A Methodology for Evaluating Energy Efficient Lighting Technologies for their Performance, Power Quality and Environmental Impacts
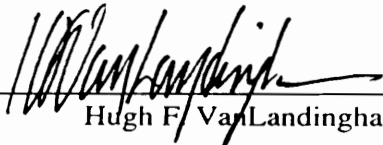
by

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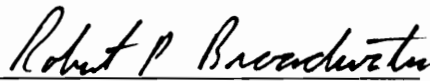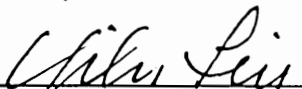DOCTOR OF PHILOSOPHY

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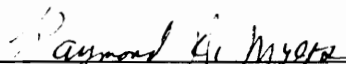ELECTRICAL ENGINEERING

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(ABSTRACT)

Recent developments in compact fluorescent lamps, electronic ballasts and adjustable speed drives have expedited the process of taping energy saving potential of these technologies. The proliferation of these loads, however, has raised new concerns about the power quality in commercial buildings. Higher cost of repair and the reduction in average life of equipment, both on the supply and load sides, could become obvious if these issues are overlooked or ignored. As lighting loads are the largest fraction of the load in most of commercial buildings, a small increase in harmonic distortion level in commercial buildings may jeopardize other loads in the building or the loads connected to the same utility bus.

As these devices were tested to quantify their energy saving potential, it was found that they can create undesirable harmonic problems. Such characteristics were quantified for different samples. It was observed that certain combinations of these lamps and ballasts are much more acceptable from power quality viewpoints than when tested individually. A generic algorithm was developed that can help to select certain energy efficient lighting technologies and will minimize the harmonic distortion level in the building. Results from the algorithm were validated on a building load model to test the accuracy of the algorithm results. The proposed algorithm helps to avoid the problems of

selecting energy efficient technologies randomly during retrofitting of commercial buildings for energy savings.

Pollution mitigation features, and a summary of environmental and power quality status of energy efficient lighting devices were also discussed. A brief description of other nonlinear loads, present in commercial facilities, was also given to evaluate their role in reaping the benefit of energy savings in new lighting technologies. Energy savings and environmental benefits of new lighting devices were highlighted in the presence of other nonlinear loads. This study provides a complete illustration of the benefits and power quality issues related to these technologies.

ABSTRACT

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I dedicate this dissertation to the memory of my late father.

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CHAPTER I

INTRODUCTION

The increasing environmental concerns and government legislation have forced electric utilities to tap the energy conservation potential to its maximum. Numbers of utilities are pursuing energy conservation programs in their service areas. Lighting accounts for 20-25% [1] of the electricity consumed in the United States. Studies made during late 1980's have shown that energy efficient lighting can save 50 to 80% electricity currently consumed in lighting. That translates into more than 10% reduction in total electricity demand. It will also reduce CO_2 emission by 4%, SO_2 emission by 7% and NO_x emission by 4% of the national average. One can expect an improvement in these numbers as a result of progress in the lighting products. There is a significant potential of energy saving by making improvements in the lighting technologies. Hence the manufacturers of lighting products are trying to improve these technologies. The ideas that were not very attractive in the past are gaining popularity among the manufacturers of lighting products. Since 1980, manufacturers of lighting systems have shown extraordinary enthusiasm in bringing the energy efficient products into the market. Due to this improvement, consumer confidence has risen. Utilities are not finding much difficulty in sponsoring efficient lighting programs in Europe and North America. Since 1987, more than 50 utilities in 11 European countries have offered financial incentives to

their customers to promote compact fluorescent lamps [2]. Recently other lighting technologies have also qualified for utility rebates. Beside conserving energy resources and the global environment through efficient lighting products, the manufactures are also addressing issues like power factor improvement and control on harmonic pollution caused by these products. The major technologies competing for utility rebates are: tungsten-halogen, fluorescent and gas discharge lamps. Among the discharge lamps, fluorescent, sodium and metal halide lamps are investigated. None of these technologies is perfect for all lighting applications. Each has one or more redeeming features.

In the light of the current state of the art lighting technologies the direction of this research was to pursue the investigation of certain techniques that can help to minimize total harmonic distortion while saving energy and protecting environment. Factors that influence the decision making while selecting energy efficient lighting technologies for retrofitting are investigated.

Chapter 2 establishes the context of the research giving brief review of energy efficient lighting technologies. Brief account of development and status of the prominent energy efficient lighting technologies is presented. Issues like energy conservation, environmental impact, health hazards, power factor, total harmonic distortion (THD), color rendering index and cost effectiveness are summarized for each technology option. The chapter establishes that the most important issues to be investigated are energy conservation, environmental impact and THD.

Due to significant correlation of nonlinear loads within the building loads, chapter 3 is devoted to the investigation of nonlinear loads. Technically these loads are just nonlinear impedances. They are used to deliver modified electrical power to various equipment. Nonlinear loads have been a concern for power engineers from early days of alternating currents. Their use at domestic power rating has been increased greatly in

1970's. Recent developments in power electronic technology has made it possible to improve efficiency of the energy use in different processes and systems. These technologies offer a better control and reliability of the systems. More recently while their use in energy efficient technologies have validated their vital importance, it has also increased the problems and concerns at system level. Rectification of these problems requires an understanding of the operation and characteristic of the nonlinear loads. Nonlinear loads have different current requirements as opposed to their linear counterpart. Hence classical definition of power and its calculation methods are not applicable to nonlinear loads. Scientists and engineers are having a difficult time to agree upon a comprehensive definition of power for nonlinear loads. Very few instruments are available in the market that can measure true power and true power factor under nonlinear load conditions. This chapter addresses these issues. Only nonlinear loads that are commonly employed in a typical utility service area are discussed in this chapter.

As the harmonics present in current drawn by certain equipment and loads are one of the most important issue, hence chapter 4 investigates this phenomenon for different linear and nonlinear loads. The problem of harmonic distortion has recently become the focus of study of many researchers. This can be easily seen when we examine the numerous conferences dedicated to the subject. International engineering societies have also devoted working groups and committees to study this phenomenon. In this chapter we have covered the sources of harmonics common to the supply and load side of the power network. In later sections, we have investigated the effects of harmonics on equipment as well as some recommendations to keep the harmonic distortion level within the prescribed limits.

Chapter 5 reviews the recent developments in power electronic technologies that have changed the requirements of electricity customers. A significant number of loads draw nonlinear current from the electric utility source and inject harmonics at the point of common connection (PCC). However, one needs to understand the phenomenon of

harmonic summation, interaction, and cancellation in the presence of multiple harmonic sources before trying to correct the problem. Lehtonen [129] has summarized same of the previous work done by different people on the issue of harmonic summation and has proposed a general solution to the harmonic summation problem. He has used a probabilistic approach to solve the problem of harmonic summation. However, this approach does not provide much help in selecting lighting technologies that do not increase the harmonic level in the building. This chapter investigates the problem at the individual harmonic frequency level and suggests a generic algorithm to select lighting technologies in a specific building environment.

The proposed algorithm for selection of energy efficient lighting technologies is based upon the same principles that are used in most of the harmonic analysis equipment. However, there is always some level of disparity between the algorithm results and the real time measurements made by using harmonic measuring instruments. This chapter starts with discussion of these factors that are responsible for the disagreement between the measured and the calculated values. The phenomenon of random occurrence of phase angles of individual harmonic frequencies and its influence on the results is explained by studying different harmonic sources (magnetic circuits, electronic circuits, etc.).

Results of the algorithm are verified by comparing them with actual measurements for the same combinations using the signal analyzer. Two case studies are included in chapter 6 to verify the generic characteristic of the proposed algorithm. These case studies help to establish the generic nature of the proposed algorithm. The salient features of the algorithm are summarized in the from of its advantages and disadvantages. Chapter concludes with a brief summary of material covered in the discussion of results and verification of the algorithm.

Until recently focus of the most of work in this area was on energy saving benefits. Chapter 7 is intended to evaluate recent progress in different energy efficient lighting technologies on the basis of their functional and technical performance and their system level impact. Energy savings and environmental benefits are evaluated while keeping track of harmonic impact on the system.

The last chapter comments on some features of the proposed algorithm for selection of energy efficient lighting technologies. Some directions to expand and extend the algorithm are also identified.

CHAPTER II

A REVIEW OF ENERGY EFFICIENT LIGHTING SYSTEMS

2.1 Introduction

Currently, a wide variety of energy efficient lighting products are available in the market. All of them are not capable of saving energy and the environment without having a negative impact on the power system. In most cases information provided by the manufacturers is not enough to decide about a product for certain applications. Every manufacturer tries to convince the decision makers that they have the solution to the problem. Most of the manufacturers simply give a positive picture of their product. Issues like power factor, THD and color rendering index are often overlooked by the manufacturers. Under these circumstances it is very important for a decision maker to have a complete picture of the energy efficient lighting products available in the market as well as their limitations and scope in future. This chapter gives a review of the popular energy efficient lighting products with their up-to-date progress in the areas of energy savings, power quality, color rendering, life and the issue of health hazards.

2.2 Tungsten Halogen Lamps

Tungsten-halogen lamps are primarily incandescent lamps. Efficiency of the lamp is increased by introducing a halogen gas into it. The addition of halogen gas and maintaining a temperature around the filament at 2000 K evaporate tungsten atoms that combine with halogen vapors to form tungsten halide. Convection current carries the tungsten halide to the bulb wall. As the bulb temperature is 500 K to 1500 K, it circulates tungsten halide back towards the filament. The temperature close to the filament is around 2800 K which helps the tungsten halide to reduce itself into tungsten and halide vapors. Tungsten deposits on the filament and halide vapors are then free to repeat another cycle. This phenomenon is known as the halogen cycle. To withstand the high wall temperature of the bulb, tungsten the halogen lamp is made from quartz.

The three basic configurations of tungsten halogen lamps are; double-ended, single-ended and halogen capsule lamps. Double ended halogen lamps are inexpensive and their efficacy is 15-25 lumens per watt. Certain techniques provide an infrared coating on the bulb wall. This approach gives an efficacy of 32-38 lumens per watt. As opposed to the double ended lamps, the single ended lamps have the single base at one end of the lamp. Lamp life is 2000 hours in both cases. The single-ended lamp has an efficacy of 20-25 lumens per watt. Infrared reflecting film enhances the efficacy of the single ended lamps. The halogen capsule lamps are available in different configuration: halogens PAR (Parabolic Aluminized Reflector) lamps, halogen PAR-IR (Parabolic Aluminized Reflector-Infra Red), bud shaped and projector type lamps. Up to 90% of the energy radiated in a tungsten halogen lamp is invisible infrared or heat energy. However, certain techniques convert part of this infrared energy to light through the application of thin film reflecting coating.

During the last decade, tungsten halogen lamp technology has gone through significant improvements. As mentioned earlier, halogen lamps radiate 90% of the energy

in the near infrared. One way of increasing lamp efficacy is to increase the filament temperature. Wasted infrared energy is recycled into useful light. During the 1970s a practical approach, using wasted energy through the so called recycling procedure was reported. Three layers, TiO_2-Ag-TiO_2 filter was used to reflect back the infrared energy on the filament. Due to temperature limitations of metal filters, they are limited to lamps having large surface area. Semiconductor type filters are easy to apply and have excellent reflection characteristics. A US manufacturer made an earlier effort to develop a multilayer dielectric filter and introduced a double ended quartz lamp in 1983. Bergman [5] has developed a compact coil and double ended quartz halogen lamp. A multilayer dielectric oxide film is incorporated to reflect IR radiations to the filament. This arrangement gives an increase in efficacy of 35% over the non-IR halogen lamp. The other benefits of the new design include lumen output variability up to 50% while it maintains most of the features of the standard halogen lamp.

In case of an ideal filter, 75% of the infrared radiation could be returned to the filament and as much as 57 lumens per watt is possible to achieve. For tempratures of 2900 K and 3000 K, the above considerations may give an efficacy from 66 to 74 lumens per watt [7]. This scenario gives us an efficacy very close to the compact fluorescent lamps, e.g., 40 to 75 lumens per watt. There are several practical limitations in achieving this target. Significant work has been reported in the literature to study system optical performance and filament absorption. Absorption of the radiations is maximized by making the coil as dense as possible.

Material selection to fabricate infrared coating is another important consideration. Selection criteria include: thermal expansion coefficients of the material, pairs matched to substrate, phase stability, resistance to oxidation, resistance to reduction, and environmental stability. The most important materials used for infrared reflecting film are Ta_2O_5/SiO_2 and TiO_2/SiO_2. Another 46-layer Ta_2O_5/SiO_2 coating infrared film is commercialized by a US manufacturer.

Several different film deposition processes have been considered for fabrication of infrared reflecting film for halogen lamps. The most important of these are: physical vapor deposition, dip coating, and chemical vapor deposition. Infrared reflecting coatings have boosted the tungsten halogen lamp efficacy. They are becoming popular in the marketplace. Still there are many obstacles in lamp making and film development technologies. A continued improvement in lamp efficacy is expected through filament geometry and high efficiency filter designs.

Tungsten-halogen lamps are presently available at market places for some residential and commercial applications. Manufacturers are marketing 90 watt halogen PAR lamps that make an excellent replacement for 150 watt R-40 lamps. Recently they have produced a 75 watt halogen lamp that replaces the 150 watt R-40 lamp. Another significant development in this category is the 60W PAR IR-halogen lamp, used for floodlighting. It replaces 150W PAR floodlamp. Energy saving in this case is 60% and a payback time of less than three months [8]. Another tungsten-halogen lamp used in the United States is the MR-16 (multifaceted reflector) lamp. It has a smaller filament that helps in better controling light distribution. Beside this significant improvement in lumen efficacy, halogen lamps, in most of the cases, have a higher power factor and insignificant harmonic pollution. For energy conservation considerations, these characteristics bring the tungsten halogen lamp at par with compact fluorescent lamp. It is expected that the manufacturers of tungsten-halogen lamps will be able to overcome the difficulties involved in different processes as mentioned earlier.

Fischer [9] has introduced an electronic dimmer for halogen lamps that gives an additive convenience as well as economical benefits. The author has offered an innovative dimmer IC for low voltage halogen lamps. The new design, SLB 0587 IC, is capable of driving resistive and inductive load alike. The brightness level of the lamp is

precisely adjusted from the minimum to the set value. Table 2.1 shows some energy efficient tungsten halogen lamps for different applications.

2.2.1 Optical Hazards of Halogen Lamps

McIntyre [10] has reported some recent work on the visual safety aspect of the quartz linear lamp(QLL). He has studied the biological and physical effects of incident radiations on the eye. The authors have concluded that there is no risk of blue light hazard or UV damage. To make a confident conclusion about the thermal retinal injury, the author has suggested more work to quantify these effects.

Bergman, Parham and McGowan [11] made a recent review of UV emissions from GE lamps. American National Standards Institute (ANSI) has circulated standard for "Photobiological Safety of Lamps and Lamp Systems" for discussion. Review of UV emissions from lamps shows that all general lighting lamps are responsible for UV emissions, however, the level of these emissions is much lower than the emissions from sunlight. UV emissions from some halogen lamps may exceed the limits proposed by ANSI standard Z-311.1. For low voltage halogen lamps, a 2-3 mm thick glass shield can significantly minimize the emission level. For all lamps, the use of a dopant in the glass or quartz can reduce the emissions. It is encourging to know that $Ta_2 O_5/Si O_2$ IR coating in halogen lamps have minimal UV emissions; however, they are the most energy efficient lamps among general lighting halogen lamps.

2.3 Fluorescent Lamps

Sir George Stokes discovered in 1852 the basic principle of transforming UV radiations into visible radiations. In 1920s it was discovered that a mixture of mercury

Table 2.1. Energy Efficient Tungsten Halogen Lamps

Watts	Bulb	Base	Life (hours)	Candle Power	Beam Spread
CAPSYLITE HALOGEN PAR LAMPS					
45	PAR-38	Medium Skirted	2500	600 1800 4500 11500	55 Deg 32 Deg 15 Deg 9 Deg
60	PAR-38	Medium Skirted	2500	3400 17500	26 Deg 9.5 Deg
75	PAR-38	Medium Skirted	2500	3500 12000 17500	30 Deg 13 Deg 10 Deg
90	PAR-38	Medium Skirted	2500	4000 6000 11500 22500	30 Deg 20 Deg 15 Deg 9 Deg
150	PAR-38	Medium Skirted	3000	2500 7500 25000 37500	55 Deg 30 Deg 10 Deg 9 Deg
50	PAR-30	Medium	2500	1100 1750 6500	42 Deg 32 Deg 12 Deg
75	PAR-30	Medium	2500	1800 3000 10500	42 Deg 32 Deg 12 Deg
35	PAR-20	Medium	2500	600 900 3000	40 Deg 30 Deg 8 Deg
50	PAR-20	Medium	2500	4600	12 Deg
55	PAR-16	Medium	2000	1300 5000	30 Deg 12 Deg
75	PAR-16	Medium	2000	2000 7500	30 Deg 12 Deg
MasterLine HALOGEN PAR LAMPS					
45	PAR-38	Medium Skirted	2500	5800 2000	12 Deg 28 Deg
60	PAR-38	Medium Skirted	2000	3500 13500 15500	28 Deg 12 Deg 9 Deg
75	PAR-38	Medium Skirted	2500	4500 14500	27 Deg 10 Deg
90	PAR-38	Medium Skirted	2500	4500 14500	28 Deg 12 Deg
50	PAR-30L	Medium	2000	1250 1900 4200 9900	40 Deg 30 Deg 16 Deg 9 Deg
75	PAR-30L	Medium	2000	2200 3400 6700 15500	40 Deg 30 Deg 16 Deg 9 Deg
50	PAR-20	Medium	2000	1400 3200 6200	30 Deg 16 Deg 9 Deg
40	PAR-16	Medium	2000	1300 5000	27 Deg 10 Deg
60	PAR-16	Medium	2000	2000 7500	27 Deg 10 Deg

vapors and an inert gas, is 60% efficient in converting electrical energy into light. In April 1938 a fluorescent lamp was introduced commercially in different colors. Since 1940, there has been very little change in the basic arc discharge system of the lamp. There have been significant changes in phosphors and electrode design.

In a fluorescent lamp, free electrons are derived from the electrodes and accelerated by the applied field. The kinetic energy of the free electrons is transformed into excitation energy of the gas atoms and finally the excitation energy is radiated as light. The structure of the fluorescent lamp consists of a glass tube whose inside surface is coated with phosphor. It is filled with argon or a mixture of krypton and argon. A small amount of mercury present inside the glass tube is vaporized during lamp operation. Electrodes are located at each end of the tube.

2.3.1 Full-Size Fluorescent Lamps

Standard full-size fluorescent lamp contains argon gas and halophosphor. Owing to the federal regulations in the United States, halophosphor replaced phosphor in cool white lamps. Fluorescent lamps are usually classified on the basis of the electronic circuits used to regulate the lamp operating voltage. Preheat lamps have an external starter to heat the electrodes before the starting of the lamp. Rapid start lamps have a ballast that regulates the voltage as required in the beginning as well as during the operation. Instant start lamps have a ballast that provides the high-voltage in the beginning to start the lamp and normal voltage during its operation. Rapid start lamps are the most commonly used fluorescent lamps. In this case, flicker is the only undesirable characteristic, however, the lamp has a long life. The instant start lamp is popular due to its quick start characteristic but it has a short life. Lamp parameters like tube length and diameter, as well as phosphor and gas type, control the characteristics of the lamp.

Presently use of rapid start lamps (F40T12) is ten times more than all the other types combined.

The US. Energy Policy Act of 1992 has set some energy efficiency standards for different lamps. Manufacturers have already developed the energy saving version of F40T12. Reduced wattage lamp (F40T12/ES) meets the standards set by the above mentioned legislation. In energy saving lamps, krypton is used instead of argon gas. These lamps reduce wattage up to 15%, whereas lumen reduction is up to 20%. Rare earth phosphor used in energy saving lamps (F40T12/ES) improves the performance of fluorescent lamps. They have better color rendering and higher lumen efficacy as compared to cool white lamps.

In some cases the rapid start lamp is used with a heater cut-out. Lamp electrodes are disconnected after the lamp has started. Although this approach decreases the lamp life up to 25%, the energy saving potential is significant. Extended output lamp has thicker and more efficient phosphor and the electrodes are redesigned and have a different tube diameter. All of these changes improve the lamp efficacy and lamp life up to 21% and 20% respectively. There is significant improvement in lumen maintenance and colour rendering. U-tube lamps are available in different configurations. They are available with holophosphor as well as rare earth phosphor coating. The average life of the Lamp is up to 18,000 hours. Slimline instant start lamps have a wide range of tube diameter and length (24-96 inch). The average life of the lamp is 12,000 hours. High output rapid start lamps have a length range of 18-96 inches. Very high output lamps have higher efficacy, yet both high output and very high output lamps are not very popular for retrofit applications. The five technical options to improve fluorescent lamp efficacy are: higher surface area to volume ratio, wattage reduction, increase in surface area, use of high efficacy phosphors, and reflectors. All of these options are widely used to improve the fluorescent lamp efficacy in different configurations.

An effort to investigate aging of the Fluorescent reflector was recently made by Nelson and Crocker [14]. A wide range of aging period for different materials was reported. A further investigation is suggested to fully understand the aging phenomenon. Numbers of studies were conducted to evaluate the performance of selected fluorescent products. Results of their work were very encouraging for electronic ballast manufacturers. The efficacy of the lamp was very high and a THD as low as 6% [15]. It was noted that the electronic ballast in industry environment needs a little modification for reliability purposes [17]. A dynamic mathematical model was developed for the electrical characteristic of fluorescent lamps. It can model the different aspects of lamp operation in electrical circuit. It helps significantly to design electronic ballast under different operating conditions [19]. Table 2.2 shows the efficacy improvements using different technical options.

Fluorescent lamps could be made more energy efficient by enrichment of the mercury isotope, an applied axial magnetic field, use of two photon phosphors, and high frequency operation of electrodes. The most promising approach is very high frequency electrodless operation. Laboratory results shows that a target of 200 lm/W and lamp life up to 100,000 hours will be achieved by the turn of the century [20].

2.3.2 Compact Fluorescent Lamps

Compact fluorescent lamp consists of the lamp, lamp holder and ballast. There are three types of compact fluorescent lamps (CFL): integral system, modular system and dedicated system. Both integral and modular systems are self ballasted packages. Modular system consists of a socket adopter, ballast and lamp. Integral systems have a one piece assembly, while modular systems have a replaceable lamp. Yet both are designed to screw into existing incandescent medium base sockets. Currently they are available in a power range of 5 to 55 watt. There has been a dramatic increase in the

Table 2.2. Performance of F40 Fluorescent Lamp Systems

Lighting System	Input Power (W)	Efficacy (lm/W)	Output (lm)	CRI
40W F40 T-12/CW[1]	40	79	3150	67
34W F40 T-12/CW[1]	34	81	2750	67
32W F32 T-8/41K[2]	32	100	3190	85

[1]Cool white lamp

[2]Tri-phosphor lamp

potential applications of CFLs. They are available in a variety of colors and wattage. There is a great variety in the CFLs for commercial applications. So it is almost impossible to give a complete picture of the whole line of products.

CFLs are suitable for a wide range of residential and commercial applications. They are appropriate for incandescent lamp replacements. Commercial applications of CFLs include down lighting, decorative lighting, exit signs and task lights. Colored lamps are also being manufactured in narrow band phosphor colors (red, blue and green) with yellow filter coating. Manufacturers are emphasizing on increasing the compactness of the fluorescent lamps. Since 1991, they are successfully making a smaller dimension lamp by joining three twin tube angles at 120°. Series of triple twin tube lamps were developed for 18, 24 and 36 watt. Another development in this regard was to arrange twin tubes side by side. Besides the conventional approach of producing illumination in CFLs, there is an excellent scope of introducing electrodless compact fluorescent lamps. In this new set-up electric power is coupled through induction to the discharge. Godyak and his colleagues [18] have demonstrated the results of RF-inductive fluorescent lamp. It is expected that development of the new energy efficient products will continue.

Love [21] has reported results of the field performance of Compact fluorescent systems. Apart from the usual benefits of longer life and energy efficiency, he has noted some additional advantages, such as reduction of cooling load, elimination of heat damage to exit sign enclosures, increased safety due to reduced wiring in exit sign enclosure, etc. At present, application of CFLs for downlights is one of the major areas of research activity. Thermal management techniques have been applied to mitigate the losses due to lamp overheating. Results from the convective venting design show that light output of the lamp increases up to 25% [22]. CFLs are gaining ground for commercial applications. In a commercial interior environment, convective venting may

cause dirt depreciation and cause reduction in light output. Work done by Siminovitch and others [23] shows that convective venting causes no dirt depreciation of CFLs.

With having all the technical knowledge about the energy efficient products, it is very important to study the managerial aspect of the retrofitting and switching to the energy efficient lighting sources. Zackrison, Jr. [25] has discussed the products from major manufacturers as a possible alternate for retrofitting. Besides the energy conservation and engineering aspects of the candidate products, he has taken into account management issues involved in the implementation of energy conservation programs. Another effort to address the management related issues, was done by Wellinghoff [26]. The main focus of his work is to point out the pros and cons of the retrofit game. Quite recently some manufacturers in US have marketed integral type compact fluorescent lamp (electronic ballast) with a THD lower than 10% and a power factor higher than 0.98 [27].

2.3.3 Ballast

Ballast is the heart of the discharge lamps. It provides high initial voltage to initiate the discharge and limits the current during the continued operation. Usually it is designed to optimally operate only one type of lamp. As mentioned earlier, there are three types of fluorescent lamps: preheat, rapid start and instant start lamps. Rapid start is the most popular mode of operation for fluorescent lamps. The salient features of rapid start are smooth start, long life and dimming capabilities.

The fluorescent lamp is a low pressure discharge lamp. A ballast is required to start and operate the fluorescent lamp. Construction of the magnetic ballast is very simple. A wire coil is wound on the iron core and connected in series with the lamp. It provides current for electrode heating, high voltage to start the lamp, and limits current during its operation. In preheat lamps, supply voltage heats the lamp filaments until

starter opens, causing a high voltage across the lamp. An instant start circuit provides a high starting voltage to initiate the lamp operation and eliminates the need of a starter. A rapid start lamp makes use of the principle of preheat and instant start circuits and eliminates the need of a starter.

Until mid 1980s, magnetic ballasts were dominating the fluorescent ballast market. The electronic ballast was introduced in 1981. In some cases a premature failure of electronic ballasts occurred. Most of the manufacturers have improved their products. As a result, after five years of operation, ballast failure rate has gone down to less than 1%. A study conducted at the University of California has demonstrated the ability of the manufacturers to design and manufacture electronic ballasts at the required level of reliability. It shows that reliable high frequency electronic ballasts could be produced and will last as long as magnetic ballast (10-20 year). High-frequency electronic ballasts operate the lamp at 20-50 kHz, reducing flicker and hum. They are 25% more efficient as compared to magnetic ballasts. Due to high frequency operation, the size of the ballast circuit is significantly reduced. It has become possible to design a CFL that replaces incandescent lamps, without any modification in existing sockets. Without the humming core, the electronic ballasts is very silent, compared with conventional magnetic ballasts. They are excellent in the office environment such as conference rooms or teleconference suites. The energy conservation office of the University of California at Berkeley has shared their field experience with high frequency ballasts. They have concluded that high frequency ballasts not only save energy from 20 to 30%, but they are also reliable, quiet, and flicker-free [29].

In the early 1980s, hybrid ballasts were introduced in the market. The key to this approach is an auxiliary transformer (filament transformer) that activates when the lamp is not ignited. A voltage sensitive switch acts as a short circuit for open circuit ballast voltage and appropriate voltage is induced in the secondary of the auxiliary transformer. After the ignition, voltage across the lamp collapses. This design results in energy

Table 2.3. Hybrid Ballast Comparison With Other Ballasts

Ballast Type	Voltage (V)	Current (A)	Power (W)	THD (%)
Energy Efficient Magnetic Ballast	120	0.73	86.5	17.09
Filament Transformer Type Hybrid Ballast	120	0.68	81.2	18.00
New Hybrid Ballast	120	0.68	80.9	16.21

saving. Owing to technical and economic constraints of the existing hybrid technology, a new design was presented in late 1990s. It maximizes energy saving, weight reduction, and is modular in design. The new electronic component dominant circuit has better control and is easy to manufacture. Table 2.3 gives a comparison of new hybrid ballasts with the existing approaches [30]. Recently, Garbowicz [31] has reported the results from a hybrid ballast developed for 32W T8 and 34W T12 lamp systems.

In 1991, a group of researchers presented a single-ended, soft switching and high frequency electronic ballast. Salient features of the proposed design are unity power factor, high efficiency, and soft switching at turn-off and turn on. Due to single-ended characteristics of the lamp, the circuit is simple enough to integrate in smart power ICs [33].

Most of the manufacturers of electronic ballasts have developed state of the art products. Some of them are marketing electronic ballasts having a crest factor below 1.5, a power factor greater than 0.99 and THD less than 10%. They are offering electronic ballasts for a complete spectrum of fluorescent lamp applications, energy control and monitoring system for dimming applications. All of these systems have power factor greater than 0.99 and THD less than 10%. Due to the potential benefits of the lighting control in energy conservation, the market has demanded a wide range of dimming control features in electronic ballasts. A common problem with the dimming circuits was that the discharge of the fluorescent lamp becomes unstable and the lamp extinguishes at a low luminance level. Researchers around the world have overcome this problem and have developed an electronic dimming ballast for fluorescent lamps that can dim the lamp from 0.3-100% [34].

Some new techniques and topologies are suggested to improve the harmonic and energy conservation status of the electronic ballasts. Tadesse, Dawson and Dewan [37]

have described three high frequency inverter topologies suitable for powering rapid start fluorescent lamps. Results from the comparison of the filter technologies show that the LCC and LCLC filters satisfy the criteria set by the authors in an optimal way.

Recently, numbers of topologies have been introduced to realize efficient electronic ballasts. Gulko and Ben-Yaakov [38] have investigated Current-Sourcing Push-Pull Parallel-Inverter (CS-PPRI) as a fluorescent lamp driver. Keeping in mind that fluorescent lamp requires a current source rather than a voltage source driver, the authors have proposed a modification in current source inverter topology. Results of this modification suggest that the present approach can realize a high frequency current source. It is particularly useful as a driver. This approach eliminates the need of an extra ballast. In this design the current is a function of the frequency ratio. This feature is used to realize a fluorescent lamp dimmer. Cosby and Nelms [39] have approached the same problem in a different way. They have used resonant inverter in electronic ballasts because of their load dependent characteristics. They have compared three types of resonant inverters using a fundamental approximation technique. Among the three types of resonant inverters, the parallel load resonant inverter is selected because of the possibility of large voltage gain. Jordan and O'Connor [40] have described a zero voltage switched resonant converter as a driver to fluorescent lamp. The circuit is reported to develop efficiently high voltage, sinusoidal power to drive cold cathode fluorescent lamps. Emergency lighting is another potential application area of high frequency electronic ballasts. A smart lighting emergency ballast is proposed by Alonso and his colleagues [41]. The microcontroller in the control circuit performs supervision and control for security purposes. High frequency technique is applied to battery chargers as well as driver circuits for discharge lamps. High power factor, high luminance efficacy, small in size and weight, low in flicker, and harmonics are the prominent features of the circuit.

2.3.4 Issues in Fluorescent Lighting Systems

Energy efficient lighting systems are acceptable as long as one does not need to compromise on human health, audio and visual comfort, and technological convenience. Whereas electric utilities are concerned with the power quality issues. Certain technological improvements have been made to address the concerns of the consumers as well as electric utilities.

(a) Health Hazards

Several aspects of fluorescent lighting may effect human health and visual comfort. Most of the studies done in this regard are not very conclusive. The following are the potential hazards to human health due to exposer to fluorescent lighting:

(i) Skin cancer

(ii) Skin photosensitivity

(iii) Skin erythema and inflammation to the eye

(iv) Lighting and stress

(v) Mood states, the pineal gland and lighting

(vi) Glare

(vii) Flicker

(viii) The 'sick building syndrome' and lighting

(ix) Polychlorinated biphenyls

Study performed by Muel and his colleagues have shown a possible skin cancer risk due to basal and squamous cell carcinomas cancer. They have reported 600 deaths in 20 years over a population of 50 million. McKinlay and his colleagues [10] conducted a

study for another type of skin cancer. Their result shows that risk of death from this particular type of skin cancer is one person in 2,500,000 per annum. Studies conducted to test skin photosensitivity shows no correlation between fluorescent lighting and skin photosensitivity. Relation of lighting and stress is not well defined. This is an area that needs further exploration. Glare and flicker have been reduced by the improvements in the lighting system technology. Although there is a positive effect of fluorescent lamps on the radio signal fading and digital communication, automatic gain control could be designed to compensate for fading at twice the power line frequency [44,45,46].

(b) Ambient Temperature Limitations

Compact fluorescent lamps are increasingly used as an alternate to the incandescent lamps. EPRI has conducted a recent survey showing that users of fluorescent lamps were dissatisfied with lumens output of the lamps. It was suspected that the improper ambient temperature may have caused this decrease in lumen output of the fluorescent lamps. Ouellette [47] demonstrated that performance of the fluorescent lamp depends upon ambient temperature. Effect of the ambient temperature is not the same for all products; instead it varies greatly from product to product. Another study shows that at -30 °C ambient temperature lumen output of fluorescent lamp is as low as 30%. However, lumen output increases after the start-up and reaches to 100% after 30 minutes. It is observed that lumen performance at low temperatures is better for high wattage luminaries. It is suggested at least 13 Watt compact fluorescent lamp (CFL) should be installed when the temperature is -10 °C. If the temperature is lower than this, CFLs are not recommended [48]. An Amalgam based CFL design has been suggested for outdoor applications. It is believed to have better performance under low ambient temperature conditions [51].

(c) Power Quality Issues

It is a fact that Fluorescent lamps are very crucial in a saving substantial amount of electricity. The savings in electricity will decrease expensive investment in generation, transmission and distribution equipment. More importantly, this approach will help to protect the global environment by reducing the amount of pollutants e g. CO_2 , SO_2 and NO_x. However, fluorescent lamps may degrade the power quality if they are allowed to proliferate without any check. In the future, power quality may deteriorate more due to higher penetration of nonlinear loads e.g. computers, peripherals, electronic equipments with switching power supplies and electronic variable speed drives. By the year 2000, the nonlinear loads, including lighting, are expected to become 50 percent (in industrialised countries) of the total load [59].

The leading manufacturers of lighting products are marketing T-8 lamps and electronic ballasts with a power factor of more than 99% and THD less than 10%. However, CFLs that are available in market have a power factor as low as 50% and THD as high as 142%. Although major manufacturers of CFLs are claiming to have high power factor and low THD technology, they are not implementing it due to the limitations of space, weight, and cost of the products. In the future, large scale penetration of high power factor and low THD CFLs will depend upon utility incentives, rebate programs, and increasingly strict standard limits.

2.4 Low Pressure Sodium Lamps

Since the introduction of the low-pressure sodium lamp (LPS) more than 60 years ago, it is the most efficient among the artificial light sources. The higher efficacy is mostly due to the presence of two yellow resonance lines of sodium at 589 and 589.6 nm;

whereas maximum human eye sensitivity is at 555 nm. The monochromatic character of LPS lamp makes it suitable to see the contrast more clearly. The contrast between the moving and stationary object is perceived more quickly. Moreover, low luminance reduces the risk of glare. Sodium light saves 10% to 15% in lumens without effecting the visibility as compared to the other sources of artificial light. These characteristics of LPS sources are highly valuable in situations where recognition of the objects and contours is essential for safety. LPS lamps are an excellent choice for motor ways with approach lanes and exits, intersections, through ducts, bridges, tunnels and parking areas.

Improvement in LPS lamp from 1932 to 1960 is mainly attributed to the development of sodium resistant glass. A sustained efficacy of 100 lm per watt was achieved through the development of sodium resistant glass. From 1960 to 1980, thermal insulation was the major area of activity. Better heat insulation was achieved by increasing the number of extra glass sleeves, a metal layer for infra-red reflection, ideal infra-red reflecting filters, semiconductor layers for infra-red reflection, and reflecting layers of In_2O_3. Since 1980, an enormous amount of work has been done on high frequency operation of LPS lamp. Low-pressure sodium lamps are available with efficacy as high as 200 lm per watt. High frequency operation of LPS lamps offers a lot more opportunities for further improvements in lumen efficacy. A lumen efficacy of 225 lm per watt for high frequency operation is possible with a practical ballast. Even greater improvements in system efficacy are possible with high frequency electronic ballasts [70,72,73]. Table 2.4 gives a summary of the performance of high efficiency, low pressure sodium lamps [73]. Since the discharge tube in the LPS lamp is not exposed to the atmosphere, lamp starting is not effected by the ambient temperature. It does not cause any starting problem until the temperature below -30 ^{O}C. However, extremely low temperatures may cause slight reduction in the light output.

Table 2.4. Performance Characteristics of Sodium Lamps

Lamp Type	Watts	Lamp (lumens per watt)	System (lumens per watt)
SOX-E 131	130	200	172
SOX-E 91	90	194	165
SOX-E 66	65	165	135
SOX-E 36	35	163	135
SOX-E 26	25	140	109

2.4.1 Electrical Control of Low Pressure Sodium Lamps

Like the other discharge lamps, the LPS lamp also needs a driver circuit for starting and operation. Similarly, the lamp has a negative current voltage characteristic. The auto-leak transformer was used for quite a long time to limit the current. Owing to high open circuit voltage, auto-leak transformers have high power loss and require a bigger ballast. Since the 1980s, significant changes have occurred in the driving circuitry of the LPS lamps. The hybrid circuit was used to replace the auto-leak transformer. The efficiency of hybrid circuits is 10 to 30% higher than auto-leak transformers. Moreover, it makes 50% savings in weight and volume, and reduces mains current distortion. De Groot and his colleagues [72] studied the high frequency operation of LPS lamps. They reported the results of high frequency

operation of LPS lamps of different wattage at different frequencies. The study shows that the efficacy of LPS lamp drops up to 25 kHz and then rises up to 400 kHz. The increase in lumen efficacy at a high frequency is due to an increase in arc efficiency and reduction of electrode losses. All future improvements in lamp efficacy lies in the development of high frequency driver circuits. The problem of main voltage dip becomes insignificant when the LPS lamp is driven with a high frequency ballast circuit. In frequency ranges of 200 to 400 kHz an efficacy gain of 10-20% could be made when compared with power frequency operation.

2.4.2 Dimming of Low Pressure Sodium Lamps

Due to the increasing cost of electricity and for the purpose of environment protection, all energy saving measures should be taken without compromising safety, comfort level, and productivity. Dimming circuits are effective sources of energy and

cost saving. Moreover, they offer a wide range of lighting flexibility to the users. Di Fraia [68] proposed a method for continuous dimming of low pressure sodium lamps. The proposed method does not need any modification to the existing circuitry. The only requirement is to install a variable frequency converter. The lamp can be operated at a very reduced wattage by increasing the supply frequency above the mains value. The author has presented the results for a 35 Watt LPS lamp at variable frequency of 50 to 500 Hz. The lumen output, lamp power, and ballast losses decrease up to 1%, 17% and 7%, respectively for the above frequency range. Since the introduction of the proposed dimming method in 1981, significant developments in the ballast circuitry have been made. Dimming circuits are now more compact and cost effective as compared to their earlier designs.

2.5 High Pressure Sodium Lamps

There are two maxima in the luminous efficacy curve of the sodium discharge lamp [79]. One is at 0.2 Pa and the second at 10^4 Pa. The 0.2 Pa leads to a low pressure sodium lamp and the 10^4 Pa is the characteristic of the high pressure sodium lamp. The high pressure sodium (HPS) lamp was developed in 1968. The main purpose of this development in discharge lamps was to provide an energy efficient lighting source for exterior and industry applications. The Europeans have already taken the lead by introducing a complete family of HPS lamps.

Vliet and Groot [79] have made an excellent early review of HPS lamp, developed in the first decade of its introduction. Since the early 1970s, HPS lamps have dominated the street light services. Researchers and manufacturers were working hard to improve the efficacy as well as color rendering of HPS lamps to make it acceptable for indoor applications. In 1987, Kemenade [81] and his colleagues explored the possibility of

applying HPS lamps for indoor applications. They continued their effort until they were able to develop a white HPS lamp with a color temperature of 2700 K while maintaining a color rendering index above 80. Primarily they introduced a nitrogen fill gas in the outer bulb to increase the arc tube wall loading. This increase in arc-tube wall loading is responsible for the increase in luminance and color properties of the lamp. At the same time Gibson [82] introduced a 70-W gas filled reflector lamp with a lumen efficacy of 77 lm per watt. The higher lumen efficacy is due to the radical differences in the concepts used in the new design. In the proposed design, Krypton fill enhances the safety of the lamp while beam performance is improved with a smaller arc-tube. As the new design is completely compatible with the existing design, it works satisfactorily with existing driving circuits. Graser [84] has demonstrated an improvement in life of high color rendering HPS lamps. The lamp arc tube is filled with high pressure (200-300 mbar) xenon gas. This approach increases the useful lamp life by a factor of four. This is due to reduction in the diffusion rate of volatile components in the corrosion process.

Pulse operation of HPS lamps was discovered in 1977 but it took quite a long time to fully understand the phenomena of pulse operation. As mentioned earlier, although high efficacy and long life are the inherent features of sodium lamps, poor color qualities make it unacceptable for indoor situations. Whereas it has been proven that pulsed operation of HPS lamps makes it possible to improve color properties of HPS discharge lamps. Under an operating pressure of 200-300 mbar, the pulsed operation technique gives a color rendering index of 60-80 with color temperatures 2500-3100 K. Spectral output of the discharge depends on the height, width and frequency of the square pulse applied to the HPS discharge. Thermodynamic properties of the gases used in the discharge also influence the spectral output of the source. Ruton and his colleagues [85] have made a parametric analysis of the pulsed HPS discharge system. They have demonstrated the system with a color temperature of 2800 K and color index greater than

70. The system has a practical design of ballast that fulfills color, life, and lumen efficacy requirements of the indoor applications.

Recent developments have made it possible to use white HPS lamps for indoor applications. It requires stabilization in order to keep the color rendering index (CRI) within the acceptable limit. Carleton and Keijser [87] have addressed this issue in their work. They have demonstrated an electronic control circuit to stabilize the color under the variable conditions of line voltage, ballast impedance, and cold spot temperature. The proposed design keeps the CRI above 80 under all circumstances. Pabst and Klien [88] with their work in Austria have introduced an electronic ballast for HPS lamps. The new product successfully determines the correct switching point between glow-to-arc transition and supplies appropriate heating power to the electrodes to overcome glow mode. Genes and Wyner [91] have given an excellent review of the recent developments in HPS lamp technology.

2.6 Metal Halide Lamps

Metal halide lamps are based on the principle that vapor pressures of many metal compounds are higher than those of metals themselves while keeping the temperature constant. At a certain wall temperature of the discharge tube, metal halide compounds start evaporating. Dissociation of the molecules occurs in the discharge area due to the high temperature of the molecules. Radiations are emitted from the excited ions and atoms. Recombination of the ions and atoms occur as soon as they move away from the discharge area. This cyclic process keeps on going throughout the life of the lamp.

In 1965, when first metal halide lamps were developed, exterior lighting and industrial lighting were the main target for application of the new lamp. Since then,

efforts have been made to develop metal halide lamps for universal applications. As a result, metal halide lamps are now available in a range of 32-1500 watts and different configurations. Sugiura [101] made a review of the development of metal halide lamps from 1980 through 1992. He has emphasized on the following four basic types of the metal halide lamps. ScI-NaI lamps were very popular until early 1980s. After that, Dysprosium-Iodide lamps took the lead due to its characteristics such as excellent color rendering, compact size, and low power. Due to demand of variety of color temperatures, tin-halide lamps have become very popular at the market place. Further improvement in metal halide lamps is expected through the use of electrodless technology and ceramic arc-tubes. Byszewski and his colleagues [92] at GTE laboratories have emphasised the glow discharge phase of the discharge lamp. They have developed a detailed model that describes glow discharge in a low wattage metal halide lamp. Accuracy of the new model has been considerably improved over the previous models.

Parrott [98] along with his group has developed a low wattage metal halide lamp with enhanced containment. It contains the forced rupture and allows cost effectiveness with greater color temperature. Features like higher efficacy, longer life, and controlled optics make it attractive for indoor applications. One of the most lucrative developments in metal halide lamps was made by Rasch and Statnic [100]. They have tested and compared regulated the electronic ballast (REB) with the conventional ballast. Results show that although REB is somewhat complicated as compared to fluorescent ballasting it is still cost effective. The main advantages of the REB are as follows:

1-Smaller dimensions
2-Lower weight
3-Reduced Flicker
4-Improved system efficacy

5-Straight arc

6-Less variation of lamp loading

7-Less variation in color

These features of metal halide lamps with a regulated electronic ballast make it more suitable for indoor applications.

2.7 Summary

Infra-red tungsten halogen lamps have a potential to save up to 60% energy without polluting the system. It competes closely to the CFL in many cases. In some applications it even surpasses the CFL. The new electronic technology and material developments are promising a lot in favor of fluorescent lamps. This is the reason that fluorescent lamps, particularly CFL, have drawn greater attention of the researchers and manufacturers.

For outdoor and industrial applications, LPS, HPS, and metal halide lamps are close competitors of one another. Each lamp has its merits and demerits. Their choice depends upon the application. Recent developments in HPS and metal halide have provided a chance to consider them for indoor applications.

CHAPTER III

NONLINEAR LOADS AND ENERGY CONSERVATION DEVICES

3.1 Introduction

A nonlinear load is one in which the load current is not proportional to instantaneous voltage. There is a discontinuity in the current drawn by nonlinear loads. They behave differently from linear loads. Load current will be non-sinusoidal even if instantaneous voltage is perfect sinusoidal. Technically these loads are just nonlinear impedances. They are used to deliver modified electrical power to various equipments.

Nonlinear loads have been a concern of power engineers from early days of alternating currents. Their use at domestic power rating has been increased greatly in 1970's. Recent developments in power electronic technology has made it possible to improve efficiency of the energy use in different processes and systems. These technologies offer a better control and reliability of the systems. More recently while their use in energy efficient technologies have validated their vital importance, it has also increased the problems and concerns at system level. Rectification of these problems require an understanding of the operation and characteristic of the nonlinear loads.

Nonlinear loads have different current requirements as opposed to their linear counterpart. Hence classical definition of power and its calculation methods are not applicable to nonlinear loads. Scientists and engineers are having a difficult time to agree upon a comprehensive definition of power for nonlinear loads. Very few instruments are available in the market that can measure true power and true power factor under nonlinear load conditions. Still, the authenticity of these measurements is questioned. This chapter will address these issues. Only nonlinear loads that are commonly employed in a typical utility service area are discussed in this chapter.

3.2 Classification of Nonlinear Loads

Nonlinear loads could be classified on the bases of their applications, function and chronological development. Resent developments in power electronic technology has pushed industrial, commercial and residential consumers of electricity toward automation and electronic control. Hence every conventional equipment that has its electronic version in the market has better efficiency and control. It is difficult to cover all of these loads on the bases of their applications. It will be more appropriate to classify nonlinear loads on the bases of static and dynamic nature. Figure 3.1 gives the general classification of nonlinear loads.
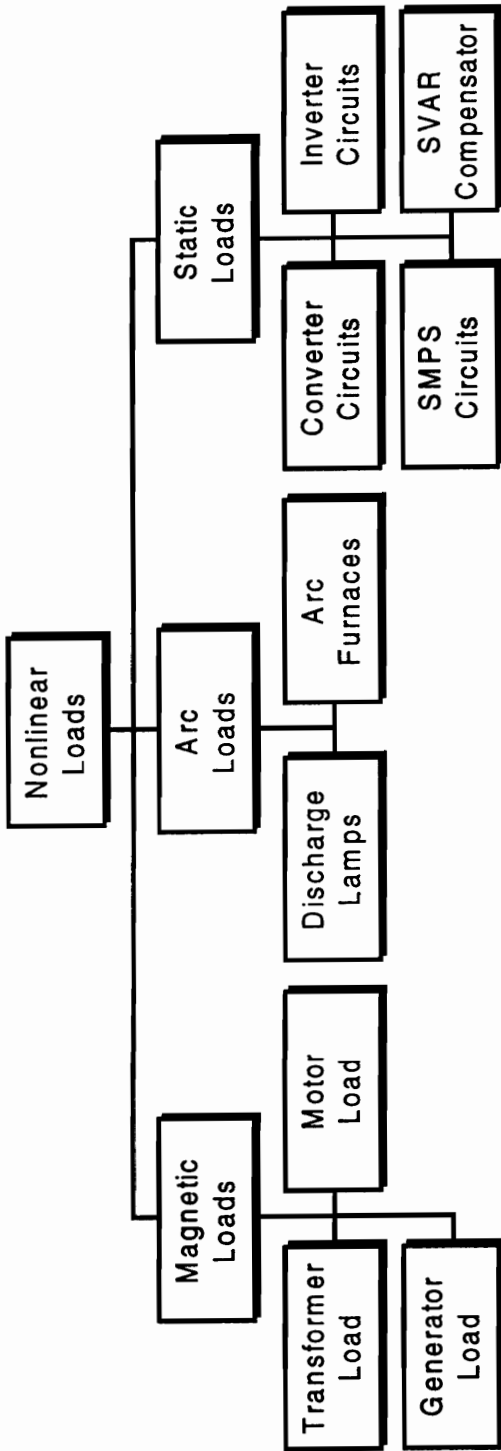
Figure 3.1. Classification of Nonlinear Loads

3.2.1 Transformers

Iron core devices like transformer have nonlinear relation of flux density with the current. Under normal operating conditions these devices produce a symmetrical non-sinusoidal excitation current when excited with sinusoidal voltage. It generates odd harmonics. However, contribution of harmonics to the magnetizing current is very small. Harmonic contribution to the magnetizing current is significant under following conditions:

       i)   Magnetizing in-rush during switching transformer under no-load conditions.

      ii)   Over-excitation of transformer caused by electric power supply system over-voltage.

    iii)   DC magnetization in the transformer core when loaded with half-wave rectifier.

Transformer switching under no-load conditions causes up to more than twice the maximum flux density. This phenomenon produces an in-rush current from seven to ten times the full load current. It generates significant second harmonic and DC components. In case of 20% over-voltage, power transformers start operating in the saturation region. Magnetizing current exceeds the full load current and transformer operates in saturation region. Due to nonlinearity of the saturation region, harmonic content become more visible. When a transformer is loaded with rectifier, it requires only unidirectional half sinusoidal wave. The AC component of this secondary output current is offset by a supplementary ac primary current. The DC component of the secondary winding

produces DC magnetization of transformer core. The core is saturated for one half cycle and generates even and odd harmonics.

3.2.2 Electrical Machines: - generator and motor

Electrical generators do not generate a perfect sine wave. Pitch factor and other design parameters are greatly pronounced as nonlinear characteristic of generator. Degree of nonlinearity in electrical machines depend upon the design parameters. Standard generator with 4/5 or 5/6 pitch generates lower order odd-harmonics. However, fractional pitch winding significantly reduces third harmonics. A 2/3 pitch winding eliminates the third harmonics and doubles the amplitude of fifth & seventh harmonic.

3.2.3 Discharge Lamps

Fluorescent, high pressure sodium and metal halide lamps have significant nonlinear arc impedance. Applied ac voltage to the lamp ignites the arc during each half cycle. Impedance of the arc keeps changing through out the cycle. This phenomenon produces nonlinear current and voltage waveforms. Magnetic choke, used to operate discharge lamp, is operated in saturation region of magnetization curve. It increases the harmonic content in the load current. Overall discharge lamps with conventional driving arrangement generate large amount of harmonics. Third and fifth harmonics are the most dominant harmonics in discharge lamps. Standard discharge lamps produce total harmonic distortion(THD) as high as 30% of the fundamental frequency.

3.2.4 Arc Furnaces

Impedance of the arc in electric arc furnaces is nonlinear as well as unpredictable. It keeps changing throughout the melting process in the furnace. Melting cycle of the

electric arc furnace could be divided into two stages. First stage is the initial melting stage. It has an active arc. Arc current is non-periodic and contains harmonics of integer and non-integer orders. Non-integer harmonics are not very significant whereas integer harmonics are between second and seventh harmonics. Amplitude of the harmonics decrease with the frequency of the harmonics. Second part of the melting cycle is the refining stage. It has a stable arc. Arc current becomes stable and harmonic current is reduced. The current becomes symmetrical, eliminating non-integer and even harmonics.

3.2.5 Converters

The ac to dc converter is used in dc motor speed control, ac motor speed control, uninteruptible power supplies, computer power supplies and numerous other applications. Conventionally, diodes were used as switching devices in converter circuits. In modern converters diodes have been replaced with thyristors. They can be switched *on* and *off* at any point of the cycle by using proper firing circuits. Three-phase converters are made by cascading three single phase converters. Converters in all configurations are nonlinear loads. They draw non-sinusoidal current from the source. Converters with diodes as switching devices are less nonlinear as compared to thyristor based converters. As . nonlinearty of the converter circuit increases they draw more non-sinusoidal current and harmonic distortion becomes a significant problem.

3.2.6 Inverters

Inverter circuits are widely used for different control applications. Adjustable speed drives are the most common user of inverter. They are used to change a dc input voltage to a symmetrical ac voltage of desired magnitude and frequency. Output voltage waveform of the inverter is non-sinusoidal and contains certain harmonic frequencies. Recent developments in semiconductor devices have made it possible to minimize

harmonics by using certain switching techniques. As inverters are the fastest growing devices in modern control applications hence they are discussed in detail in this chapter. Classification of the inverter is shown below in Figure 3.2.

Both single phase and three phase inverters have four categories each. Pulse width modulation(PWM) inverter is the most popular inverter presently used in adjustable speed drives and other control circuits. Followings are the commonly used techniques in PWM inverter:

a) Single pulse width modulation.
b) Multiple pulse width modulation.
c) Sinusoidal pulse width modulation.
d) Modified sinusoidal pulse width modulation.
e) Phase displacement control.

Power electronics: circuits, devices, and applications [110] is an excelent reference to review different types of inverters.

3.2.7 Switch Mode Power Supplies (SMPS)

Conventional power supplies with a transformer and iron core choke are clumsy, inefficient and uneconomical. They have been replaced with efficient, compact and economical switch mode power supplies. Presently, all manufacturers of microprocessor based equipment use SMPS. Switching phenomenon in these power supplies take place at a frequency range from 20 to 100 kHz. High switching frequency helps to reduce the transformer size, used in the power supply. Usually ferrite core is used instead of iron core. A very sophisticated control circuitry is used to produce the required voltage under varying
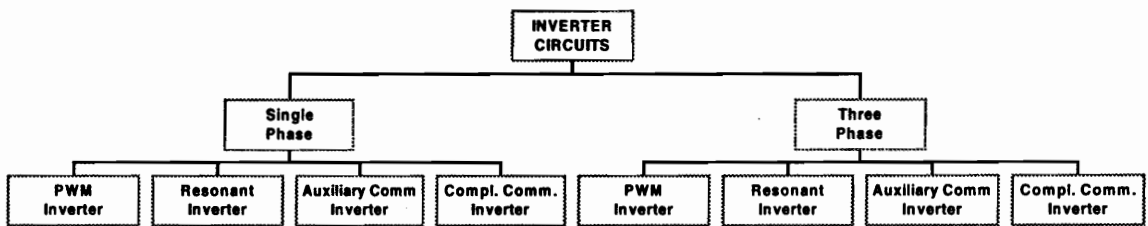
Figure 3.2. Classification of Inverter Circuits

load conditions. Current requirements are within a very narrow time span of each half cycle. It makes SMPS a highly nonlinear load.

3.2.8 Static VAR Compensators

A static VAR compensator (SVC) supplies a variable amount of reactive power to a power network. It consists of numbers of fixed capacitors, in parallel and a switched inductor. Thyristor controlled reactor is used quite extensively as a static VAR compensator. It helps to reduce voltage flicker, improve power factor, power system stability and correct phase imbalance. However, gating phenomenon in thyristor, being a nonlinear device, changes the current from sinusoidal to non-sinusoidal form. Nonlinearity of SVC generates harmonic currents of odd frequencies.

Main advantages of static VAR compensator are:

- High speed of operation.
- Compact size.
- Low loss.

3.3 Power Measurements in Nonlinear Loads

The increasing use of power electronic technology for energy conservation purposes has made the measurement process in nonlinear loads a bit complicated. Conventional instruments used for control and measurement purpose, are obsolete now. However, digital techniques have made it possible to measure voltage, current, power and power factor for nonlinear loads. Results of different measurements made during this research shows that nonlinearity of the loads significantly effect the measurements.

Although sampling technique is an effective tool to measure true power under nonlinear conditions but industry prefer to keep on using conventional instrumentation and measurement techniques. Following section is intended to clarify the discrepancies in power measurements that occur due to nonlinearities in the power electronics equipment and other nonlinear loads.

Apparent power is a widely used term in power engineering practice and applications. Usual definitions are restricted only to linear loads. Whereas nonlinear loads are delt, separately. The procedure of determining VA takes into account the RMS values of harmonics and their order in case of nonlinear loads. Active power and apparent power in a nonlinear system is defined as:

$$P = \frac{1}{T}\int_0^T v(t)\,i(t)\,dt \qquad \text{............ ....(3.1)}$$

$$S = V_{RMS}\,I_{RMS} \qquad \text{......................................(3.2)}$$

Where

$v(t)$ = Instantaneous voltage.

$i(t)$ = Instantaneous current.

V_{RMS} = RMS voltage.

I_{RMS} = RMS current.

One popular notation used to relate apparent power, active power, and reactive power is:

$$|S|^2 = P^2 + Q^2 \qquad \text{...(3.3)}$$

Equation 3.3 is true for a pure sinusoidal system while reactive power (S) is very much controversial for non-sinusoidal systems. Reason for this deviation from Eq. 3.3 is the fact that nonlinear loads follow the relationship: $|S|^2 > P^2 + Q^2$. It is due to the cross terms in the products of the Fourier series that coresspond to voltages and currents of different harmonic frequencies. Active power(P) and reactive power(Q) coresspond to the voltage and current products of terms of the same frequency. The Equation 3.4 incorporates the cross terms that explains the distortion effect of nonlinear loads.

$$|S|^2 = P^2 + Q^2 + D^2 \qquad\qquad ....(3.4)$$

Where

$D = $ Distortion volt-amperes.

Distortion volt-amperes correspond to the products of voltages and currents of dissimilar frequencies in the Fourier series of $v(t)$ and $i(t)$. D can also be interpreted as:

$$D^2 = |S|^2 - (P^2 + Q^2) \qquad\qquad ....(3.5)$$

Although the above interpretation, about the reactive power for nonlinear and non-sinusoidal systems is not widely accepted, a number of electrical engineers are using these equations for reactive power measurements. Makram [111] has developed an algorithm to determine the power components in a system having nonlinear loads and non-sinusoidal voltage and/or current waveform, based upon notion (3.1)-(3.5).

3.4 Impact of Nonlinearity on Power Factor

In case of linear loads, terminal voltage is proportional to the load current and are displaced with certain phase angle. Cosine of the phase angle between the voltage and current is termed as the power factor of the linear load. The nonlinear loads only draw current during a portion of the voltage cycle. This results in non-sinusoidal current waveform. As shown in figure 3.4, current drawn by CFLs is no longer sinusoidal. Current waveform of CFLs is made up of fundamental frequency and number of harmonics, added together. Only the fundamental portion of current waveform contributes to the real power. Harmonics present in the current waveform do not contribute to the real power or the apparent power. Hence power factor calculated in this way is not a true power factor. True power factor consists of displacement factor and distortion factor.

a) Displacement Factor

Displacement factor is the phase displacement between the supply voltage and fundamental frequency component of the current. Displacement angle depends upon the circuit configuration of the rectifier. It needs to be calculated carefully because it has significant impact on the overall power factor of the system.

$$Displacement \quad Factor = \frac{P_s}{E_s I_s (fundamental \ frequency \ component)}$$

Where
P_s = System Power   ....(3.6)

E_s = System Voltage

I_s = System Current

Compact Flourescent Lamps
(Exp. 03/28/94)
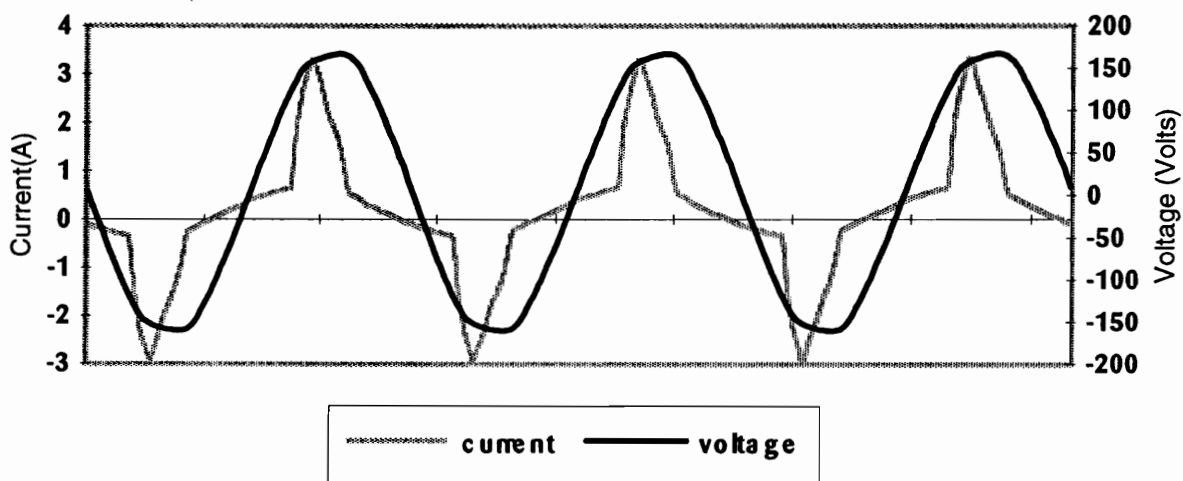
Figure 3.3. **Voltage and Current Drawn by Compact Fluorescent**
Lamps

b) Distortion Factor

The ratio of fundamental current to the total current is known as distortion factor. It is a measure of current distortion due to nonlinear character of the load impedance.

$$Distortion \quad Factor = \frac{Fundamental \; Current}{Total \; Current}$$

$$= \frac{I_{s_1}}{I_s}$$

....(3.7)

Due to the complex nature of the current waveform in nonlinear loads, power factor could not be measured with conventional power factor meters. Recent developments in digital technology have made it possible to measure distortion factor with digital instruments. Manufacturers of nonlinear loads in general and lighting loads in particular do not mention the method of power factor calculations. Preliminary investigation shows that so called power factor in above cases is just displacement factor and distortion factor is not included in the power factor.

c) Impact of Harmonic Distortion on Power Factor Calculations

Real power drawn by nonlinear load is affected by voltage, current, phase shift between voltage and current, and ratio between fundamental current and total current. If the displacement factor is very small then the power factor of the nonlinear load will be the following:

$$Distortion \quad Factor = \frac{1}{(1 + THD)^{1/2}}$$

$$.............(3.8)$$

$$Power \quad Factor \quad = Displacement \; factor \times Distortion \; factor$$

Where

$$Displacement \; Factor = Cos\varphi_{s1}$$

and $$...(3.9)$$

$$Distortion \quad Factor = \frac{I_{s1}}{I_s}$$

$$Power \quad Factor = Cos\varphi_{s1} \times \frac{I_{s1}}{I_s} \quad ....(3.10)$$

3.4.1 Power Factor of Nonlinear Load With Non-Sinusoidal Supply Voltage

In case of high line impedance, current distortion has a significant impact on voltage distortion. Under these circumstances, both current and voltage waveforms are distorted and power factor calculations become more complicated.

$$Power \ \ Factor = \frac{P_s}{S_s} \quad \dots\dots\dots(3.11)$$

$$S_s^2 = E^2 I_s^2 \quad \dots\dots\dots(3.12)$$

$$= \left(\sum_1^{n_1} E_{n_1}^2 + \sum_1^{n_2} E_{n_2}^2 \right) \left(\sum_1^{n_1} \left(E_{n_1}^2 n_1^2 \omega^2 C^2 + I_{L_{n_1}}^2 - 2 E_{n_1} I_{L_{n_1}} n_1 \omega C \sin \varphi_{L_{n_1}} \right) + \sum_1^{n_2} \left(E_{n_2} n_2 \omega C \right)^2 + \sum_1^{n_3} I_{L_{n_3}}^2 \right)$$

$$\dots\dots\dots(3.13)$$

$$P_s = P_L = \sum_1^{n_1} E_{n_1} I_{L_{n_1}} \cos \varphi_{L_{n_1}}$$

$$Power \ \ Factor = \frac{P_s}{S_s} = \frac{P_s}{EI_s} \quad \dots\dots\dots(3.15)$$

Substituting Eq(3.13) and Eq(3.14) in Eq(3.15)

$$Power \ \ Factor = \frac{\sum_1^{n_1} E_{n_1} I_{L_{n_1}} \cos \varphi_{L_{n_1}}}{\left[\left(\sum_1^{n_1} E_{n_1}^2 + \sum_1^{n_2} E_{n_2}^2 \right) \left(\sum_1^{n_1} \left(E_{n_1}^2 n_1^2 \omega^2 C^2 + I_{L_{n_1}}^2 - 2 E_{n_1} I_{L_{n_1}} n_1 \omega C \sin \varphi_{L_{n_1}} \right) + \sum_1^{n_2} \left(E_{n_2} n_2 \omega C \right)^2 + \sum_1^{n_3} I_{L_{n_3}}^2 \right) \right]^{\frac{1}{2}}} \quad \dots(3.16)$$

Shepherd and Zand [112] have given a complete derivation of power factor for nonlinear load and non-sinusoidal supply voltage.

3.4.2 Power Factor Calculations Using Sampling Technique

Voltage and current waveforms are defined in the beginning of the program. Mostly voltage waveform is sinusoidal or close to sinusoidal. Current waveform is usually extremely nonlinear, depending upon the nonlinear load. Active power P is calculated using the relationship:

$$P = \sum_{t=0}^{N} v(t)i(t)$$

V_{RMS} and I_{RMS} are calculated using the sampling technique.

Hence apparent power S will be:

$$S = V_{RMS} \bullet I_{RMS}$$

$$PF = \frac{P}{S}$$

3.4.3 Programming Tool and Solution Methodology

Sampling technique can be implemented by using any programming language or software packages like MATLAB, Mathematica, etc. A program was written in MATLAB to calculate power factor for a given sinusoidal voltage and non-sinosoidal current. However, the program is effective for sinusoidal as well as non-sinusoidal

systems. One hundred and one samples from a cycle of each signal were taken to calculate power factor.

First, program was tested for a sinusoidal current and voltage signal. For 101 samples computed power factor was 0.7071 and calculated power factor was 0.7106. This discrepancy in power factor was due to low sampling rate. Sampling rate was increased to 1001 and computed power factor was 0.7068 which is close to the calculated power factor. Table 1 gives some results for sinusoidal signal $i_a(t)$ and non-sinusoidal signals $i_b(t)$, $i_c(t)$ and $i_d(t)$. Complete program is given in Appendix and flow chart for the program is given in Figure 3.4.

Table 3.1. Power Factor and Displacement Angle for Different Current Waveforms

Current	Voltage Ref. Angle	Current Phase Angle	Displacement Angle	Power Factor
$i_a(t)$	$\pi/4$	0	$3\pi/4$	0.710598687
$i_b(t)$	$\pi/4$	$-\pi/2$	$3\pi/4$	-0.698440509
$i_c(t)$	$\pi/4$	$-\pi/2$	$3\pi/4$	-0.640010217
$i_d(t)$	$\pi/4$	$-\pi/2$	$3\pi/4$	-0.560379403
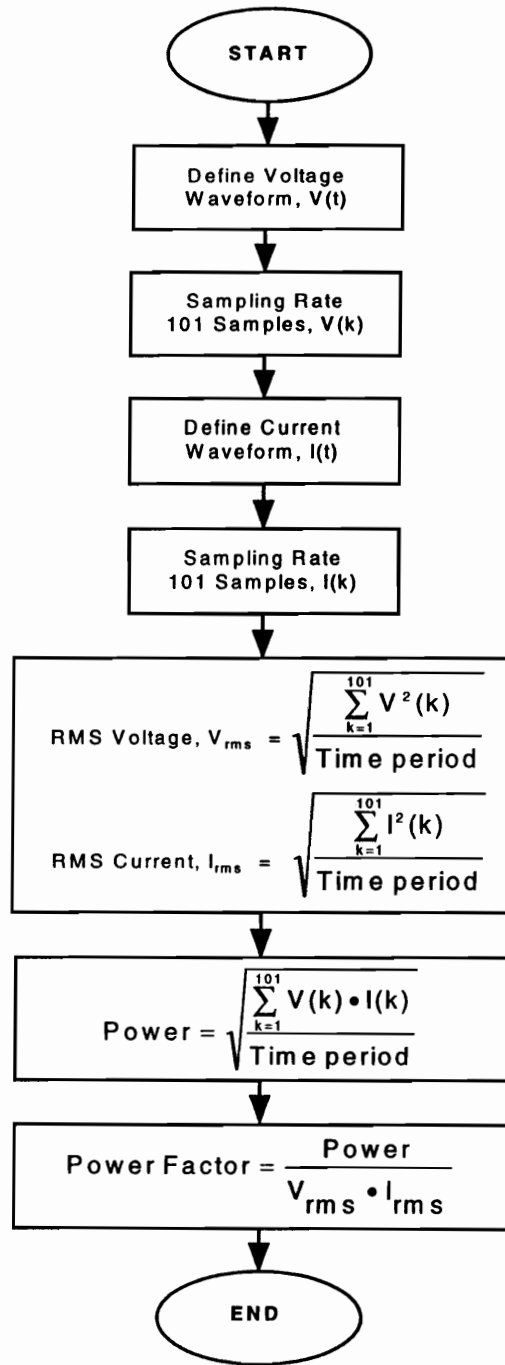
Figure 3.4. Flow Chart for Power Factor Calculation Using Sampling Technique.

3.5 Impact of Nonlinear Loads on Power Factor Correction Capacitor

Shunt capacitors are used to improve the distribution system performance by reducing power and energy losses. Most of the techniques in this regard were developed for the power system that have most of its load as nonlinear load. However, with the growing interest in energy efficiency and advancement of power electronic technology, more proliferation of nonlinear loads is taking place. Capacitor on the distribution systems with nonlinear loads can introduce a severe harmonic resonance problem.

Figure 3.5 shows the equivalent circuit of a two bus system with nonlinear loads. Harmonic load flow is carried out to identify the harmonic current source with various load components more precisely.

3.6 Correlation Between Nonlinear Loads and Energy Conservation Technologies

Static nonlinear loads have a very important role in achieving higher stadards of conservation in electrical energy use. Power electronic technology has revolutionized the control of power conversion in different classes of energy use. Two third of the electricity consumed in United states goes to rotating electrical machines. Efficiency and performance of electrical machines could be better controlled and improved, using power electonic technology. Lighting accounts for one fourth of the electricity used in industrilized countries. Power electronic control has made possible to save energy up to 77% by replacing conventional lighting sources with energy efficient discharge lamps. Table 3.2 shows a wide range of applications of power electronic devices in different background.
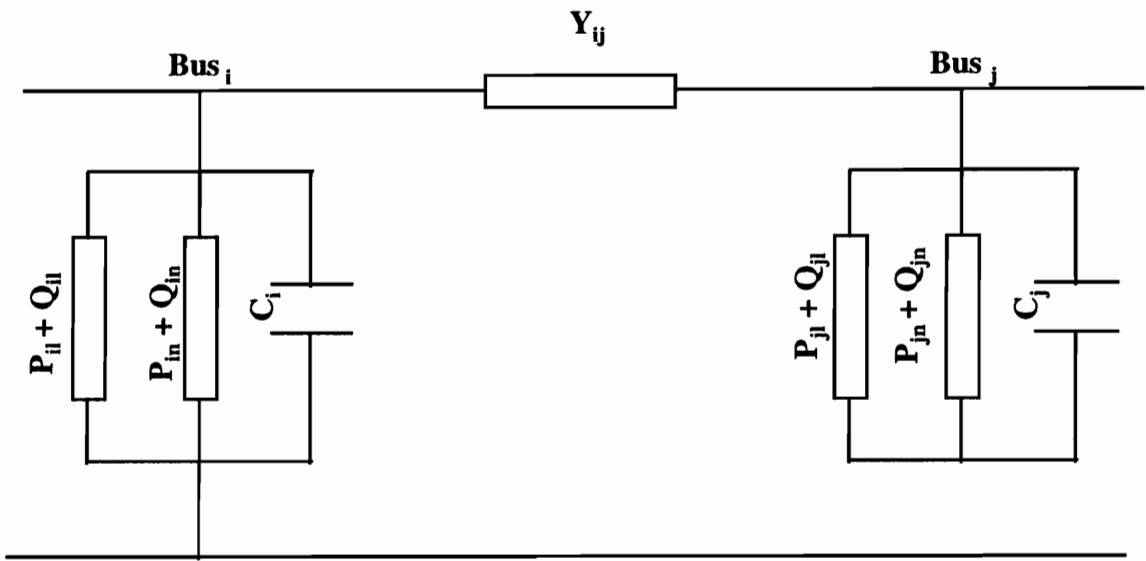
Figure 3.5. Equivalent Circuit of Two Bus System With Nonlinear Loads

This category of nonlinear loads (power electronic devices) combine power, electronics, and control. Control is all about steady state and dynamic characteristics of closed-loop systems. Power deals with static and dynamic power equipment for generation, transmission and distribution of electronic power. Electronic devices are used in control circuitry of the signal processing, required to achieve desired control in different applications. These devices have tremendous switching speed and power handling capabilities and have broadened the scope of their application in every area of electric energy use. Table 3.2 gives a summery of selected applications of power electronic devices. It gives an idea about the level of involvement of nonlinear loads in power distribution system.

Table 3.2. Some Applications of Power Electronic Devices

Advertising	Garage door openers	Pumps and compressors
Air conditioning	Gas turbine starting	Radar/sonar power supplies
Alarms	Generator exciters	Range surface unit
Appliances	Grinders	refrigerators
Audio amplifiers	Hand power tools	Regulators
Battery charger	Heat controls	RF amplifiers
Blenders	High frequency lighting	Security systems
Blowers	High voltage DC	Servo systems
Boilers	Induction heating	Sewing machines
Burglar alarms	Laser power supplies	Solar power supplies
Cement kiln	Latching relays	Solid-state contactors
Chemical processing	Light dimmers	Solid-state relays
Clothes dryers	Light flashers	Space power supplies
Computers	Linear motor control	Static circuit breakers
Conveyers	Locomotives	Static relays
Cranes and hoists	Machine tools	Steel mills
Dimmers	Magnetic recordings	Synch. machine starting
Displays	Magnets	Synthetic fibers
Electric blankets	Mass transits	Television circuits
Electric door openers	Mining	Temperature controls
Electric dryers	Model trains	Timers
Electric fans	Motor controls	Toys
Electric vehicles	Motor drives	Traffic signal controls
Electromagnets	Movie projectors	Trains
Electroplating	Nuclear reactor control rod	TV deflections
Electronic ignition	Oil well drilling	Ultrasonic generators
Electrostatic precipitators	Oven controls	UPS systems
Elevators	Paper mills	Vacuum cleaners
Fans	Particle accelerators	VAR compensators
Flashers	People movers	Vending machines
Food mixers	Phonographs	VLF transmitters
Food warmer trays	Photocopiers	Voltage regulators
Forklift trucks	Photographic supplies	Washing machines
Furnaces	Power supplies	Welding

3.7 Summary

Nonlinear loads are a growing concern for electric utilities. The increased use of power electronic devices on distribution system have created unusual problem for the customers. Consumers of electricity are spending billions of dollars to protect their sensitive equipment from harmonics, injected by nonlinear loads into the electric distribution system. Good engineering practice demands that a problem should be fixed at its source i.e. nonlinear loads. A filter could be installed inside the supply circuit of the equipment or in the vicinity of the equipment. This will significantly block the harmonics to effect the other sensitive loads. The other solution is to de-rate the equipment. Whatever measure is taken to address the issue, one should fully comprehend the problem of low power factor, resonance, and overheating of transformers, motors and generators.

CHAPTER IV

HARMONIC DISTORTION: Sources, Effects, and Standards

4.1 Introduction

The phenomenon of harmonic generation has been known since the inception of alternating current systems. However, it has not been a threat to the power system until the recent developments in switching devices and the accompanying proliferation of power electronic devices at large scale. These devices are universally used in consumer products.

The problem of harmonic distortion has recently become the focus of study of many researchers. This can be easily seen when we examine the numerous conferences dedicated to the subject. International engineering societies have also devoted working groups and committees to study this phenomenon.

Voltage and current waveforms in a power network are perfectly sinusoidal under ideal operating conditions. In case of abnormal circumstances, however, voltage and current are not linearly related to each other. The current drawn by nonlinear loads is nonsinusoidal and results in multiples of the fundamental frequency in addition to the fundamental frequency component. In most of the cases, where the source is power

electronic equipment, the line current waveform has a half-wave symmetry. Hence, odd multiples of the fundamental frequency are initiated in the waveform. Without the half-wave symmetry, the waveform may also include some even harmonics. However, even harmonics are very rare in the line current, which is drawn by power electronic devices.

In this chapter we will cover the sources of harmonics common to the supply and load side of the power network. In later sections, we will discuss the effects of harmonics on equipment as well as some recomendations to keep the harmonic distortion level within the prescribed limits.

4.2. Sources of Harmonics

In chapter III, we described the nonlinear loads. In order to focus on the harmonic generation aspect of these loads, we will revisit some of the characteristics of the nonlinear loads. Due to the nonlinearity in electrical loads in general and power electronic devices in particular, these loads draw a non-sinusoidal current from the source. It is only the fundamental frequency portion of the line current that serves the useful purpose. Other multiple frequencies, that are included in the sinusoidal current, are reflected back to the electric source.

We can conveniently group harmonic sources into two general categories: conventional and non-conventional sources. Conventional sources constitute the sources that were in place before the recent developments in electronic technology, and the related concerns to energy conservation and the global environment The conventional harmonic sources include:

I.   A transformer operating under saturation condition.

II.   A transformer inrush current.

III.   MMF distribution in AC rotating machines.

IV.   Electric furnaces.

V.   Fluorescent lighting.

VI.   Imperfect AC sources.

VII.   Static converters.

Most of the conventional harmonic sources do not assert any serious threat to the electrical system. Electric furnaces and static converters are the only loads that generate a high level of harmonics. These loads are usually isolated and harmonic filters are installed at the site of these loads. Further discussions on these sources are beyond the scope of this work.

Recent proliferation of power electronic and information technology has substantially changed the load culture in electric power distribution system. The non-conventional harmonic sources are well distributed in the electric utility network. This group includes:

I.   Desktop personal computer.

II.   Battery charger.

III.   Static VAR compensator.

IV.   Adjustable speed drives (ASD).

V.   DC converter.

VI.   Inverter.

VII.   Television.

VIII.   Visual cassette recorder (VCR).

IX.   Laser printer.

X.   Photocopier.

XI.   High frequency electronic ballast.

XII. Compact fluorescent lamp.

These loads are almost uniformly distributed in residential, commercial, and industrial sectors. Moreover, they are the fastest growing loads in all the three electric load sectors. Also, energy conservation programs contitute a factor in the growth of these loads. Incandescent lamp is a very inefficient source of light. Compact fluorescent lamps (CFLs) are good replacement of incandescent lamps due to their high efficacy. Adjustable speed drives are also expected to find their way in residential, commercial and industrial applications. Adjustable speed drives (ASDs) are energy efficient compared to conventional electric drives. Also, their role in complex industrial processes is very crucial and unique. Most of the high-tech processes can be performed only with adjustable speed drives. Three phase power supplies are playing an important role in industrial automation and efficient processes. Single phase switch mode power supplies (SMPS) have numerous applications in domestic appliances and office equipment. Further discussion about sources of harmonics can be found in references [115,116].

4.3 Effects of Harmonics [115-117]

Harmonics generated from different sources in a power system affect both the individual loads and the power system collectively. We will first discuss the effect of harmonics on individual loads.

a) Capacitors

Shunt capacitors have been traditionally used to improve power factor in commercial and industrial facilities. In the presence of harmonic frequencies, they may

create resonant conditions. If a capacitor tunes the system to resonate near any harmonic frequency, that is already present in the load current, it will generate a high voltage at that frequency. The high voltage may blow the capacitor fuse or destroy it completely. Another possible effect of harmonics could be additional heating and dielectric stress on the capacitor.

b) Circuit Breakers and Fuses

Load current with harmonic distortions can result in higher *di/dt* at zero crossing than a sinusoidal waveform, and hence making interruption more difficult. Fuse is an inherently RMS over-current device. Distortions in the load current do not have much impact on the operation of fuses.

c) Conductors

Higher frequencies in the distorted load current contribute to the heat losses in the conductor due to skin effect. Skin effect increases with the frequency and diameter of the conductor. A conductor carrying a distorted load current can distort the current distribution in an adjacent conductor. Usually, in commercial buildings, each phase of three phase four wire system is loaded with office equipment that have significantly high triplens in the load current. These frequencies are added up in the neutral, as opposed to the normal situation when all phases cancel each other in the neutral. Neutral current goes as high as three times of the phase current. This situation can lead to conductor failure.

d) Electronic Equipment

The electronic equipment is affected by harmonic distortions in many ways. One of the most common effects is the increase in zero crossings as compared to fundamental frequency current due to harmonic distortions. It can disrupt the operation of electronic equipment. Digital clocks are the common example of malfunctioning due to additional zero crossings from harmonic distortions in the supply voltage. Switching in electronic devices is carried out at zero crossing to avoid electromagnetic interference. Increase in the number of zero crossings could disrupt the operation of the equipment. Voltage-peek-sensitive operations are affected by the presence of harmonic distortions in the voltage signals, that could flatten the voltage peak.

e) Lighting

The most common effect of harmonic distortions is the reduction in life of incandescent lamps for extended time. Harmonic distortions usually increase operating RMS voltage. The continuous operation of incandescent lamp at 105% of rated voltage can decrease the lamp life to 47%. Discharge lamp generates audible noise due to harmonic distortions present in the supply voltage. Resonance problems could occur as a result of inductive choke and power factor improvement capacitors in conventional fluorescent lamps.

f) Meters

Conventional voltmeter, ammeter, watt-meter, and energy meter have an induction type. They are not suitable for currents and voltages having harmonic distortions. This is due to two reasons. First, they produce error in measurements, depending on the level of harmonic distortions of the signals. In conventional induction

meters registration error could be as high as -20%. Second, there is a possibility of mechanical resonance failure in the range of 400-1000 Hz, when utilizing one of these meters.

g) Protective Relaying

Harmonic distortions in the current and voltage signal could cause malfunctioning of protective relays. Different relays may respond differently to the fault current with the same level of harmonic distortions. Variation of phase angle between harmonic frequency and fundamental frequency may significantly alter a relay response. Hence, the relay under may not respond to the fault or cause nuisance tripping when there is no fault. Most experts agree that it is very difficult to generalize the impact of harmonic distortions on protective relays.

h) Rotating Electrical Machines

The distorted supply voltage applied to electric drives may cause overheating, pulsating torque, and noise. Rotor overheating is another significant problem related to non-sinusoidal voltage supply. Both of these problems will contribute to reduction of motor operating life. Motor overheating due to nonsinusoidal voltage supply is not uniform throughout the motor structure. Instead, there are some hot spots inside the motor structure. This phenomenon is perceptible near the conductors within the iron core portions.

Air gap flux and the fluxes produced by different harmonic frequencies, that are present in rotor current, interact with each other and produce pulsating torque. This torque could be damaging in adjustable speed drives due to possibility of mechanical resonance speed.

i) Telephone Interference

Keeping telephone and power line together on utility poles create the problem of interference of power line frequencies with telephone communication. Interference problem is magnified at harmonic frequencies near 1 kHz, i.e., the 15th and 17th harmonics. Details of the interference mechanism and mitigation techniques are given in Ref. [115].

j) Transformers

The harmonic distortions related problems in transformers could be overheating, possibility of resonance, mechanical insulation stresses, and core vibration. Transformers are usually derated to compensate for additional heat losses due to harmonic distortions. However, the best solution to the problem is to use specialty transformers particularly designed for certain level of harmonic distortions in the load currents.

4.4 Single Phase Harmonic Interaction in Power System

The widespread use of low voltage appliances such as television, light dimmer, phase control load, fluorescent lamp, personal computer, laser printer, and copier may contribute to public supply system distortion in a significant way. Harmonic distortion level in the supply system depends on the collective effect of harmonic sources supplied by the common utility bus. If the line currents drawn by each harmonic source have the same phase angles at respective harmonic frequency, the total line current distortion will be the algebraic sum of contributions by each source. In real life, electronic equipment generates harmonics having a different phase angle. However, the nature of amplitude

and phase angles of the harmonic frequencies is probabilistic. The summation of large scale, of similar order, harmonic vectors, that is generated by different sources, are carried out using different summation techniques. Kazbwe [118] have given a comparison of different methods of summation, applied to study collective harmonic effect of multiple harmonic sources.

In electric power system, voltage and current having mutually the same frequency transmit real power. In probabilistic methods of harmonic summation, the phase angle variation range at each harmonic frequency is an important factor. Lehtonen [119] has developed a probabilistic method for assessing harmonic power losses in electricity distribution network.

Additive current on the neutral is a common phenomenon in personal computers (PCs) intensive building. Zero sequence currents (3rd, 9th, 15th, etc.), generated by PCs or same kind of equipment, accumulate on the common neutral wire. Single phase harmonic sources contribute to the harmonic current buildup on the neutral wire [120]. Waggoner [121,122] has discussed the problem of harmonic interaction through case studies of harmonic load intensive commercial buildings.

4.5 Impact of Varying Impedances on Harmonic Distortion

The distortion current generated from a harmonic source interacts with impedances of the network itself. Sizable variation in impedance on alternating sources feeding large nonlinear loads can create high voltage distortion. Most of critical loads, i.e., hospitals, data centers, critical industrial process, etc., require an emergency or standby electricity source. Because most of the above mentioned facilities have nonlinear loads, they draw nonsinusoidal current. Loads other than harmonic sources have

impedance as high as 20 times the impedance of the electric utility network. Most of the generated harmonic current will flow towards the utility network. Figure 4.1 shows flow of harmonic current into low impedance utility network.

Some commercial and industrial facilities have in-plant generation. They have sufficient generation to meet up to 2/3 of their load demand. Electric utility in the service area supplies to rest of 1/3 load in the facility. In other words, in-plant generation is running in parallel to the utility source. Figure 4.2 shows this scenario of parallel operation of in-plant generator to the electric utility.

In-plant generator has much higher impedance as compared to electric utility network. Although electric utility is supplying 1/3 of the facility load, it has to absorb almost all the harmonics generated in the plant. This makes the utilities worry about parallel operation of in-plant generation to that of electric utility.
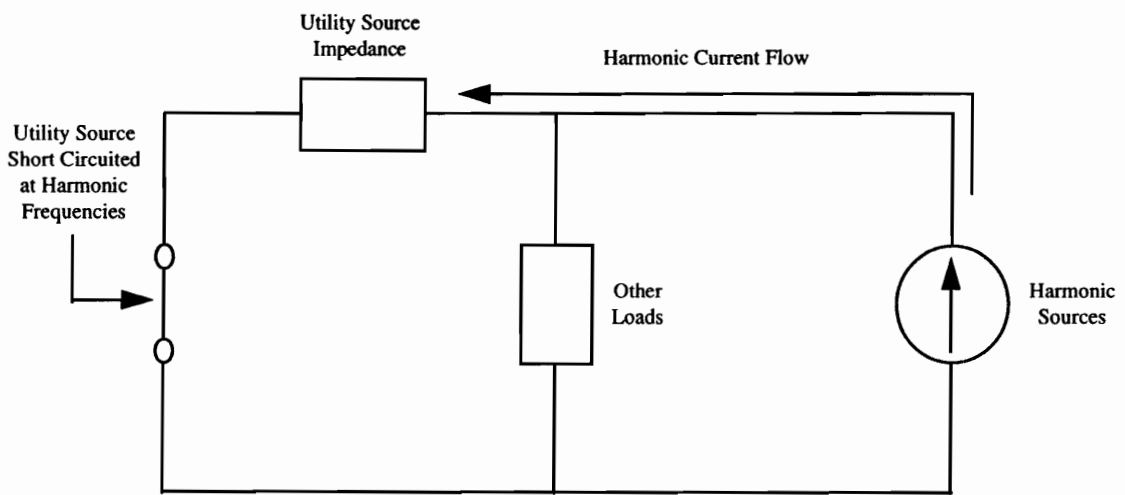
Figure 4.1. Harmonic Current Flow and Description of Utility and Load Impedances

Electric Utility

$I_{Harmonic}$ $I_{Fundamental}$

PCC

I_G

$I_{Harmonic}$ $I_{Fundamental}$

In-Plant
Generation

Load
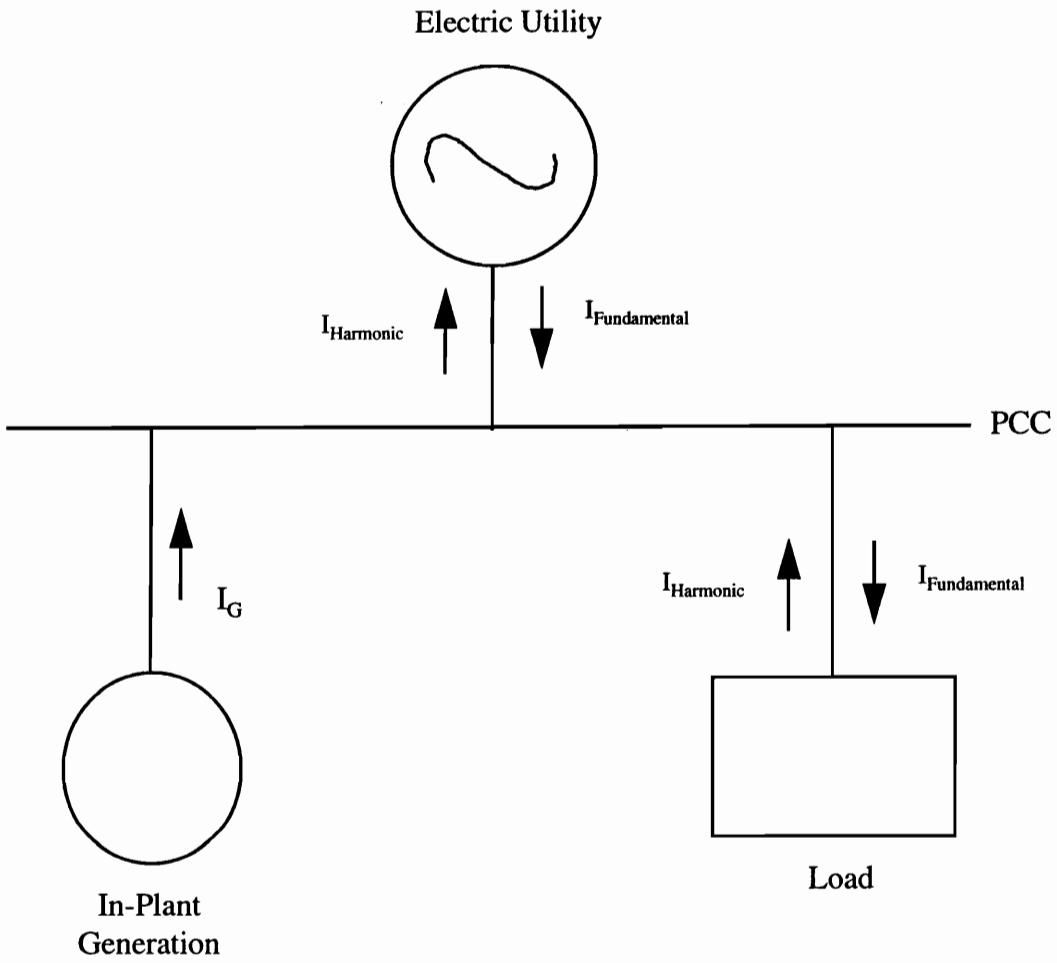
Figure 4.2. Parallel Operation of In-plant Generation With the Electric Utility

4.6 Resonant Phenomenon in the Presence of Harmonic Frequencies

As mentioned in the previous section, harmonic voltages in the network result from the interaction of the harmonic sources with the network impedances at each harmonic frequency. In purely inductive network, harmonic voltage is reduced when it moves from the source of harmonic to the network source. In the presence of significant capacitance, harmonic propagation is different and a complex phenomenon to understand. The mixed capactive inductive networks create a resonant condition. The resonance is of two types, i.e., series resonance and parallel resonance.

4.6.1 Series Resonant Network

The magnitude characteristics of network shown in Figure 4.3 approaches zero for very low and very high values of ω. The magnitude reaches its maximum when $\omega = \dfrac{1}{\sqrt{LC}}$ rad/s. The peaking of magnitude is referred to as a resonant effect. The condition under which peaking occurs is referred to as resonant condition or resonant network. The frequency at which the magnitude is maximum is called resonant frequency. The resonant effect is caused by cancellation of the imaginary components in the denominator of the function shown in Eq. 4.1, referred to circuit of Figure 4.3.

$$\frac{V_R}{V_1} = \frac{R}{R + j[\omega L - (\frac{1}{\omega C})]} \qquad \text{-----------------------(4.1)}$$
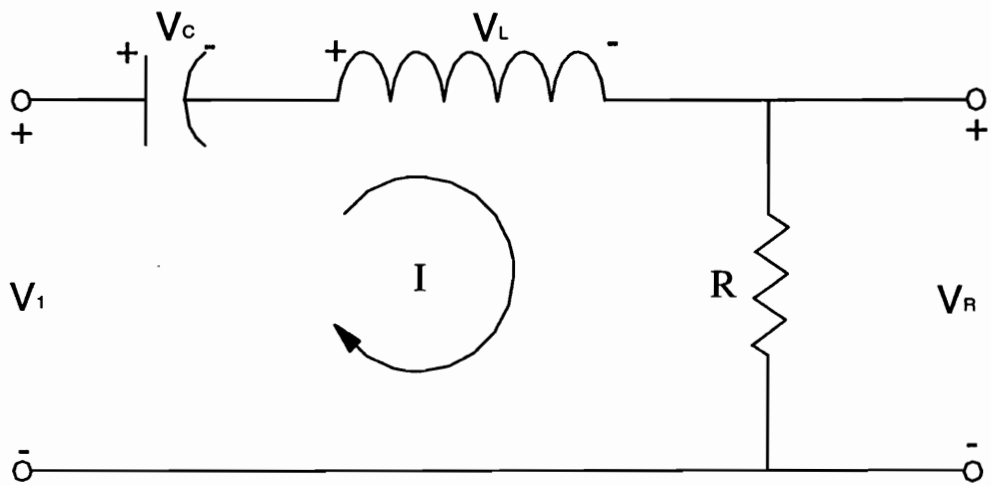
Figure 4.3. Series Resonance Network

4.6.2 Parallel Resonant Network

A parallel resonant circuit is shown in Figure 4.4. Eq. 4.2 refers to the relationship between the phaser variables and the driving point impedance. Resonance occurs in the parallel resonant circuit of Figure 4.4 when the imaginary part of the denominator in Eq. 4.2 goes to zero. A parallel RLC circuit is an inductive circuit at frequency less than the resonant frequency. For frequencies higher than resonant frequency, it behaves as a capacitive circuit. At resonant frequency, the network acts as a pure conductance. For a constant input current the magnitude of the voltage will be a maximum at the resonant frequency.

$$\frac{V}{I_1} = \frac{1}{G + j[\omega C - (\frac{1}{\omega L})]} \quad\quad\quad \text{-----------------------(4.2)}$$

Practical examples of parallel and series resonance are given in Figure 4.5. Parallel resonance often produces high voltage distortion at the source of harmonics. Series resonance can produce high voltage distortion remote to the harmonic source. While parallel resonance offers high impedance to the harmonic current, series resonance has low impedance for harmonic current. The high oscillation current in case of parallel resonance cause voltage distortion.
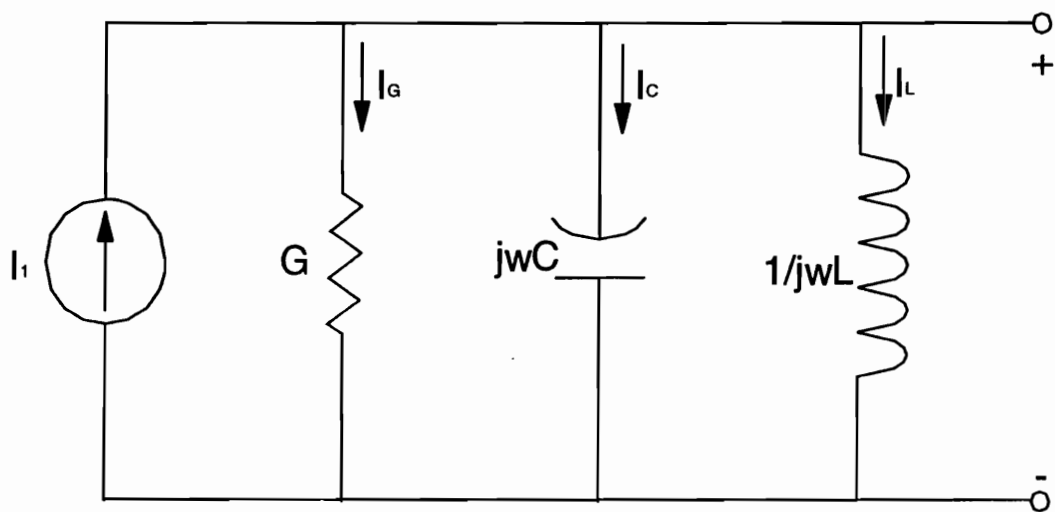
Figure 4.4. Parallel Resonant Network
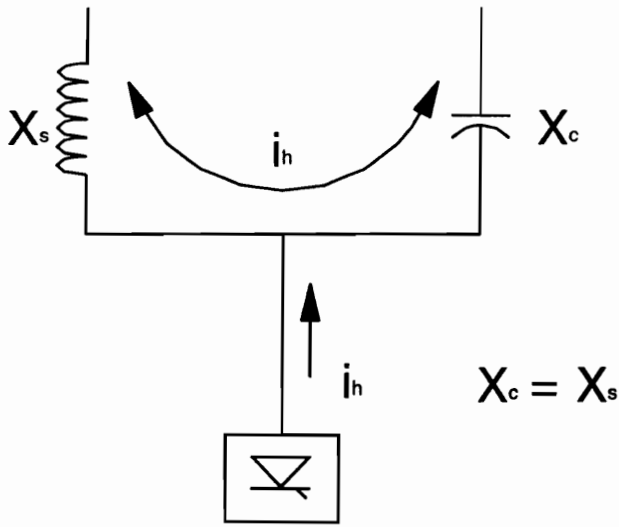
(a) Parallel resonance condition.

$$X_c = X_s$$

$$X_t = X_c$$
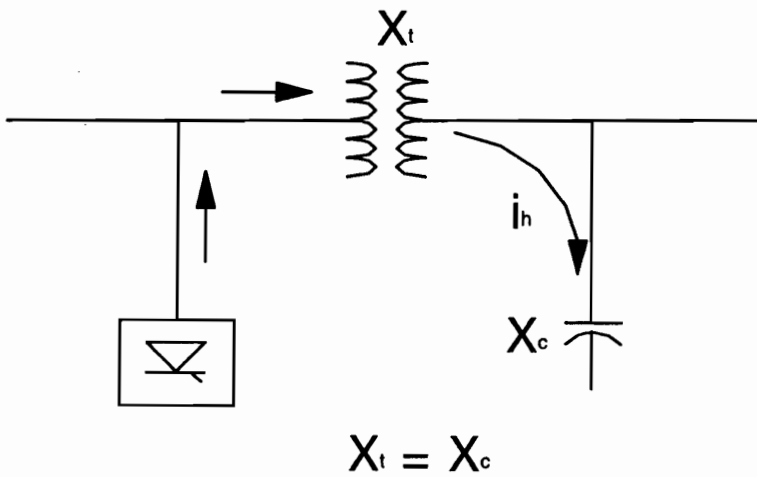
(b) Series resonance condition.

Figure 4.5. Practical Examples of Parallel and Series Resonance Conditions

4.7 International Harmonic Standards

This section covers standards, guide lines, and recommendations that govern the harmonic level in the power system and generation from different harmonic sources. These standards are intended to control the harmonic distortion level in the power system so that the power system equipment on the supply side, and the consumer equipment on the load side, could function securely. There are certain factors that influence the establishment of the adequate limits for harmonic distortions. These factors are summarized below:

- The definition of system harmonic.
- Total harmonic content, i.e., THD, TDD, etc.
- System voltage reference, i.e., 69 kV, 161 kV, etc.
- Ability of the system to withstand harmonics.
- The definition of limiting harmonic level.
- Data acquisition technique and equipment.
- The type of disturbing load.
- Possible interference with other electrical systems.

A combination of the above mentioned factors are usually the base of any standard or limits. The standards by itself can be classified into system standards, equipment standards, or acceptance criteria and connection standards. Measurements are usually made to monitor harmonic distortion level in the power systems. In general, standards do not suggest any specific method or equipment for measurements and monitoring of harmonic distortion. There are few standards that suggest certain

equipment for measurement of voltage and current harmonic distortion.   The most significant standards in the world are:

- ❏ France - Regulations Concerning the Installation of Power Converters, Taking into Account the Characteristics of the Supply Network.
- ❏ Germany - DIN 57160 (VDE0160/11.81).
- ❏ United Kingdom - Engineering Recommendations G5/3.
- ❏ Sweden - SEF Thyristor Committee Report.
- ❏ Australian - AS2279-1979.
- ❏ Finland - Restriction of harmonics in electrical network.
- ❏ New Zealand - Limitation of harmonic levels notice 1981.
- ❏ IEEE - Std 519-1992.
- ❏ IEC - Std 555.
- ❏ CIGRE - CIRED.

The French standard defines the total voltage distortion at a point of common coupling (PCC) in terms of the individual consumer's contribution to the voltage distortion at the PCC.   These limits are applicable to the individual even and odd harmonics.   The United kingdom, New Zealand, and Finish standards set the limits on current harmonics that an individual customer is allowed to draw.   The New Zealand and Finish standards also cover telephone interference and weighted current or voltage limit is used instead of total harmonic distortion (THD).   In UK and Australia, limits are imposed on the PCC. The consumers at that point are allowed to add harmonic generated load up to the set limit. All the consumers are allowed to add their load until the limit is reached. Later on, the consumers who want to add the harmonic generating loads are required to add filters to mitigate the harmonic effect.   In other words, a first come first serve approach is adopted in these standards.   In New Zealand, standard harmonic capacity is

shared by all the customers at the PCC. A portion of harmonic capacity is allocated to each customer at the PCC.

4.7.1 The Most Commonly Used Standards Around the World

The harmonic standards are set on the basis of certain requirements of the country or professional organization. The standards themselves could have either system, equipment, or acceptance approach. Indeed, each standard represents a compromise for the particular system between the ability of the utility to maintain its sinusoidal characteristics and ability of the customer to use loads having a non-sinusoidal current requirement. A review of different harmonic standards shows that non of the existing standards is perfect for universal applications. A set of currently available standards can be used to make a comprehensive harmonic evaluation of the system. Following is a set of international harmonic standards that can help to make an evaluation of a system:

- CIGRE WG 36.05:   acceptance approach.
- IEC Std-555:   equipment approach.
- IEEE Std-519-1992:   system approach.

CIGRE WG 36.05

The goal of *CIGRE WG 36.05* is to preserve voltage quality of the electric utility supply system. It gives harmonic limits for medium voltage as well as high voltage systems separately. Finally, the standard determines the requirements for connection industrial loads to the public power systems. The standard sets a compatibility criterion for the harmonic generating loads and industrial processes. It limits the probability of voltage fidelity at 95%. Planning limits set by the standard, are used to evaluate new loads.

Compatibility Criteria:

- Describes Voltage Fidelity at 95% probability
- Voltage THD Limit = 8%
- Individual Harmonics from 6% to 0.2%

CIGRE Planning Limits:

- Used to Evaluate New Loads
- Voltage THD Limit = 6.5%
- Individual Harmonics From 5% to 0.2%

Table 4.1. Compatibility Levels for Individual Voltage Harmonics

Odd Harmonics				Even Harmonics	
Non Triplens		Triplens			
Order (h)	Harmonic Voltage (%)	Order (h)	Harmonic Voltage (%)	Order (h)	Harmonic Voltage (%)
5	6	3	5	2	2
7	5	9	1.5	4	1
11	3.5	15	0.3	6	0.5
13	3	21	0.2	8	0.5
17	2	>21	0.2	10	0.5
19	1.5			12	0.2
23	1.5			>12	0.2
25	1.5				
>25	0.2+(1.3•25/h)				

Table 4.2. Planning Limits for Individual Voltage Harmonics

Odd Harmonics						Even Harmonics		
Non Triplens			Triplens					
Order (h)	Harmonic Voltage (%)		Order (h)	Harmonic Voltage (%)		Order (h)	Harmonic Voltage (%)	
	MV	HV		MV	HV		MV	HV
5	5	2	3	4	2	2	1.6	1.5
7	4	2	9	1.2	1	4	1	1
11	3	1.5	15	0.3	0.3	6	0.5	0.5
13	2.5	1.5	21	0.2	0.2	8	0.4	0.2
17	1.6	1	>21	0.2	0.2	10	0.4	0.2
19	1.2	1				12	0.2	0.2
23	1.2	0.7				>12	0.2	0.2
25	1.2	0.7						
>25	0.2+(1.3•25/h)							

The standard IEC-555-2 sets the harmonic limits for household appliances and similar electrical equipment. Many household appliances and similar equipment are liable to generate harmonics of the supply frequency. These harmonics are reflected into the supply system network at the point of common connection (PCC). Classification of appliances and similar devices is given in the following:

Class A:

Balanced three phase equipment, 3-phase ASDs.

Class B:

Small (<5 HP) single-phase ASDs, appliances with ASDs, and portable tools..

Class C:

Fluorescent Lighting (other than compact fluorescent lamp), and lighting dimmers.

Class D:

Computers, Compact fluorescent lighting, controllers, and consumer electronics. Equipment shall be deemed to be class D if the current half-wave drawn by the equipment is within the envelope shown in Figure 4.6.

.
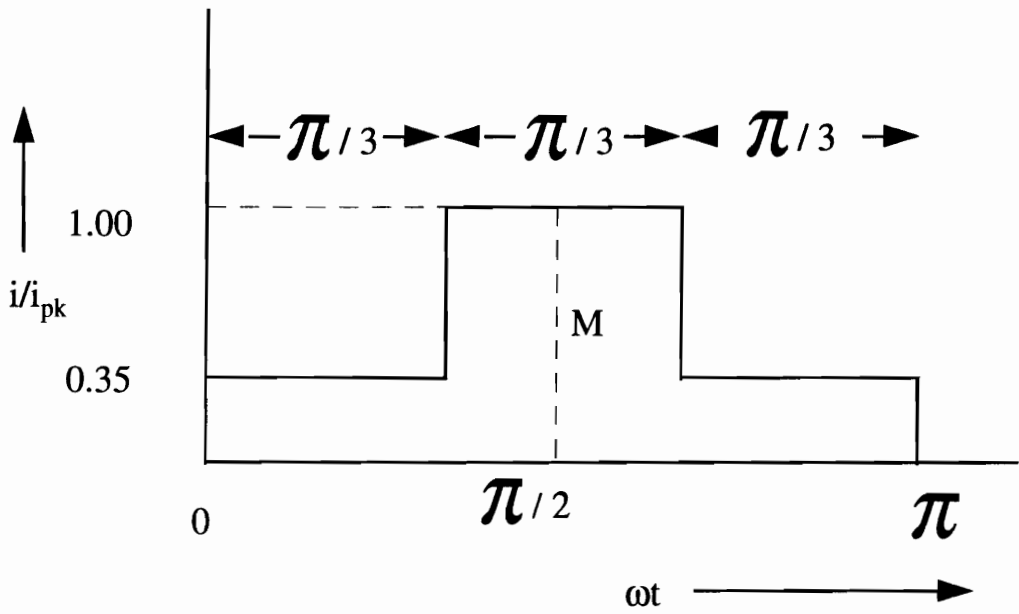
Figure 4.6. Envelope of the Input Current to Define the Special Wave Shape and Classify an Equipment into Class D

Table 4.3-4.5 shows the limits for equipment Class A-D. These limits are applicable with effect from the beginning of 1995. For equipment other than Class A-D, the harmonics of the input current shall not exceed the values that can be calculated from Table 4.4. These values apply to line and neutral currents and for all types of power connection of the equipment. These limits are applicable to steady-state harmonics. For transitory period of few seconds the harmonics are disregarded. However, for the lower order harmonics these limits are equally applicable. Limits for Class B equipment are 1.5 times the values shown in Table 4.3.

Table 4.3. Limits for Class A Equipment

Harmonic Order (*n*)	Permissible Current (mA/W)	Maximum Permissible Current (A)
Odd Harmonics		
3	3.4	2.30
5	1.9	1.14
7	1.0	0.78
9	0.5	0.40
11	0.35	0.33
13	0.30	0.21
≥15	3.85/n	0.15•15/n
Even Harmonics		
2	1.8	1.08
4	0.7	0.42
6	0.5	0.30
≥8	3/n	1.80/n

Table 4.4. Limits for Class C Equipment

Harmonic Order (n)	Maximum value expressed as a percentage of the fundamental input current of luminaries.
2	2
3	30•(circuit power factor)
5	10
7	7
9	5
11≤n≤39	3

Table 4.5. Limits for Class D Equipment

Harmonic Order (n)	Permissible Current (mA/W)	Maximum Permissible Current (A)
3	3.4	2.30
5	1.9	1.14
7	1.0	1.14
9	0.5	0.44
11	0.35	0.33
≥13	Linear extrapolation using 3.85/n	Same as Table 4.4.

The goal of this recommended practice is to help in the design process of a power system with linear and nonlinear loads. The point of interference between sources and loads is defined as a point of common coupling or PCC. The recommendations provided in this standard are designed to help to minimize interference between electrical equipment. The limits are set to provide quality power at the point of common coupling. This document establishes the guidelines to design a power system with nonlinear loads. These recommendations are for steady-state under the worst case conditions. Tables 4.6, 4.7, and 4.8 gives current distortion limits for general distribution, sub-transmission, and transmission systems respectively.

Table 4.6. Current Distortion Limits for General Distribution Systems (120 V through 69 kV)

	Maximum Harmonic Distortion in percent of I_L					
	Individual Harmonic Order (Odd Harmonics)					
I_{sc}/I_L	<11	11≤h<17	17≤h<23	23≤h<35	35≤h	TDD
<20	4.0	2.0	1.5	0.6	0.3	5.0
20<50	7.0	3.5	2.5	1.0	0.5	8.0
50<100	10.0	4.5	4.0	1.5	0.7	12.0
100<1000	12.0	5.5	5.0	2.0	1.0	15.0
<1000	15.0	7.0	6.0	2.5	1.4	20.0

Even harmonics are limited to 25% of the odd harmonic limits

Current distortions that result in a dc offset, e.g., half-wave converters, are not allowed.

*All power generation equipment is limited to these values of current distortion, regardless of actual I_{sc}/I_L.

Where,

I_{sc} = maximum short circuit current at PCC.

I_L = maximum demand load current (fundamental frequency component) at PCC.

TDD = harmonic current distortion in % of maximum demand load current (15 or 30 minute demand)

4.7. Current Distortion Limits for General Sub-transmission Systems (69 001 V - 161 kV)

	Maximum Harmonic Distortion in percent of I_L					
	Individual Harmonic Order (Odd Harmonics)					
I_{SC}/I_L	<11	11≤h<17	17≤h<23	23≤h<35	35≤h	TDD
<20*	2.0	1.0	0.75	0.3	0.15	2.5
20<50	3.5	1.75	1.25	0.5	0.25	4.0
50<100	5.0	2.25	2.0	0.75	0.35	6.0
100<1000	6.0	2.75	2.5	1.0	0.5	7.5
<1000	7.5	3.5	3.0	1.25	0.7	10.0

Even harmonics are limited to 25% of the odd harmonic limits

Current distortions that result in a dc offset, e.g., half-wave converters, are not allowed.

*All power generation equipment is limited to these values of current distortion, regardless of actual I_{SC}/I_L.

Where,

I_{SC} = maximum short circuit current at PCC.

I_L = maximum demand load current (fundamental frequency component) at PCC.

TDD = harmonic current distortion in % of maximum demand load current (15 or 30 minute demand)

4.8. Current Distortion Limits for General Transmission Systems (>161 kV)

	Individual Harmonic Order (Odd Harmonics)					
I_{sc}/I_L	<11	11≤h<17	17≤h<23	23≤h<35	35≤h	TDD
<50*	2.0	1.0	0.75	0.3	0.15	2.5
≥50	3.0	1.5	1.15	0.45	0.22	3.75
Even harmonics are limited to 25% of the odd harmonic limits						
Current distortions that result in a dc offset, e.g., half-wave converters, are not allowed.						
*All power generation equipment is limited to these values of current distortion, regardless of actual I_{sc}/I_L.						

Where,

I_{sc} = maximum short circuit current at PCC.

I_L = maximum demand load current (fundamental frequency component) at PCC.

TDD = harmonic current distortion in % of maximum demand load current (15 or 30 minute demand)

4.8 Summary

This chapter was devoted to discuss sources of harmonics, their effects on electrical equipment, and the standards around the world to limit the harmonics in power system. Sources of harmonics are classified into two groups; conventional and non-conventional sources. The non-conventional harmonic sources are discussed in detail; because they are deteriorating the most power quality of the public supply system. The explosion of information technology and the energy conservation devices are blamed to aggravate the harmonic distortions in electric power system.

The presence of harmonics in the electric supply system is believed to affect the performances of different equipment, both supply-side and load-side. Effect of harmonic on some important equipment is studied. It is concluded that engineers and scientists need to devote more effort to get complete understanding of the problem. Harmonic interaction in the presence of a mix of linear and different types of nonlinear loads is another potential area of research. This problem still needs to be explored to deal with design of power system with nonlinear loads.

There are so many harmonic standards around the world to limit the harmonics in the power system. A brief description of some international and national harmonic standards was given to get a universal picture of the problem. Three international standards were selected to evaluate harmonic distortions in power system. Each one of these three standards has a different approach to deal with the harmonic problem. The chapter concludes with the limits recommended by each standard and the approach used in each standard to address the harmonic distortion problem.

CHAPTER V

AN ALGORITHM FOR SELECTION OF ENERGY EFFICIENT LIGHTING TECHNOLOGIES

5.1 Introduction

Recent developments in power electronic technologies have changed the requirements of electricity customers. A significant number of loads draw nonlinear current from the electric utility source and inject harmonics at the point of common connection (PCC). Emanuel [127] has reported forecasts of nonlinear loads on some typical feeders in the northeastern USA. These feeders will constitute 60% to 73% nonlinear loads in commercial buildings by the year 2000. The forecast shows that the ratio of nonlinear load to the total load is consistently increasing. There is a number of factors that are contributing to the increase in nonlinear loads. The explosion of information technology and proliferation of personal computers and their peripherals have contributed the most to the harmonic distortion problem. In many countries, the legislation to promote energy conservation, and the electric utility's desire to avoid new generation capacity through energy saving programs is also a factor that increases harmonic distortion level in the distribution network. The former factor has also increased the energy consumption in office equipment during the last decade. Energy consumption in office equipment was the fastest growing end-use of electricity in the commercial sector [128]. That means more harmonics at the utility bus, and

failure of equipment in the distribution system will become a norm of life, if the issue of harmonic distortion is not addressed in a proper manner. However, one needs to understand the phenomenon of harmonic summation, interaction, and cancellation in the presence of multiple harmonic sources before trying to correct the problem.

Lehtonen [129] has summarized same of the previous work done by different people on the issue of harmonic summation and has proposed a general solution to this problem using a probabilistic approach. Such an approach, however, does not provide much help in selecting lighting technologies that do not increase the harmonic level in the building. This chapter investigates the problem at the individual harmonic frequency level and suggests a generic algorithm to select lighting technologies in a specific building environment.

5.2 Selection of Appropriate Lighting Technology

The goal of energy efficient lighting programs is to save resources for the nation, capacity for the electric utilities, and expenses for the customers. Constraints in achieving these goals are to keep the electrical system reliable and trouble free. The evaluation of energy and capacity savings is simple. However, the desirable level of penetration of these technologies into the system and the harmonic impact of these technologies on the system is very difficult to determine. Each harmonic generated from its source interacts with respective harmonic frequency, generated from all the sources sharing the same bus or point of common connection. If phase angles of a particular order of frequency generated from different sources are widely distributed then overall amplitude of the particular frequency at point of common connection (PCC) will be minimized. These individual frequencies contribute to the overall level of harmonic distortions at the PCC.

Loads controlled by power electronic circuits exhibit this phenomenon: they draw nonsinusoidal currents from the source and inject multiple harmonic frequencies into the system. The individual harmonic currents generated by each of the harmonic sources can be viewed as random phasors with random amplitude and phase angle. The total harmonic current injection at the point of common connection is the sum of these random phasors in each harmonic order. The randomness of these phasors results in large amount of vectorial cancellation. The proposed algorithm provides a method for evaluation of various lighting technologies at individual harmonic levels and assesses the impact of harmonics on the system in the presence of new technologies.

5.3. Summary of the Algorithm

The flow chart shown in Figure 5.1 gives an overview of the algorithm proposed to select suitable technologies for harmonic compatibility. The input to the program consists of a description of the various loads to be considered and their specific harmonic profiles. The loads are divided into two groups i.e., fixed and variable. The fixed group contains loads like personal computers, induction motors, etc. The contribution of these loads remains constant for each loading contributions. However, contribution of fixed loads can be varied by using appropriate data sets that represent the load make up for a given facility. This issue will be further elaborated in the development of the data file. The variable load group contains existing lighting technologies and alternate energy efficient technologies (those shall replace the existing ones without any reduction in the illumination level). The algorithm generates all possible combinations of energy efficient technologies that are candidates for retrofitting. Each combination of the candidate technology may contain only one technology or a partial contribution of more than one technology. The goal of each combination is to provide the same amount of light that conventional source is already providing in the facility. Incremental fraction is the fraction of the candidate technologies that the consecutive

combinations may have each time a combination is generated. The user can define any positive integer as the incremental fraction. For example "4" means each consecutive combination will be generated with 25% increment of each candidate technology.

The program reads frequency, amplitude and phase angle of the harmonic current profile from the data file, explained in the next section. Individual profiles of each participant load are then added for each combination using rectangular vector addition. Thus a profile of total harmonic current is generated. These profiles are used to calculate the total harmonic distortion (THD). The algorithm compares the THDs from each combination with the base case THD, and prints all combinations. Base case is the existing load make-up of the building. The final output of the program is the make-up of the load contribution which provides an equivalent amount of lighting as the base case with a minimal THD.
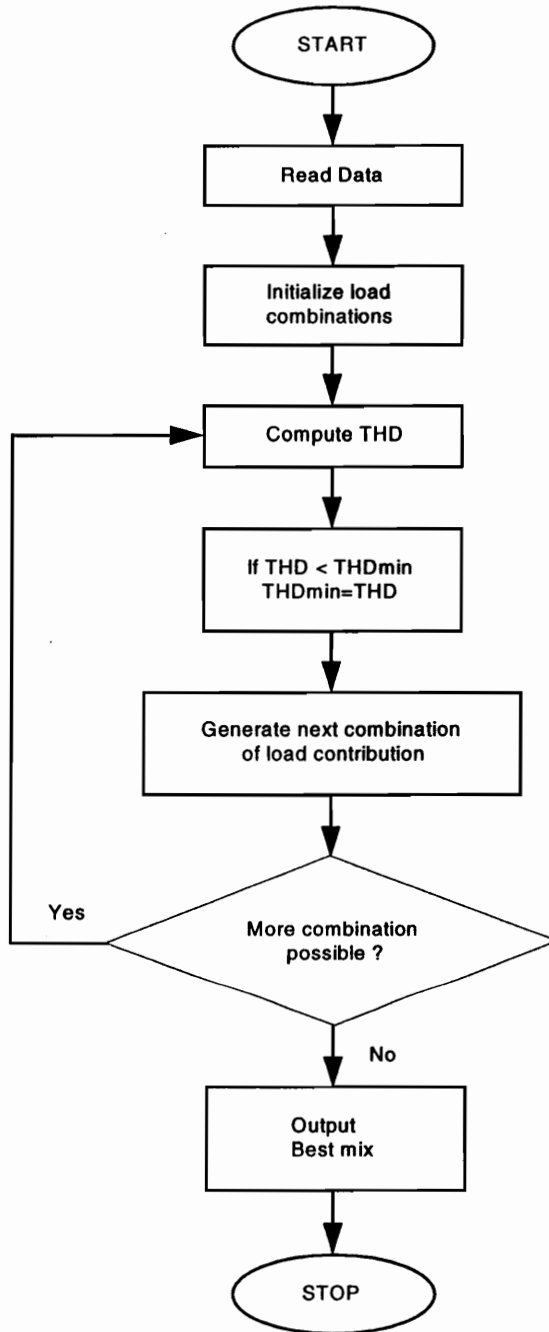
Figure 5.1. Flow Chart for the Algorithm to Calculate and Compare THDs for Different Combinations

5.4 Program Structure

The program consists of one main procedure and six sub-routines written in C language. The main routine reads the device information and harmonic profiles from a data file and finds all possible combinations of alternate lighting technologies. For each combination, the contribution of the technology is selected by the user (i.e., 10, 20, 40 or 50 %, etc.). For each combination of the new technologies and the base case, the sub-routine performs vector addition of respective harmonic frequencies. THD is calculated for each combination by using following formula:

$$THD = \frac{\sum_{i=2}^{n} h_i^2}{h_1^2}$$

$h = harmonic\ frequency$

$h_1 = fundamental\ frequency$

$i = 2, 3, 4, 5, ..., n$

The base case THD is calculated for the existing system and lighting technologies. A sub-routine calculates the THDs for all combinations and compares that with the base case THD. Only those cases are printed where THD is less than the base case. At the end of the output, the program prints the summary with base case THD, minimum THD case and contribution of each load in the minimum THD case.

5.5 Input Data File

The program expects the data in a format shown in Figure 5.2. First part of the data file describes load types. Numbers of load types are mentioned in the beginning of the data

file.   Second step is the description of each individual load group and its capacity requirement in the facility.   As mentioned earlier, electrical loads are divided into fixed and variable groups.   All non-lighting loads (computers, motors, office equipment, etc.) are considered in the category of fixed load group.   From this section the program reads the harmonic current profile of each fixed load type.   The lighting loads, both existing and energy efficient alternates, are placed in variable load group.   The variable load group has two types of lighting loads i.e., fluorescent and incandescent.   Our choice of lighting technologies in the data file is due to their universal acceptance as light sources in commercial and residential sectors.

Magnetic ballast fluorescent lamps are replaced with electronic ballast T-8 lamps, and incandescent with CFLs with equivalent amount of lumens.   The program can accept any number of replacement technologies.   Harmonic current profile for each existing and candidate technology is available in the data file.   Base case lighting technologies, fluorescent and incandescent lamps, are the last items in each sub-group among the variable load group.   If the existing lighting technologies are selected as base case, the program will ignore the technology options having higher THD than the base case.   The user can explore all possible combinations by making highest THD technologies as the base case technology from each sub-group.   The user can set the data file the way be feels appropriate.

```
┌─────────────────────────────┐
│                             │
│      No. of load types      │
│                             │
└─────────────────────────────┘


┌───────────────────────────────────────┐
│                                       │
│  Capacity(Watt)    Load description   │
│                                       │
│                                       │
│                                       │
│                                       │
└───────────────────────────────────────┘


┌───────────────────────────────────────┐
│  Fix Load harmonic Profiles           │
└───────────────────────────────────────┘
┌───────────────────────────────────────┐
│   ┌─────────────────────────┐         │
│   │            1            │         │
│   └─────────────────────────┘         │
│   ┌─────────────────────────┐         │
│   │            2            │         │
│   └─────────────────────────┘         │
│                 I                     │
│                 I                     │
│                 I                     │
└───────────────────────────────────────┘


┌───────────────────────────────────────┐
│  Variable Load harmonic Profiles      │
└───────────────────────────────────────┘
┌───────────────────────────────────────┐
│   ┌─────────────────────────┐         │
│   │            1            │         │
│   └─────────────────────────┘         │
│   ┌─────────────────────────┐         │
│   │            2            │         │
│   └─────────────────────────┘         │
│                 I                     │
│                 I                     │
│                 I                     │
└───────────────────────────────────────┘
```

Figure 5.2. Description of Input Data File

Figure 5.3 shows a sample of typical input data file. First line of the data file gives the number of load types. In this case we have four load types and lines 2 through 5 give capacity requirement in watts for each load category followed by the name of load type. Where the former two load types (computers and induction motors) are considered in fixed load groups and later two types (fluorescent and incandescent lamps) are in variable load group. Line 8 gives the total number of load items in fixed and variable load groups, including energy efficient lighting technologies to be tested for minimum harmonic impact on the system. Line 9 gives the first load category, i.e., computers (starting from 0) then number of frequencies in the harmonic profile and category name. Next six lines record the harmonic number, amplitude and phase angle, respectively, of each frequency included in the harmonic profile of the current drawn by the computer. The data for the induction motors is recorded in the same way as computers, from line 17 through 20. Here ends the data for the fixed loads. The data for fluorescent lamps starts from line 22. The data format is same as the fixed loads. All the harmonic profiles for the electronic ballast T-8 lamps are recorded and the last load item in this category is the magnetic ballast fluorescent lamp. Next category among the lighting loads is the incandescent lamps and the compact fluorescent lamps that replace former lamp without any reduction in the illumination level. All the compact fluorescent lamps are recorded first and then come the incandescent lamp at the end of data file.

```
1    4
2    53         Computers
3    201        Induction Loads
4    205        Fluorescent Lamps
5    78         Incandescent Lamps
7
8    9
9    0 21 1.0 Computers
10   1 2 3 4 5 6 7 8 9 11 13 15 17 19 21 23 25 27 29 31 33
11   0.4513 0.0026 0.3698 0.00386 0.2512 0.00345 0.1286 0.00169 0.03495 0.03148
12     0.04212 0.02869 0.01085 0.01214 0.014 0.00899 0.0057 0.00759 0.00683
13     0.00403 0.00395
14   2.3 105.4 4.9 111.5 6.6 120.1 5.8 134.7 -16.3 -126.1 -140.8 -149.1 172.8 92.0
15     71.5 49.9 -13.2 -56.1 -75.8 -112.4 184.6
16
17   1 8 1.0 Induction Motor
18   1 2 3 5 7 9 11 13
19   2.417 0.00162 0.1507 0.04603 0.00468 0.00226 0.0032 0.00183
20   -1.0 155.0 -44.8 -78.1 138.1 -24.2 -49.8 -116.6
21
22   2 17 0.6 Fl. Electronic Ballast (AT)
23   1 2 3 4 5 7 9 11 13 15 17 19 21 23 25 27 29
24   1.033 0.00213 0.1119 0.00048 0.09199 0.02282 0.02783 0.01407 0.01072
25     0.00895  0.00447 0.00455 0.00272 0.00199 0.00171 0.00062 0.0007
26   6.4 -187.4 -130.8 143.4 -74.6 89.4 149.9 -72.3 22.2 151.1 -88.5 17.7 160.2
27     -104.5 33.2 143.4 -107.4
28
29   2 16 1.0 Fl. Magnetic Ballast
30   1 2 3 4 5 7 9 11 13 15 17 19 21 23 25 27
31   1.726 0.00088 0.3296 0.00115 0.1513 0.04487 0.02572 0.01527 0.00692
32     0.00675 0.00445 0.00323 0.00241 0.00183 0.00147 0.00104
33   -1.9 -53.7 51.8 137.7 -119.4 149.2 15.6 -93.5 157.3 24.0 -98.3 121.4 -5.6
34     -153.4 81.5 -66.1
35
36   3 i9 0.25 Compact Fluorescent (OS)
37   1 2 3 4 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33
38   0.1606 0.00017 0.03972 0.00016 0.00951 0.0021 0.00499 0.00644 0.0024
39     0.00192 0.00181 0.00169 0.00156 0.00037 0.00061 0.00084 0.00092 0.00057 40
       0.00023
41   2.7 -159.4 -2.9 -135.7 -36.6 -25.6 187.5 143.2 155.3 87.1 -51.1 -30.4 -87.0
42     -63.4 -173.7 88.1 116.2 40.8 183.1
43
44   3 9 1.0 Incandescent
45   1 3 5 7 9 11 13 15 19
46   0.646 0.00264 0.01001 0.00751 0.00073 0.00082 0.00191 0.00046 0.00041
47     -0.9 -152.8 181.0 -146.6 110.4 -152.3 54.3 -49.1 -135.0
```

Figure 5.3. Sample of Typical Input Data File

5.6 Data Collection

The harmonic current profile data for each load component was obtained on a test bench using HP3561A Dynamic Signal Analyzer in the laboratory. Utmost care was taken to keep the laboratory conditions fixed. Each device was allowed to stabilize before capturing the harmonic profile. Another constraint was to capture the harmonic profile at a particular reference phase angle. On the average it took up to six hours to capture harmonic current profile for 11 technologies at a particular reference phase angle. There are some state of the art harmonic data acquisition systems that can improve the quality and accuracy of the harmonic data. It is expected that in the future manufacturers of electronic equipment and devices will be able to provide harmonic profile for their products and results of the algorithm will be more realistic and precise. Moreover, the harmonic profiles of the load current gives a better insight into the equipment and its harmonic impact on the system. The higher growth in power electronic equipment and use of information technology in the commercial sector require more comprehensive information about harmonic current requirements of these technologies. The legislations like Energy Policy Act of 1992 encourages the manufacturers to provide such information.

5.7 Summary

This chapter describes the current status of the end use loads. Energy efficient lighting programs are viewed as an attractive option for electric utilities to meet the future capacity requirements. At the same time, the electric utilities are worried about the adverse impact of these technologies on the system. The algorithm proposed in this chapter provides an opportunity to select the appropriate lighting technologies that save energy, reduce

capacity requirements in the future and do not deteriorate harmonic distortion level at the consumer bus.

The role of the data file is very important in the algorithm. The chapter explains the structure of the data file. Different components in the data file are explained with the help of a sample data file. Methods and equipment used in the data acquisition process are reviewed briefly. The future development in the data acquisition systems and their impact on the accuracy of the algorithm is explored.

———————

CHAPTER VI

DISCUSSION OF RESULTS AND ALGORITHM VERIFICATION

6.1 Introduction

The proposed algorithm for selection of energy efficient lighting technologies is based upon the same principles that are used in most of the harmonic analysis equipment. However, there is always some level of disparity between the algorithm results and the real time measurements made by using harmonic measuring instruments. This chapter starts with discussion of these factors that are responsible for the disagreement between the measured and the calculated values. The phenomenon of random occurrence of phase angles of individual harmonic frequencies and its influence on the results is explained by studying different harmonic sources (magnetic circuits, electronic circuits, etc.).

Results of the algorithm are verified by comparing them with actual measurements for the same combinations using the signal analyzer. Two case studies are included in this chapter to verify the generic characteristic of the proposed algorithm. These case studies help to establish the generic nature of the proposed algorithm. The salient features of the algorithm are summarized in the from of its advantages and disadvantages. The chapter

concludes with a brief summary of material covered in the discussion of results and verification of the algorithm.

6.2 Issues in Harmonic Summation

There is a fundamental difference between the nature of the harmonics generated by a magnetic ballast and an electronic ballast operating fluorescent lamps. As shown in Table 6.1, the magnetic ballast draws current that includes the multiples of fundamental frequency. These harmonics are the result of the operation of the magnetic ballast in the saturation region. The profiles 1 and 2 are captured for the magnetic ballast with a time difference of 0.4 degree. While the amplitudes of individual harmonic frequencies do not vary significantly, their phase angles show significant variations. In Table 6.1 there are two harmonic profiles of the current drawn by magnetic ballast. The data for harmonic current profile 1 was captured at a fundamental frequency phase angle of 7.4 degree and profile 2 was captured at a fundamental frequency phase angle of 7.8 degree. The last column in Table 1 shows that with a 0.4 degree increase in phase angle of fundamental harmonic frequency, there is a consistent increase in phase angles of ascending order harmonic current frequencies.

Table 6.1. Harmonic Current Profiles of a Magnetic Ballast and T-12 Lamp With a Variation in Fundamental Frequency Phase Angle

Harmonic Frequency	1		2		$\Delta\phi = \phi_2 - \phi_1$
	Amplitude (mA)	Phase (Deg)	Amplitude (mA)	Phase (Deg)	
Fundamental	839.5	7.4	839.0	7.8	+0.4
3	152.1	76.3	152.4	77.6	+1.3
5	74.1	-74.9	74.4	-73.6	+1.3
7	20.5	-153.8	20.4	-151.7	+2.1
9	12.8	93.2	12.8	96.3	+3.1
11	8.2	-6.3	8.2	-3.2	+3.1
13	3.4	-111.9	3.4	-107.1	+4.8
15	3.1	142.7	3.1	148.4	+6.3
17	1.8	44.3	1.9	50	+5.7
19	1.5	-73	1.5	-67.7	+5.3
21	1.2	-181	1.2	-176.5	+4.5
23	0.9	38.5	0.9	47.9	+9.4
25	0.8	-61.5	0.8	-56.7	+4.8
27	0.7	161	0.5	176.9	+15.9

Table 6.2. Harmonic Current Profiles of a CFL With a Variation in Fundamental Frequency Phase Angle

Harmonic Frequency	1		2		$\Delta\phi = \phi_2-\phi_1$
	Amplitude (mA)	Phase (Deg)	Amplitude (mA)	Phase (Deg)	
Fundamental	150	2.3	149.2	2.4	+0.1
3	38.5	-12.3	37.1	-13.6	-1.3
5	9.3	-29.5	9.3	-28.7	1.2
7	1.9	-53.9	1.9	-57.1	-3.2
9	4.5	162.9	4.0	164.1	+1.2
11	6.0	131.7	5.8	132.2	+0.5
13	2.7	132.9	2.7	132.8	-0.1
15	1.4	67.8	1.5	76.6	+8.8
17	1.7	-79.4	1.6	-79.3	+0.1
19	2.3	-65.4	2.1	-64.9	+0.5
21	1.3	-107.5	1.4	-105	+2.5
23	0.4	-99.1	0.4	-83.5	+15.6
25	1.0	105.3	0.8	117.7	+12.4
27	0.7	61.5	0.7	60.2	-1.3
29	1.1	74.1	1.1	78	+3.9
31	0.3	-56.7	0.3	-33.6	+23.1

In Table 6.2 harmonic profiles of the load current drawn by a compact fluorescent lamp are given. Two harmonic current profiles in this case were measured with 0.1 degree difference in phase angle of fundamental frequency. In this case, the variation in phase angle of the harmonic frequency was observed to be random. The last column shows the pattern of randomness of harmonic frequencies for compact fluorescent lamps.

Figure 6.1 shows a comparison of the phase angle variations between phase angles of harmonic frequencies generated by a magnetic ballast fluorescent lamp and an electronic CFL. The harmonic profiles 1 and 2 in Tables 1 and 2 were captured with a time delay of 0.4 degree and 0.1 degree respectively. In case of magnetic ballast fluorescent lamp, the variability in the phase angles of respective harmonic frequencies increases with the order of the harmonic frequency. While the variability in phase angles of electronic ballast lacks any well defined pattern. The random occurrence of phase angles of harmonic frequency in electronic fluorescent lamps is one of the factors that increase the difference between the measured and calculated THD values.
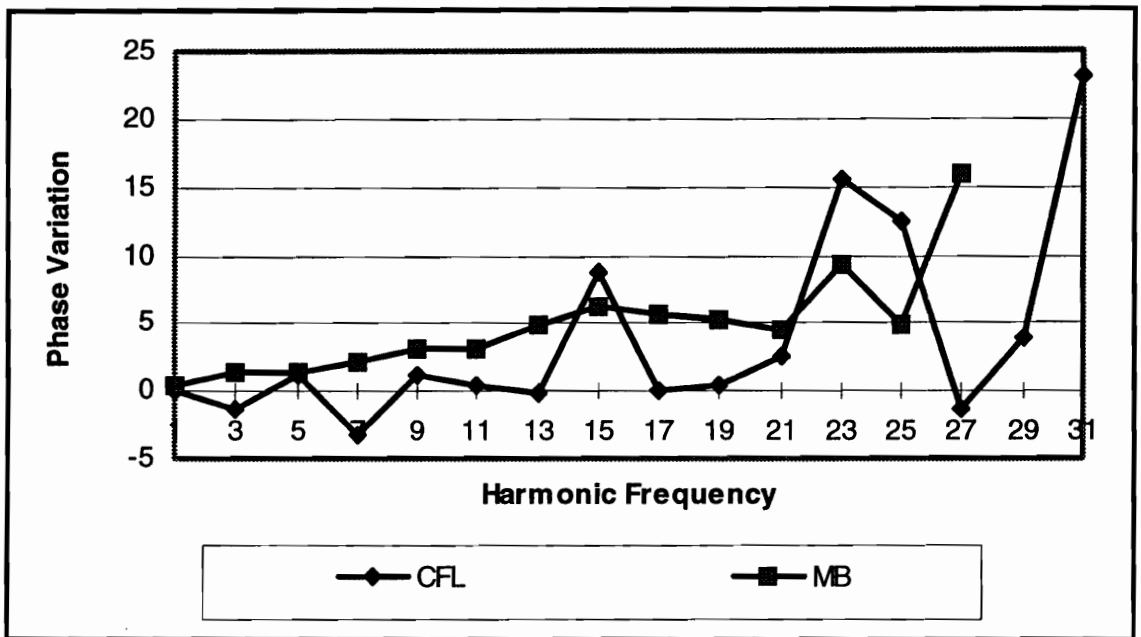
Figure 6.1. Comparison of Random Occurrence of Phase Angles at Individual Frequencies, Between Magnetic Ballast Fluorescent Lamp and CFL

6.3 Algorithm Verification

In view of the above discussions about harmonic amplitudes and phase angles of magnetic ballasts and electronic compact fluorescent lamps, let us look into the results in Table 6.3. Column 1 in this table lists the combinations of lighting technologies selected for comparison. Our goal is to compare the results of the algorithm with the actual measurements for respective combinations. We have selected the combinations with 100% contribution of each participating lighting technology. The reason for this constraint is that, it is practical to get the measurement results for these combinations by simply replacing existing lighting technologies with their energy efficient equivalents. We have selected 15 combinations all with single technologies, and the base case for comparing the computed and measured results. Column 2 gives the computed values of THD for base case and each selected combination. Column 3 records the measured values of THD for respective combinations. Let the computed and measured THDs be denoted by THD_C and THD_M respectively. Column 4 gives the deviation of the algorithm results from the respective measured value. Column 5 gives the capacity requirement in watts, for the building load model used for verification of the proposed algorithm [130]. The last column in Table 6.3 gives capacity savings as a result of retrofitting, using different technology combinations. Measured data of column 3 for THDs were obtained by using the HP3561A Dynamic Signal Analyzer. A comparison between two sets of THD values shows that the algorithm gives higher values of THDs than the measured ones. It was observed that the measured value of THD is always lower than the calculated value, but the relative changes are consistent between these two cases. However, the difference between the measured and calculated values is not consistent. The following factors are considered to be responsible for the inconsistency between measured and computed values:

1. THDs of participating loads;
2. Random characteristic of harmonic frequency phase angles;

3. Instrumentation and data acquisition errors;

4. Ambient harmonics; and

5. Total number of harmonic frequencies involved in the summation process in the program.

As shown in Table 6.3, in most of the cases, the difference between the measured and the computed THD value increases with the increase of the THD of participating load. In the base case, a magnetic ballast fluorescent lamp and an incandescent bulb are used as the lighting source. An incandescent lamp does not generate any significant harmonic distortion. Level of randomness of the phase angles of the harmonic frequencies generated by standard magnetic ballast fluorescent lamp is not significant. Hence the difference between the algorithm results and measurement values for base case is minimal. As we proceed further, the level of randomness in phase angles of individual frequencies of participating load will increase and so will be the difference in computed and measured THD values.

Our main goal to develop the suggested algorithm was to select energy efficient lighting technologies on the basis of their harmonic distortion impacts at the system level. In Table 3, the selected combinations were arranged on the basis of the THD of the participating technologies. Each set of 3 combinations contains electronic ballast T-8 lamps from three manufacturers that replaces the magnetic ballast T-12 lamps. The CFL replaces the incandescent lamp and it is same for the whole set of three combinations. Combinations 1-3 consist of three different electronic ballasts with T-8 lamps and incandescent lamps. Due to insignificant THD contribution, the incandescent lamp keeps the difference between THD_C and THD_M values at low. In combinations 4-6, the three different electronic ballasts are repeated in the same

sequence as before and the incandescent lamp is replaced with low THD (<10%) CFL. Due to low THD of CFL, difference between THD_C and THD_M is small. In combinations 7-9, the sequence of the electronic ballasts is same but the CFL used has moderate THD (<30%). In combinations 10-12, and 13-15, again the electronic ballasts are the same as used in the previous combinations but CFLs used are of older design having THDs 114% and 138% respectively. As the THD of participating lamps increase, the difference between THD_C and THD_M values become wider.

As the number of harmonic frequencies involved in the summation process increases, the level of overall randomness of phase angles also increases causing an increase in the difference between THD_C and THD_M. However, the relative order of system level THD impact of lighting technology combinations obtained with the algorithm is same as the measured THD impact for respective combinations.

Table 6.3. Comparison of THD_C and THD_M for Different Combinations of Lighting Technologies

Technology Combination	THD_C (%)	THD_M (%)	ΔTHD (%)	Capacity (Watts)	Capacity Saving (Watts)
Base Case	15.2	13.6	1.6	537	-
1	12.8	10.2	2.6	453	84
2	12.0	9.0	3.0	460	77
3	12.5	9.3	3.2	453	84
4	14.5	11.7	2.8	396	144
5	13.6	10.4	3.2	403	134
6	14.2	10.9	3.3	395	145
7	15.4	12.4	3.0	396	144
8	14.5	10.9	3.6	404	133
9	15.0	11.3	3.7	396	144
10	18.3	12.8	5.5	393	144
11	17.5	11.4	6.1	401	136
12	18.1	11.6	6.5	393	144
13	17.7	10.9	6.8	393	144
14	16.9	9.4	7.5	401	136
15	17.4	9.2	8.2	393	144

6.4 Program Output

The program output includes all combinations of energy efficient lighting technologies that have lower THD impact than the base case. As mentioned in Sec. 6.3, non-lighting loads (induction motors, computers, etc.) are fixed for a particular case. In base case, non-lighting load is 48% of the total and lighting load is 52%. Figure 6.2 gives a truncated output file because the actual output file contains 525 combinations that have lower THDs than the base case. Program prints the load contributions, THD, and load capacity for base case in the beginning of the output file. All the technologies are arranged from left to right in the order they appear in the data file. From top to bottom it prints the combinations that are selected for lower THD impact on the system and gives the percentage participation of each load and lighting technology for that combination. As the base case lighting technologies are replaced with the alternate lighting technologies of equivalent lumen output hence the lumen output in each combination remains constant. The program tests combinations with fractional contribution depending upon the increment step selected in the program.

At the end of output file, program lists all participating loads and their percentage contributions in the selected combination. Contribution of lighting load and the loads other than lighting, depend upon data file setting. We can vary the ratio between the lighting load and the non-lighting loads. We can further vary the electronic power supply load and the induction motor load among the non-lighting load groups.

The algorithm serves as a tool for selection of lighting technologies on the basis of lower THD impact on the system. The algorithm can be used effectively to find the fractional technology combinations of different energy efficient lighting devices. One can select the best combination suitable for specific requirements of capacity savings, environmental benefits, harmonic reduction, etc. Energy savings depend upon the time of use factor. Energy savings for the same technology option will vary from facility to facility depending upon the requirements of lighting and work environment.

```
========= Base Case =========
12.1 35.9  0.0  0.0  0.0 38.0  0.0  0.0 14.0 => THD=15.5% (529.00 W)
=============================
 1   2   3   4   5   6   7   8   9
12.6 37.3 05.9 00.0 00.0 29.6 00.0 00.0 14.5 => THD=14.6% (508.90 W)
13.1 38.9 12.3 00.0 00.0 20.6 00.0 00.0 15.1 => THD=13.8% (488.80 W)
13.7 40.5 19.3 00.0 00.0 10.7 00.0 00.0 15.8 => THD=13.2% (468.70 W)
14.3 42.4 26.9 00.0 00.0 00.0 00.0 00.0 16.5 => THD=12.8% (448.60 W)
12.6 37.3 00.0 05.9 00.0 29.6 00.0 00.0 14.5 => THD=14.5% (508.90 W)
13.1 38.9 06.2 06.2 00.0 20.6 00.0 00.0 15.1 => THD=13.6% (488.80 W)
13.7 40.5 12.9 06.4 00.0 10.7 00.0 00.0 15.8 => THD=13.0% (468.70 W)


14.8 43.8 00.0 00.0 13.9 23.2 00.0 04.3 00.0 => THD=15.4% (433.30 W)
15.5 46.0 07.3 00.0 14.6 12.2 00.0 04.5 00.0 => THD=14.7% (413.20 W)
16.3 48.3 15.3 00.0 15.3 00.0 00.0 04.7 00.0 => THD=14.3% (393.10 W)
15.5 46.0 00.0 07.3 14.6 12.2 00.0 04.5 00.0 => THD=14.5% (413.20 W)
16.3 48.3 07.7 07.7 15.3 00.0 00.0 04.7 00.0 => THD=14.1% (393.10 W)
16.3 48.3 00.0 15.3 15.3 00.0 00.0 04.7 00.0 => THD=13.9% (393.10 W)
15.5 46.0 00.0 00.0 21.9 12.2 00.0 04.5 00.0 => THD=14.8% (413.20 W)
16.3 48.3 07.7 00.0 23.0 00.0 00.0 04.7 00.0 => THD=14.4% (393.10 W)
16.3 48.3 00.0 07.7 23.0 00.0 00.0 04.7 00.0 => THD=14.1% (393.10 W)
16.3 48.3 00.0 00.0 30.7 00.0 00.0 04.7 00.0 => THD=14.5% (393.10 W)


Base case THD = 15.48%
After testing 525 combinations, obtained
best THD value of 11.99% with the following mix:
1  14.27%  Computers
2  42.35%  Induction Motor
3   0.00%  Fl. Electronic Ballast (AT)
4  26.88%  Fl. Electronic Ballast (S&Y)
5   0.00%  Fl. Electronic Ballast (GOLD)
6   0.00%  Fl. Magnetic Ballast
7   0.00%  Compact Fluorescent (OS)
8   0.00%  Compact Fluorescent (GE)
9  16.50%  Incandescent

Corresponding capacity: 448.60 Watts
```

Figure 6.2. Sample Output of the Program

6.5 Case Study No. 1

Our goal in this case study is to verify the proposed algorithm for different load configurations. Instead of replacing standard fluorescent lamps with a single electronic ballast technology, it is replaced with combination of two electronic ballast technologies. Incandescent lamp, however, is replaced with a single compact fluorescent lamp technology. Impact of this change in experimental design is studied on reduction in total harmonic distortions and on the algorithm performance.

6.5.1 Building Load Model

A building load model was developed using 24 hour load data for a typical commercial building. Actual building load was scaled down in size to 500 watt to match the laboratory set up consisting of different loads. Main load components of the model are induction motor, computer, and lighting loads. During peak hours lighting load accounts for 51% of the building load, induction motor load is 37% and 12% computer load. This building load model is then used to verify the proposed algorithm for minimum harmonic distortion.

6.5.2 Description of Lighting Technologies

Most of the lighting needs in the building are met with full size fluorescent and incandescent lamps. A single fixture of full size fluorescent lamp contains the standard magnetic ballast and two T-12 fluorescent lamps. On the average, such fixture consumes 100 watts of electricity. Energy efficient alternate to the standard full size fluorescent lamp contains an electronic ballast and two T-8 fluorescent lamps. On the average it saves up to 40% energy as compared to standard full size fluorescent lamp.

In this case study electronic ballasts from four manufacturers are tested. These ballasts draw the current with total harmonic distortion (THD) in a range of 10% to 20% of the fundamental. The standard magnetic ballast generates total harmonic distortion in the order of 30% of the fundamental. Incandescent lamp used in this case study consumes 75 watt per lamp and its harmonic contribution is negligible. For energy saving purposes incandescent lamp is replaced with electronic compact fluorescent lamp (CFL) that produces an equivalent amount of light to that of the incandescent lamp. A compact fluorescent lamp that replaces 75 watt incandescent, consumes less than 20 watts and produces the same amount of light. However, the harmonic contribution of CFLs is very significant. The compact fluorescent lamps available in the US market generate THD in a range of 10% to 140% of the fundamental. In this case study we have included four popular models available in the US market.

6.5.3 Discussion of Results

In this case study each electronic ballast technology consists of 50% of each two available electronic ballasts. In this way six exclusive pairs of four electronic ballasts were generated. Each pair was used as an independent electronic ballast technology. These exclusive pairs will be allowed to replace standard magnetic ballast fluorescent lamps. Incandescent lamp will be replaced with a single compact fluorescent lamp in each combination generated by the proposed algorithm. Computers and induction motor load contribution in each combination remain constant throughout the case.

The base case consists of the fixed load (computers and induction motors), standard magnetic ballast fluorescent lamps and incandescent lamp. The THD content in the load current drawn by the base case is 15.1% of the fundamental. A comparison of the calculated and the measured THDs is given in Table 6.4. All the 30 combinations listed in the table have lower THD than the base case. The combinations with incandescent lamp have the minimum THD impact on the system. In this case study we have almost same results as

Table 6.4. Comparison of THD$_C$ and THD$_M$ for Different Combinations of Lighting Technologies

Technology Combination	THD$_C$ (%)	THD$_M$ (%)	ΔTHD (%)	Capacity (Watts)	Capacity Saving (Watts)
Base Case	15.1	12.2	2.9	530	-
GS+S&Y+Incan	12.3	8.1	4.2	445	85
AT+S&Y+Incan	12.2	7.9	4.3	449	81
AT+GS+Incand.	12.4	8.1	4.3	443	87
MT+S&Y+Incan	12.7	7.8	4.9	450	80
MT+GS+Incand	12.9	8.7	4.2	443	87
AT+MT+Incand.	12.8	8.0	4.8	447	83
GS+S&Y+GE	14.0	9.4	4.6	389	141
AT+S&Y+GE	13.9	9.3	4.6	393	137
AT+GS+GE	14.1	9.6	4.5	387	143
MT+S&Y+GE	14.4	9.2	5.2	393	137
MT+GS+GE	14.6	10.0	4.6	386	144
AT+MT+GE	14.6	9.6	5.0	390	140
GS+S&Y+OS	14.8	9.8	5.0	389	141
AT+S&Y+OS	14.7	9.7	5.0	393	137
AT+GS+OS	14.9	10.0	4.9	386	144
MT+S&Y+OS	15.2	9.8	5.4	393	137
MT+GS+OS	15.5	10.5	5.0	386	144
AT+MT+OS	15.4	9.8	5.6	390	140
GS+S&Y+PH	17.2	8.5	8.7	388	142
AT+S&Y+PH	17.1	7.8	9.3	391	136
AT+GS+PH	17.3	8.3	9.0	384	146
MT+S&Y+PH	17.6	8.3	9.3	392	138
MT+GS+PH	17.8	9.0	8.8	384	146
AT+MT+PH	17.8	8.1	9.7	388	142
GS+S&Y+SYL	17.8	10.2	7.8	388	142
AT+S&Y+SYL	17.8	9.8	8.0	392	138
AT+GS+SYL	17.9	10.2	7.7	384	146
MT+S&Y+SYL	18.2	10.1	8.1	392	138
MT+GS+SYL	18.4	10.8	7.6	385	145
AT+MT+SYL	18.4	10.1	8.3	389	141

obtained in our earlier experiment set up discussed in Section 6.3. The algorithm results gave us the same pattern of THD impact as obtained by the actual measurements obtained using the building load model and the Dynamic Signal Analyzer. In terms of overall ranking of the combinations, the ranking of last two set of combinations in Table 6.4 is different from that of Table 6.4. It is mainly due to the changes made in the design of the experiment in the latter case.

6.6 Case Study No. 2

We have used the same load model as in case study 1. The energy efficient lighting technologies and the design of the experiment are the same as the earlier case study. The wattage size of the model has been doubled as compared to that of case study No. 1. This case study was designed to verify that the algorithm results are independent of the size of the load model as long as the make up of the contributing loads do not change. All the loads in the experiment are almost two time in power requirement as compared to the previous one discussed in Section 6.5. Power requirement for the base case is 1052 watt. The fixed and variable loads are 48% and 52% respectively.

6.6.1 Discussion of Results

The results shown in Table 6.5 are very close to that as recorded in Table 6.4. It shows that by increasing the size of the model the proposed algorithm for selection of energy efficient lighting technologies remains valid. The only important thing is to extract the representative harmonic current profile for each category of the load. The ranking of the lighting technologies shown in Table 6.5 is exactly same as the one shown in Table 6.4. The difference between the measured and calculated THD values increase

Table 6.5. Comparison of THD$_C$ and THD$_M$ for Different Combinations of Lighting Technologies

Technology Combination	THD$_C$ (%)	THD$_M$ (%)	ΔTHD (%)	Capacity (Watts)	Capacity Saving (Watts)
Base Case	14.6	12.6	2.0	1052	-
GS+S&Y+Incan	12.2	9.9	2.3	878	174
AT+S&Y+Incan	12.3	9.6	2.7	878	174
AT+GS+Incan	12.4	9.9	2.5	872	180
MT+S&Y+Incan	12.5	9.8	2.7	878	174
MT+GS+Incan	12.8	10.5	2.3	870	182
AT+MT+Incan	12.8	10.3	2.5	872	180
GS+S&Y+GE	13.9	11.6	2.3	768	284
AT+S&Y+GE	14.0	11.4	2.6	767	285
AT+GS+GE	14.1	11.8	2.3	759	293
MT+S&Y+GE	14.3	11.7	2.6	770	282
MT+GS+GE	14.6	12.3	2.3	753	299
AT+MT+GE	14.7	11.9	2.8	759	293
GS+S&Y+OS	14.8	12.2	2.6	764	288
AT+S&Y+OS	14.8	12.0	2.8	765	287
AT+GS+OS	15.0	12.3	2.7	758	294
MT+S&Y+OS	15.2	12.1	3.1	767	285
MT+GS+OS	15.5	12.7	2.8	769	283
AT+MT+OS	15.5	12.3	3.2	760	292
GS+S&Y+PH	17.1	11.3	5.8	762	290
AT+S&Y+PH	17.1	10.4	6.7	760	292
AT+GS+PH	17.2	11.2	6.0	751	301
MT+S&Y+PH	17.5	10.9	6.6	762	290
MT+GS+PH	17.8	11.7	6.1	761	291
AT+MT+PH	17.8	10.8	7.0	756	296
GS+S&Y+SYL	17.7	13.0	4.7	762	290
AT+S&Y+SYL	17.7	12.4	5.3	761	291
AT+GS+SYL	17.8	13.1	4.7	751	301
MT+S&Y+SYL	18.1	12.7	5.4	762	290
MT+GS+SYL	18.3	13.5	4.8	762	290
AT+MT+SYL	18.4	12.8	4.6	757	295

as we approach to the combinations with energy efficient lighting technologies having higher individual THD value.

6.6.2 Effect of Ambient Harmonics

As mentioned in Section 6.3, one of the factors that increases the difference between the THD_C and THD_M is the level of ambient harmonics. The level of ambient harmonics varies throughout the load cycle. As there is a significant gap between the time of capturing harmonic profiles used in the data file and the time when measurements for THD_M are made to verify the results obtained from the algorithm. Hence the difference in the level of ambient harmonics in the supply voltage will affect the difference between THD_C and THD_M. We can observe this phenomenon clearly from the results of case studies 1 and 2. The THD_C values in Tables 6.4 and 6.5 are same. There is no significant difference between these values because the harmonic profiles used in both the data files were captured within a short time span and there was no significant variation in the level of ambient harmonics of the power supply. If we compare THD_M values from the results of the case studies we can see a consistant increase in the THD_M values of the latter case. This is due to a big gap between the measurement of two values and level of ambient harmonics could have significantly increased. The above comparison shows that there is an increase of 2% to 5% in THD_M in latter case as compared to former case. That is attributed to the increase in ambient harmonics of the supply voltage.

6.7 Advantages of the algorithm

Some of the significant advantages of the algorithm are listed in the following.

1. The algorithm evaluates the lighting technologies on the basis of their harmonic distortion impact on the system. It provides significant information in the output file for the decision maker to select a particular technology in a specific lighting environment.

2. Only those technology combinations are presented which have lower THD impact than the base case (existing lighting system). Hence there is no risk of additional harmonic distortion, in retrofitting energy efficient lighting technologies. Instead, it will help to reduce harmonic distortion level if the best option is selected for retrofitting.

3. The algorithm can easily be extended to select other energy efficient devices like adjustable speed drives (ASDs). There is no need to change the program itself. Modification in data file will enable one to use it for ASD retrofits in industrial and commercial facilities.

4. Performance of the algorithm will improve with improvement and standardization of data acquisition techniques. If manufacturers of nonlinear loads in general and electronic equipment in particular are encouraged to provide harmonic current profile of their products then the results of the algorithm will be more precise.

6.8 Disadvantages

1. Harmonic profiles of lighting devices and other equipment are not currently provided by manufacturers.

2. Methods and equipment to measure harmonic profile data are not widely accessible.

6.9 Summary

Significant energy conservation and environmental benefits of new lighting technologies will encourage their market penetration. However, such proliferation of electronic equipment is going to cause deterioration of power quality of the supply system at the distribution level. Lighting devices form a significant portion of the load in a commercial building. Energy efficient alternates to the standard lighting sources may enhance or mitigate the harmonic distortion level at the PCC. However, random choice of energy efficient lighting technologies could deteriorate the power quality of the supply system. Minimum requirement is that the harmonic level in the building should remain the same, if not improve.

The proposed algorithm can generate a large number of combinations of energy efficient lighting technologies that lower harmonic impact than the base case. Selection of the least harmonic impact technology can be facilitated by the use of this algorithm. Results have been confirmed by making actual measurements for certain combinations. The proposed algorithm is simple to apply and can be used at all levels of lighting retrofits i.e., industrial, commercial, etc. Generic nature of the algorithm can help to use it for other nonlinear load applications as well. We can conclude from the results of the case study that the proposed algorithm is independent of the size of the load model. Hence a building load can be conveniently scaled down to collect the data required in the data file of the proposed algorithm. The results obtained by doing so will be equally good under the actual load conditions in the building.

CHAPTER VII

ENERGY SAVINGS, ENVIRONMENTAL BENEFITS AND RELIABILITY

7.1 Introduction

Energy Policy Act of 1992 has created a significant enthusiasm among manufacturers of energy efficient devices, electric utilities and customers in the U.S. Largest potential of energy savings lie in adjustable speed drives (ASD) and energy efficient lighting systems. Approximately 76% of the electric energy being used in the U.S. is consumed by motors, whereas 20% of national electricity consumption is for lighting. Maximum energy saving potential of ASDs is 30-50%. While energy efficient lighting devices can reduce energy requirement from 50 to 80% [12,131]. The higher energy saving potential of energy efficient lighting systems have prompted many energy efficient lighting programs sponsored by electric utilities.

Recent estimates predict that the annual consumption of energy by office equipment will be more than 65×10^9 kWh by year 1995 [132]. The corresponding capacity requirements are expected to rise from 5 GW in the year 1988 to 15 GW in year 1995 [132]. Energy efficient lighting devices are gaining popularity among residential, commercial and industrial customers. The potential of energy savings is the major

driving force for customers. On the other hand, energy efficient lighting programs are the most feasible option for electric utilities to meet future requirements of capacity addition. Capacity addition is becoming more expensive for electric utilities. This has diverted the electric utility attention toward demand side management options. Environmental Protection Agency of USA has sponsored a number of programs to encourage the use of energy efficient lighting products among customers resulting in both energy and capacity savings opportunities. Until recently focus of most the of work in this area was on energy saving benefits. This chapter is intended to evaluate recent progress in different energy efficient lighting technologies on the basis of their functional and technical performance and their system level impact.

7.2 Energy Conservation Potential and Progress

Environmental Protection Agency (EPA) in the United States has launched an extensive campaign to invite businesses, organizations and government agencies to join their Green Light Program. EPA provides information about state-of-the-art lighting technologies and guidance to finance lighting retrofit programs. EPA also educates masses about the damaging effect of pollution, caused by electricity generation, on environment and motivate them to participate in the Green Light Program to reduce environmental pollution. Although main target of EPA is to reduce environmental pollution, however, it is done through energy conservation programs.

Lighting accounts for 20-25 percent of all electricity sold in the United States. 80-90 percent of total lighting energy is consumed in public places, businesses and offices. If all the cost effective lighting retrofit programs are implemented, the nation's demand for electricity will be reduced by more than 10 percent [133]. During last couple of years 1000 organizations have joined the Green Light Program of EPA. They include

industries like oil, manufacturing and pharmaceutical; retailers, hotel and restaurant chains; federal agencies, state and county governments; newspapers, cable networks, university and schools. Green Light Programs have been proved very effective in increasing productivity and boosting the moral of employees, in addition to the usual energy saving and environmental benefits.

In Europe electric utilities are actively involved in pursuing their customers to join efficient lighting programs. Since 1987 more than 50 utility sponsored programs in Europe have offered financial incentives to their customers to promote compact fluorescent lamps. Data from different efficient lighting programs shows that cost per kWh saved through efficient lighting programs is less than the cost of adding new capacity to the system.

There exists a clear difference between energy efficient lighting programs in Europe and the U.S. Manufacturers in Europe are more actively involved in such programs. Higher per unit cost of electricity encourage customer participation at individual levels. Energy is conserved at lessor cost compared to the United States. However, a broader spectrum of energy efficient lighting technologies exist as compared to Europe. Voluntary government programs like EPA and Federal Energy Management Program (FEMP) are in place that help to promote energy efficient lighting programs at different levels.

Table 7.1. Summary of Some Energy Conservation Programs

Company	Old System	New System	Project Cost	Annual Savings	Lighting Load Reduction	Pollution Avoided per yr		
						CO$_2$ (kg)	SO$_2$ (kg)	NO$_x$ (kg)
American Express	T-12 Lamps Mag. Blst Incandescent Manual Switches	T-8 Lamps Elect. Blst CFLs. Occupancy Sensors	$710,000	$280,000	37%	1,812,360	12,641	4325
Browning Ferris Industry	T-12 Lamps Mag. Blst. Incandescent	T-8 Lamps Elect. Blst. CFLs	$210,000	$107,000	50%	4,69,563	1,437	1,437
Dresser Rand	T-12 Lamps Mag. Blst	T-8 Lamps Elect. Blst Reflector	$230,000	$78,800	69.9%	5,45,258	3,803	1,301
Elkhart General Hospital	T-12 Lamps Mag. Blst Manual Switches	T-8 Lamps Elect. Blst Occupancy Sensors. Time Switches	$85,446	$102,150	70+%	1,391,278	11,850	5,108
Mobil	T-12 Lamps Mag. Blst. Incandescent	T-8 Lamps Elect. Blst. Halogen Lamps. CFLs	$392,400	$125,000	25%	1,021,500	7,500	3,400
Education H.Q. of MD State	T-12 Lamps Mag. Blst. Incandescent	T-8 Lamps Elect. Blst. CFLs.	$208,749	$100,513	64%	1,217,350	11,932	4,022
Union Camp	T-12 Lamps Mag. Blst. Incandescent	T-12 Lamps Elect. Blst. Reflectors Lenses CFLs	$280,000	$100,000	51+%	3,06,402	2,025	1,446
Westin Hotel & Resort	Incandescent Lamps	CFLs.	$75,915	$85,200	82+%	3,93,978	3,355	1,446

Source: Environmental Protection Agency

Table 7.1 gives a sample of recent green light upgrades, published by EPA [134]. Lighting load reduction ranges from 25 to 82%. Maximum saving is achieved when incandescent lamps are replaced with CFLs. When incandescent lamps at Westin Hotel and Resort in San Francisco were replaced with CFLs, Lighting load was reduced by 82% and project cost was recovered through the energy savings in less than one year.

7.3 Impact of Energy Conservation Technologies on Power System

Since the inception of integrated resource planning, energy efficient lighting programs are one of the most important one among DSM options. Demand Side Management (DSM) programs have influenced the developments in energy efficient lighting technologies. Tungsten halogen, fluorescent, compact fluorescent (CFL), high pressure sodium (HPS) and metal halide lamps are energy efficient devices, mostly used for different lighting applications. The latter four types of lamps fall in a bigger group called discharge lamps. This major group is the focus of most of the energy efficient lighting activities. Table 7.2 gives a comparison of important features of lamps, available in the current lighting market. These lamps cover most of the lighting application areas. They are available in wide range of color and power ratings. High pressure sodium and metal halide lamps are more efficient for higher ratings. They are not available in power ratings below 35 watts. This constraint makes them less attractive for most residential and commercial lighting applications. Full size fluorescent and compact fluorescent lamps are best suited for residential and commercial lighting applications. These lamps are available in wattage ratings as low as 4 watts.

Table 7.2. Characteristics of Energy Efficient Lighting Technologies

Lamp Type	Lumens per Watt	Color Rendering Index	Average Life (hour)
Fluorescent	75-104	62-92	7500-30,000
CFL	44-67	82-85	10,000
HPS	60-140	20-85	15,000-40,000
Metal Halide	80-125	65-93	3000-20,000

7.4 Energy Savings and Environmental Benefits

In the US, average cost of a fluorescent bulb is 4%, labor is 8% and electricity makes up 88% of the total cost of lighting. Total operating cost of a F40CW (cool white) standard bulb, over its life is $66.35[1]. The energy efficient alternate, F40CW/WM (Watt-Miser), costs $57.77. In this case, the individual costs of the bulbs are $2.35 and $3.37, respectively. Although the Watt-Miser bulb is little expensive but the savings in electricity are significant [137]. Increasing the energy efficiency of lighting systems can achieve significant savings in the electricity required for illumination. A 20 Watt compact fluorescent lamp provides almost same amount of light as 75 watt incandescent lamp. Replacement of a magnetic ballast with an electronic ballast and a T-12 with a T-8 lamp saves 40% electricity. This enormous potential of energy savings justifies the investment in energy efficient lighting technologies, even with higher initial price tags.

From environmental considerations, the electricity required to provide lighting is responsible for 6% and 25% of the total CO_2 emissions from residential and commercial sector, respectively [138]. The CO_2 emissions from residential and service sector emission is shown in Figure 7.1. Use of energy efficient lighting technologies will significantly reduce the CO_2 emissions level, specially in the big metropolitan areas all over the world.

The Electric Power Research Institute (EPRI) [139] predicts annual energy savings, through commercial lighting DSM programs, of 33 billion kWhrs in the year 2000. The demand reduction at the same time is projected at 7.34 GW. Besides the direct energy savings through replacement of non-efficient lighting technologies with energy efficient devices, there is a significant potential for indirect saving of energy in

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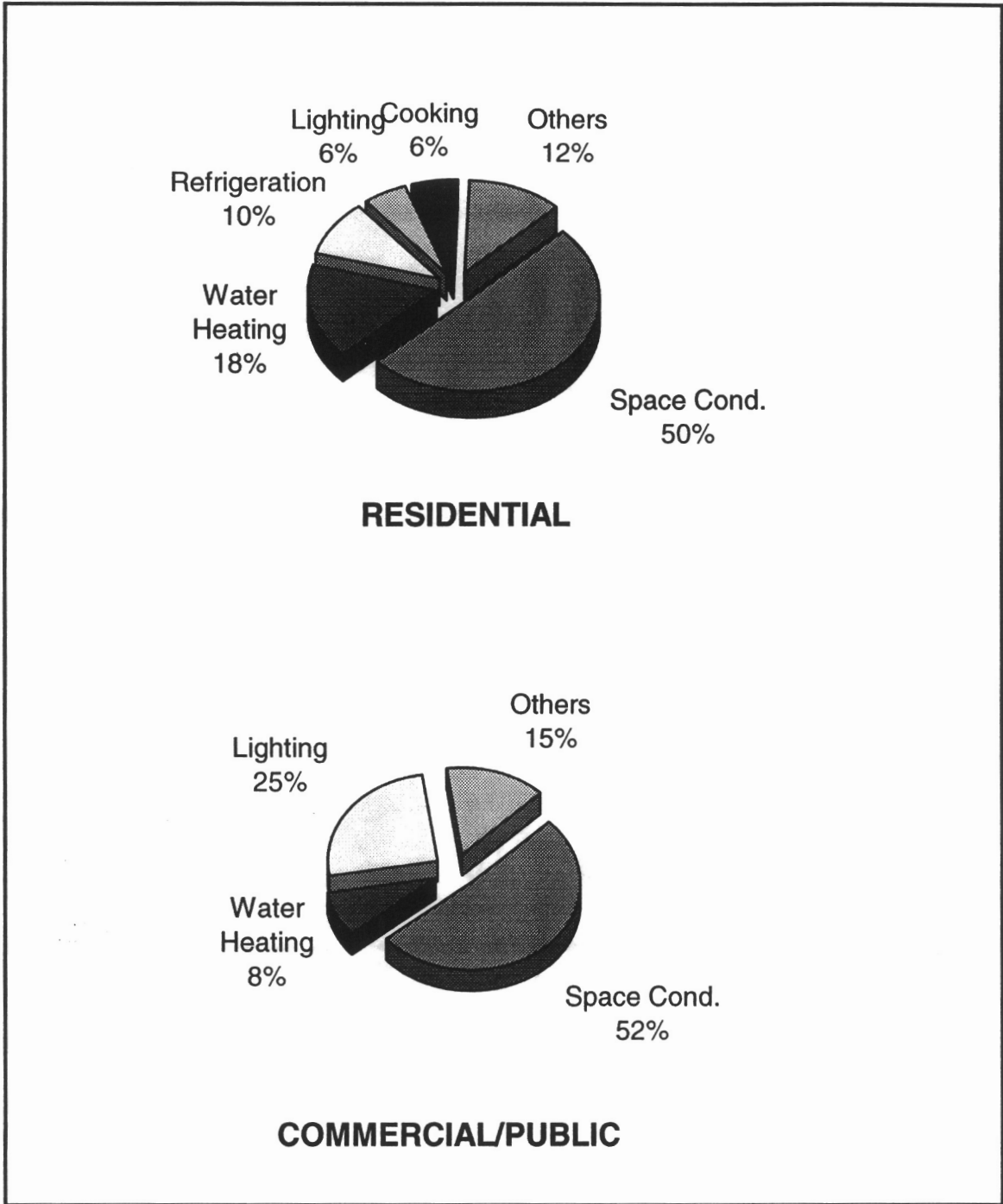[1] At $0.08/kWh over average lamp life.

Figure 7.1. CO$_2$ Emissions for Residential and Service Sector, in OECD Member Countries

cooling requirement of commercial buildings. Mendelsohn [140] reports on a study to assess the energy savings in cooling load through energy efficient lighting products. Study shows that reduction in cooling load is significant even when increase in heating load during winter season was taken into account. However, these benefits strictly depend upon the local weather pattern i.e., number of cooling degree days in the year. US Department of Navy has prepared data for length of cooling season in weeks for the major US cities. It shows that cooling season in US varies from 9.4 to 50.1 weeks. Depending upon the weather, energy savings in cooling load can vary from 6% to 32%. These benefits are more pronounced for the southern and western regions of the United States.

Moreover, Energy Policy Act of 1992 in US has reshaped the entire lighting industry. Many popular lighting products will be eliminated with next three years. Table 7.3 gives lumen efficacy of energy efficient devices in comparison with incandescent lamps. Energy saving impact of individual lighting units on the system is very straight forward. Energy efficiency of individual products is translated into total saving of energy at system level. However, studies have shown that as a result of energy efficient lighting programs, summer peak demand is reduced by 3.7% for annual energy reduction of 1.3% [104]. This gives a significant relief to electric utilities from near future capacity addition. Environmental benefits are the function of utility mix. In case of higher dependance of utility on coal for electricity generation will realize more environmental benefits. The environmental benefits realized by replacing 75 watt incandescent lamp with 20 watt compact fluorescent lamp are as follows:

$$SO_2 \text{ (Acid rain component)} = 6.4 \text{ lbs}$$

$$NO_x \text{ (Smog)} = 3.4 \text{ lbs}$$

$$CO_2 \text{ (Greenhouse gas effect)} = 880 \text{ lbs}$$

Table 7.3. Lumen Efficacy of Different Type of Lamps

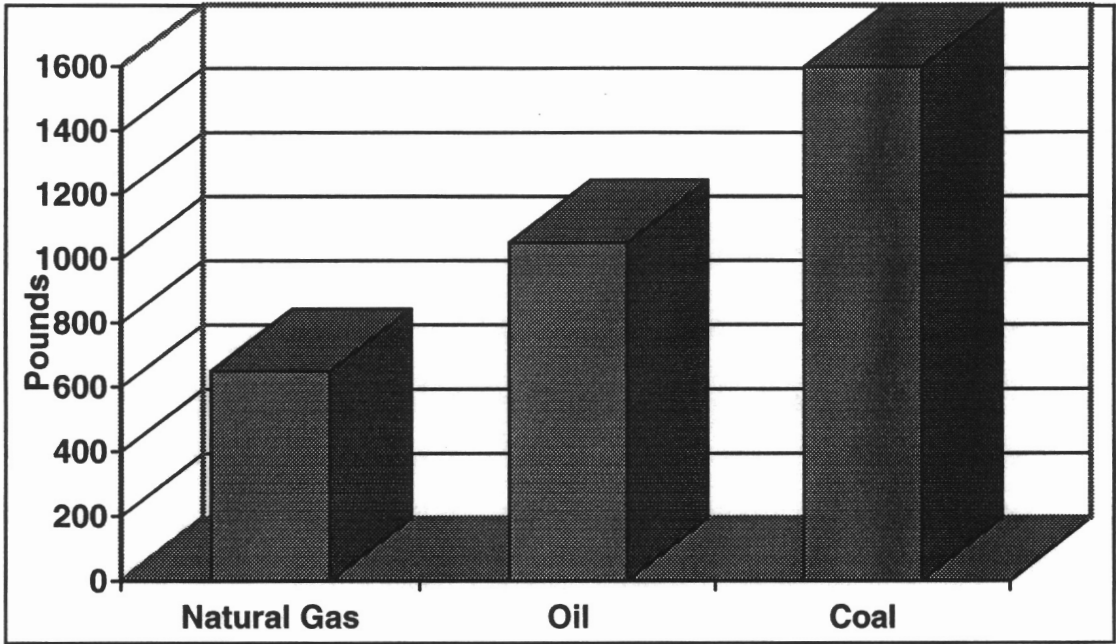| Lamp Type	Minimum (LPW)	Maximum (LPW)
Incandescent	15	25
Tungsten halogen	25	45
Fluorescent	70	100
Metal halide	80	120
High pressure sodium	65	140

Figure 7.2. CO_2 Avoided Over Lamp Life of 23 watt CFL vs
Incandescent Lamp
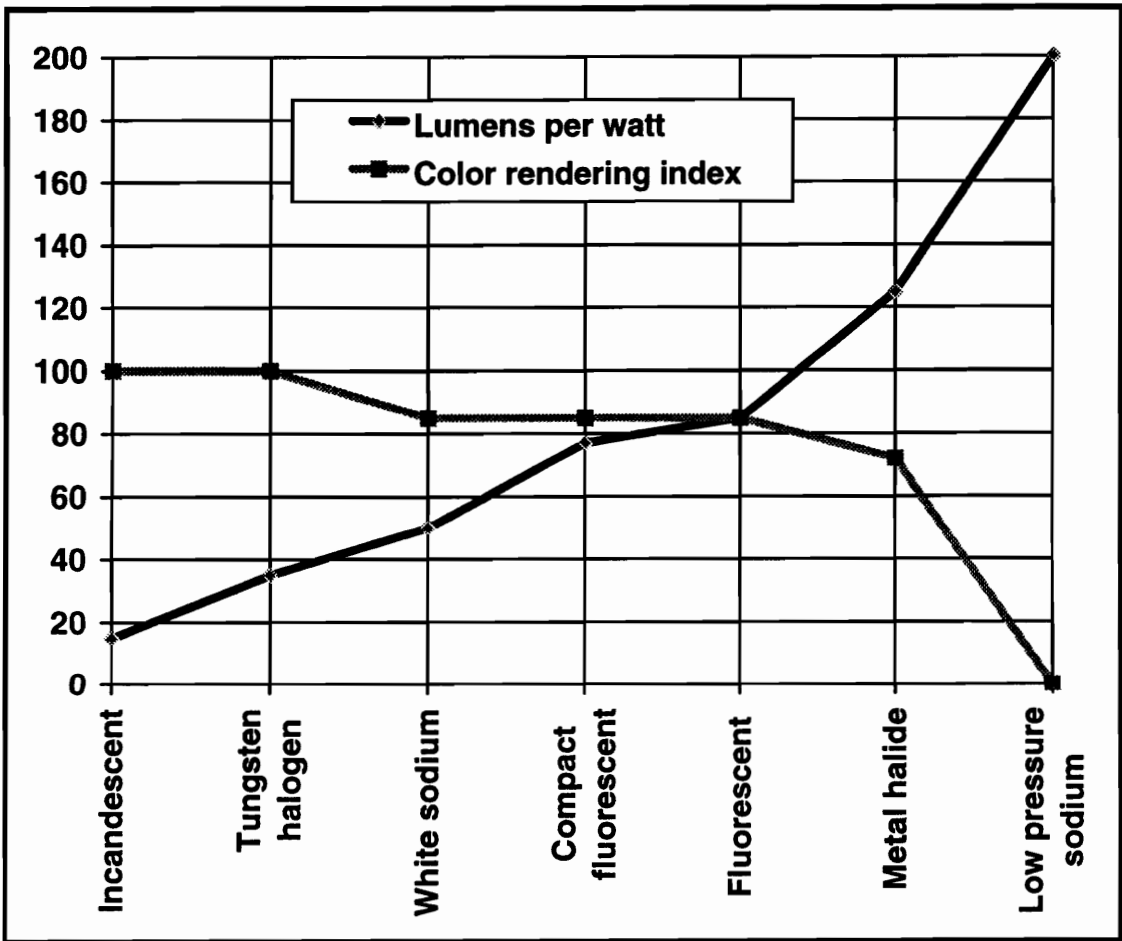
Fig. 7.3. Correlation Between Lumens Efficacy and Color Rendering Index

Figure 7.2 gives a comparison of CO_2 avoided over lamp life of a 23 watt CFL vs 90 watt incandescent lamps for different fuel types. This comparison gives an idea about the CO_2 pollution as a result of different fuel types.

It is interesting to note that energy saving has a correlation with color rendering index of the lighting technology. Figure 7.3 shows this correlation between color rendering index and energy saving potential of different lighting technologies. It shows that incandescent lamp has the best color rendering index and minimum efficacy while on the other extreme low pressure sodium lamp has the highest lumen efficacy and lowest color rendering index.

7.5 Optimum Mix of Energy Efficient Lighting Technologies

It is clear from our discussions in previous chapters that besides energy saving and environment benefits of energy efficient lighting technologies they inherit some power quality problems. These technologies can be divided in to following two categories:

(1) Discharge lamps

(2) Tungsten Halogen Lamps

All discharge lamps needs device called as ballast, to start and operate the discharge lamp. Ballasts in energy efficient discharge lamps have non linear impedance and hence source of harmonic currents. Harmonic currents become a serious threat to the system if they exceed certain thresholds as prescribed by IEEE std 519 [135]. Manufacturers of lighting devices try to reduce harmonic current requirement of the

devices through active and passive filtering techniques. However, cost and size constraints on the lamps force manufacturers to compromise with certain level of distortion current. Our focus in chapters 5 and 6 was to find the ways and means to reduce harmonic impact of energy efficient lighting technologies on the system. In this chapter we will discuss the energy savings and environmental benefits of these technologies.

Second type of energy efficient lamps, Tungsten halogen lamps have less lumen efficacy compared to discharge or fluorescent lamps. However, they do not need any additional circuit for their starting or operation. Tungsten halogen lamps have limited role compared to fluorescent lamps among overall lighting applications. Their common applications are floodlighting and spot lighting in commercial and industrial environment. Due to their high color rendering index (CRI), they produce light that is very close to natural sun light. More over they do not need any modification of the fixture to replace standard PAR lamps. Tungsten halogen lamp has a potential to save energy up to 60% compared to standard PAR lamps.

A mix of fluorescent and CFLs can be used to keep harmonic distortion level within the limit. In case this mix violates harmonic distortion limit, tungsten halogen lamps can be inducted as per requirement to meet harmonic limits. As tungsten halogen lamp is considered a linear impedance, hence it does not contribute to the lighting load harmonic current. Instead overall harmonic distortions are reduced, depending upon percentage of tungsten halogen lamps among lighting devices. Energy savings and environmental benefits will be slightly reduced, however, power quality benefits overweighs the former benefits. An optimal mix of fluorescent, metal halide, HPS and tungsten halogen is calculated far a particular building load configuration.

Tungsten halogen technology is expected to play an important role in future to improve power quality at micro and macro system level. First, tungsten halogen technology has potential to be more efficient in future compared to its present day status [136]. Second, load forecast shows that in year 2010, approximately 74-83% of the commercial and 55-58% of industrial load will be of nonlinear type. That is a signal of more harmonic distortion at customer bus. Under these two conditions, tungsten halogen technology will be very important in future. Technology mix of fluorescent and tungsten halogen will be an option for passive harmonic mitigation in hostile environment of nonlinear loads. It is worth mentioning that both, commercial and industrial customers, have significant requirement of floodlighting and spotlighting.

At present, a full line of energy efficient lighting products is available in market. Manufacturers provide information about energy savings, environmental benefits, P.F., and harmonic distortion for individual products. This information is not enough to assess the impact of energy efficient lighting devices at system level. Energy savings and color rendering capabilities of candidate technologies attract utility customers while utilities are concerned about the power quality impact of these products on the system. However, in the long run utility customers will too start feeling the impact of harmonic distortions on their sensitive equipments. That could create the so called customer backlash as a result of increasing proliferation of harmonic generating loads. Hence these issues need to be addressed now, both at building as well as system level.

Generally performance of different lighting technologies is judged on the basis of their functional and technical capabilities. Figure 7.4 gives the description of the criteria for functional and technical performance of lighting products. This criterion helps to optimize energy savings, technology cost, illumination requirement and other benefits. Technologies are required to be tested for manufacturers claim about energy savings, power factor, harmonic distortions and luminance values.
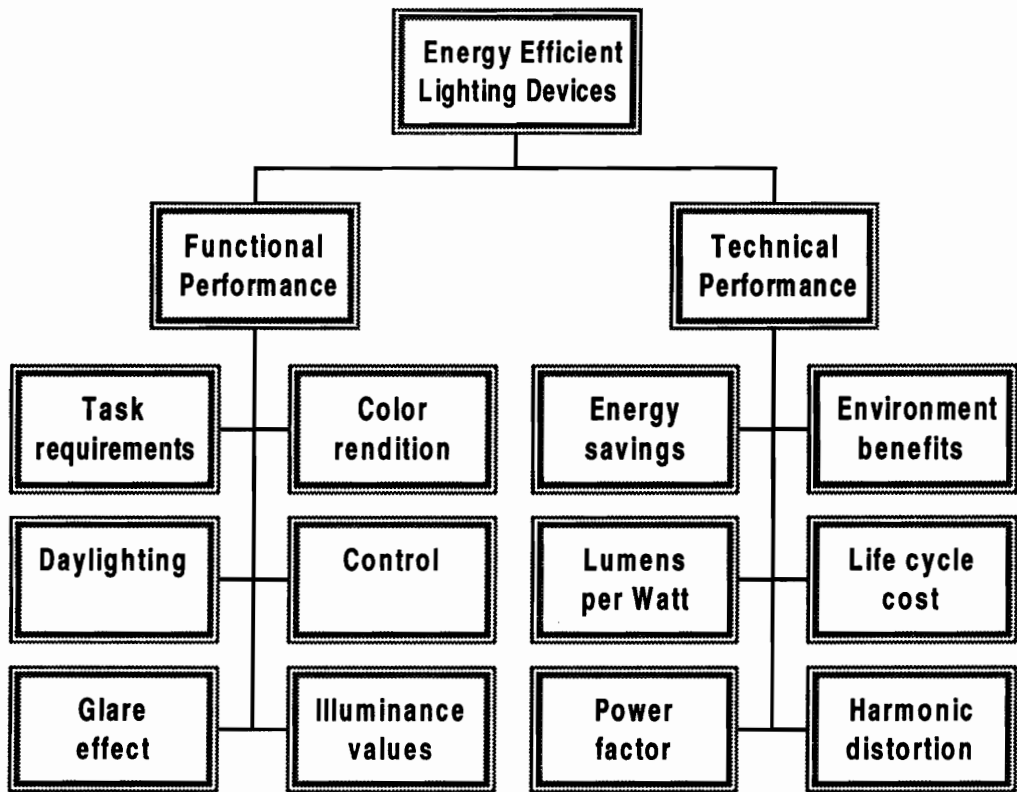
Figure 7.4. Functional and Technical Performance Criteria

Energy efficient lighting technologies are available in wide range of wattage and illuminance ratings. This flexibility facilitates to use these technologies for all kind of tasks. Electronic ballast fluorescent lamps are available with control circuitry that has capability to control lumen level from 10 to 100%. That could be used in combination with daylighting technologies to enhance energy savings and environmental benefits.

7.6 Case Study Results

7.6.1 Building Load Model

A building load model was built, using 24 hour load data for a typical building. Main load components of the model are induction motor, computer, and lighting load. During peak hours lighting loads account for 60% of the building load, induction motor load is 30%, and 10% computer load.

7.6.2. Benefits and Issues

This research was conducted to study the impact of energy efficient lighting devices on the system. Building lighting needs are presently met by standard magnetic ballast T-12 fluorescent lamps and incandescent lamps. Magnetic ballast and T-12 lamps were replaced with high frequency electronic ballast T-8 lamps. Incandescent lamps were replaced with electronic ballast compact fluorescent lamps. Electronic ballast T-8 lamps have power factor and THD 0.95 and 15% respectively. Compact fluorescent lamps have P.F and THD as 0.96 and 26% respectively. First load, THD and power factor were studied without any penetration of new lighting technologies. Individual P.F. and THD

Figure 7.5. Block Diagram for Building Load Model

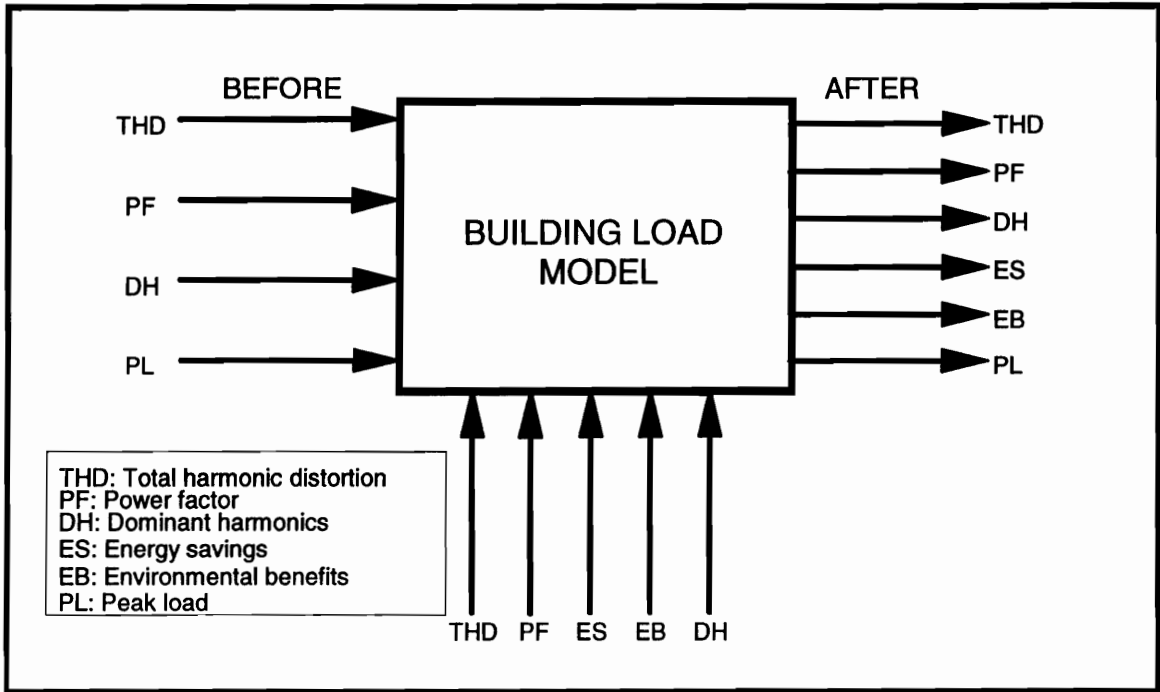for standard magnetic ballast is >0.90 and 20% respectively. While incandescent lamp has unity P.F. and negligible current harmonics. For each penetration level parameters like energy savings, peak load, THD, P.F. and dominant harmonics were measured, both, before and after penetrating new lighting technologies.

7.6.3 Results

Power factor, THD and energy savings are analyzed using the building load model for different level of penetration of new lighting technologies. Results are analyzed for 20, 25, 46, 54, 73, and 100 percent penetration of different lighting technologies. It is observed that evaluation of energy savings and power quality at lower penetration becomes uncertain due to following reasons:

- Variation in utilization pattern of lighting in same building.
- Requirement of different lighting technologies for different kinds of tasks.
- Different attitude of the personals working in the same building towards energy savings and environmental protection.

Choice of lighting area, selected for a certain penetration level will have impact on energy savings and power quality. If area of less use is selected, due to one or the other reason, for retrofitting then it will have different impact compared to other choices for same level of penetration. As we proceed towards higher penetration level energy saving become more visible and pronounced. Power quality is not different from lower penetration level if energy efficient lighting technologies are selected carefully. Figures 7.6-7.11 presents the capacity and energy savings; power factor and THD at 73 and 100 percent penetration of energy efficient lighting technologies. It is interesting to note that higher penetration of energy efficient technologies do not deteriorate power quality if technologies are selected carefully. Significant harmonic cancellation takes place for certain set of technologies.

Figure 7.6. Energy Savings at 73% Penetration of Energy efficient Lighting Technologies

Figure 7.7. Power Factor at 73% Penetration of Energy Efficient Lighting Technologies

Figure 7.8. THD at 73% Penetration of Energy Efficient Lighting Technologies
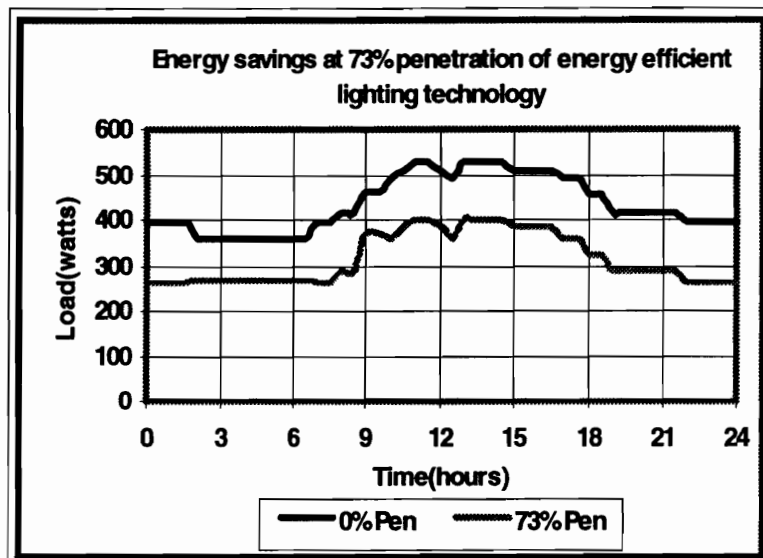
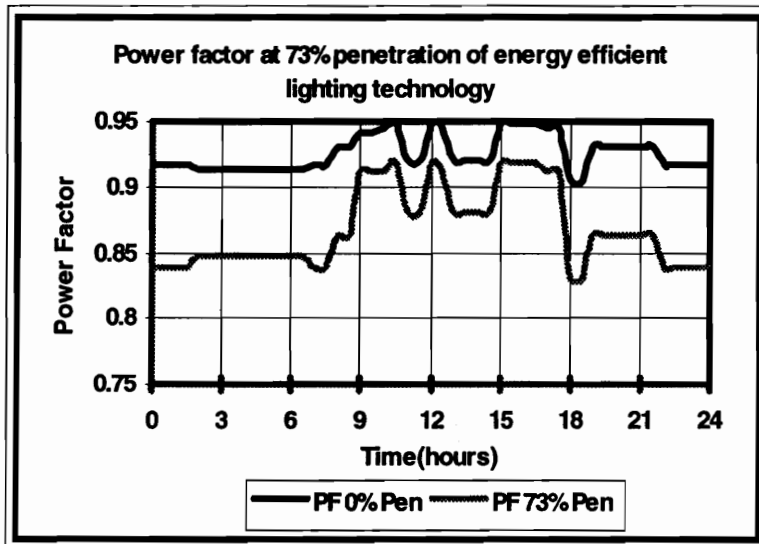**Figure 7.9. Energy Savings at 100% Penetration of Energy Efficient Lighting Technologies**

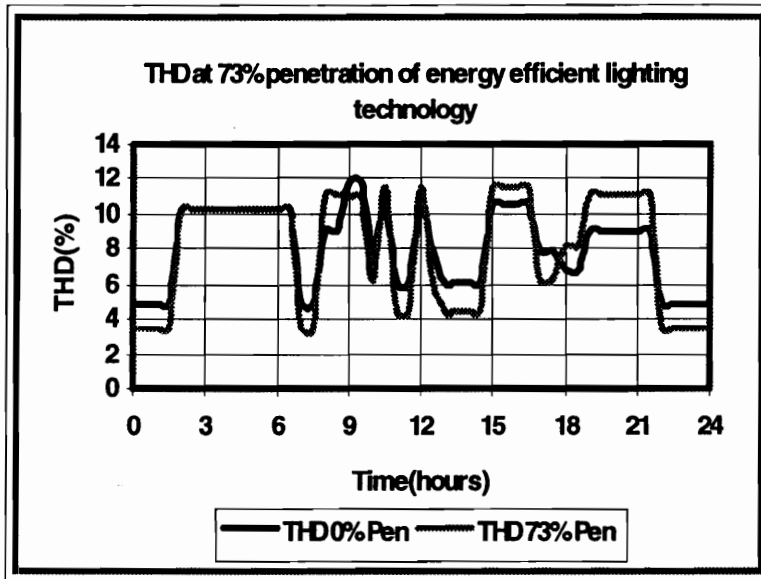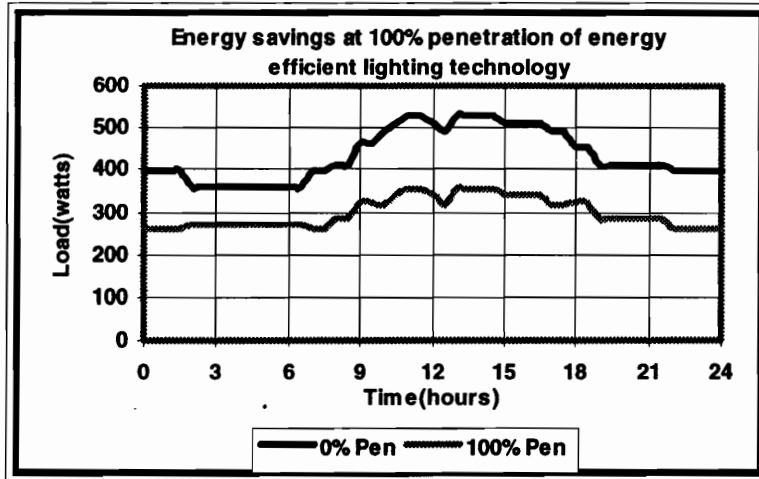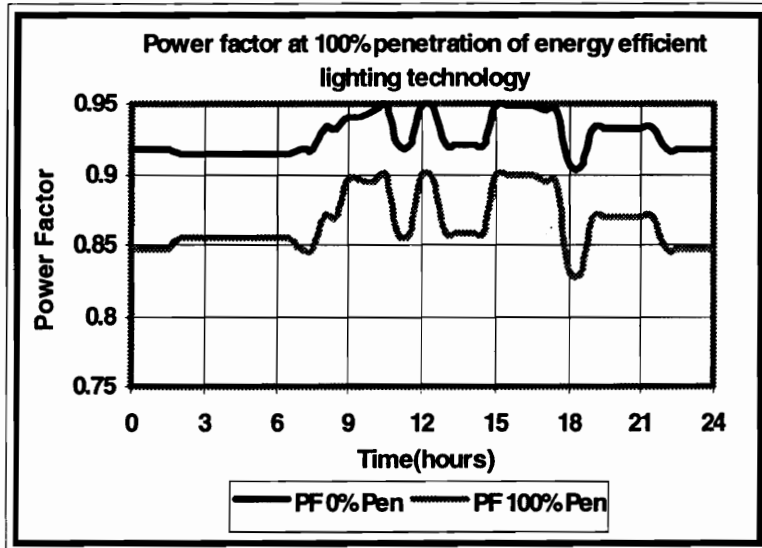**Figure 7.10. Power factor at 73% Penetration of Energy Efficient Lighting Technologies**

THD at 100% penetration of energy efficient lighting technology
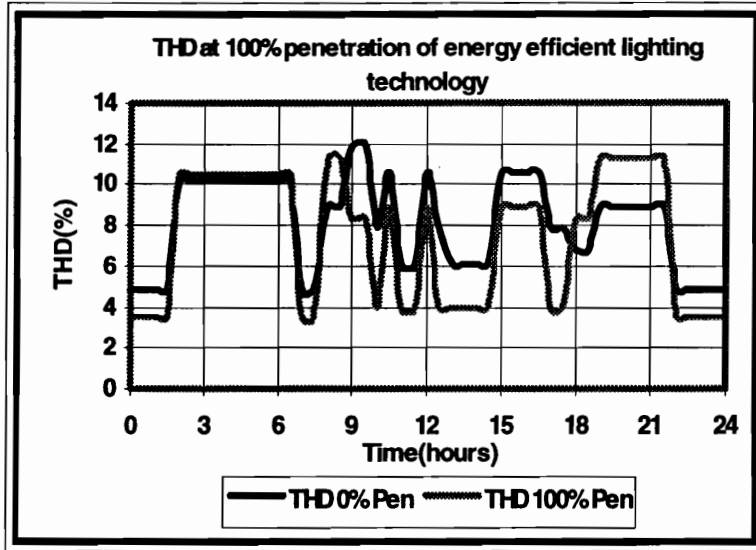
Figure 7.11. THD at 73% Penetration of Energy Efficient Lighting Technologies

7.7 Performance of Fluorescent Lamps

Since 1970s there have been efforts to develop electronic ballasts to operate discharge lamps at high frequencies. It was not possible until early 1980s, to market a feasible electronic ballast. The electronic ballasts received a significant share of the ballast market only in late 1980s. Since then electronic ballast technology has grown very fast. The high frequency electronic ballast has significantly improved the life and efficacy of fluorescent lighting systems. Verderber [141] has reviewed the developments and market share of the ballast technology. Figure 7.12 gives a comparison of the shipment of electronic and magnetic ballasts over the last ten year period. Until 1989, the electronic ballasts had a very slim share in the ballast market. The electronic ballasts started taking over the magnetic ballasts from 1990 and onwards. After this period the activity has been increased by a factor of three. By the year 1993, the electronic ballasts have a market share of more than 27% of the total ballasts. In Figure 7.12 the data for years 1994 and 1995 are the projections on the basis of previous trend of the ballast market. Figure 7.13 gives a comparison of past and future market share of electronic and magnetic compact fluorescent lamps. Due to electronic ballasts and electronic compact fluorescent lamp (CFL) becoming a significant portion of the demand side loads, these technologies are required to be investigated in a system prospective. Datta [142] has made a comparative analysis of electronic and magnetic ballasts. He made a comparison between electronic and magnetic ballasts on the basis of total harmonic distortions (THD), power factor, light output, ballast efficacy factor, power input, and the temperature of the lamp and ballasts themselves.

The electric utilities and the supplier of electricity around the world are adopting certain practices that allow the system to work at over and below the rated voltage and frequency limits. In some parts of the world the electricity suppliers operate the system at
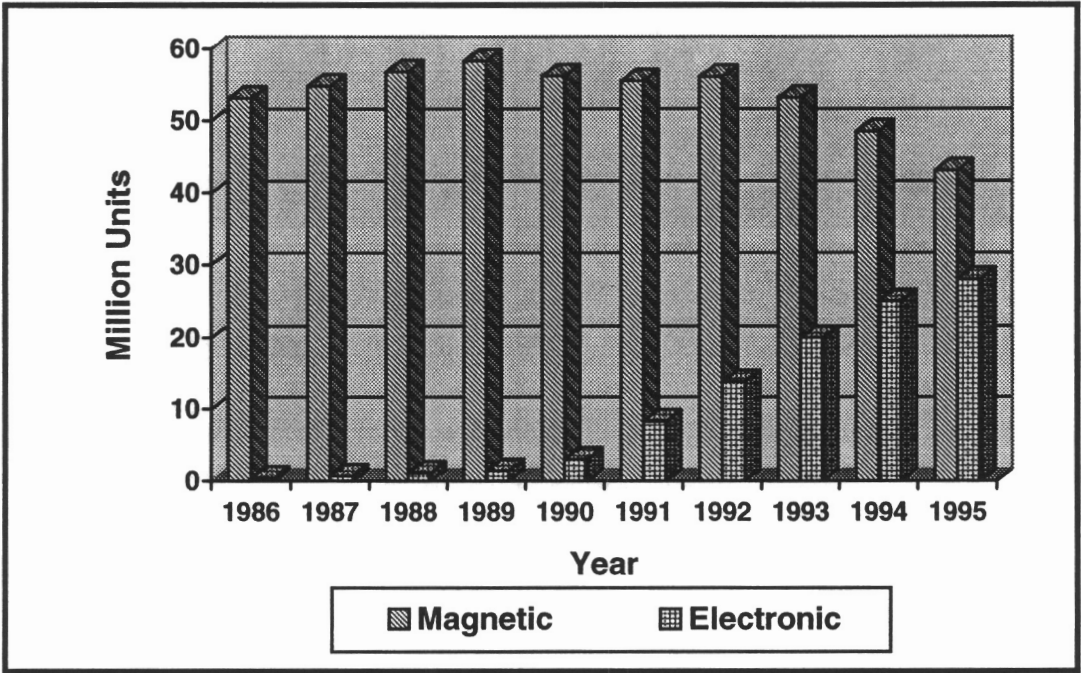
Figure 7.12 Shipment of Fluorescent Lamp Ballasts
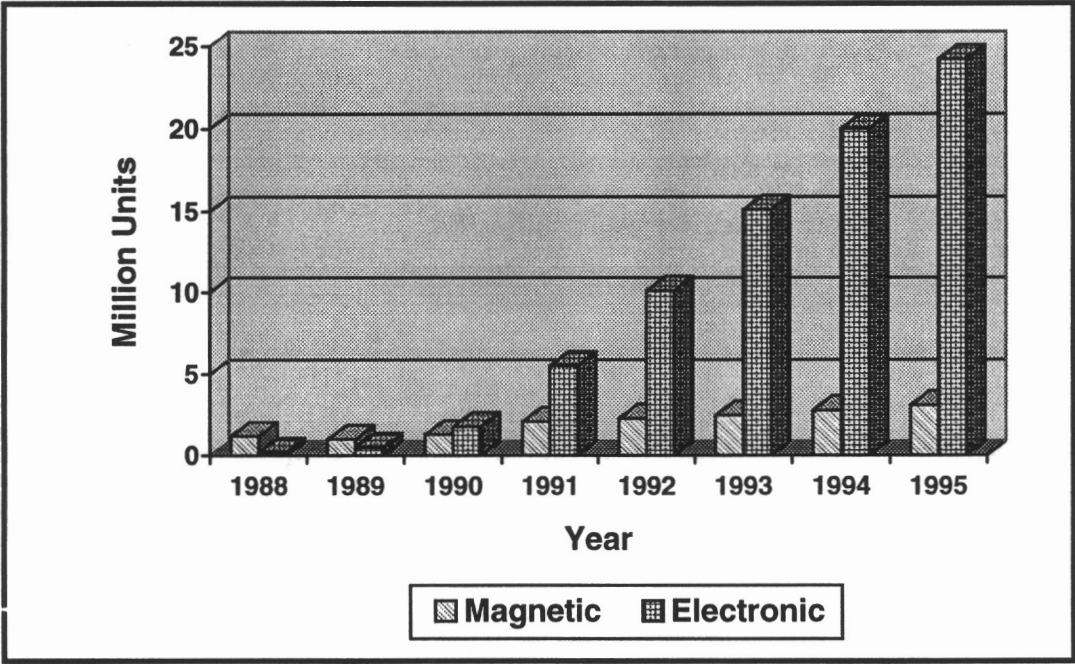
Figure 7.13 Shipment of Compact Fluorescent Lamps

frequency above the rated frequency to increase the system stability during fault conditions. Many underdeveloped countries are suffering from acute shortage of generation capacity and allow the system to work at a voltage up to 30% less than the rated voltage. System overloading also causes the under frequency conditions. Switching on and off of large industrial load also causes voltage and frequency fluctuations. Some researchers have also reported the problem of voltage and frequency fluctuation in an environment of generation mix. This section investigates the electronic and magnetic ballasts with T-8 and T-12 fluorescent lamps; electronic and magnetic compact fluorescent lamps under varying voltage and frequency conditions.

7.7.1 Methodology to Investigate Fluorescent Lamps at Varying Supply Voltage

Our main goal in this investigation was to compare different models of electronic and magnetic ballasts for the minimum supply voltage requirements to fire the fluorescent lamp. The investigation was carried out in following three stages:

1. Each ballast technology was tested for the minimum supply voltage required to fire the fluorescent lamp. Lighting system was studied for flicker, lumens, power requirements, power factor, and THD under the minimum voltage conditions.

2. The supply voltage for each ballast and lamp fixture was increased to a level where there is no significant flicker and the lamp has a stable discharge. This voltage was described as stable discharge voltage and power requirements, power factor, and THD was studied at the stable discharge.

3. Performance of each lamp-ballast fixture at reduced voltage was analyzed with reference to the rated supply voltage. For this purpose, each lighting technology was studied for power requirements, power factor, and THD.

7.7.2 Analysis of Electronic and Magnetic Ballasts for Reduced Supply Voltage

Table 7.4 gives a comparative analysis of fluorescent lamp ballasts for reduced supply voltage. There are three types of magnetic ballasts and four types of electronic ballasts. Fluorescent lamps are standard T-12 and energy efficient T-8 types. Description of each fluorescent lamp fixture is given below:

Std. MB T-12: Standard magnetic ballast with T-12 fluorescent lamp.

ES1 MB T-12: Energy saving type 1 magnetic ballast with T-12 fluorescent lamp.

ES2 MB T-12: Energy saving type 2 magnetic ballast with T-12 fluorescent lamp.

ES2 MB T-8: Energy saving type 2 magnetic ballast with T-8 fluorescent lamp.

EB1 T-8: Electronic ballast manufacturer 1 with T-8 fluorescent lamp.

EB2 T-8: Electronic ballast manufacturer 2 with T-8 fluorescent lamp.

EB3 T-8: Electronic ballast manufacturer 3 with T-8 fluorescent lamp.

EB4 T-8: Electronic ballast manufacturer 4 with T-8 fluorescent lamp.

Among the electronic ballasts, EB1 T-8 and EB3 T-8 fire at lowest voltage. While ES2 T-12 has the lowest firing voltage among the magnetic ballasts. Besides the lower firing voltage for electronic ballasts, it starts without any significant flicker as compared to magnetic ballast. Magnetic ballast can not start T-8 lamp at supply voltage lower than 100 volt. In case of electronic ballast and T-8 lamp, the only back draw of low voltage is that lumens output is low. For a stable discharge the supply voltage requirements for ES2 MB T-8 are 105 volt. While electronic ballasts can give a stable discharge 75 volt and provides significant lumens output without any visible flicker.

Most of the magnetic ballasts generate more harmonics at supply lower than the rated voltage. Electronic ballasts generate less harmonics at lower voltage than the

harmonics at rated voltage. Under the reduced voltage operation electronic ballasts have less harmonic impact on the system as well as the loads sharing the common utility bus.

Due to higher Ballast Efficacy Factor (BEF), the electronic ballasts consume less power than the magnetic ballast with equivalent lumens output. The less power consumption reduces the heat loss in the ballast and hence the electronic ballast improves the safety and reliability of the lighting system. Also greater energy savings can be realized by operating T-8 lamps with electronic ballasts instead of magnetic ballasts. EB1 T-8 lighting system consumes 60 watts compare to 82 watt consumed by ES2 MB T-8 lighting system.

Table 7.4 shows that in most of the cases, electronic ballasts have a slight decrease in THD at stable discharge compared to that at 120 volt. Ouellette and Arseneau [143] have also reported similar results for the old models of electronic compact fluorescent lamps. Their results show THDs of 82.9% and 81.5% at 120 Volt and 100 volt supply voltage respectively. Discussions about the rectifier/filter design, presented by Wood [144] show that the current THD is function of the crest factor of the circuit. For supply voltage lower than the rated value, rectifier/filter circuit becomes oversized and helps to filter out more harmonic frequencies than the rated supply voltage. This phenomenon could be explained more precisely by making nonlinear model analysis of the electronic ballast.

Table 7.4 gives a comparison of power factor for reduced and rated supply voltage for electronic and magnetic fluorescent lighting systems. At stable discharge voltage, power factor is almost the same for electronic and magnetic ballast lighting systems. In some cases, electronic ballast has higher power factor (0.99) than magnetic ballast (0.96). However, for rated supply voltage electronic ballasts have slightly better power factor (0.99) than magnetic ballasts.

Table 7.4 Impact of Reduced Supply Voltage on 48" Fluorescent Lamps

Lamp Parameters	Std. MB T-12	ES1 MB T-12	ES2 MB T-12	ES2 MB T-8	EB1 T-8	EB2 T-8	EB3 T-8	EB4 T-8
Starting Voltage with Flicker	85.0	80.0	75.0	100.0	65.0	70.0	65.0	85.0
Voltage at Stable Discharge	95.0	85.0	80.0	105.0	75.0	75.0	80.0	100.0
Rated Voltage	120	120	120	120	120	120	120	120
THD (%) at Flicker	17.0	15.0	14.0	29.0	20.0	25.7	31.3	25.4
THD (%) at Stable Discharge	21.5	32.2	18.4	15.6	8.15	9.70	12.8	11.2
THD (%) at rated Voltage	20.4	32.6	7.00	11.5	11.2	12.4	14.0	11.0
Power (Watts) at Flicker	7.80	6.50	5.80	33.0	2.20	2.00	1.80	13.5
Power (Watts) at Stable Discharge	79.0	54.0	37.0	71.0	33.0	34.0	32.5	43.0
Power (Watts) at Rated Voltage	100.0	82.0	74.0	82.0	60.0	60.0	62.0	63.0
Power Factor at Flicker	0.61	0.69	0.79	0.73	0.54	0.47	0.35	0.80
Power Factor at Stable Discharge	0.97	0.94	0.94	0.93	0.92	0.95	0.88	0.99
Power Factor at Rated Voltage	0.97	0.93	0.97	0.96	0.98	0.97	0.98	0.99

7.7.3 Analysis of Electronic and Magnetic Compact Fluorescent Lamps

Table 7.5 gives a comparison of electronic and magnetic compact fluorescent lamps (CFL) under reduced voltage conditions. There are six electronic CFLs and one magnetic CFL included in this analysis. Electronic CFLs are that of different models and power rating. Minimum supply voltage required to fire a magnetic CFL is 100 volt. While all models of electronic CFL fires at supply voltage between 60 and 90 volts. Magnetic CFL fires at reduced voltage with an annoying flicker and it keeps flickering at the 100 volt supply voltage. The electronic CFLs fire with time delay of few seconds. There is no flicker, but in some cases the discharge is uneven. At 110 volt, magnetic CFL has less flicker and lamp discharge is stabilized. All model of electronic CFLs has stable discharge at voltage as low as 65 volt and the glow even throughout the lamp discharge tube. Hence the electronic CFLs have much better performance at reduced voltage as compared to magnetic CFLs.

Magnetic CFL has lower BEF and has more heat losses in the ballast as compared to electronic CFLs. Due to space constraints, it is difficult to include power factor correction capacitors in magnetic ballasts. Hence the power factor of magnetic CFLs is very low as compared to new design of electronic CFLs. However, in all cases, both electronic and magnetic CFLs, power factor at reduced supply voltage is better than the power factor at rated supply voltage.

It was also noted during this course of study that in case of some models of electronic CFLs a reduced voltage less than the minimum voltage mentioned in Table 7.5, for an extended period could damage the lamp. While the magnetic ballast simply does not fire at voltage less than 100 volts. However, it is very rare that supply system has a low voltage less than 65 volts. Most of the manufacturers of electronic CFLs warn to not to use with dimmer circuits.

7.5 Impact of Reduced Supply Voltage on Compact Fluorescent Lamps

Lamp Parameters	Magnetic CFL	Electronic CFL1	Electronic CFL2	Electronic CFL3	Electronic CFL4	Electronic CFL5	Electronic CFL6
Voltage at Flicker	100	75.0	60.0	60.0	75.0	65.0	90.0
Voltage at Stable Discharge	110.0	80.0	65.0	70.0	80.0	70.0	95.0
Rated Voltage	120	120	120	120	120	120	120
THD at Flicker	22	85	109	110	15.5	10.8	28.0
THD (%) at Stable Discharge	13.5	108	111	113	17.5	14.8	27.0
THD (%) at rated Voltage	9.90	115	117	120	26.6	25.6	9.50
Power (Watts) at Flicker	6.1	11.3	5.30	4.40	11.4	8.00	13.1
Power (Watts) at Stable Disch.	8.80	9.30	5.70	5.10	12.4	8.90	15.0
Power (Watts) at Rated Voltage	11.0	15.0	10.1	8.50	18.5	15.0	17.0
Power Factor at Stable Disch.	0.60	0.58	0.58	0.57	0.97	0.99	0.95
Power Factor at Rated Voltage	0.54	0.57	0.57	0.56	0.96	0.94	0.98

7.7.4 Methodology to Investigate Fluorescent Lamps at Varying Frequency of Supply Voltage

The methodology provides a systematic procedure of analyzing fluorescent lamp under varying frequency conditions. Power supply frequency was varied from 59 Hz to 61 Hz to test the fluorescent lamps designed for 60 Hz supply voltage. *PACIFIC* AC Power Analyzer was used to supply variable frequency voltage to the fluorescent lamp. Power supply frequency was varied from 59 Hz to 61 Hz with steps of 0.2 Hz. Lamp parameters (THD, Power, Power Factor, etc.) were measured using **Voltech** Universal Power Analyzer. The analysis procedure is given in the following:

1. Each fluorescent lamp was tested for a frequency range of 59 - 61 Hz in steps of 0.2 Hz. The lamps were tested for minimum supply voltage that stabilizes the lamp discharge, the rated and the over voltage. To test the lamp for over voltage the supply was increased to 130 Volts.

2. Each lamp was tested for THD at stable, rated and over voltage with prescribed frequency variation. Electronic CFL was compared with magnetic CFL and electronic ballast T-8 fluorescent was compared with magnetic ballast T-12 fluorescent lamp for harmonic impact in frequency range 59 Hz to 61 Hz.

3. Impact of frequency variation on power consumption and power factor of compact CFL and 48" fluorescent lamps was studied. Magnetic CFL was compared with electronic CFL and magnetic ballast

7.7.5 Impact of Varying Frequency on Compact Fluorescent Lamp

Table 7.6 shows the analysis of a typical new design of electronic CFL in a power frequency range 59 Hz to 61 Hz. Table 7.7 gives same type of analysis of full size fluorescent lamps. Electronic CFL has no significant impact of frequency variation on THD of the lamp in the above mentioned frequency range. However, frequency variation cause fluctuation in THD of the magnetic CFL. Table 7.7 shows that THD of magnetic CFL fluctuate between 10.7-11.4, 9.5-10.1, and 10.7-11.1 at stable, rated and over voltage respectively.

There is no significant impact of frequency variation on power consumption of electronic CFL within 59 Hz to 61 Hz of supply voltage. Due to frequency variation, there is a slight decrease in power consumption of magnetic CFL with the increase of supply frequency. This reduction in power consumption in magnetic CFL can be explained by the following relationship:

$$Z = j2\pi fL$$

Where Z is impedance of the magnetic core, f is frequency of supply voltage, and L is inductance of magnetic core in magnetic CFL. The above relationship shows that impedance of magnetic CFL is directly proportional to the frequency of the supply voltage. Hence the lamp draws more current that increases the power consumption in the lamp.

Table 7.6 Impact of Varying Frequency on the Electronic Compact Fluorescent Lamps

Lamp Parameters	61.0 Hz	60.8 Hz	60.6 Hz	60.4 Hz	60.2 Hz	60.0 Hz	59.8 Hz	59.6 Hz	59.4 Hz	59.2 Hz	59.0 Hz
Stable Discharge. Voltage	65	65	65	65	65	65	65	65	65	65	65
Rated Voltage	120	120	120	120	120	120	120	120	120	120	120
Over Voltage	130	130	130	130	130	130	130	130	130	130	130
THD (%) at Stable Discharge	16.6	16.6	16.7	16.6	16.6	16.6	16.6	16.8	16.8	16.8	16.8
THD (%) at rated Voltage	27.5	27.5	27.5	27.4	27.6	28.0	28.0	27.6	27.6	27.6	27.6
THD (%) at Over Voltage	22.0	22.0	22.0	22.0	22.0	22.0	22.0	22.0	22.0	22.0	22.0
Power(Watts) at Stable Discharge	8.1	8.1	8.1	8.1	8.1	8.1	8.1	8.1	8.2	8.2	8.2
Power(Watts) at 120 Voltage	14.4	14.4	14.4	14.4	14.4	14.4	14.4	14.4	14.4	14.4	14.4
Power at Over Voltage	15.7	15.7	15.7	15.7	15.7	15.7	15.7	15.7	15.7	15.7	15.7
P F at Stable Discharge	0.983	0.983	0.983	0.983	0.983	0.983	0.983	0.983	0.983	0.983	0.983
P F at Rated Voltage	0.954	0.954	0.954	0.954	0.954	0.954	0.954	0.954	0.954	0.954	0.954
P F at Over Voltage	0.966	0.966	0.966	0.966	0.966	0.966	0.967	0.967	0.967	0.967	0.967

Table 7.7 Impact of Varying Frequency on the Magnetic Compact Fluorescent Lamps

Lamp Parameters	61.0 Hz	60.8 Hz	60.6 Hz	60.4 Hz	60.2 Hz	60.0 Hz	59.8 Hz	59.6 Hz	59.4 Hz	59.2 Hz	59.0 Hz
Stable Discharge. Voltage	100	100	100	100	100	100	100	100	100	100	100
Rated Voltage	120	120	120	120	120	120	120	120	120	120	120
Over Voltage	130	130	130	130	130	130	130	130	130	130	130
THD (%) at Stable Discharge	18.6	18.6	18.5	18.7	19.0	19.0	19.0	19.0	18.5	18.5	18.5
THD (%) at rated Voltage	11.0	11.4	10.8	10.8	10.8	10.7	10.7	10.8	10.8	10.9	10.9
THD (%) at Over Voltage	9.9	9.9	9.8	10.0	10.1	9.8	10.0	9.5	9.5	9.5	9.5
Power(Watts) at Stable Discharge	6.3	6.3	6.3	6.2	6.4	6.4	6.4	6.4	6.5	6.5	6.5
Power(Watts) at 120 Voltage	10.7	10.8	10.9	11.0	11.0	11.0	11.0	11.0	11.1	11.1	11.1
Power at Over Voltage	12.7	12.8	12.9	13.0	13.1	13.1	13.2	13.1	13.2	13.2	13.3
P F at Stable Discharge	0.660	0.660	0.659	0.659	0.659	0.656	0.658	0.660	0.660	0.660	0.660
P F at Rated Voltage	0.554	0.553	0.552	0.549	0.544	0.542	0.541	0.543	0.547	0.546	0.546
P F at Over Voltage	0.513	0.512	0.508	0.510	0.515	0.508	0.510	0.506	0.501	0.498	0.497

Power factor of electronic CFL remains constant at all voltage levels in the frequency range shown in Table 7.6. Power factor of the magnetic ballast does not has any well defined impact of frequency variation. However, it keeps fluctuating between 0.656-0.660, 0.541-0.554, and 0.497-0.515 for stable, rated and over voltage respectively.

7.7.6 Impact of Varying Frequency on Full Size Fluorescent Lamp

Analysis of electronic and magnetic ballast fluorescent lamp for frequency variation is shown in Table 7.8 and Table 7.9. All the measurements are made for stable, rated, and over voltage in frequency range 59 Hz to 61 Hz. Both type of lamps are compared for THD, power consumption, and power factor with the help of above mentioned tables. Electronic ballast T-8 lamp does not have any impact of frequency variation on THD in the range 59 Hz to 61 Hz for stable discharge voltage. For the rated and over voltage there is some decrease in THD of the electronic ballast while going from 59 Hz to 61 Hz. Table 7.8 shows that impact of frequency variation becomes more significant with the increase of supply voltage. Magnetic ballast also has the same pattern of impact of frequency variation on THD as the electronic ballast. Table 7.9 shows that impact of frequency variation on THD of magnetic ballast becomes significant at higher supply voltage.

Table 7.8 shows that there is no significant impact of frequency variation on power consumption of electronic ballast at stable discharge voltage. At rated and over voltage, there is slight reduction in power consumption with the increase in frequency of supply voltage. The reduction in power consumption can be explained with impedance analysis of electronic ballast that is beyond the scope of this work. However, it is shown in the Table 7.8 that reduction in power consumption is visible at higher supply voltages. In magnetic ballasts, reduction in power consumption with increasing frequency is more

pronounced than electronic ballast. Magnetic ballast mainly consists of magnetic core and power factor correction capacitor. Impedance relationship can be written as:

$$Z = j\frac{2\pi fL}{1 - 4\pi^2 f^2 LC}$$

Where Z is impedance of magnetic ballast, f is frequency of supply voltage, L is inductance of the magnetic core, and C is the capacitance of power factor correction capacitor. The above relationship reduces the impedance with the increase of frequency hence the ballast draws more current and increase power consumption in the ballast. However, power consumption for the above frequency range increases with the increase of supply voltage.

In case of the electronic ballast, power factor remains almost constant in the frequency range shown in Table 7.8. There is slight reduction in power factor at a voltage lower than the rated voltage. As shown in Table 7.9, the magnetic ballasts have small decrease in power factor at rated and higher voltages with the reduction in the frequency of supply voltage. Factors that can contribute to the reduction in the power factor are (i) magnitude of the current, (ii) phase shift between voltage and current, and (iii) current total harmonic distortions. Impedance measurements show that in frequency range of 61 to 59 Hz, the magnetic CFL has impedance drop of 27 and 30 ohms at 120 and 130 volt respectively. The lower impedance draws more current and contributes to the reduction in power factor. For magnetic CFL, THD is increasing with decrease in frequency of the supply voltage.. The increase in THD distortion also contributes to the reduction in the power factor.

Table 7.8 Impact of Varying Frequency on Electronic Ballast 48" T-8 Fluorescent Lamps

Lamp Parameters	61.0 Hz	60.8 Hz	60.6 Hz	60.4 Hz	60.2 Hz	60.0 Hz	59.8 Hz	59.6 Hz	59.4 Hz	59.2 Hz	59.0 Hz
Stable Discharge. Voltage	50	50	50	50	50	50	50	50	50	50	50
Rated Voltage	120	120	120	120	120	120	120	120	120	120	120
Over Voltage	130	130	130	130	130	130	130	130	130	130	130
THD (%) at Stable Discharge	9.4	9.4	9.5	9.4	9.5	9.4	9.4	9.4	9.5	9.4	9.5
THD (%) at rated Voltage	12.9	12.9	13.0	13.0	13.1	13.2	13.3	13.3	13.4	13.5	13.6
THD (%) at Over Voltage	13.5	13.6	13.7	13.8	13.9	14.1	14.2	14.3	14.3	14.4	14.5`
Power(Watts) at Stable Discharge	12.8	12.8	12.8	12.8	12.9	12.9	12.8	12.9	12.9	12.9	12.9
Power(Watts) at 120 Voltage	60.5	60.4	60.3	60.3	60.3	60.3	60.2	60.2	60.2	60.2	60.1
Power at Over Voltage	65.4	65.4	65.2	65.1	65.1	65.1	65.0	64.9	64.9	64.9	64.8
P F at Stable Discharge	0.945	0.946	0.946	0.947	0.948	0.948	0.948	0.949	0.950	0.951	0.951
P F at Rated Voltage	0.991	0.991	0.991	0.991	0.991	0.991	0.991	0.991	0.990	0.990	0.99
P F at Over Voltage	0.990	0.990	0.990	0.990	0.990	0.989	0.989	0.989	0.988	0.988	0.988

Table 7.9 Impact of Varying Frequency on Magnetic Ballast 48" T-12 Fluorescent Lamps

Lamp Parameters	61.0 Hz	60.8 Hz	60.6 Hz	60.4 Hz	60.2 Hz	60.0 Hz	59.8 Hz	59.6 Hz	59.4 Hz	59.2 Hz	59.0 Hz
Stable Discharge. Voltage	80	80	80	80	80	80	80	80	80	80	80
Rated Voltage	120	120	120	120	120	120	120	120	120	120	120
Over Voltage	130	130	130	130	130	130	130	130	130	130	130
THD (%) at Stable Discharge	17.5	17.5	17.6	17.5	17.6	17.6	17.6	17.6	17.5	17.7	17.7
THD (%) at rated Voltage	7.5	7.5	7.6	7.9	7.9	7.9	8.0	8.3	8.3	8.5	8.5
THD (%) at Over Voltage	7.0	7.0	7.2	7.3	7.4	7.7	7.8	7.8	8.0	8.0	8.0
Power(Watts) at Stable Discharge	38.0	38.0	38.3	38.3	38.5	38.5	38.6	38.7	38.8	38.9	39.1
Power(Watts) at 120 Voltage	74.1	73.6	73.2	72.8	72.4	72.0	71.6	71.2	70.8	70.4	70.1
Power at Over Voltage	78.4	78.0	77.6	77.2	76.8	76.4	76.0	75.6	75.2	74.9	74.5
P F at Stable Discharge	0.943	0.947	0.948	0.949	0.950	0.950	0.951	0.951	0.950	0.950	0.950
P F at Rated Voltage	0.990	0.989	0.987	0.987	0.986	0.985	0.984	0.983	0.982	0.981	0.970
P F at Over Voltage	0.978	0.976	0.975	0.973	0.971	0.969	0.967	0.965	0.963	0.960	0.958

7.8 Summary

Energy efficient lighting technologies (e.g. compact fluorescent lamps, electronic ballast T-8 lamps and tungsten halogen lamps) offer significant energy and peak saving as well as pollution mitigation opportunities. However, they have certain drawbacks in terms of lower color rendering indices, harmonics and lower power factors. It is shown that by carefully selecting the mix of different lighting technologies for the type of application necessary, it is possible to minimize the aggregate impact of their undesirable characteristics.

Energy savings and environmental benefits of high efficacy fluorescent lamps are reality of life. Electric utilities are relying on energy efficient lighting programs to postpone or delay their future capacity addition. However, the growing proliferation of nonlinear loads is offering a new challenge for electric utilities. There is much work ahead to completely understand harmonic interaction between nonlinear loads in general and lighting and power supply loads in particular. This understanding about the harmonic distortion, summation, cancellation and mitigation is very much required to comprehend the impact of energy efficient lighting devices on the utility system in the presence of other type of nonlinear loads. Any technique to reduce harmonic distortion level through their mutual cancellation will help to reap the energy conservation and environmental benefits of high efficacy lighting technologies.

Analysis of fluorescent lamps at varying frequency and supply voltage shows that the electronic CFLs and electronic ballast fluorescent lamps are more reliable and efficient than their magnetic counter parts.

CHAPTER VIII

CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

An exhaustive study of the energy efficient lighting technologies has been conducted during this research. This has been a necessary step towards the evaluation of benefits and issues related to these technologies. Moreover, it determined the direction in which this research can contribute to the solution of the problem of harmonic distortions. Through this comprehensive study, it has been found that higher THD of individual lighting products do not automatically mean a higher THD impact at system level. Even though such information is important in initial screening of energy efficient devices,a complete harmonic spectrum of the current drawn by these devices provides more comprehensive picture of the harmonic characteristics of these technologies. Barriers and obstacles in the procurement of these technologies have been detailed during this research. Generally speaking, manufacturers have been found to be cooperative in passing on necessary information and the hardware required for the research. This is very encouraging in pursuing further research and development in this area.

This study has presented a survey of major energy efficient technologies. Adjustable speed drives and energy efficient lighting devices were found to be having

largest potential of energy savings and environmental benefits. It was discovered that the developments in the energy efficient lighting technologies are superseding that of the adjustable speed drives. From the power quality point of view, state-of-the-art lighting devices are less problematic than the adjustable speed drives. Some of the lighting devices tested in the laboratory have total harmonic distortions as low as 10 percent. Whereas the manufacturers of adjustable speed drives are still struggling to reduce the harmonic impact of their products at system level. Moreover, the energy efficient lighting technologies have higher potential of energy savings, environmental protection and capacity reduction and less power quality impact on the system.

This research provides an insight into the harmonic interaction problem. The state-of-the-art lighting technologies were tested for the harmonic generation, interaction, and cancellation at the building level. Results show that the individual harmonic frequencies generated from different sources do not have the same harmonic impact at the system level. The lower order triplens are the most problematic for their system level impact. Findings of the study show that the harmonic profile of a particular device or equipment provides a more comprehensive information than the total harmonic distortion.

A methodology was designed to evaluate energy efficient lighting technologies for their performance, power quality and environmental impacts. It was found that the energy savings and environmental benefits can be calculated from the manufacturers data by using a simplistic approach. Most of the new models of energy efficient technologies have power factor as high as 0.99. There is no significant loss of real power and all energy savings of individual lighting fixtures shall be reflected at the system level.

The methodology provides a generic algorithm to select energy efficient lighting technologies for their minimum impact of total harmonic distortions at the system level. It is shown that by carefully selecting the mix of different lighting technologies for

certain applications, it is possible to minimize the aggregate impact of their undesirable characteristics. It was found that some combinations of energy efficient lighting technologies have their minimum harmonic impact on the system, although the individual total harmonic distortion of the lighting technologies in the combination have relatively high total harmonic distortion. Results show that the energy efficient lighting technologies (e.g. compact fluorescent lamps, electronic ballast T-8 lamps and tungsten halogen lamps) offer significant energy and peak saving as well as pollution mitigation opportunities.

It is known that many electric utilities around the world operate at below the rated voltage to reduce the electricity demand during the peak hours and times of insufficient generation. Similarly, some utilities operate their generation units at higher than the rated frequency to cope with emergency situations such as loss of generation unit. Performance analysis of lighting technologies shows that the electronic ballasts have superior performance than the magnetic ballasts under varying voltage and frequency conditions. Most of the electronic ballasts can operate at a voltage as low as 65 volt without any visual discomfort. Whereas, magnetic ballasts have visible flicker at the supply less than the rated voltage. Moreover, magnetic ballasts generate annoying noise and more distortions while operating at low voltages. At higher frequencies magnetic ballasts show significant increases in power consumption. Electronic ballasts have no significant impact of frequency variation on harmonic distortions, power factor and power consumption.

8.2 Recommendations

The proposed algorithm for selection of energy efficient lighting technologies for minimizing total harmonic distortion has provided a valuable tool in screening the use of these technologies. There is a significant potential of increasing the scope of the

algorithm. The algorithm can be extended for evaluation of energy savings, environmental benefits, power factor, THD, and cost effectiveness. As the harmonic characteristics of most of energy efficient technologies operated with electricity are identical, the algorithm may be extended to the non-lighting energy efficient technologies also. Most important among these are adjustable speed drives. Followings are some of the more specific topics where research in this area could be extended:

- It has been pointed out in this study that harmonic profiles of the current drawn by harmonic loads provide more comprehensive knowledge than just a number showing the so-called THD value, because each category of the harmonic frequencies has unique impact on the system. For example, zero sequence harmonics cause more damage to the system by adding up in the neutral wire of the three phase four wire system. Hence it will be a beneficial to study the implications of making it mandatory for manufacturers of electrical equipment and instruments to provide harmonic profile of the current drawn by them.

- There are many factors that influence the real spectrum of harmonic current profile. For example, the precision of the equipment used to measure harmonic current profile. Another important factor is the ambient harmonics in the supply system that can increase the level of harmonics of the current profile and many other factors. Hence it is required to set the standard procedure to capture the harmonic profile of current drawn by electrical loads.

- As mentioned in this research that there are many conclusions that one can draw by just having a look of the harmonic profile. For example, the current flowing in the neutral wire, harmonics that will cancel in a three phase system, etc. Hence a comparative study of harmonic current profile versus total harmonic distortions

will be helpful to persuade the professional bodies to develop harmonic profile standards.

REFERENCES

[1]   C. Eley, "Advanced Lighting Guidelines: 1993," *EPRI TR-101022, R1 Research Project 2285-26*, Final Report, May 1992.

[2]   E. Mills, "Efficient Lighting Programs in Europe: Cost Effectiveness, Consumer Response, and Market Dynamic," *Energy(Oxford)*, Vol. 18, No. 2, 1993, pp 131-144

[3]   Hubbell Lighting, "Commercial and Industrial Fluorescent Products: Electronic Capabilities," *Product Bulletin*, 2000 Electric Way, Christiansburg, Virginia, 1991.

[4]   A. Gough, "Survey and Forecast of Marketplace Supply and Demand for Energy-Efficient Lighting Products," *EPRI TR-100288, Project 2418-09*, December 1992.

[5]   R. S. Bergman, "Halogen-IR Lamp Development: A System Approach," *Journal of the Illuminating Engineering Society*, Vol. 20, No. 2, Summer 1991, pp. 10-16

[6]   H. Kostlin and G. Frank, "Thin-Film Reflection Filters," *Philips Res. Reports*, Vol. 41, 1983, 225p

[7]   R. S. Bergman and T. G. Parham, "Applications of Thin Film Reflecting Coating Technology to Tungsten Filament Lamps," *IEE PROCEEDINGS-A*, Vol. 140, No. 6, November 1993, pp. 418-428

[8]   L. E. Hogeler and T. K. McGowan, "Practical High Efficiency Tungesten-Halogen Lamps Using IR Reflecting Films," *Journal of the Illuminating Engineering Society*, Vol. 14, No. 1, October 1984.

[9]   K. Fischer, "Inductive Load Made Lighter: Dimmer IC SLB 0587 Controls Low Voltage Halogen Lamps from Power Transformer," *Seimens Components*, Vol. 28, No. 2, March 1993, pp. 23-26

[10]   D. A. McIntyre, W. N. Charman, and I. J. Murray, "Visual Safety of Quartz Linear Lamps," *The Annals of Occupational Hygiene*, Vol. 37, No. 2, April 1993, pp. 191-200

[11]   R. S. Bergman, T. G. Parham, and T. K. McGowan, "UV Emission from General Lighting Lamps," *Proceeding of 1994 IESNA Annual Conference*, August 7-11, 1994, pp. 687-720

[12]   E. Mills and M. A. Piette, "Advanced Energy Efficient Lighting Systems: Progress and Potential," *Energy(Oxford)*, Vol. 18, No. 2, 1993, pp. 75-97

[13]   J. B. Murdoch, "Illumination Engineering: From Edison's Lamp to the Laser," *Macmillan Publishing Co.*, New York, 1985.

[14]   J. B. Neilson and B. N. Crocker,"U V Aging of Fluorescent Reflectors," *Proceedings of the 1993 IEEE Industry Application Society Annual Meeting*, Vol. III, pp. 2348-2350

[15]   D.K. Tiller, R. R. Jaekel, and K. M. Chan, "Performance of Selected Fluorescent Lighting Products," *Proceedings of the 1992 IEEE Industry Application Society Annual Meeting*, Vol. II, pp. 1900-1907

[16]   L. Lamarre, "Shedding Light on the Compact Fluorescent," *EPRI Journal*, March 1993, pp.23-27

[17]   S.K. Biswas and R. P. Dhanuka, "Reliability of Electronic Ballasts in Industrial Fluorescent Light Applications," *Proceedings of the 1992 IEEE Industry Application Society Annual Meeting*, Vol. II, pp. 1915-1919

[18]   V.A. Godyak, R.B. Piejak, and B.M. Alexandrovich, "Electrical and Light Characteristics of RF-Inductive Fluorescent Lamps," *Journal of the Illuminating Engineering*, Vol. 23, No. 1, Winter 1994, pp. 40-44

[19]   U. Mader and Dr. P. Horn, "A Dynamic Model For The Electrical Charactristics of Fluorescent Lamps," *Proceedings of the 1992 IEEE Industry Application Society Annual Meeting*, Vol. II, pp. 1928-1934

[20]   A. Heidemann, S. Hien, E. Panofski, and U. Roll, "Compact Fluorescent Lamps," *IEE PROCEEDINGS-A*, Vol. 140, No. 6, November 1993, pp. 429-434

[21]   J. A. Love, "Field Performance of Compact Fluorescent Systems," *Proceedings of the 1993 IEEE Industry Application Society Annual Meeting*, Vol. III, pp. 2254-2259

[22]   M. Siminovitch, "Veriation in Convective Venting to Increase the Efficiency of Compact Fluorescent Lamp", *Proceedings of the 1993 IEEE Industry Application Society Annual Meeting*, Vol. III, pp. 2260-2265

[23]   M. Siminovitch, "Dirt Depriciation of Compact Fluorescent Lamp Downlight," *Proceedings of the 1993 IEEE Industry Application Society Annual Meeting*, Vol. III, pp. 2272-2273

[24]   Chr. Meyer and H. Nienhuis, "Discharge Lamps," *Kluwer Technische B. V., Deventer*, 1988.

[25]   H. B. Zackrison, Jr, "Lighting Energy Conservation and Management," *Proceedings of Interscociety Energy Conversion Engineering Conference*, Vol. 5, August 1992, pp. 5.139-5.148

[26]   J. Wellinghoff, "Winning the Lighting Retrofit Game," *Electrical Construction and Maintenance*, May 1993, pp. 65-75

[27]   J. J. de Groot and H. Houkes, "Triple-U Electronic Compact Fluorescent Lamps with Reduced Harmonics," *Journal of the Illuminating Engineering*, Vol. 23, No. 1, Winter 1994, 45-51

[28]   C. R. Sullivan and A. C. Drescher, "Influence of On-Time and Use Frequency on Cost-Effectiveness of Compact Fluorescent Lamps," *Proceedings of the 1993 IEEE Industry Application Society Annual Meeting*, Vol. III, pp. 2283-2290

[29]   R. S. Abesamis, P. Black, and J. Kessel, "Field Experience with High-Frequency Ballasts," *IEEE Transactions on Industry Applications*, Vol. 26, No. 5, September/October 1990, pp. 810-811

[30]   G. D. Garbowicz, "An Improved Hybrid Fluorescent Lamp Ballast," *Journal of the Illuminating Engineering Society*, Vol. 21, No. 2, Summer 1992, pp. 42-45

[31]   G. D. Garbowicz, "Hybrid Ballast II: High-Efficiency-Type Ballasts for 32-W T8 and 34-W T/12 Lamp Systems," *Journal of the Illuminating Engineering Society*, Vol. 23, No. 1, Winter 1994, pp. 22-30

[32]   E. J. P. Mascarenhas, "Application of Electronic Circuits in Lighting," *IEE PROCEEDINGS-A*, Vol. 140, No. 6, November 1993, pp. 435-442

[33]   C. Licitra, "Single-Ended Soft-Switching Electronic Ballast with Unity Power Factor," *Proceedings of the 1991 IEEE Industry Application Society Annual Meeting*, Vol. I, pp. 953-958

[34]   A. Okude, A. Ueoka, Y. Kambara, and M. Mitani, "Development of an Electronic Dimming Ballast for Fluorescent Lamps," *Journal of the Illuminating Engineering Society,* Vol. 21, No. 1, Winter 1992, pp. 15-21

[35]   K. E. Yarnell, "The Switch Is On To Electronic Ballast," *Consulting-Specifying Engineer,* April 1993, pp. 52-56

[36]   Electronic Ballast Technology, Inc., "Winning Technology-Saving Energy & Environment, 2510 W. 237th Street, Torrance, CA 1993.

[37]   D. Tadesse, F. P. Dawson, and S. B. Dewan, "A Comparison of Power Circuit Topologies and Control Techniques for a High Frequency Ballast," *Proceedings of the 1993 IEEE Industry Application Society Annual Meeting,* Vol. III, pp. 2341-2347

[38]   M. Gulko and S. Ben-Yaakov, "Current-Sourcing Push-Pull Parallel-Resonance Inverter (CS-PPRI): Theory and Application as a Fluorescent Lamp Driver," *Proceedings of the 1993 IEEE 8th Applied Power Electronic Conference,* pp. 411-417

[39]   M. C. Cosby and R. M. Nelms, "Designing a Parallel-Loaded Resonant Inverter for an Electronic Ballast Using the Fundamental Approximation," *Proceedings of the 1993 IEEE 8th Applied Power Electronic Conference,* pp. 418-423

[40]   M. Jordan, J. A. O'Connor, "Resonant Fluorescent Lamp Converter Provides Efficient and Compact Solution," *Proceedings of the 1993 IEEE 8th Applied Power Electronic Conference,* pp. 424-431

[41]   J. M. Alonso, et al., "A Smart-Lighting Emergency Ballast for Fluorescent Lamps Based on Microcontroller," *Proceedings of the 1993 IEEE 8th Applied Power Electronic Conference,* pp. 549-555

[42]   J. M. Moravek and C. Gallina, "What To Ask About Electronic Ballasts," *Electrical Construction and Maintenance,* June 1993, pp. 55-61

[43]   D. P. Masher and J. S. Smith, "Impact of Advanced Power Semiconductor Systems on Utilities and Industry," *EPRI EM-2112 Research Project 1201-12,* Final Report, November 1981.

[44]   P. T. Stone, "Fluorescent Lighting and Health," *Lighting Research & Technology,* Vol. 24, No. 2, 1992, pp.55-62

[45]   P. Melancon and J. Lebel, "Effects of Fluorescent Lights on Signal Fading Characteristics for Indoor Radio Channels," *Electronics Letters,* Vol. 28, No. 18, 1992, pp. 1740-1741

[46]   A. J. Wilkins, "Health and Efficiency in lighting Practice," *Energy(Oxford),* Vol. 18, No. 2, 1993, pp 131-144

[47]   M. Ouellette, "The Effect of Temprature on Starting and Stabilization of Compact Fluorescent Systems," *Proceedings of the 1993 IEEE Industry Application Society Annual Meeting,* Vol. III, pp. 2238-2244

[48]   A. Laperriere and R. Martel, "Performance of Compact Fluorescent Lamps in Exterior Lighting Fixtures at Cold Temprature," *Proceedings of the 1993 IEEE Industry Application Society Annual Meeting,* Vol. III, pp. 2305-2308

[49]   E. V. Clancy, "Thermal Characterizati-on of Fluorescent Fixtures," *Proceedings of the 1993 IEEE Industry Application Society Annual Meeting,* Vol. III, pp. 2331-2333

[50]   D. S. P. Li, "Computer-Aided Lamp Temprature Measuring Apparatus and Maximum Lamp Profile Temprature," *Proceedings of the 1993 IEEE Industry Application Society Annual Meeting,* Vol. III, pp. 2351-2357

[51]   A. W. Serres and W. Taelman, "Amalgams and Compact Fluorescent Lamps," *Proceedings of the 1993 IEEE Industry Application Society Annual Meeting,* Vol. III, pp. 2341-2347

[52]   S. A. Kalinowsky, J. J. Martello, A. K. Yee, and M. Forte, "Harmonic Content and Illumination Characteristics verses Voltage for Energy Saving Fluorescent Lighting Systems," *Proceedings of the 1991 IEEE Industry Application Society Annual Meeting,* Vol. II, pp. 1820-1827

[53]   N. Grimshaw, "A Review of the Canadian Standards Association C22.2#0.16 Standard on the Measurement of Harmonic Currents and the Rational Used in its Development," *Proceedings of the 1991 IEEE Industry Application Society Annual Meeting,* Vol. II, pp. 1828-1832

[54]   T. Jednacz, "Power Quality Design Implications of High Frequency Lighting Ballasts and Control," *Proceedings of the 1991 IEEE Industry Application Society Annual Meeting,* Vol. II, pp. 1833-1835

[55] J. J. Spangler, "Power Factor Correction Techniques Used For Fluorescent Ballasts," *Proceedings of the 1991 IEEE Industry Application Society Annual Meeting,* Vol. II, pp. 1836-1842

[56] S. Datta, "Power Pollution Caused by Lighting Control Systems," *Proceedings of the 1991 IEEE Industry Application Society Annual Meeting,* Vol. II, pp. 1842-1852

[57] R. Verderber, "Harmonics From Compact Fluorescent Lamps," *Proceedings of the 1991 IEEE Industry Application Society Annual Meeting,* Vol. II, pp. 1853-1858

[58] R. Christiansen, "Effects of High Levels of Harmonics from Lighting Equipment and Systems," *Proceedings of the 1991 IEEE Industry Application Society Annual Meeting,* Vol. II, pp. 1859-1862

[59] R. Zavadil, "Assessing The Impacts of Nonlinear Loads on Power Quality in Commercial Buildings - An Overview," *Proceedings of the 1991 IEEE Industry Application Society Annual Meeting,* Vol. II, pp. 1863-1869

[60] F. V. Topalis, "Efficiency of Energy Saving Lamps and Harmonic Distortion in Distribution Systems," *IEEE Power Engineering Society Meeting, Columbus, OH, January 31 - February 5,* 1993, 7p

[61] A. Domijan, G. T. Heydt, A. P. S. Meliopoulos, S. S. Venkata, and S. West, "Directions of Research on Electric Power Quality," *IEEE Transactions on Power Delivery,* Vol. 8, No. 1, January 1993, pp. 429-436

[62] A. T. De Almeida, "Overcoming Problems With Harmonics and Low Power Factors," *Energy(Oxford),* Vol. 18, No. 2, 1993, pp 99-106

[63] D. J. Pileggi, E. M. Gulachenski, C. E. Root, T. J. Gentile, and A. E. Emanuel, "The Effect Of Modern Compact Fluorescent Lights On Voltage Distortion," *IEEE Transactions on Power Delivery,* Vol. 8, No. 3, July 1993, pp. 1451-1457

[64] W. K. E. Osterhaus and I. L. Bailey, "Large Area Glare Sources and Their Effect on Visual Performance at Computer Workstations," *Proceedings of the 1992 IEEE Industry Application Society Annual Meeting,* Vol. II, pp. 1825-1829

[65] Philips Lighting Handbook, *Philips Lighting Company,* 1984.

[66] C. Eley, "Advanced Lighting Guidelines: 1990," *EPRI TR-101022,* Research Project 2285-26, Final Report, September 1992.

[67] " The Low Pressure Sodium Lamp," *IES Lighting Review,* Vol. 41, No. 4, August 1979, pp. 99-101

[68] S. Wada and K. Tanigawa, "A Mathematical Model for the Starting Process of Discharge Lamps," *Journal of the Illuminating Engineering Institute of Japan,* Vol. 65, No. 10, October 1981, pp. 473-477

[69] L. Di Fraia, "A method to Achieve Continuous Dimming of Low Pressure Sodium and Other Gas Discharge Lamps," *Journal of the Illuminating Engineering Society,* Vol. 10, No. 4, July 1981, pp. 245-52

[70] J. W. Denneman,Jr, "Low-Pressure Sodium Discharge Lamps," *IEE Proceedings,* Vol. 128, Pt. A, No. 6, September 1981, pp. 397-414

[71] R. A. Hargroves, "Road Lighting," *IEE Proceedings,* Vol. 130, Pt. A, No. 8, November 1981, pp. 420-441

[72] J. J. de Groot, A. G. Jack, and H. Coenen, "High Frequency Operation of Low Sodium Lamps," *Journal of the Illuminating Engineering Society,* Vol. 13, No. 5, October 1984, pp. 188-210

[73] L. Sprengers, R. Campbell, and H. Kostlin, " Low Pressure Sodium Lamps with a Luminous Efficacy of 200 lm/W," *Journal of the Illuminating Engineering Society,* Vol. 14, No. 2, April 1983, pp. 607-615

[74] S. Roy Chowdhury, "Low Pressure Sodium Vapour Lamps and Their Application," *Electrical India,* Vol. 27, No. 10, May 1987, pp. 17-20

[75] R. M. Boynton and K. F. Purl, "Categorical Colour Perception Under Low-Pressure Sodium Lighting with Small Amount of Added Incandescent Illumination," *Lighting Res. & Tech.,* Vol. 21, No. 1, 1989, pp. 23-27

[76] D. M. Paylor, "Putting Colour Back into Main Road Lighting," *Lighting Journal,* Vol. 54, No. 4, December 1989, pp. 227-229

[77] B. Ruston, "Discharge Lamp Circuits: the Choice and its Implications," *Lighting Journal,* Vol. 55, No. 1, March 1990, pp. 15-17

[78] J. Beerman, "IES Approved Method for the Electrical and Photometric Measurements of Low Pressure Sodium Lamps," *Journal of the Illuminating Engineering Society,* Vol. 12, No. 4, July 1983, pp. 210-214

[79]   J. A. J. M. van Vliet, Ir. and J. J. de Groot, Dr. Ir., "High-Pressure Sodium Discharge Lamps," *IEE PROC.,* Vol. 128, Pt. A, No. 6, September 1981, pp. 415-441

[80]   A. Anders, "Electrode Behaviour of Pulsed High-Pressure Sodium Lamps," *Lighting Research and Technology,* Vol. 23, Iss. 1, 1991, pp. 81-84

[81]   S. Carleton, R. A. J. Keijser, and J. T. C. Kemenade, "White HPS Lamps with a Color Temprature of 2700 K," *Journal of the Illuminating Engineering Society,* Vol. 20, No. 1, Winter 1991, pp. 134-139

[82]   R. G. Gibson, "Design Features of a 70-W HPS Gas Filled Reflector Lamp," *Journal of the Illuminating Engineering Society,* Vol. 20, No. 1, Winter 1991, pp. 84-90

[83]   A. Yonezawa, K. Araki, Y. Ike, and K. Suzuki, "Supper-High-Power High Pressure Sodium Lamp," *Journal of the Illuminating Engineering Society,* Vol. 20, No. 2, Summer 1991, pp. 83-87

[84]   W. Graser, "Improving the Life Performance of High-CRI HPS Lamps," *Journal of the Illuminating Engineering Society,* Vol. 20, No. 2, Summer 1991, pp. 22-28

[85]   D. Rutan, L. Nerone, and D. Kachmarik, "Practical Application of Pulsed High Pressure Sodium Lamp Technology," *Journal of the Illuminating Engineering Society,* Vol. 21, No. 1, Winter 1992, pp. 60-68

[86]   D. E. Brabham and C. A. Jacobs, "Ignition and Life Performance of Color Improved HPS Lamps," *Journal of the Illuminating Engineering Society,* Vol. 21, No. 1, Winter 1992, pp. 41-46

[87]   S. Carleton and R. A. J. Keijser, "Stabilization of White HPS Lamps," *Journal of the Illuminating Engineering Society,* Vol. 21, No. 1, Winter 1992, pp. 47-51

[88]   W. Pabst, and D. Klien, "Igniting High-Pressure Lamps with Electronic Ballasts," *Journal of the Illuminating Engineering Society,* Vol. 21, No. 2, Summer 1992, pp. 14-20

[89]   J. M. Strok, "High-Pressure Sodium Lamps: Practical Design Model," *Lighting Research and Technology,* Vol. 24, No. 3, 1992, pp. 149-154

[90]   J. Melis, "Ballast Curves for HPS lamps Operating on High Frequency," *Proceedings of the 1992 IEEE Industry Application Society Annual Meeting,* Vol. II, pp. 1825-1829

[91]. R. Geens and E. Wyner, "Progress in High Pressure Sodium Lamp Technology," *IEE PROCEEDINGS-A,* Vol. 140, No. 6, November 1993, pp. 450-464

[92] W. W. Byszewski, A. B. Budinger, and Y. M. Li, "HID Starting: Glow Discharge and Transition to the Thermionic Arc," *Journal of the Illuminating Engineering Society,* Vol. 20, No. 2, Summer 1991, pp. 3-9

[93] S. R. Hunter and A. Bowman Budinger, "Starting Processes and the Influence of the Radioactivity of Thorium on the Statistical Lag Time in Metal Halide," *Proceedings of Gaseous Dielectronics VI,* Knoxville.TN, September 23-27, 1990, pp. 273-278

[94] J. F. Waymouth, "LTE and Near-LTE Lighting Plasmas," *IEEE Transactions on Plasma Science,* Vol. 19, Iss. 6, December 1991, pp. 1003-1012

[95] J. T. Dakin, "Nonequilibrium Lighting Plasmas," *IEEE Transactions on Plasma Science,* Vol. 19, Iss. 6, December 1991, pp. 991-912

[96] T. Otsuka, "Photometric Effect of Operating Position of Floodlight for HID Lamps," *Journal of the Illuminating Engineering Institute of Japan,* Vol. 76, Iss. 6, June 1992, pp. 281-286

[97] K. Fukud, "Single-Ended Compact Metal Halide Lamp," *National Technical Report,* Vol. 38, Iss. 6, 1993, pp. 52-58

[98] R. Parrott, E. Nortrup, E. Wyner, and J. Scholz, "Low-Wattage Metal Halide Lamps with Enhanced Containment," *Journal of the Illuminating Engineering Society,* Vol. 21, No. 1, Winter 1992, pp. 52-59

[99] W. W. Byszewski, P. D. Gregor, A. B. Budinger, and Y. M. Li, "Tungsten Radiation Measurements During the Starting of Metal Halide Lamps," *Journal of the Illuminating Engineering Society,* Vol. 21, No. 1, Winter 1992, pp. 85-91

[100] E. Rasch an E. Statnic, "Behavior of Metal Halide Lamps with Conventional and Electronic Ballasts," *Journal of the Illuminating Engineering Society,* Vol. 20, No. 2, Summer 1991, pp. 88-96

[101] M. Sugiura, "Review of Metal-Halide Discharge-Lamp Development 1980-1992," *IEE PROCEEDINGS-A,* Vol. 140, No. 6, November 1993, pp. 443-449

[102] L. Cifuentes, G. M. Forsdyke, and N. W. O'Brien, "The Corrosion of Tungesten in Metal Halide Lamps: A Review," *Corrosion Science,* Vol. 33, No. 10, 1992, pp. 1581-1592

[103] D. O. Wharmby, "Electrodeless Lamps for Lighting: A Review," *IEE PROCEEDINGS-A,* Vol. 140, No. 6, November 1993, pp. 465-473

[104] D. A. Avery and J. B. Wellinghoff, "System Approach to Commercial Lighting," *Proceedings of the 1992 IEEE Industry Application Society Annual Meeting,* Vol. II, October 1992, pp. 1837-1839

[105] V. Hines, "Demand-Side Management Rebate Programs: Which Way Are They Headed?," *Strategic Planning for Energy and the Environment,* Vol. 11, No. 3, Winter 1992, pp. 50-63

[106] J. C. Genzer, "Highlights of the New Energy Act of 1992," *Strategic Planning for Energy and the Environment,* Vol. 12, No. 4, Spring 1993, pp. 8-22

[107] J. R. Knisley, "Practical Guide to HID Lighting - Part 1," *Electrical Construction and Maintenance,* Vol. 93, No. 4, 1994, pp. 45-56

[108] F. Davis, "Engines of Energy Innovation: Smaller Manufacturers of Efficient Lighting Products," *Energy,* Vol. 18, No. 2, 1993, pp. 185-190

[109] Electrical Construction and Maintenance, "Lighting," *Electrical Construction and Maintenance,* Vol. 93, No. 12, 1994, pp. 76-87

[110] M. H. Rashid, "Power Electronics: circuits, devices, and applications," Prentice Hall, Englewood Cliffs, N.J. (1993).

[111] E. B. Makram, R. B. Haines, and A. A. Girgis, "Effect of Harmonic Distortion in Reactive Power Measurement," IEEE Transactions on Industry Applications, Vol. 28, No. 4, July/August 1992, pp. 782-787

[112] W. Shepherd and P. Zand, "Energy Flow and Power Factor in Nonsinusoidal Circuits," Cambridge University Press, Cambridge, (1979).

[113] C. S. Chen, and Y. H. Yan, "Optical Capacitor Placement for Power Systems with Nonlinear Loads," Electrical Power & Energy Systems, Vol. 14, No. 6, 1992, pp. 387-392

[114] A. E. Emanuel and M. Yang, "On the Harmonic Compensation in Nonsinusoidal Systems," IEEE Transactions on Power Delivery, Vol. 8, No. 1, January 1993, pp. 393-399

[115] J. Arrillaga, D. A. Bradley, and P. S. Bodger, "Power System Harmonics," *John Wiley & Sons*, New York (1985).

[116] G. T. Heydt, "Electric Power Quality," *Stars in a Circle Publications, Indianapolis*, Indiana (1991).

[117] V. E. Wagner, "Effects of Harmonics on Equipment," IEEE Transactions on Power Delivery, Vol. 8, No. 2, April 1993, pp. 672-680

[118] W. E. Kazibwe, T. H. Ortmeyer, and M. S. A. A. Hammam, "Summation of Probabilistic Harmonic Vectors," IEEE Transactions on Power Delivery, Vol. 4, No. 1, January 1988, pp. 621-628

[119] M. Lehtonen, "Probabilistic Methods for Assessing Harmonic Power Losses in Electricity Distribution Networks," *Third International Conference on Probablistic Methods Applied to Electric Power Systems*, July 1991, pp. 37-42

[120] R. Waggoner, "Beware of Single-Phase Harmonic Distortions-Part 1," *Electrical Construction and Maintanance*, Vol. 93, No. 6, June 1994, pp. 18

[121] R. Waggoner, "Beware of Single-Phase Harmonic Distortions-Part 2," *Electrical Construction and Maintanance*, Vol. 93, No. 7, July 1994, pp. 13-14

[122] R. Waggoner, "Beware of Single-Phase Harmonic Distortions-Part 3," *Electrical Construction and Maintanance*, Vol. 93, No. 8, August 1994, pp. 17-18

[123] A. V. Ranst, "Harmonics, Causes, Consequences, Remedial Actions," *Revue E,* Vol. 110, No. 1, January 1994, pp. 5-14

[124] W. A. Moncrief, "International Harmonic Standards," *1994 IEEE Power Engineering Society Winter Meeting, HWG Panel Session*, p. 17, Feburary 3, 1994.

[125] W. M. Grady, "Review of Harmonic Standards: IEEE 519 and IEC 555," *45th Anual Power Distribution Conference*, October 20, 1992, 18p

[126] IEC, "Disturbances in Supply Systems Caused by Household Appliances and Similar Electrical Equipment," *International Electromechanical Commission Publication*, IEC 555, 1982

[127] A. E. Emanuel, J. Janczak, D. J. Pileggi, E. M. Gulachenski, M. Breen, T. J. Gentile, and D. Sorensen, "Distribution Feeders with Non-linear Loads in the Northeast USA: Part I - Voltage Distortion Forecast," *IEEE/PES 1994 Winter Meeting*, 94 WM 089-3 PWRD, 1994, 7p

[128] G. R. Newsham and D. K. Tiller, "The Energy Consumption of Desktop Computers: Measurement and Savings Potential," *IEEE Transactions on Industry Applications*, Vol. 30, No. 4, 1994, pp. 1065-1072

[129] M. Lehtonen, "A General Solution to the Harmonics Summation Problem," *European Transactions on Electrical Power Engineering*, Vol. 3, No. 4, August 1993, pp. 293-297

[130] M. Choudhry, S. Rahman, and P. K. Dash, "Energy Efficient Devices and their Impact on Energy Demand and Power Quality," *8th National Power System Conference*, New Delhi, India, December 1994, 5p

[131] A. Domijan, Jr, "A Summary and Evaluation of Recent Developments on Harmonic Mitigation Techniques Useful to Adjustable Speed Drives," *IEEE Transactions on Energy Conversion*, Vol. 7, No. 1, March 1992, pp. 64-71

[132] T. Acquaviva and G. C. Hartmann, "Survey of Energy and Power Usage in Copiers, Duplicators, and Electronic Reprographic Devices," *IEEE Transactions on Industry Applications*, Vol. 30, No 4, (July/August 1994), pp. 1058-1064

[133] OSRAM *SYLVANIA* Product Catalog, *PRODUCT DATA,*1993.

[134] Green Lights: An Enlightened Approach To Energy Efficiency and Pollution Prevention, *United States Environmental Protection Agency*, July 1993.

[135] IEEE Recomended Practices and Requirements for Harmonic Control in Electrical Power Systems, *IEEE Std 519-1992*, April 1993.

[136] R. S. Bergman and T. G. Parham, "Applications of Thin Film Reflecting Coating Technology to Tungsten Filament Lamps," *IEE PROCEEDINGS*, Vol. 140, No. 6, November 1993, pp. 418-428

[137] GE Lighting, "Federal Energy Policy Guide," *GE Lighting Brochure 205-31158*, (1993)

[138] International Energy Agency, "Energy Efficiency and the Environment," *OECD*, Paris, France, (1991)

[139] K. F. Johnson, "Following the Lighting DSM Phenomenon," *1994 Proceedings Illuminating Engineering Society of North America,*(August 1994), pp. 677-686

[140] C. Mendelsohn, "Saving Energy Twice: The Lighting /Air Conditioning Domino Effect," *Conference and Exposition on Energy & Environment,* (1992) 12p.

[141] R. R. Verderber, "Analysis of Past and Future Electronic Ballast Markets," *High Frequency Power Conversion Conference,* Intertec International Inc., San Jose, (April 17-21 1994) 7p.

[142] S. Datta, "Comparative Analysis of Fluorescent Lighting With Electronic and Magnetic Ballasts," *High Frequency Power Conversion Conference,* Intertec International Inc., San Jose,   (April 17-21 1994) 7p.

[143] M. J. Ouellette and R. Arseneau, "The Effects of Undervoltage on the Performance of Compact Fluorescent Systems," *Proceedings of the 1992 IEEE Industry Application Society Annual Meeting,* Vol. II, October 1992, pp. 1872-1879.

[144] P. N. Wood, "Simplified Ballast Designs Using High Voltage MOS Gate Drives," *High Frequency Power Conversion Conference,* San Jose, Intertec International Inc., (April 17-21 1994) 7p.

APPENDIX A

—

% This matlab m-file will get the power factor values for the

% given voltage and current combinations

%

% t is time variable

% vt is the voltage

% Vrms is the rms value of voltage

% T is the period of the waves and is 2

% iat is the first waveform ...

% Iarms is the rms value of iat ...

% Define the voltage and current waveforms here

% N+1 is the number of samples, si is the sampling interval

%

```
N     = 100;
T     = 2;
si    = 2/N;
t     = 0:si:2;
vt    = cos(pi.*t+pi/4);
```

% Current Waveform (a)

```
iat    = cos(pi.*t);
```

—

% Current Waveform (b)

```
_t1_= 0:si:.5;
_t2_= .5+si:si:1.5;
_t3_= 1.5+si:si:2;

_ibt1_= 2.*t1;
_ibt2_= 2.*(1-t2);
_ibt3_= 2.*(t3-2);
_ibt_= [ibt1 ibt2 ibt3];
```

–

% Current Waveform (c)

```
_t1c_= 0:si:1;
_t2c_= 1+si:si:2;
_ict1_= ones(size(t1c));
_ict2_= -1.*ones(size(t2c));
_ict_= [ict1 ict2];
```

–

% Current Waveform (d)

```
_idt_= zeros(size(t));
_t1d_= .3:si:.7;
_t2d_= 1.3:si:1.7;
_idt(.3/si:.7/si)_= ones(size(t1d));
_idt(1.3/si:1.7/si)_= -1.*ones(size(t2d));
```

—

% Calculate the rms value of voltage and currents
% vsqd is the squared value of vt, iasqd is the squared value of iat...

```
    vsqd   = vt.^2;
    iasqd  = iat.^2;
_ibsqd_= ibt.^2;
_icsqd_= ict.^2;
_idsqd_= idt.^2;


    Vrms   = sqrt(sum(vsqd)/T);
    Iarms  = sqrt(sum(iasqd)/T);
_Ibrms_= sqrt(sum(ibsqd)/T);
_Icrms_= sqrt(sum(icsqd)/T);
_Idrms_= sqrt(sum(idsqd)/T);
```

% pra is the product of iat and vt ...
% Pa is the active power with iat ...
% pfa is the power factor with iat ...

```
    pra   = vt.*iat;
_prb_= vt.*ibt;
_prc_= vt.*ict;
_prd_= vt.*idt;


    Pa    = sum(pra)/T;
_Pb_= sum(prb)/T;
```

```
_Pc_= sum(prc)/T;
_Pd_= sum(prd)/T;

_
```

pfa   = Pa/(Vrms*Iarms)

pfa =

_ 0.71059868776230

pfb= Pb/(Vrms*Ibrms)

pfb =

-0.69844050861032

pfc= Pc/(Vrms*Icrms)

pfc =

-0.64001021690641

pfd= Pd/(Vrms*Idrms)

pfd =

-0.56037940276967

Vita

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