is susceptible to future deterioration.

6 Conclusions

In this day and age, we must do what is necessary to ensure the safety, security and reliability of our energy supply. As was presented at the beginning of this report, the problems are real and although backup programs, such as the Million Solar Roof Initiative (MSR), provide a tool of overcoming power outages, harmonic distortion is somewhat overlooked and such programs will be possibly doing further harm in this area.

The complexity of power grid and load interactions requires a methodical study, which covers all relevant aspects. Only after rewards versus disadvantages are weighted properly, can power quality standards be implemented with maximum efficiency and fairness. With the growing trends of power disturbances, and losses to the U.S. economy, ratification becomes a near-future necessity.

Solutions to power quality problems can be implemented in such way that long-term damages, such as premature equipment failures, are minimized. In the end, governmental intercession along with contributions from distributors, equipment manufacturers, and consumers, will ameliorate the current trends of power quality. As a general advice, interested parties should be proactive and take preventive measures. California blackouts are a good example where passivity caused major economical damage.

7 Appendices

7.1 Appendix A

Voltage and current are two important physical quantities, which are related by virtue of Ohm's Law:

$\tilde{I} = \frac{\tilde{V}}{Z}$, where I denotes the current, V the voltage and Z the impedance of the component.

The impedance of a component can be comprised of a real part and imaginary part $Z = R + j \cdot X$, where R is the resistance, X the reactance, and $j = \sqrt{-1}$, which indicates an imaginary number.

For capacitors the reactance is $Z = \frac{1}{j \cdot \omega \cdot C}$, where $\omega = 2 \cdot \pi \cdot f$ with f being the frequency in Hertz (Hz), and C the capacitance.

For inductors the reactance is $Z = j \cdot \omega \cdot L$, where $\omega = 2 \cdot \pi \cdot f$ with f being the frequency in Hertz (Hz), and L the inductance.

The $\tilde{I}$ and $\tilde{V}$ symbols indicate current and voltage phasors. For a sinusoid in the form of:

$I = A \cdot \sin(2 \cdot \pi \cdot f \cdot t + \theta)$, the current phasor is simply represented by: $\tilde{I} = A \cdot e^{j \cdot \theta}$, with A being the peak of the sinusoid.

It is also possible to define the root mean square value of an AC waveform:

$I_{RMS} = \sqrt{\frac{1}{T} \cdot \int_T I^2 \cdot dt}$, where T is the period of the AC waveform. The same definition can be used for voltage as well.

For a sinusoid, the RMS value is approximately 0.707 times the peak value, or 0.354 times the peak-to-peak value.

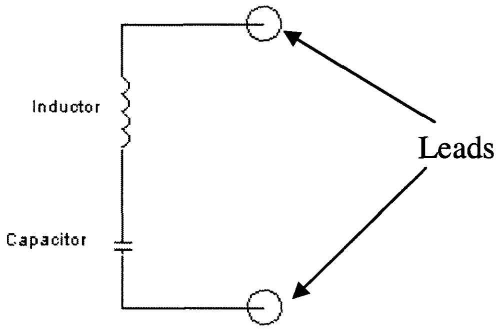
The average power delivered to the load will then be: $P = I_{RMS} \cdot V_{RMS}$

The average power does not indicate anything about usefulness of delivered power. The power factor is the ratio of the actual power to the apparent power: $PF = \frac{P}{S}$, where P is the actual power and S the apparent power. It has been calculated (1) that for three-phase systems with undistorted sinusoidal waveforms: $P = \tilde{V} \cdot \tilde{I} \cdot \cos\theta \cdot \sqrt{3}$ (in kW), and $S = \tilde{V} \cdot \tilde{I} \cdot \sqrt{3}$ (in kVA) Therefore, the power factor comes up to be: $PF = \cos\theta$, where θ is the phase shift between the current and voltage phasors.

The quality of voltage is related to total harmonic distortion (THD), which is defined as: $THD = \frac{\sqrt{VH_2^{\ 2} + VH_3^{\ 2} + \ldots + VH_N^{\ 2}}}{\sqrt{V_1^2 + VH_2^{\ 2} + VH_3^{\ 2} + \ldots + VH_N^{\ 2}}}$, where V_1 represents the fundamental voltage, and VH represent the harmonic voltages with the subscripts representing the harmonic order.

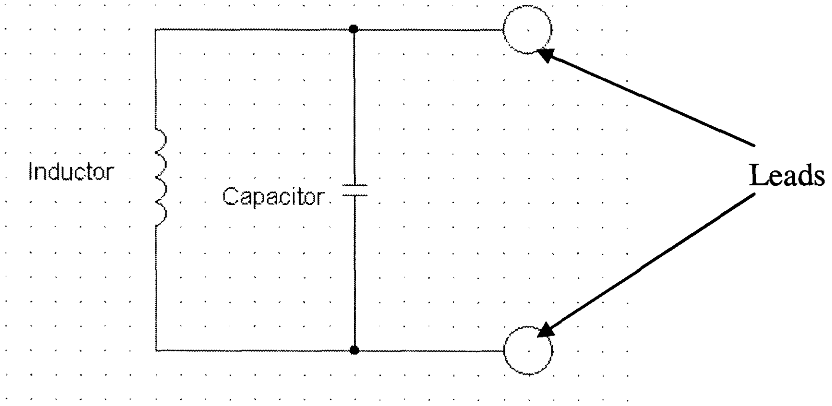
7.2 Appendix B

A simple series passive filter can be seen in the below schematic.



The resonant frequency of this configuration is: $f = \frac{1}{2 \cdot \pi \cdot \sqrt{L \cdot C}}$, with L being the inductance and C the capacitance.

A parallel passive filter has the below-displayed topology:



The resonant frequency of this configuration is also: $f = \frac{1}{2 \cdot \pi \cdot \sqrt{L \cdot C}}$, with L being the inductance and C the capacitance.

7.3 Appendix C

The decibel (dB) unit is mathematically defined as:

$dB(power) = 10 \cdot Log_{10}(\frac{P_{out}}{P_{in}})$, where P_{out} is the output power of a device, or system, versus P_{in} the input power to a device, or system. In general, a quantity is expressed in dB with respect to some other known quantity. In the case of current or voltage the decibel definition becomes:

$dB(voltage) = 20 \cdot Log_{10}(\frac{V_{out}}{V_{in}})$, where V_{out} is the output voltage of a device, or system, versus V_{in} the input power to a device, or system.

One half of a known power is usually known as -3dB, whereas one half the voltage becomes -6dB.

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