8-2010

AN INVESTIGATION OF THE RESPONSE OF INCANDESCENT LAMPS AND COMPACT FLUORESCENT LAMPS TO VOLTAGE FLUCTUATION

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AN INVESTIGATION OF THE RESPONSE OF INCANDESCENT LAMPS AND COMPACT FLUORESCENT LAMPS TO VOLTAGE FLUCTUATION

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Electrical Engineering

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by
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August 2010

Accepted by:
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ABSTRACT

This thesis presents the results of tests that were performed on incandescent lamps and compact fluorescents lamps (CFLs) in order to observe their sensitivity to voltage fluctuations that can occur on a power system. The lamps tested were designed for use in a 120V, 60Hz system. They are models that are commonly available in the United States.

In this research, the lamps in question were exposed to four separate tests. The first set of tests analyzed the response of each lamp to a series of long voltage fluctuations that were applied long enough to allow the light output from the lamps to reach a new steady state output. The second set of tests consisted of short duration voltage sags that were applied for only a few 60Hz cycles. The third set of tests consisted of non-rectangular voltage fluctuations that resemble those found in a real system. In the final tests, data was collected to propose a new flicker curve that is based on CFLs.

In each test performed, the response of the CFL was shown to be superior to that of the incandescent lamp. In the long duration tests, the percentage reduction in light observed by the incandescent lamp was 4 to 6 times greater than that observed by the CFL. The light fluctuation of the CFL during the short duration tests was also shown to be less than that of the incandescent lamp. The drop and recovery times recorded indicated that the response of the CFL to the voltage fluctuation was much quicker than that of the incandescent. The non-rectangular tests provided confirmation that the trends observed in the previous tests apply to real conditions. The final tests performed provided data to propose a new flicker curve based on CFLs.

ACKNOWLEDGMENTS

First, I would like to thank my parents, Gary and Kay May, who have always supported and encouraged me in everything I have done and who have taught me the importance of working hard to achieve my goals. You have always been there for me and believed in me. Without your love and support, completing this project would have been difficult, if not impossible.

I would like to thank my committee chair, Dr. Randy Collins, as well as Dr. Michael Bridgwood and Dr. John Komo, who have never hesitated to help me and give me advice throughout both my undergraduate and graduate careers.

I would like to thank Curtiss Fox and Bharath Sridhar who have been endless sources of technical advice for me and have never hesitated to help me when asked.

Finally, I would like to thank ELCOM and, within ELCOM, Jordan Price and Barb May, for supplying the light sensor and evaluation board and for providing advice on proper usage of the device.

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CHAPTER 1: BACKGROUND

This thesis presents an assessment of the response of incandescent lamps and compact fluorescent lamps (CFLs) to voltage fluctuations on the electric power system. This first chapter provides some necessary background information. It begins with the motivation for performing this research. It then moves into an overview of incandescent lamps and fluorescent lamps and introduces the types of ballasts used to supply fluorescent lamps. Next is an explanation of the different forms of light measurement that are commonly used. A brief explanation of common causes of the voltage fluctuation that cause lighting flicker is provided. A discussion is provided of the methods currently used for measuring and assessing the severity of voltage fluctuations with respect to their impact on lighting flicker. Included in this explanation are flicker curves and the International Electrotechnical Commission (IEC) Flickermeter. Finally, some prior research on this topic is described.

Chapter 2 provides a description of the experimental setup that was designed and built for this research. Included in this discussion is the identification and explanation of the equipment used as well as the reasoning behind the choice of this equipment.

Chapter 3 provides a discussion on the actual tests performed. A thorough explanation is given of the tests performed and the analysis used to evaluate the data.

Chapter 4 provides the numerical test results along with a discussion explaining the significance of the results.

Motivation

Electric lighting makes up a large portion of the load on an electric power system. Unfortunately, the power system is not an ideal entity and cannot economically provide service that is completely free from disturbances. Voltage fluctuations are common on a power grid when a large load that is connected to the system is turned on or off. These voltage fluctuations can become unacceptable when they affect the light output from electric lighting.

A voltage fluctuation on a system will cause the light output from a lamp supplied by the system to fluctuate. This fluctuating light output can become irritating to humans. The effects of a flickering lamp can be from as minimal as a slight annoyance or eye strain to as severe as epileptic seizures [1]. From an industrial standpoint, it can decrease work quality [2]. In any case, if the voltage fluctuations on a system are severe enough to cause objectionable light flicker, there is a good chance that complaints will be filed by the customers of utilities who want the matter alleviated. The utility will then be forced to review the complaint and, if deemed it is the responsibility of the utility, pay for any actions needed to fix the issue.

In an effort to reduce the number of complaints filed by customers, utilities have developed ways in which to predict how voltage fluctuations on their systems will affect lighting. Many utilities have developed standards based on flicker curves that relate voltage fluctuation to lighting disturbances that will be either perceptible or annoying to humans. More recently, the IEC has issued its Standard 61000-4-15 describing the requirements of a device, called a flickermeter, which provides a numerical indication as to the severity of a voltage fluctuation on lighting.

The flickermeter and most flicker curves provide a reference based on incandescent lighting. It is well known, however, that the incandescent lamp is very inefficient in that much of the energy that is supplied to the lamp is given off as heat instead of light. In recent years, as people have become more economically and environmentally conscious, the inefficiencies of incandescent lamps have led to a desire to find an alternative source of light. In many areas, that alternative source has come in the form of compact fluorescent lamps. Many nations have made the transition from incandescent lamps to CFLs. Some nations, such as Australia, have even taken action to create standards that will phase out inefficient incandescent lamps [3]. Compact fluorescent lamps are also becoming increasingly prominent in the United States.

This transition in lighting technology means that many of the procedures used by utilities to determine acceptable voltage fluctuation on their systems are quickly becoming outdated. The way in which a voltage fluctuation will affect an incandescent lamp may not affect a compact fluorescent lamp in the same way. In fact, there have been studies that point to the notion that CFLs are actually less sensitive to voltage fluctuation than are incandescent lamps. Many of these studies, which will be described in more detail later in this thesis, have focused on how interharmonics affect compact fluorescent lamps. A few studies reflect a comparison of incandescent lamps and CFLs when subjected to a modulated voltage. Many of these studies, however, lack depth and do not provide information over a wide range of modulation frequencies or sag depths. Many studies comparing incandescent lamps to CFLs also have been performed on lamps designed for use on a 230V, 50Hz system, while less have tested lamps designed for a 120V, 60Hz system such as that used in the United States. There has also been little consideration given to the characteristics of the response of the two lighting technologies, such as the time constant of the light output associated with each lamp. Such information can help to point to the mechanisms at play in determining why one lighting technology may be superior to the other when exposed to a voltage fluctuation.

In this thesis, a comprehensive study is performed to compare the response of incandescent lamps to that of compact fluorescent lamps commonly available in the United States when subjected to voltage sags of varying magnitude, duration, and shape. The compact fluorescent lamps used in this study are non-dimmable. The desire is to either confirm or dismiss the notion that compact fluorescent lamps are less susceptible to voltage fluctuations than are incandescent lamps, and if they are less susceptible, to what extent. The study also provides data related to the time response of each lighting technology. Finally, a new flicker curve will be proposed that is based on the compact fluorescent lamp.

While the ballast that supplies the compact fluorescent lamp is discussed in this thesis, it is not observed in depth. As will be described, the electronic ballasts that supply CFLs in the United States use very similar topologies and, therefore, do not provide significant differences when it comes to the CFL's response to voltage fluctuations. Therefore, the research is limited to analyzing the light output of the lamps in question.

This comparison of incandescent lamps to CFLs will be of value to utilities in need of addressing this changing trend in lighting technology. If it is found that a transition to compact fluorescent lamps will cause the lighting load to become less susceptible to voltage fluctuation, it may be found that current voltage fluctuation standards could be relaxed. On the other hand, if it were found that compact fluorescent lamps actually do not perform any better, or possibly worse, than incandescent lamps, action could be taken to proactively stiffen standards before customer complaints increase. Either way, research results comparing the incandescent lamp to the compact fluorescent lamp will eventually save the utility money and the public the irritation caused by lighting flicker.

Overview of Common Lighting Technologies

Incandescent Filament Lamp

The incandescent filament lamp is one of the oldest and most widely recognized forms of electrical lighting technology today. The basic design of the incandescent filament lamp is still basically the same as the design that was developed by Thomas Edison in the late nineteenth century. It consists of a metal filament that is surrounded by either a vacuum or an inert gas, all of which is housed in a glass enclosure. When a large enough electrical current is passed through the resistance of the filament, the filament begins to heat up and glow, thus producing light [4]. The light that is produced by an incandescent lamp tends to be of a warm color temperature. According to EnergyStar, the color temperature of an incandescent lamp tends to fall between 2400 and 2900 K [5].

In order to design an incandescent lamp that produces useful light and also has a long life, the materials for the metal used for the filament and the gas that surrounds the filament have to be chosen correctly. Since the filament of the incandescent lamp produces light from heat, it needs to have a high melting point. In the past, carbon was the metal of choice. Today, tungsten has taken the place of carbon due to the ease with which it can be worked and its high melting point [4].

One cause of failure in an incandescent bulb is filament evaporation. When current is passed through the filament, some of the molecules of the filament gain enough energy to "jump" away, thus weakening the filament until it breaks. One way to reduce this effect is to strategically choose the gas that surrounds the filament. This gas exerts a pressure on the filament in order to slow down the rate of escape of the molecules that compose the filament. In doing so, the time taken for the filament to evaporate increases, and with it, so does the life of the lamp. The gas must also have a sufficiently low thermal conductivity. If the thermal conductivity is too high, it will conduct heat away from the filament, thus cooling the filament and reducing the light output. The gas should not ionize under normal operating conditions. In today's incandescent lamps, the gas of choice is argon mixed with some nitrogen to minimize ionization [4].

One of the benefits of the incandescent lamp is its simplicity. The lamp can be directly connected to the power source without the need for a complicated power supply. Within the bulb itself, the lamp is basically just a wire that conducts current. The wire is fused to prevent a high arc current when the filament fails. Some additional electronics can be added optionally, such as a thyristor dimmer [4], but this is not strictly necessary for lamp functionality (and is also fairly simple when compared to power supplies that are required for other lamps).

Despite its simplicity, there has been recent pressure to eliminate the incandescent filament lamp. The main reason cited for this is the incandescent lamp's low efficiency. As compared to other lighting technologies, an incandescent lamp consumes much more energy in order to create the same light output. According to EnergyStar, the efficacy of an incandescent lamp is between 12 and 18 lumens per watt. This is low as compared to fluorescent lighting, compact fluorescent lighting, and LED lighting, which all rate between 65 and 90 lumens per watt [5]. The low efficiency of the incandescent lamp is clearly visible when one observes the spectrum of light that is emitted from the incandescent lamp. This lamp emits a wide band spectrum that extends from around 300nm to well into the infrared region of the light spectrum. Therefore, a very small portion of the light emitted from the incandescent lamp is within the visible spectrum. In fact, the emitted wavelengths with the highest energy are at around 900nm. This is well outside of the visible light spectrum, which is generally taken to be from around 380nm to 780nm [6]. In a world in which economical and environmental concerns are increasing, this could spell the end of the incandescent bulb.

Incandescent bulbs also have shorter lifetimes than other lighting technologies. According to EnergyStar, an incandescent bulb is expected to last between 750 and 1500 hours. This is short when compared to compact fluorescent lamps, which last between 6000 and 10000 hours, linear fluorescent lamps, which last up to 20000 hours, and white LEDs which last up to 100000 hours [5]. The lifetime of an incandescent lamp can be increased by lowering the voltage at which it is operating, but in doing so, the efficacy of the lamp decreases [4].

Finally, incandescent lamps tend to have high inrush current when they are switched on. This is due to the fact that the filament has a lower resistance when it is cool than when it heats up. Tungsten, for example, has a cold resistance that is about 14 times lower than its resistance when conducting current for the lamp. This means that when the power is switched on, there is little resistance and so a large current flows until the filament heats up. This usually takes between one tenth and one half of a second. This can cause problems for any peripheral electrical equipment that is attached to the lamp, such as dimmer switches [4].

Fluorescent Lamp

The fluorescent lamp does not directly depend upon a heated filament to emit light. Instead the lamp emits light by using an electrical current to excite electrons, thus lifting them to higher and less stable energy levels. Since these electrons are not stable at their new energy level, they will fall back to their old energy levels, thus emitting quanta of radiation. This radiation can be used for lighting [4]. Since this light source is less dependent upon heat than the incandescent lamp, it is a much more efficient light source. This has given fluorescent lighting an advantage over incandescent lighting.

The construction of the fluorescent lamp is more complicated than that of the incandescent lamp. The fluorescent lamp consists of a tube that contains a gas. The gas of choice is a mixture of mercury vapor at a low pressure (around 1.07 Pa) and argon or a mixture of inert gases (at around 200 Pa). The mercury is the main element used to produce light while the argon is used to help start and maintain ionization [4], [6]. At both ends of the tube are electrodes. One of these is a cathode and the other is an anode. Since the voltage applied to the tube is AC, the cathode and anode alternate as the voltage switches polarity [4].

The general fluorescent lamp is what is referred to as a “hot cathode” fluorescent lamp. (There is also a “cold cathode” lamp, but this will not be discussed as these lamps are only used in specialist applications.) In a “hot cathode” lamp, each electrode is a tungsten filament that is coated in an alkaline earth oxide. The cathode filament emits electrons which pass through the gas in the tube to the anode, creating an electrical current within the tube. The current flowing through the gas excites electrons in the mercury atoms, thus raising them to higher energy levels. As was mentioned before, when these electrons fall back to the lower energy levels they emit radiation. The radiation from these two sources is emitted at a number of wavelengths, with the dominant ones being 254, 313, 365, 405, 546, and 578nm [4].

While different for each person, the generally accepted range of light that is visible to humans is from 380nm to 780nm [6]. Therefore, many of the wavelengths that are emitted from the process described above are outside or just on the edge of the visible light range. This would result in a useless lighting source. In order to solve this problem, the inside of the tube containing the gas is coated with phosphors. The radiation emitted from the above process transmits energy to the electrons of the phosphors, thus pushing them to higher energy levels. When the electrons fall back to their normal energy levels, they emit radiation at a wavelength within the visible light spectrum causing these phosphors to fluoresce, or emit light. In contrast to the incandescent lamp, fluorescent lamps generally give off bands of narrow spectrum light. The spectrum of light given off depends on the light that is desired and, therefore, on the phosphors that are used [4].

The choice of the phosphor used in the fluorescent lamp is dependent upon the use of the lamp. If the lamp is in an environment where excellent color rendering is not necessary, a halophosphate phosphor could be used. Halophosphates are cheaper, but they produce a Color Rendering Index (CRI) of only around 56. In environments where better color rendering is required, triphosphors can be used. These phosphors are composed of three different rare earth phosphors, one of which emits red, another of which emits green, and the third of which emits blue wavelengths. In using this type of phosphor, a CRI between 80 and 85 can be reached. Even better CRI values can be obtained by using multi-band phosphors, but in doing this the light becomes less efficient. Some lights will use a mixture of halophosphates and triphosphors in order to get an intermediate CRI value [4].

Since fluorescent lamps do not directly use heat as a source of light, they are more efficient than incandescent lamps. According to EnergyStar, a fluorescent lamp will have an efficacy of 80 to 100 lumens/W and could actually reach higher values [5]. Fluorescent lamps also tend to emit light of a cooler color temperature than incandescent lamps. Their color temperature can range between 2700 K and 6500 K [5].

Compact Fluorescent Lamp

The obvious economic advantages of fluorescent lamps are offset by their less than desirable appearance. Most consumers prefer the small profile of an incandescent lamp when installing lighting in their homes and the linear fluorescent lamp is generally reserved for less commonly seen areas such as the garage or basement.

In order to combine the economic benefits of the fluorescent lamp with the visual benefits of the incandescent lamp, the compact fluorescent lamp has been developed. These lamps provide the light output of tube fluorescent lamps in a compact profile by twisting the tube onto itself [6]. In doing so, an economic lamp has been created that is approximately the size of an incandescent bulb. According to EnergyStar, compact fluorescent lamps have an efficacy between 60 and 70 lumens/W [5].

While compact fluorescent lamps provide an efficient form of lighting in a desirable package, there are some concerns over the use of these lamps. One common complaint is that the lamps exhibit a run-up period at startup during which the light output climbs to its final value. This run-up period is a characteristic of all fluorescent lamps. During this time, the mercury in the tube vaporizes and the pressure inside the tube increases to operating conditions. Once this process is complete, the lamp gives off its full light output [6]. Compact fluorescent lamps can vary in their run-up periods depending upon the chemical composition of the materials within the tube, but many can reach full light output in about a minute. Some manufacturers include an additive called amalgam, which slows down the run-up period, thus forcing the light to take more time to reach full brightness. Amalgam is commonly used in lamps that are expected to operate in a wide temperature range. A compact fluorescent lamp operating in cold temperatures without amalgam will take much longer to reach full-light output than a lamp that contains amalgam [7]. In general, the addition of amalgam can make a CFL operating in cold conditions reach full-light output faster than if it was not included, but will slow down the run-up time for normal operating conditions. The fact that a compact fluorescent lamp takes some time to reach full light output has been a cause for complaint from customers who are used to the nearly instantaneous light output from an incandescent lamp.

Another complaint concerning CFLs is the fact that each bulb contains a small amount of mercury. As CFLs become more abundant as a lighting source, the question of how to dispose of them becomes a concern. If disposal is not handled properly, this mercury will be released into the environment where it could have significant negative effects.

It is feared that compact fluorescent lamps can also have adverse effects on the power system. Since compact fluorescent lamps use an electronic ballast, which will be described in more detail later, they have highly distorted current waveforms. Therefore, compact fluorescent lamps inject harmonics into the power system. While the harmonic injection from one CFL is of little concern, as the number of compact fluorescent lamps grows on the system, the impact will become increasingly noticeable. This CFL load can also create a harmonic load that is difficult to deal with simply due to the fact that the harmonic content is not sourced from one large unit that can be analyzed, but from many small loads scattered throughout the system [8]. Harmonics present on a system can have many detrimental effects on the power system, including, but not limited to, line heating, capacitor failure, metering issues, and audible noise [9]. As CFLs become abundant, their harmonic content can become destructive if not dealt with properly.

Fluorescent Lamp Ballasts

A fluorescent lamp with no external control is an unstable device. The ionized atoms allow the current to flow through the tube which, in turn, ionizes more atoms, thus allowing more current. This positive feedback system would eventually produce a large current capable of blowing a fuse or destroying the lamp. In order to prevent this, a current limiting device must be used with the fluorescent lamp. This device is called a ballast.

There are two categories of fluorescent ballasts. The older and simpler ballasts are electromagnetic ballasts. The newer and more complex ballasts are electronic ballasts. Since both ballasts are still used today, both will be discussed.

Electromagnetic Ballasts

Electromagnetic ballasts use an inductive reactance to limit the current flowing through the fluorescent tube. A reactance, as opposed to a resistance, is used in order to make the device more efficient. Ideally, inductors do not consume active power and so all of the active power is transferred to the process of making light instead of being consumed by the current limiting device. Inductors do, however, oppose a change in current and thus constitute an impedance to alternating current. If chosen correctly, the inductor will limit the current to an acceptable level. There are three main types of electromagnetic ballasts. These are pre-heat starting ballasts, rapid starting ballasts, and instant starting ballasts [4].

One example of a pre-heat starting ballast is shown in Figure 1.1 below. Initially, the starter switch is closed and so current flows through the current-limiting inductor, both filaments, and the starter switch, while bypassing the fluorescent tube. This current heats the filaments to the point at which they are able to emit electrons [4]. At this point, the starter switch opens and the voltage from the source in addition to a voltage spike from the inductor is applied across the tube, thus striking the arc [4]. Once the arc has struck, the filaments are no longer heated by the starting circuit. They are, however, kept at an acceptable temperature by ion bombardment and the arc current. Therefore, once the arc has been struck, it can be maintained until the circuit is powered down. If the arc is not maintained when it is first struck, the starter switch again closes and the process starts over. This process is repeated until the arc is maintained [4]. The pre-heat ballast may cause the light to flash on and off until the arc is maintained [10].

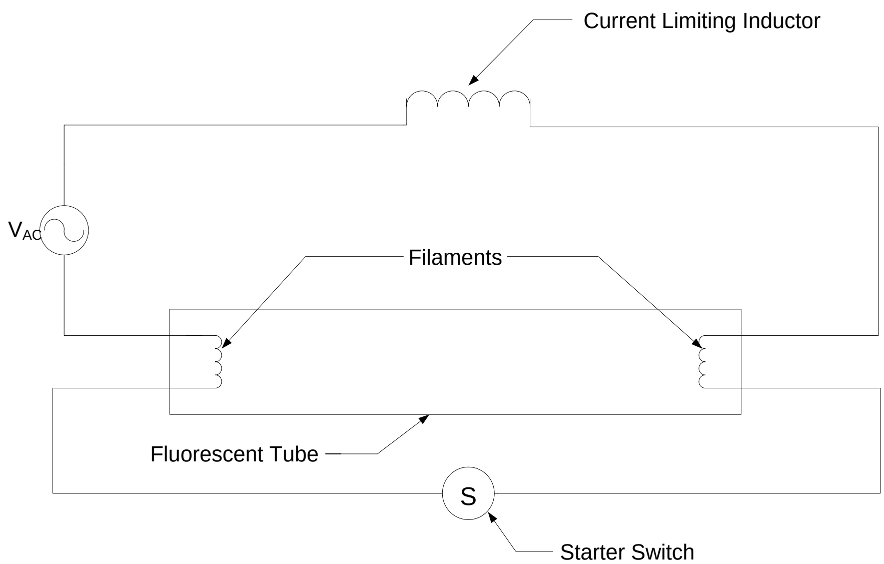

Figure 1.1: Basic Pre-Heat Electromagnetic Fluorescent Ballast

A rapid start fluorescent lamp ballast is very similar to the pre-heat starting ballast. The main difference is that in a rapid start ballast, there is a set of low voltage windings dedicated to heating the filaments [10]. Unlike the pre-heat ballast, the heating of the elements from the external source continues even after the arc is struck in the fluorescent tube. While this ballast requires a 1 to 2 second waiting period before starting the lamp, it is able to start the lamp without the flickering that is seen in pre-heat ballasts [10].

An instant start ballast does not provide any filament heating. Instead, it applies a very large voltage in order to force the current to arc from one end of the fluorescent tube to the other without heating. The voltage required to perform this task is in excess of 400V for 4 foot tubes and is even higher for longer tubes. Since no power is dissipated in filament heating, these ballasts are more energy efficient than the rapid start ballasts. They are also able to turn on without any flashing. Even so, if compared in similar environments, instant start ballasts provide shorter lamp lives than ballasts that heat the filaments [10].

Electronic Ballasts

The relatively recent advances made in solid state technologies have allowed the development of the smaller and more efficient electronic ballast. The electronic ballast is a device that takes a voltage at 60 Hz (in the United States) and outputs a voltage at a frequency somewhere between 20 kHz and 60 kHz, depending on the design. In comparison, an electromagnetic ballast does not change the frequency of the supply and simply outputs 60 Hz to the fluorescent lamp. The higher frequency of the electronic ballast is beneficial to both light quality and economics [10]. A block diagram of an electronic ballast used in compact fluorescent lamps is given in Figure 1.2 below.

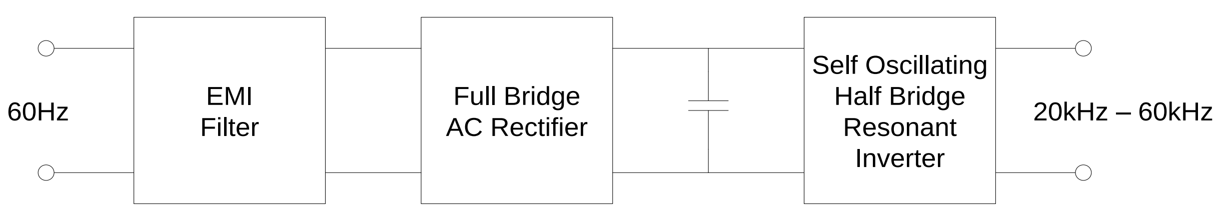

Figure 1.2: Block Diagram of an Electronic Ballast

This ballast topology was determined through disassembly of some commonly available compact fluorescent lamps in the United States. During disassembly, [11] was referenced to assist in deciphering the ballast circuit. Although this paper was written in the Netherlands, and therefore was not based on CFLs commonly available in the United States, it provided some insight into what was being observed in the ballast [11]. It was found that each ballast disassembled had very similar topologies. The United States has no harmonic standards for the ballasts in these lamps, and so each manufacturer finds the cheapest topology it can develop. Therefore, all topologies used are very similar. This similarity means that it is reasonable to believe that these ballasts will behave similarly to the voltage fluctuations that are imposed upon them.

The light output of a fluorescent lamp (and an incandescent lamp, for that matter) inherently fluctuates with its supply. The voltage from a 60 Hz system hits a zero crossing 120 times a second. This means that the light output from a fluorescent lamp supplied from an electromagnetic ballast will flicker at a frequency of 120 Hz. Studies have shown that, while a light flicker at a frequency of around 100 Hz is not visible, it does have some adverse effects on humans. There have been instances of headaches and eyestrain due to this flicker [6]. The higher frequency outputs of electronic ballasts, however, do not have this effect. Therefore, the electronic ballasts have a clear advantage over electromagnetic ballasts when considering health benefits.

It has also been shown that the efficacy of a fluorescent lamp increases with increasing frequency. The efficacy of a lamp can increase between 10% and 15% when increasing the frequency from 60 Hz to above 20 kHz [10]. Therefore, the electronic ballast is more economical than the electromagnetic ballast.

The advantages of the electronic ballast have led to the use of this technology in the power supplies of compact fluorescent lamps. It provides the lamp with an efficient power supply that is small in size. There are some drawbacks to this ballast topology, however. As has been mentioned, the current drawn by a compact fluorescent lamp is high in harmonic content. This characteristic stems directly from the electronic ballast. As is shown in Figure 1.2, the second block of the ballast is a full bridge AC rectifier which outputs to a smoothing capacitor. This rectifier topology draws current for only a small portion of the electrical cycle, and therefore, the input current to the lamp is non-sinusoidal. This harmonic content could have negative effects on the power system.

Another drawback of electronic ballasts is that as frequencies increase, so does electromagnetic interference (EMI). In order to limit the potential for EMI radiation from fluorescent ballasts, electronic ballast designers generally keep operation frequency between 20 kHz and 60 kHz [10]. These frequencies allow for a good compromise between high efficacy and low EMI. The ballast design also incorporates an EMI filter on the front end to help deal with this problem, as is shown in Figure 1.2.

The electronic ballast that supplies power to the compact fluorescent lamp can have an effect on the way in which the lamp reacts to a voltage fluctuation. As has been stated, though, all ballasts observed have very similar topologies and are expected to react to voltage fluctuations in the same way. Therefore, an exhaustive analysis of the electronic ballast is beyond the scope of this research and not performed.

Overview of Light Measurement

Once an understanding is established as to how these different lamps create light, it becomes important to understand how this light can be measured. Taking a quantitative measurement of light output from a source is a perplexing task. The output from a single source of light can be measured in a number of ways, depending upon what exactly the researcher intends to achieve. In this section, the basic ideas behind measuring light will be put forth as well as a description of the different quantities that can be used to describe a lamp's output.

Planck's Equation

Much like in an electrical or mechanical system, the output of a lighting system can be described in terms of power and energy. Light consists of packets of energy called photons [4]. The foundation to measuring the light output of a source is the ability to determine the amount of energy contained in each photon that contributes to light output. The energy that is contained within a photon of light can be determined using Plank's equation, which is given below in Equation 1.1. In this equation, Q is photon energy measured in Joules (J), h is Planck's constant (6.623×10^{-34}Js), c is the speed of light (2.998×10^{8}m/s) and λ is the wavelength of radiation, measured in meters [12].

$$Q = \frac{hc}{\lambda} \qquad (1.1)$$

Through observation of this equation it can be readily shown that the energy of light is dependent only upon the wavelength of the light in question. Since the wavelength of the light shows up on the denominator, the energy associated with a photon of that light is inversely proportional to its wavelength [12].

Measurement of Visible Light

In using Planck's equation, the light energy output (and hence the light power output) can be determined merely by knowing the wavelength of the light. While this is helpful, it is not necessarily useful when an attempt is made at measuring the brightness of a light source. This is because of the fact that visible light makes up only a small portion of the electromagnetic spectrum. As has been mentioned, humans can only see light that is in the range from approximately 380nm to 780nm [6]. Even within this range, there are certain wavelengths to which the human eye is more sensitive. It has been found that the human eye is most sensitive to a wavelength of approximately 555nm [4]. The sensitivity of the human eye to differing wavelengths is shown in Figure 1.3 below (reproduced from [6]) [6]. In this research, the photopic curve is of interest. The photopic curve is the human eye's response to normal daylight. The scotopic curve, which is also presented in Figure 1.3, is the human eye's response to light in dark conditions, but is of little interest here [6].

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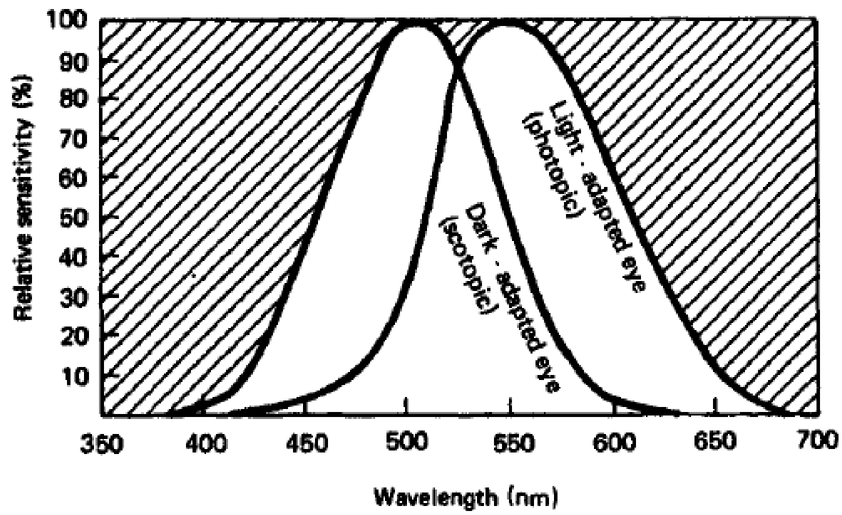

Figure 1.3: Human Eye Sensitivity to Various Wavelengths of Light

The fact that the human eye's sensitivity to light is affected by the wavelength of the light means that the result of Planck's equation must be modified to be useful in determining the brightness of a lamp as viewed by a human. Planck's equation may give the same energy calculation for a wavelength of 555nm as it does for wavelengths of 450nm and 250nm. The human eye, though, will see the wavelength of 555nm as being brighter than the wavelength of 450nm and will not see the wavelength of 250nm at all. In order to account for this, a different unit, called the lumen, has been developed. The lumen takes the output from Planck's equation (converted to power by dividing by time) and then scales it by a factor dependent upon how sensitive the human eye is to that particular wavelength [12]. The result is called luminous flux and is given in units of lumens [4]. In this way, the calculated number gives an indication of the brightness of a source as perceived by the human eye. For example, light at a wavelength of 555nm that is measured to be 1W by Planck's equation will produce 683 lumens of light. Light at a wavelength of 500nm also measured to by outputting 1W by Planck's equation will only produce 220.6 lumens [12].

While the lumen is a very useful measurement of light, the candela is the base unit of light measurement [12]. A source that is 1 candela is defined to emit 1 lumen of light per steradian in all directions. A steradian is a measurement of a solid angle that has its vertex at the center of a sphere and cuts off an area that is the square of the radius of the sphere [12].

Another common measurement of visible light is Illuminance. Illuminance is defined as the concentration of luminous flux on a surface. This measurement is given units of lumen per square meter, which is commonly referred to as lux [4].

Yet another measurement of light is irradiance. Irradiance is like illuminance except that it does not correct for human visual sensitivity. Irradiance is measured in watts per square meter or watts per square centimeter [12]. This measurement is commonly used on specification sheets for light sensors.

Causes of Light Flicker

The research that is performed in this study focuses on measuring the light output of incandescent lamps and compact fluorescent lamps while they are subjected to conditions that cause light flicker. Therefore, a crucial concept to understand is the mechanism that causes this flicker in the first place. The light output from an electrical lamp is caused by a current flowing through the bulb due to a voltage that is usually supplied by the power grid. Obviously, if that voltage decreases for some reason, the current in the bulb will also decrease, thus resulting in a drop in the light output. The cause of this decrease in system voltage could be the result of many incidents. A major disruption at a generation facility or substation could cause a voltage collapse. A fallen tree branch could cause a short circuit on the system. More commonly, though, the voltage fluctuations of interest in a lighting study result from large system loads that are regularly switched on and off.

Certain loads, such as arc furnaces, arc welders, and electric motors are known for drawing high currents from the system while active. Electric motors have the characteristic of drawing larger currents while accelerating than they do at their final speed. The high currents that flow through the system as a result of these large loads cause voltage fluctuations for others who are being fed by the same system.

The reason behind this phenomenon is due to the fact that every electrical conductor, including cables used for power transmission, contains a certain amount of impedance. This impedance comes in the form of a resistance, an inductance, and a capacitance. For simplicity, this discussion, it will be assumed that the dominant sources of impedance are the series equivalent resistance and inductance of the lines.

Consider Figure 1.4, in which there is a system feeding both an AC motor and a light source (this can be assumed to be a residential load). During normal operating conditions, the motor draws rated current, depicted here as I_{motor}, from the power system. This current must flow through the impedance of the lines supplying the power, thus causing a voltage drop in the lines shown here as $V_{impedance}$. The final output voltage, V_{out}, during steady state is the difference between V_{in} and $V_{impedance}$.

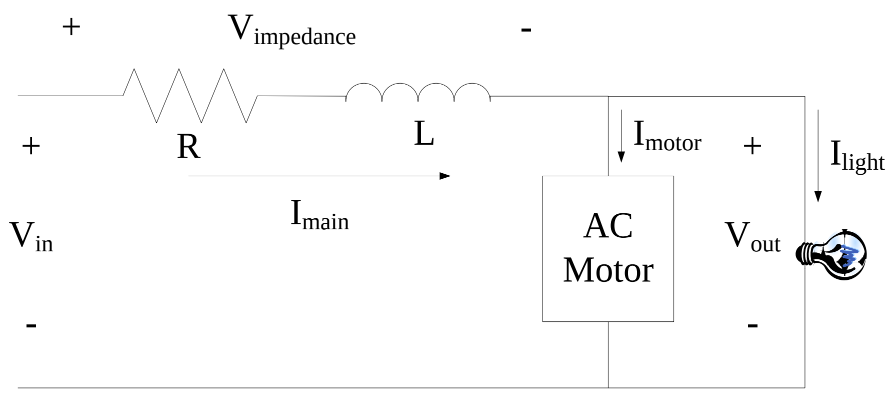

Figure 1.4: Sample System for Flicker Explanation

Now consider the conditions where the motor is switched from an off condition to an on condition. As has been mentioned, an electric motor draws more current while accelerating from zero speed its final speed than it does at its final speed. During this time of acceleration, a larger current flows through the impedance of the power lines than is observed when the motor is running at its final speed. Due to Ohm's Law, $V_{impedance}$ increases due to the increase in I_{motor} and I_{main}. This reduces V_{out}. Assuming the resistance of the light bulb is constant, I_{light} decreases with the decreasing V_{out}. This causes a lower light output. Once the motor reaches its final speed, I_{motor} and I_{main} settle at normal operating conditions, thus allowing V_{out} to increase back to close to its normal value (in this situation, V_{out} does not completely recover simply because the motor is still drawing more current at its final operating speed than it did when it was off). The starting of the motor has caused a light drop that can be visible to the human eye. This can become irritating to humans, especially if the motor starts regularly throughout the day. Other loads, such as automatic spot welders and compressors, may cyclically draw current multiple times per second [13]. These loads can become exceptionally annoying to humans who need to deal with their lights flashing at a period on the order of 1 second or less.

Overview of Flicker Measurement

It is well known that the electric power grid is not a static entity. As has been shown, when loads are switched on and off, the voltage of the system inherently fluctuates. Many times, this fluctuation, while not severe enough to cause damage to loads, is severe enough to cause flicker in electric lighting. Under certain conditions, this lighting flicker can become irritating to humans and will cause complaints with which utilities will have to contend. As a result, it has been beneficial for utilities to know the extent to which their system voltages can fluctuate before complaints are expected. In the past, there have been two common methods used by utilities to attempt to predict customer complaints. The older of the two methods is the use of flicker curves. The more recent method is the use of the IEC flickermeter. In this section, these two methods are discussed.

Flicker Curves

One tool a utility uses to determine the severity of voltage fluctuations on its system is through the use of a flicker curve. Throughout the history of electric lighting, many of these curves have been created and adopted. A flicker curve usually consists of two separate plots. One plot gives the relationship between the severity of a voltage drop and the frequency of that voltage drop at which, when applied to the supply of a lamp, it will cause a flicker that is perceptible to a human. The second plot provides the relationship between the voltage drop and the frequency at which, when applied to the supply of a lamp, it will cause a flicker that is irritating to a human. Many times, these tests were conducted by subjecting a large group of individuals to lamps that were being subjected to voltage fluctuations of varying severity and frequency [13].

Every individual is different. A light fluctuation that one person is able to see may go undetected by another. Further, a light fluctuation that is intolerable for one person may not adversely affect another. Even so, by involving a large enough number of participants in the test, it has been possible to establish fairly accurate results for flicker curves. Some additional considerations beyond just voltage fluctuation magnitudes and frequencies when performing this type of study were factors such as the lighting level, the size and type of lamp being used, room decorations, the abruptness of the voltage dip, and the activities of the participants. Another factor that is difficult to test for is the idea that a person is less likely to be annoyed by a flicker caused by their own equipment [13]. If the lights in a person's home blink once an hour because their air conditioner turns on, they are less likely to become annoyed and complain to the utility than if the flicker was caused by equipment turning on at a mill down the road.

Even with all of these difficulties, flicker curves have been established which have become useful to utilities. One of the most widely recognized of the flicker curves is the General Electric (GE) Curve, which was developed around 1930 [13]. This curve is shown in Figure 1.5 below (reproduced from [14]) [14]. Many utilities have used this curve to set their voltage fluctuation standards [13]. In this figure, the two limitations of interest discussed above are readily observed. The lower line, or the "Borderline of Visibility of Flicker," is the threshold at and above which a human is expected to detect the light flicker. The upper line, or the "Borderline of Irritation," is the threshold at and above which a human is expected to find the light flicker annoying.

Through observation of the GE Flicker Curve, a few interesting trends can be found. First, it can be noted that at low frequency voltage dips, the actual magnitude of the voltage dip can be larger than at the higher frequency voltage dips. It can also be noted that at the low frequency voltage dips, the difference in percent voltage dip between where it is visible and where it is irritating is much larger than at the higher frequency voltage dips. As the frequency of the voltage dip approaches about 8 Hz, the two lines increasingly get closer. This indicates that as the frequency increases, humans become increasingly intolerant to a light flicker. This gets to the point where, at around 8 Hz, humans are intolerant of just about any flicker that they are able to see [13]. As the frequency of the voltage dip increases past around 8 Hz, both the borderline of visibility and the borderline of irritation begin to rise as both the human eye and the lamp begin to blend the light fluctuations together.

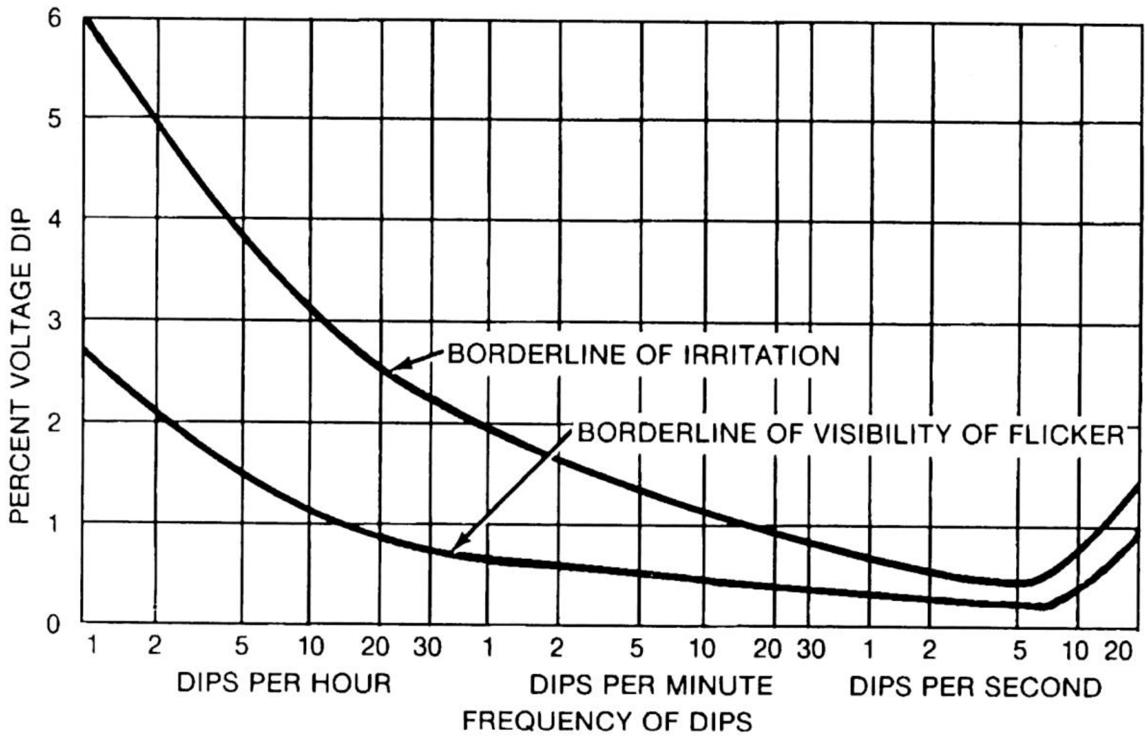

Figure 1.5: GE Flicker Curve

Another commonly used flicker curve was developed by Consolidated Edison of New York in 1958. A comparison of the Consolidated Edison flicker curve to the GE flicker curve is shown in Figure 1.6 below (reproduced from [13]) [13]. As is shown here, the "Threshold of Objection" for the Consolidated Edison flicker curve is less restrictive than the "Borderline of Irritation" for the GE flicker curve. Consolidated Edison's application of this flicker curve, as of 1979, was limited to radial secondary service and underground service networks with loads ranging from a single residence to small industries that constitute loads over 100 kW. Figure 1.7 below shows Consolidated Edison's application of the Consolidated Edison flicker curve (reproduced from [13]) [13]. As can be found in Figure 1.7, the only instance in which the voltage dip was allowed to go above 6V was when the only customer who was affected by the voltage fluctuation was the one who was causing it. If there were others affected by the voltage fluctuation, the maximum voltage drop allowed would be 6V [13]. This stems from the idea that tolerance to flicker differs when the flicker is caused by one's own equipment as compared to when it is caused by another's equipment. Even with only one service affected, the voltage drops at or above 8V were not allowed more than three times per hour. A 9V flicker that occurred very occasionally would be permitted so long as only the one service affected by the fluctuation was the one who created the drop [13].

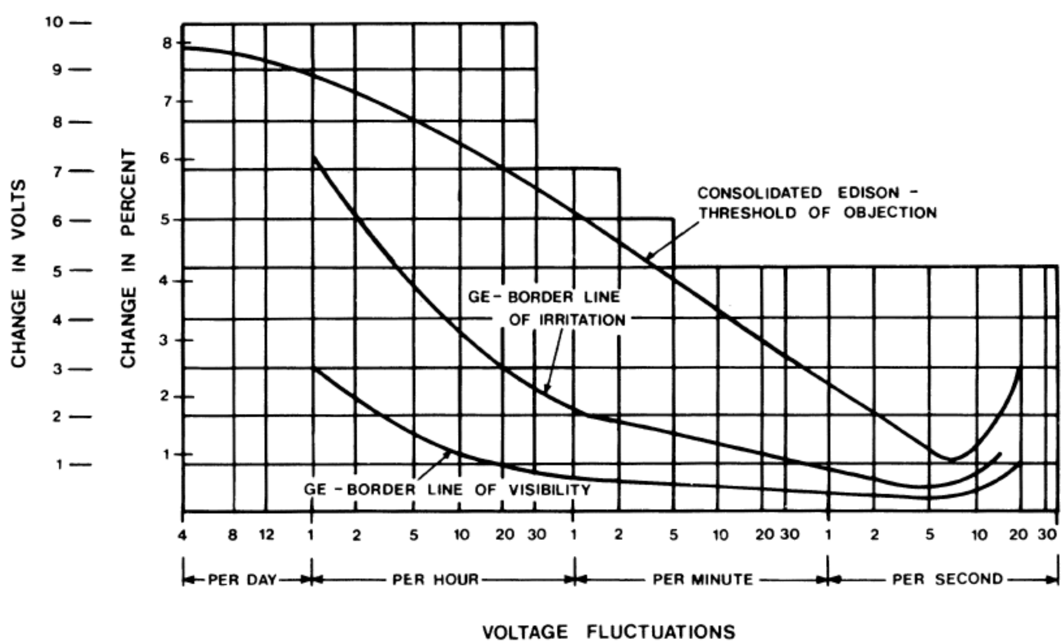

Figure 1.6: Comparison between Consolidated Edison Flicker Curve and GE Flicker Curve

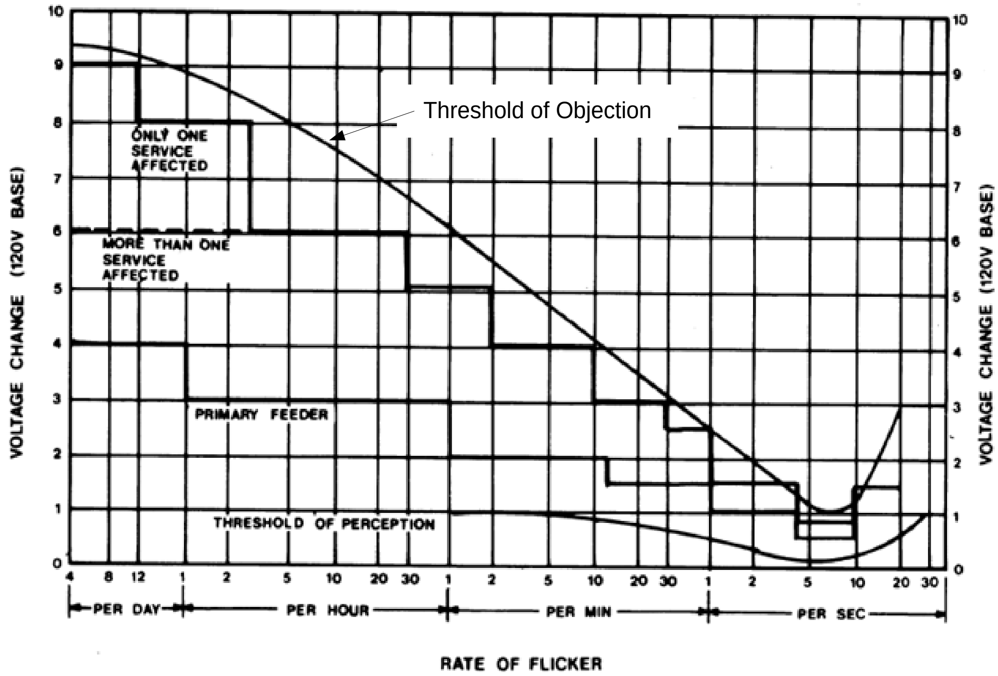

Figure 1.7: Consolidated Edison of New York Flicker Curve

Even though the Consolidated Edison flicker curve is less strict than the GE flicker curve, Consolidated Edison's limitations became more restrictive when primary lines were considered. The third line down in Figure 1.7 shows Consolidated Edison's limitations when primary lines were of concern. Through comparison between Figures 1.6 and 1.7, one can see that Consolidated Edison's restrictions for primary lines actually began to track the GE flicker curve "Borderline of Irritation" fairly well and at the very low frequency fluctuations, the Consolidated Edison restrictions were actually more restrictive than the GE flicker curve "Borderline of Irritation" [13].

Another curve that provides this information was developed in 1937 by C.P. Xenis and W. Perine through the study of 21 groups of observers. Their results are shown in Figure 1.8 below (reproduced from [13]) [13].

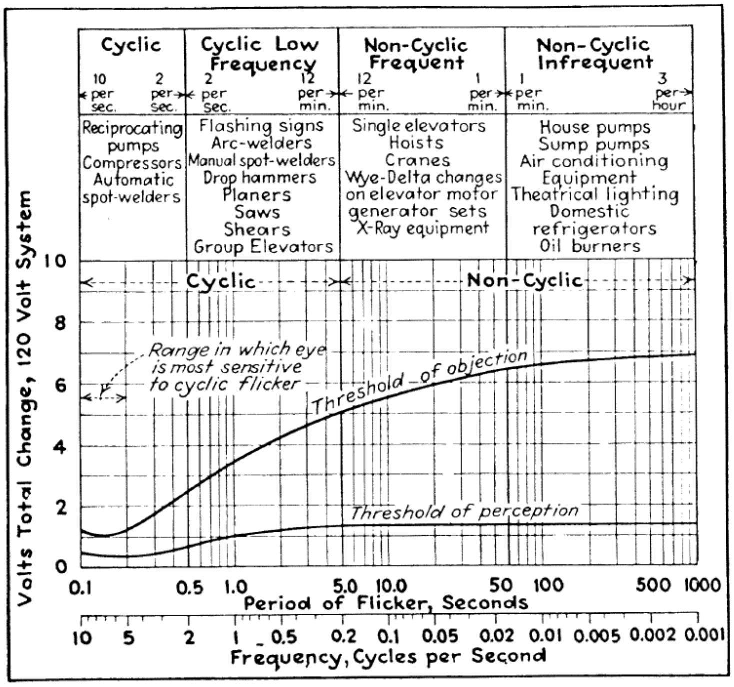

Figure 1.8: Flicker Curves Developed by C.P. Xenis and W. Perline

In 1979, a paper was written by Michael K. Walker entitled "Electric Utility Flicker Limitations" which described the regulations to which utilities of that time adhered. It was found that many of these companies either used flicker curves described here or a flicker curve similar to the ones described here to provide a basis for their regulations. Information detailing flicker regulations was provided by 109 different utilities that provided service to over 59 million metered customers. Of these 109 utilities, only six were without some form of established flicker regulation. Of the remaining companies, 35 used one of the published flicker curves described in this section, 24 used one of the published curves with other added regulations, and 44 had established their own regulations. Even within the 44 utilities who established their own criteria, 24 of them had developed their own curves that were similar to the flicker curves described. The remaining 20 limited their flicker to a set percentage [13].

Many of the companies who were surveyed mentioned that the regulations that were put in place were merely guidelines. They inform the utility where a problem may occur and then a further investigation of the situation is performed before action is taken [13].

Along with utility regulations, flicker curves have also been included in IEEE standards. IEEE Standard 141-1993 and IEEE Standard 519-1992 each provide a flicker curve as a recommendation for acceptable voltage fluctuation [15],[16]. The wide acceptance of flicker curves shows that this procedure has been able to accurately predict customer power quality complaints.

IEC Flickermeter

The flicker curves that are used in IEEE Standard 141-1993 and IEEE Standard 519-1992 appear to have been developed by testing 120V, 60W incandescent light bulbs that were subjected to rectangular voltage fluctuations. As power electronic utilization has increasingly become a larger portion of the load on the power system, another method of determining the effects of voltage fluctuation on lighting has become necessary. A method used to quantitatively evaluate the effects of arbitrary voltage fluctuation on light flicker of an incandescent bulb has therefore been developed via

IEEE Standard 1453-2004, which adopts the IEC 61000-4-15 Standard. The method of flicker measurement described in IEEE Standard 1453-2004 was to replace the flicker curve method provided in IEEE Standard 141-1993 and IEEE Standard 519-1992. The flickermeter method described in IEEE Standard 1453-2004 is best suited to evaluate flicker events that occur on a fairly frequent basis (on the order of once or more per hour) [14].

Device Description

The IEC Flickermeter is composed of an input transformer followed by a series of five functional blocks. The block diagram for the device is shown in Figure 1.9 below (reproduced from [14]) [14]. The first block of the flickermeter is used to calibrate the device and also to scale the input voltage to a reference voltage. Blocks 2, 3, and 4 are used to simulate the lamp-eye-brain response. Block 5 is used for statistical calculations of the data collected via blocks 1 through 4 [14].

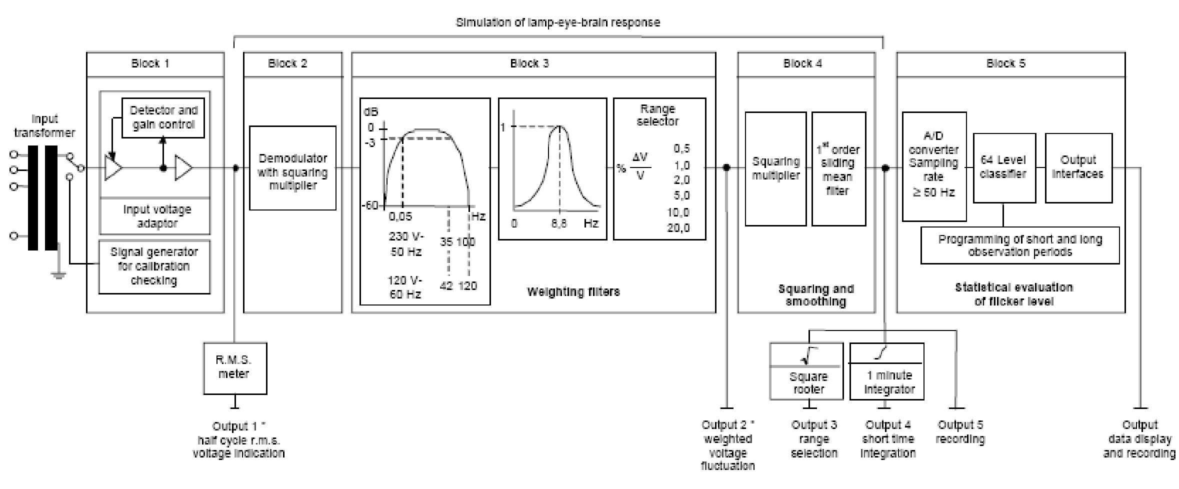

Figure 1.9: IEC Flickermeter Block Diagram

As has been mentioned, the first block to the IEC flickermeter is used for scaling of the input voltage as well as for calibration checking of the device. The scaling component of block 1 maintains the input voltage at a constant reference value [14].

Block 2 consists of a squaring demodulator. This effectively squares the output of block 1, thus simulating the behavior of an incandescent light bulb [14].

Block 3 consists of a series of two filters. The first filter is used to eliminate the unwanted double mains frequency and DC components of the signal created by the squaring demodulator in Block 2. This filter consists of a first order high-pass filter with a suggested 3-dB cut-off frequency of 0.05 Hz and a low pass 6^{th} order Butterworth filter for eliminating the double mains frequency. The Butterworth filter is suggested to have a 3 dB cut-off frequency of 35 Hz for a 230 V, 50 Hz system and a 3 dB cut-off frequency of 42 Hz for a 120V, 60 Hz system [14]. Effectively, these two filters create a band-pass filter through which only the flicker frequency should pass.

The second filter incorporated into block 3 is used to weight the voltage fluctuation to simulate the lamp-eye-brain sensitivity [14]. This filter is a band-pass filter with a very specific weighting profile centered around 8.8 Hz [17]. The value of 8.8 Hz was chosen as the center of this filter due to the results of a flicker study conducted on a group of participants. In this study, the participants were subjected to lamp flicker and questioned on whether or not the flicker was visible. From this, the frequency at which humans are most susceptible to flicker was ascertained. The results of this test were documented in IEC868 and are shown in Figure 1.10 below (reproduced from [18]) [18].

From this curve, it becomes clear that the most visible flicker for humans is around 9 Hz. Upon closer inspection, a value of 8.8 Hz was chosen as the center point for the lamp-eye-brain sensitivity band-pass filter. This filter essentially puts a stronger emphasis on the flicker frequencies at which human vision is the most sensitive.

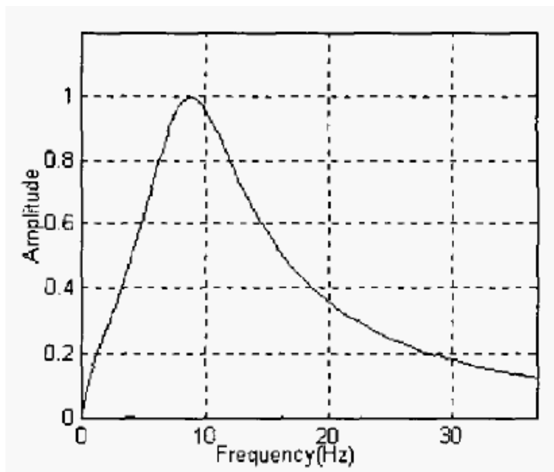

Figure 1.10: IEC Instantaneous Flicker Level Curve

The final component of block 3 is the range selector. The range selector is used in order to make the device as sensitive as possible. In the final block of the flickermeter, the data provided is divided up into 64 classes, each of which represents a certain sensation level, which is measured in units of perceptibility threshold (this will be described in more detail when block 5 is discussed). One unit of perceptibility threshold signifies that this flicker would be visible to a human. Obviously, if the fluctuation being sensed is on the order of a 0.5% dip in voltage, 64 evenly spaced classes can provide a much higher resolution than a fluctuation being sensed that is on the order of a 20% dip.

The relationship between the range selector values and the highest sensation level to be tested for, as given in IEC 61000-4-15, is shown in Table 1.1 [14].

Table 1.1: Flickermeter Range Selector

$\frac{\Delta V}{V}\%$	Sensation Levels in Units of Perceptibility Threshold
0.5	4
1	16
2	64
5	400
10	1600
20	6400

Through observation of Table 1.1, one can see the benefit of the range selector. If a voltage dip of 0.5% is expected, the highest sensation level is set to 4 perceptibility thresholds. Since 64 classes are used, there is a resolution of 0.0625 perceptibility thresholds. If a voltage dip of 20% is expected, then the highest sensation level is set to 6400, meaning that the resulting resolution is 100 perceptibility thresholds. The best resolution possible is desired, and this is provided by the range selector [14].

The requirement of 64 classes is merely a minimum, meaning that many more classes can be used. Some implementations of the flickermeter use 1024 logarithmically scaled classes or more. In these cases, the range selector is no longer necessary [17].

Block 4 of the flickermeter performs the final steps in simulating the lamp-eye-brain response. Specifically, block 4 simulates the eye-brain response. The two components of block 4, as is shown in Figure 1.9, are a squaring multiplier and a 1^{st} order sliding mean filter. The squaring multiplier simulates the non-linear eye-brain perception. The 1st order sliding mean filter simulates the storage effect of the brain. According to the IEC Standard 61000-4-15, the sliding mean filter is to be designed to have the transfer function of a first order low-pass resistance/capacitance filter that has a time constant of 300ms. The output of block 4 provides an indication as to how perceptible the flicker from an incandescent bulb subject to the voltage fluctuation at the input of the flickermeter is to a human. An output from block 4 of one unit represents a light flicker that will be on the human perceptibility threshold. Table 1.2 and Table 1.3, respectively, represent the sinusoidal and rectangular voltage fluctuations that will result in a one unit output from block 4 (reproduced from [14]) [14]

Table 1.2: Sinusoidal Voltage Fluctuations that will Create One Unit of Perceptibility from Block 4

Hz	Voltage fluctuation %		Hz	Voltage fluctuation %	
	120-V lamp 60 Hz system	230-V lamp 50 Hz system		120-V lamp 60 Hz system	230-V lamp 50 Hz system
0,5	2,457	2,340	10,0	0,339	0,260
1,0	1,463	1,432	10,5	0,355	0,270
1,5	1,124	1,080	11,0	0,374	0,282
2,0	0,940	0,882	11,5	0,394	0,296
2,5	0,814	0,754	12,0	0,420	0,312
3,0	0,716	0,654	13,0	0,470	0,348
3,5	0,636	0,568	14,0	0,530	0,388
4,0	0,569	0,500	15,0	0,593	0,432
4,5	0,514	0,446	16,0	0,662	0,480
5,0	0,465	0,398	17,0	0,737	0,530
5,5	0,426	0,360	18,0	0,815	0,584
6,0	0,393	0,328	19,0	0,897	0,640
6,5	0,366	0,300	20,0	0,981	0,700
7,0	0,346	0,280	21,0	1,071	0,760
7,5	0,332	0,266	22,0	1,164	0,824
8,0	0,323	0,256	23,0	1,262	0,890
8,8	0,321	0,250	24,0	1,365	0,962
9,5	0,330	0,254	25,0	1,472	1,042
			33,33	Test not required	2,130
			40,0	4,424	Test not required

Table 1.3: Rectangular Voltage Fluctuations that will Create One Unit of Perceptibility from Block 4

Hz	Voltage fluctuation %		Hz	Voltage fluctuation %	
	120 V lamp 60 Hz system	230 V lamp 50 Hz System		120 V lamp 60 Hz system	230 V lamp 50 Hz system
0,5	0,600	0,514	10,0	0,264	0,205
1,0	0,547	0,471	10,5	0,280	0,213
1,5	0,504	0,432	11,0	0,297	0,223
2,0	0,471	0,401	11,5	0,309	0,234
2,5	0,439	0,374	12,0	0,323	0,246
3,0	0,421	0,355	13,0	0,369	0,275
3,5	0,407	0,345	14,0	0,411	0,308
4,0	0,394	0,333	15,0	0,459	0,344
4,5	0,371	0,316	16,0	0,513	0,376
5,0	0,349	0,293	17,0	0,580	0,413
5,5	0,323	0,269	18,0	0,632	0,452
6,0	0,302	0,249	19,0	0,692	0,498
6,5	0,282	0,231	20,0	0,752	0,546
7,0	0,269	0,217	21,0	0,818	0,586
7,5	0,258	0,207	22,0	0,853	0,604
8,0	0,255	0,201	23,0	0,946	0,680
8,8	0,253	0,199	24,0	1,072	0,743
9,5	0,257	0,200	33,33	Test not required	1,67
			40,0	3,46	Test not required

Block 5 is the final component of the flickermeter and performs a statistical analysis on the data acquired from the first four blocks of the device. The block first converts the data from block 4 into a digital representation with at least 6 bits of resolution. As was alluded to in the discussion of block 3, the data is then organized into a suitable number of classes. When a flicker level of a certain amplitude occurs, a counter of the class corresponding to that amplitude is incremented by one [14]. The IEC Standard 61000-4-15 specifies that at least 64 classes be included, but many times, many more are used [17]. In dividing the data into classes, a cumulative probability function can be created that describes the frequency at which certain flicker levels occur. IEC 61000-4-15 Standard provides an example of a graph of flicker level over a certain period of time along with its corresponding cumulative probability function. For the sake of simplicity, the number of classes in this example is limited to 10. In order to convey the idea of the cumulative probability function, these graphs are given in Figure 1.11 and Figure 1.12 below. Figure 1.11 displays the flicker level over time and Figure 1.12 displays the corresponding cumulative probability function (both reproduced from [14]) [14].

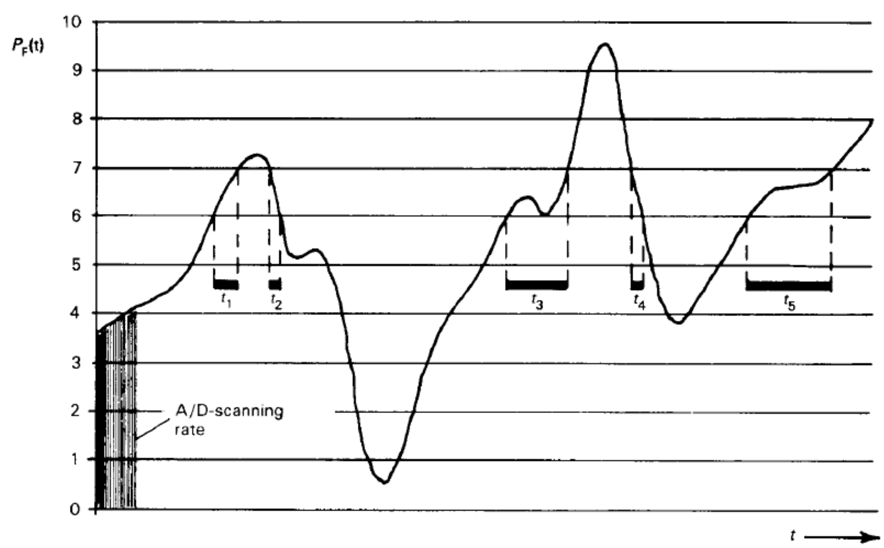

Figure 1.11: Flicker Level as a Function of Time

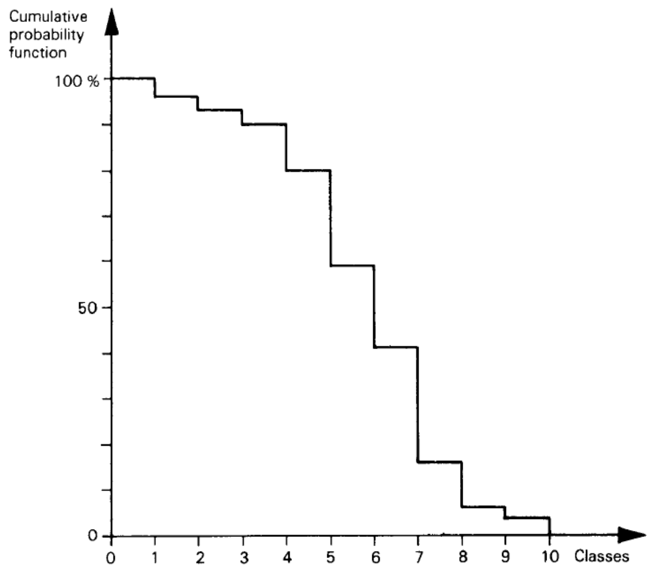

Figure 1.12: Cumulative Probability Function Corresponding to Figure 1.11

There are two time frames, designated "observations periods," for which analysis in block 5 proceeds. The two time frames are T_{short} and T_{long}. The length of time for T_{short} can be 1 minute, 5 minutes, 10 minutes, or 15 minutes. T_{long} is an integer multiple of T_{short} and can be as large as a value of 1008, which would correspond to seven days with a T_{short} of 10 minutes. Within block 5, when the length of time T_{short} has expired, the results are made available for the output and the next interval analysis is begun. Once the results from n short intervals have been acquired, the analysis on the long interval can be completed [14].

Calculation of P_{st} and P_{lt}

The outputs of the flickermeter that are of the greatest interest to the user are the values of Short-Term Perception (P_{st}) and Long-Term Perception (P_{lt}). The value of P_{st} is a measure of the flicker severity with an observation period of 10 minutes. A P_{st} value of one indicates that the light flicker experienced due to the voltage fluctuation being analyzed is on the borderline of irritation [14].

The value of P_{st} is calculated from the information given in the probability distribution function that was built in block 5. The formula for P_{st} is given in Equation 1.2 below [14].

$$P_{st} = \sqrt{0.0314P_{0.1} + 0.0525P_{1s} + 0.0657P_{3s} + 0.28P_{10s} + 0.08P_{50s}} \qquad (1.2)$$

In this equation, $P_{0.1}$, P_{1s}, P_{3s}, P_{10s}, and P_{50s} are the flicker levels that had been exceeded for 0.1%, 1%, 3%, 10%, and 50% of the time during the interval in question, respectively. The "s" that appears in the subscript of many of these flicker levels indicate that the value is to be smoothed using Equations 1.3 – 1.6 [14].

$$P_{50s} = \frac{(P_{30} + P_{50} + P_{80})}{3} \qquad (1.3)$$

$$P_{10s} = \frac{P_6 + P_8 + P_{10} + P_{13} + P_{17}}{5} \qquad (1.4)$$

$$P_{3s} = \frac{P_{2.2} + P_3 + P_4}{3} \qquad (1.5)$$

$$P_{1s} = \frac{P_{0.7} + P_1 + P_{1.5}}{3} \qquad (1.6)$$

The value for $P_{0.1}$ does not need to be smoothed due to the 0.3 second time constant in the sliding mean operator of the flickermeter [14].

The value calculated for P_{st} gives an indication of the human tolerance for the lighting flicker expected for the voltage fluctuation observed over a 10 minute interval, but there are many instances where equipment connected to a circuit will cause voltage fluctuations that have long and variable duty cycles. In such situations, a calculation that takes the longer duty cycle into account is necessary. In order to provide this information, the long-term perception calculation (P_{lt}) has been developed. P_{lt} is simply a mathematical calculation that combines a number of P_{st} values together over an appropriate period of time. The formula for P_{lt} is given in Equation 1.7 below [14].

$$P_{lt} = \sqrt[3]{\frac{\sum_{i=1}^{N} P_{sti}^{3}}{N}} \qquad (1.7)$$

In this formula, N is number of P_{st} values used in the calculation of P_{lt}. The value of N is a point of contrast between IEC Standard 61000-4-15 and IEEE Standard 1453-2004. The IEC Standard 61000-4-15 implies that the value of N is to be made appropriate to the situation. IEEE Standard 1453-2004, however, defines P_{lt} as consisting of 12 consecutive P_{st} values, which would imply a two hour time period [14].

Flickermeter Use for Determining Acceptable Flicker Levels

The purpose of the IEC flickermeter is to provide the user with an indication as to how a human would respond to the light flicker caused by the voltage variation that is observed on the system. The IEC Standard 61000-4-15, however, gives no specific recommendation as to how the user should apply the results of the flickermeter. IEEE Standard 1453-2004 does provide a recommendation for the use of the results. This

IEEE Standard gives recommended limits for values of P_{st} and P_{lt} for specific situations. One aspect of the power system that is a point of interest for the IEEE recommendations is the voltage level. The voltage levels that are considered are low voltage (LV), medium voltage (MV), high voltage (HV), and extra high voltage (EHV). The voltages that are associated with these terms are given in Table 1.4 below are consistent with the IEC 61000 series [14].

Table 1.4: Definitions of Voltage Levels

Low Voltage (LV)	LV ≤ 1kV
Medium Voltage (MV)	1kV < MV ≤ 35kV
High Voltage (HV)	35kV < HV ≤ 230kV
Extra High Voltage (EHV)	EHV > 230kV

Also under consideration when determining the recommended acceptable level for P_{st} and P_{lt} is whether new equipment is being planned for or is already installed. The recommendations provided for a system in which new equipment is being planned are defined as Planning Levels. The recommendations provided for a currently functioning system are defined as Compatibility Levels [14].

Also taken into consideration with the IEEE Standard 1453-2004 recommendation is the statistical compliance with which the recommendations should be met. The statistical compliance is given as a probability level to be attained by the system. As an example, a 95% probability level for P_{st} would mean that the P_{st} level would not exceed the recommended level more than 5% of the time. In an assessment period of one week, this would mean there were a total of 1008 ten-minute P_{st} levels.

Therefore, a 95% probability level would mean that the recommended level for P_{st} would not be exceeded for more than 50 ten-minute intervals throughout that week. In the same situation, a 99% probability level would mean that the recommended level could not be exceeded for more than 10 ten-minute intervals throughout that week [14].

The planning levels and compatibility levels recommended in IEEE Standard 1453-2004 are given in Table 1.5 and Table 1.6 respectively. For planning levels, the recommended levels for P_{st} and P_{lt} are based on a 99% probability level with a minimum assessment level of one week. For compatibility levels, the recommended levels for P_{st} and P_{lt} are based on a 95% probability level [14].

Table 1.5: IEEE 1453-2004 Recommended Planning Levels Based on a 99% Probability Level

	MV	HV-EHV
P_{st}	0.9	0.8
P_{lt}	0.7	0.6

Table 1.6: IEEE 1453-2004 Recommended Compatibility Levels Based on a 95% Probability Level

	LV and MV
P_{st}	1.0
P_{lt}	0.8

Prior Research

There has been research conducted in the past in order to help determine how compact fluorescent lamps compare to incandescent lamps under flicker conditions. A few papers have been written on the topic of how interharmonics affect compact fluorescent lamps. While a harmonic is defined as an integral multiple of the fundamental frequency, an interharmonic is a non-integral multiple of the fundamental frequency [19]. A description of one such experiment is given in [19]. In this research, the authors propose a system in which a series of voltage waveforms that have been corrupted by interharmonics are applied to compact fluorescent lamps. The light output from the tested lamps is observed using a photodiode. The proposed system then compares this light output to a reference of perceptible flicker from an incandescent lamp. The magnitude of the interharmonic is increased until the light output from the compact fluorescent is within 0.02% of the reference. In this way, the system records the magnitude of the interharmonic that will create a perceptible light flicker in a compact fluorescent lamp. Once the magnitude of a particular interharmonic has been found, the next interharmonic of interest is put through the same process. In this way, the automated system can perform the laborious task of testing the lamp without the need for human intervention [19].

From this testing, plots were produced that represented the necessary interharmonic magnitude at a particular interharmonic frequency to create a light flicker within 0.02% of the incandescent reference. In the research described in [19], three compact fluorescent lamps (with power consumptions of 5W, 11W and 15W) were placed in this system and analyzed. Three tests were performed for each lamp. The first test described interharmonics around the fundamental frequency of 50Hz, the second around the 3rd harmonic of 150Hz, and the third around the 5th harmonic of 250Hz. The results of the three tests are shown in Figures 1.13 through 1.15 below (reproduced from [19]), respectively [19]. For a reference, Figure 1.16 gives the interharmonic voltages necessary to cause perceptible light flicker in an incandescent lamp (reproduced from [19]) [19].

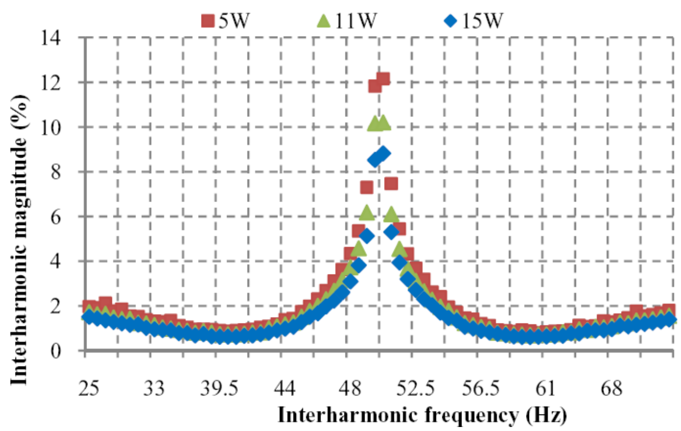

Figure 1.13: Interharmonics about the Fundamental Frequency that cause Flicker in CFLs

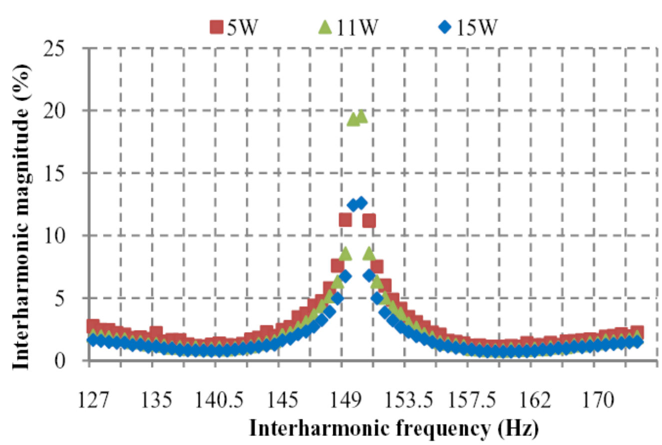

Figure 1.14: Interharmonics about the 3rd Harmonic that cause Flicker in CFLs

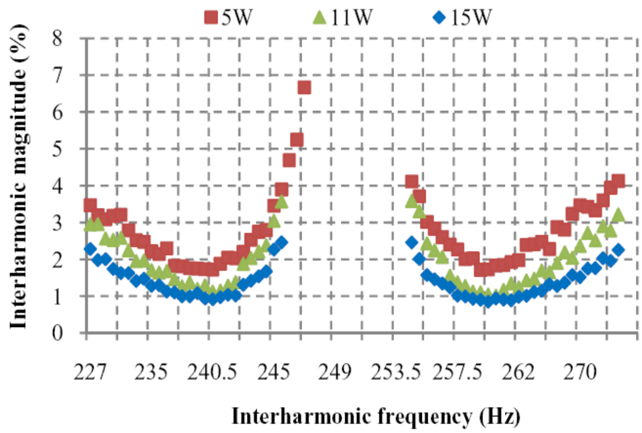

Figure 1.15: Interharmonics about the 5th Harmonic that cause Flicker in CFLs

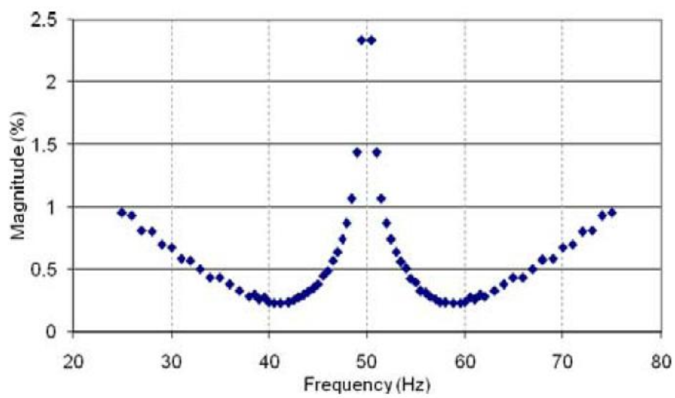

Figure 1.16: Interharmonics about the Fundamental Frequency that cause Flicker in an Incandescent Lamp

From these results, the authors of [19] were able to conclude that the lamps were most capable of creating perceptible light flicker at interharmonics that were around 9Hz away from the harmonic component. This interharmonic required the smallest magnitude to reach the reference value. Another conclusion from this paper is that compact fluorescent lamps are more robust to interharmonic voltage disturbances than are incandescent lamps. This conclusion comes from the fact that the magnitudes necessary from the interharmonics to produce flicker within the reference tolerance for CFLs was larger than those needed to produce flicker within the reference tolerance for incandescent lamps [19]. A similar result is found in [2].

Another interesting observation found in [2] resulted from the study of fluorescent lamps with electromagnetic ballasts. According to the paper, while the performance of a fluorescent lamp with an electromagnetic ballast is comparable to that of a fluorescent lamp with an electronic ballast at the fundamental frequency, when the 3rd and 5th harmonics are observed, the lamp with the electromagnetic ballast has a superior performance [2]. The studies performed in [19] and [2] were performed on lamps designed for use on a 50Hz system [19],[2].

A comparison of incandescent lighting, fluorescent lighting supplied by an electromagnetic ballast, desk lamps, and compact fluorescent lamps is presented in [20]. In this study, the lamps tested were exposed to a 10Hz voltage fluctuation with a sag depth of varying magnitude. In this test, it was found that the compact fluorescent lamps were the least sensitive lamps to the voltage flicker of those tested. It was also found that the fluorescent lamps with the electromagnetic ballasts performed the worst when fed the voltage fluctuation [20]. This is an interesting contrast with the results of the study presented in [2], where the fluorescent lamp with the magnetic ballast was equal to or superior to the lamps with electronic ballasts when interharmonics were considered [2]. The study performed in [20] was limited to a modulation frequency of 10Hz and was performed on bulbs used on a 60Hz system [20].

CHAPTER 2: EXPERIMENTAL SETUP AND EQUIPMENT

A testing strategy had to be developed to accurately measure the way in which the light output of the lamps in question would be affected by voltage fluctuations imposed on the lamp. In order to properly compare the light output from an incandescent lamp to that from a compact fluorescent lamp, a testing system had to be designed that would allow for each lamp to be subjected to the same voltage fluctuations without being influenced by any outside factors. Through the use of a sensor, the light output had to be converted into a form that could be mathematically analyzed. In this section, the system that was designed and used is presented.

Experimental System Description

Testing Apparatus

The system used to test the various light bulbs in question consisted of the light bulb, an ELGAR SW5250A arbitrary waveform generator, an Intersil ISL29101 light sensor, an NI PCI-6250 data acquisition (DAQ) card, a Tektronix P5200 high voltage differential probe, a computer, and an enclosure. The light bulb under test and the light sensor were placed inside the enclosure to eliminate ambient light from affecting the results. The inner surfaces of the enclosure were lined with black paper to reduce light reflection.

The test data was collected by the data acquisition card. This data included the output of the light sensor, the power supply of the light sensor, and the voltage waveform imposed upon the lamp under test. According to the specification sheet for the NI PCI-

6250 data acquisition card, the maximum analog input voltage with respect to earth ground is 11V [21]. The light sensor output was at a voltage on the order of 0.5V and the sensor power supply was at a voltage of 3V. Therefore, these could both be directly applied to the data acquisition card. The voltage waveform that powered the light bulb, however, was on the order of 120Vrms, and therefore, was connected to the data acquisition card through the voltage isolator, which scaled the voltage down by a factor of 500.

The acquisition of the data was performed through the use of a National Instruments Virtual Instrument (VI) that was written in National Instruments LabVIEW 8.6. This VI stored the data as a text file which could later be opened in MATLAB for analysis.

A representation of the testing apparatus is given in Figure 2.1 below.

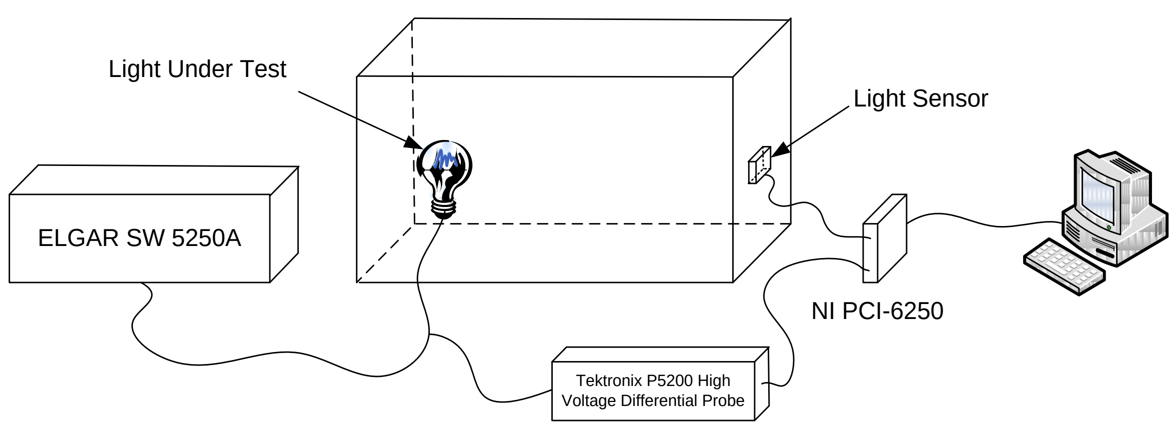

Figure 2.1: Testing Apparatus

ISL29101 Light Sensor Description

One of the requirements of this research was that the tests gave an accurate indication as to how a human would perceive the light and the lighting flicker. In order to do this, a sensor had to be selected that gave an output based on the human eye response, shown previously in Figure 1.3. Many light sensors on the market today provide filtering that limits its response to visible light, thus reducing the influences of ultraviolet and infrared light, but only a small subset of these can filter the light close to that of the human visual spectrum. One such light sensor that can provide accurate filtering is the ISL29101. As is shown in the sensor's specification sheet, the spectral response of the sensor tracks the human eye response well. Figure 2.2 below shows the relationship between the ISL29101 spectral response and the human eye response (reproduced from [22]) [22].

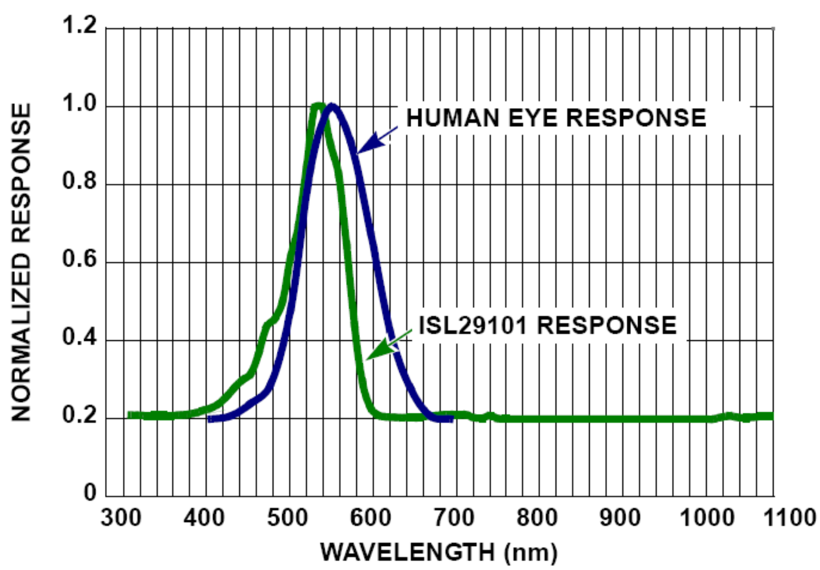

Figure 2.2: Comparison of the ISL29101 Response to the Human Eye Response

Since the ISL29101 spectral response is very close to the human eye response, the sensor will detect the light given off from incandescent lighting as being nearly identical to the light given off by fluorescent lighting, assuming that the two lights emit the same number of lumens. The relationship for the ISL29101 output for three lighting technologies (incandescent, halogen, and fluorescent) is given in Figure 2.3 below (reproduced from [22]) [22]. The fact that the outputs for the three lighting technologies deviate slightly from one another is to be expected since the light sensor's spectral response is not a perfect match for the human eye response. Even so, they give very similar results, especially when one notes the fact that the lighting dealt with in this study is on the order of 300lux.

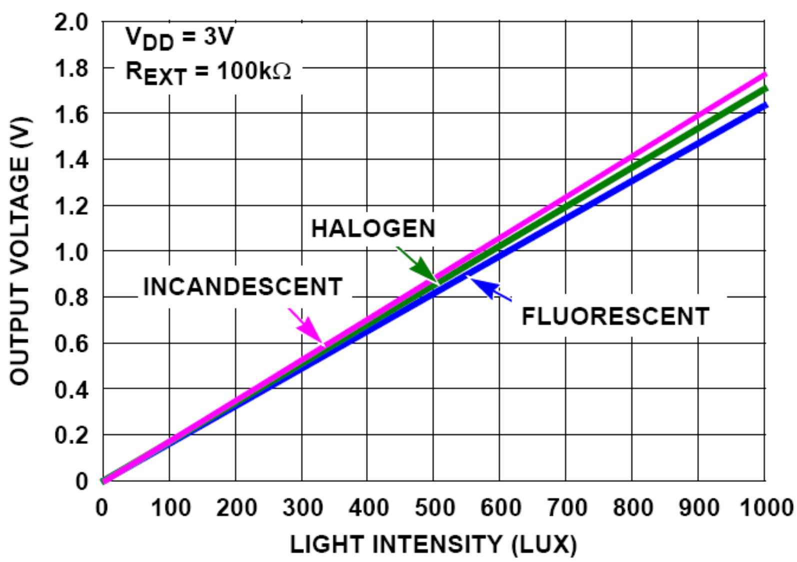

Figure 2.3: ISL Voltage Output as a Function of Light Input for Three Lighting Technologies

Another advantage of the ISL29101 is that the sensor output provides a close to linear representation of light intensity. This means that the percentage change in voltage output corresponds to the same percentage change in light intensity. Since this study recorded the percentage change in lighting, the fact that the output is linear means that the slight difference between the outputs for incandescent lighting and fluorescent lighting will not affect the results. A percentage change in voltage output will indicate the same percentage change in light output independent of the slope of the trend.

Finally, the response time of the light sensor was found to be fast enough to collect all necessary data. According to the specification sheet for the device, the sensor can respond to a step change of 300lux in approximately 600us. This value represents 1/14 of a cycle of light that is supplied from a 60Hz system (a 60Hz system produces a light oscillating at 120 Hz) for a step change in light, which would represent a worst case scenario. In actuality, this research applied smooth changes in light. Since these changes were slower than the step changes for which the specifications were written, it can be expected that the sensor will be able to track these smoother changes even more accurately than is presented in the specifications.

In order to test the response time of the sensor to these smooth changes, an LED was connected to a function generator. The voltage to the LED was fluctuated at 120Hz with a DC offset to cause a 120Hz light fluctuation indicative of that which would be found in the incandescent lamp or compact fluorescent lamp connected to a 60Hz system. It was found that a delay of merely 230us was observed. This is only 1/36 of a light cycle. Therefore, the response time of the sensor was found to be desirable for the tests to be performed.

ELGAR SW 5250A

The ELGAR SW 5250A is an arbitrary waveform generator that can be used to simulate disturbances in a power system. In the testing performed in this research, the ELGAR was used to generate voltage fluctuations that would be applied to the lamps.

In order to make the operation of the ELGAR easier and more time efficient, an interface was created in Visual Basic 6.0. This interface allowed the user to select the desired test and then, depending upon the test chosen, select the properties of that test. This eliminated the need to reprogram the ELGAR each time a new test was run. A description of this interface is provided in Appendix A.

Data Acquisition System

System Overview

The central component of the data acquisition system used in this research was the NI-PCI 6250 DAQ card. This DAQ card allowed the use of 8 differential channels to be sampled at a maximum of 1 MS/s, meaning that if all 8 channels were utilized, each could theoretically be sampled at 125 kS/s [21]. The actual sample rate that was possible was determined by the composition of the VI that controlled the system. Blocks used in the VI needing more processing time would lower the attainable sample rate.

In the testing performed in this research, the data that was sampled included the light sensor output, the voltage provided to the lamp under test, and the power supply to the light sensor at three different locations. Therefore, five total channels were sampled. The sample rate that was chosen for the data acquisition of most tests was 20 kS/s, which allowed for approximately 333 samples per electrical cycle. Tests that required data acquisition for longer periods of time were found to create large files that were difficult to process when sampled at 20 kS/s. These tests were therefore sampled at 10 kS/s, which allowed for approximately 167 samples per electrical cycle.

The NI-PCI 6250 DAQ card allowed for various analog input ranges, each with corresponding absolute accuracies and sensitivities. Accuracy was defined as how close to the actual value the DAQ card could measure whereas sensitivity was defined as how small of a change the DAQ card could accurately detect. For the tests performed, the lamp input voltage (after being scaled down by the voltage isolator) was sampled on the scale of -1V to 1V. This scale corresponded to an absolute accuracy of 220μV and a sensitivity of 12.8μV [21]. The light sensor output and light sensor power supply channels were sampled on the scale of -5V to 5V. This scale corresponded to an absolute accuracy of 1.010mV and a sensitivity of 56μV [21]. Since the test was conducted to determine the fluctuation in light as a function of a fluctuation in voltage, the most important DAQ card specification was that of the sensitivity of the channel taking data from the light sensor output. The sensitivity of 56μV was found to be acceptable for giving accurate results.

Data Acquisition Virtual Instrument

In order to record the data acquired by the DAQ card, a VI was written in National Instruments LabVIEW 8.6. The block diagram and front panel for this VI are shown in Figure 2.4 and Figure 2.5 respectively.

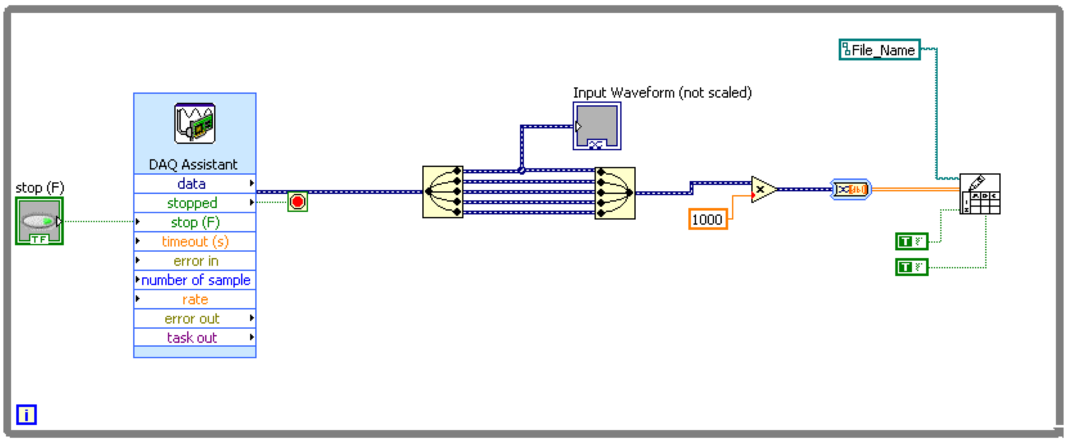

Figure 2.4: VI Block Diagram

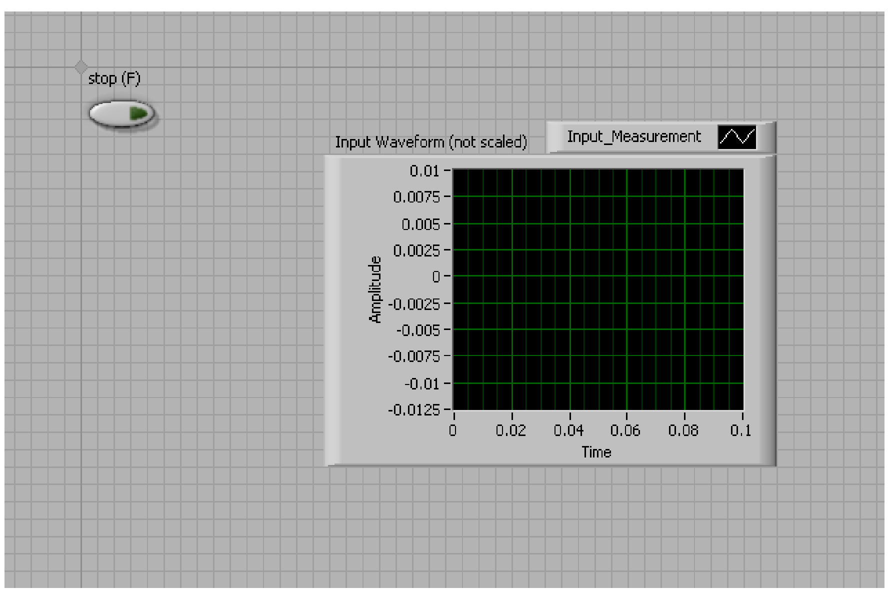

Figure 2.5: VI Front Panel

The VI shown in Figure 2.4 and Figure 2.5 converts the acquired data into a text file that can later be imported into MATLAB for analysis. The front panel was kept as simple as possible for the purposes of utilizing a desired sample rate. The one output on the front panel is a graph of the input waveform that is applied to the lamp under test. Since there is no communication between the ELGAR and the VI, the data acquisition must be started and stopped by the user. This graphical display of the input waveform informed the user as to when the input waveform was turned off so that the data acquisition could be stopped.

Another point of interest on the block diagram is the multiplication of the data by 1000. It was found that the block that was used to convert the data to a text file could only record values down to the millivolt, i.e. it only allowed three digits to the right of the decimal place. As has been discussed, it was known that the DAQ card had a sensitivity in the range of tens of microvolts. In order to obtain the most accurate data possible, the data was multiplied by 1000 so that values in the microvolt range would be placed in the third digit to the right of the decimal point. Once the data was imported into MATLAB, it was divided by 1000 to get it back to its original value.

CHAPTER 3: EXPERIMENTAL PROCESS

Tests Performed

In this research, several separate tests were performed in order to compare the incandescent lamp to the compact fluorescent lamp. These were the steady state tests, the short duration tests, and non-rectangular tests. Once these tests were complete, comparisons were run to create a new flicker curve for compact fluorescent lamps. All of these tests were performed on two different lighting technologies, i.e. incandescent lamps and compact fluorescent lamps. The lamps chosen are commonly available lamps in the United States and are designed for installation within a 120 V, 60 Hz system. The CFLs are non-dimmable. The tested lamps are summarized in Table 3.1 below.

Table 3.1: Lamps Tested

Lamp Identification	Light Technology	Rated Power Consumption (Watts)	Light Output (lumens)	Light Characteristics
A	Incandescent	60	840	Soft White
B	Incandescent	60	840	Soft White
C	Incandescent	60	850	Soft White
D	Incandescent	60	780	Soft White, Double Life
E	CFL	13	825	Soft White
F	CFL	14	800	Soft White
G	CFL	13	900	Soft White
H	CFL	13	825	Soft White
I	CFL	14	900	Soft White
J	CFL	14	800	Soft White
K	Incandescent	60	630	Color Enhanced Full Spectrum
L	CFL	14	650	Natural Light
M	CFL	14	800	Daylight
N	CFL	14	700	Daylight
O	CFL	14	800	Bright White

The main focus of this research was on soft white light bulbs. However, for completeness, some lamps of alternate colors were also tested for their flicker characteristics. Performing an exhaustive study on each of the lamps listed in Table 3.1 would have taken an inadmissible amount of time. Therefore, as will be described in more detail later, exhaustive testing was performed on Lamps A, B, E, F, and H. The remaining lamps were studied in selected tests in order to determine whether or not there were any significant differences between these and Lamps A, B, E, F, and H.

Steady State Tests

The first test performed on the lighting sources in question was a steady state test. In this test, a rectangular voltage dip was applied to the voltage input to the lamp and the lamp was given a sufficient amount of time to respond. The light response was recorded via the data acquisition card and later imported into MATLAB for analysis.

The two obvious considerations for the steady state tests were the depth and duration of the applied voltage sag. The choice of sag depths was taken directly from the IEC 61000-4-15 Standard. As a testing procedure on a 120 V, 60 Hz system for the flickermeter described in this standard, the IEC provides seven voltage fluctuations corresponding to seven sag durations. (The standard also provides testing procedures for a 230 V, 50 Hz system, but those are not of interest in this research.) The standard states that each voltage fluctuation along with its corresponding sag duration should result in a P_{st} value of 1.00 ± 0.05. The values provided by the IEC Standard 61000-4-15 are shown in Table 3.2 below [14]. In the tests performed, the rectangular changes per minute were not of interest. The voltage changes, however, provided a good basis for the sags that were to be imposed on the lamps. As has been mentioned, and exhaustive study was performed on Lamps A, B, E, F, and H. Therefore, data for these lamps was collected for each voltage change mentioned in Table 3.2. The remaining bulbs were exposed to only the 4.834% voltage drop and the 1.044% voltage drop.

Table 3.2: Flickermeter Test Conditions as Per IEC61000-4-15

Rectangular Changes Per Minute*	Voltage Change (%rms)
1	3.166
2	2.568
7	1.695
39	1.044
110	0.841
1620	0.547
4800	4.834

The duration of the voltage sag was determined by observing the amount of time it took for the light output of the lamp to steady out once a voltage fluctuation had occurred. It was important in the testing to allow an appropriate amount of time for the light sources to reach a steady value after the fluctuation occurred so that the final results would be as accurate as possible. Figure 3.1 and Figure 3.2 below show the output of the light sensor for incandescent lamps A and B when a voltage sag of 4.834% was applied to the lamp supply. Figure 3.3 through Figure 3.5 show the output of the light sensor for three compact fluorescent lamps when the same voltage sag of 4.834% was applied to the lamp supply. The 4.834% voltage sag was used to determine the necessary amount of time for stabilization since it would make logical sense that the largest voltage applied would cause the longest settling time.

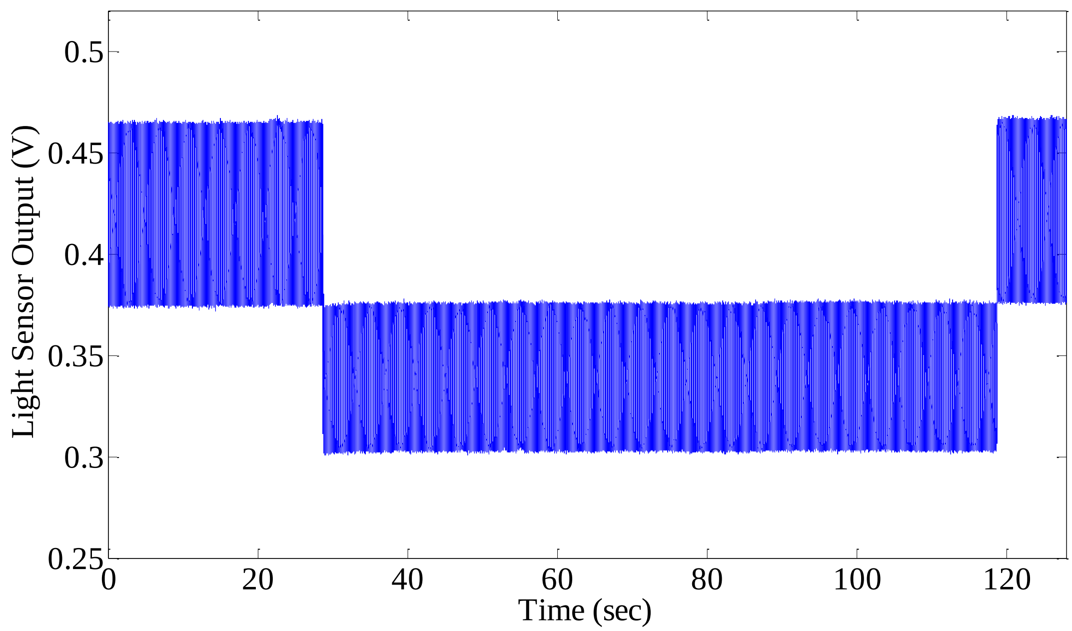

Figure 3.1: Light Sensor Output for a Voltage Sag of 4.834% on Incandescent Lamp A

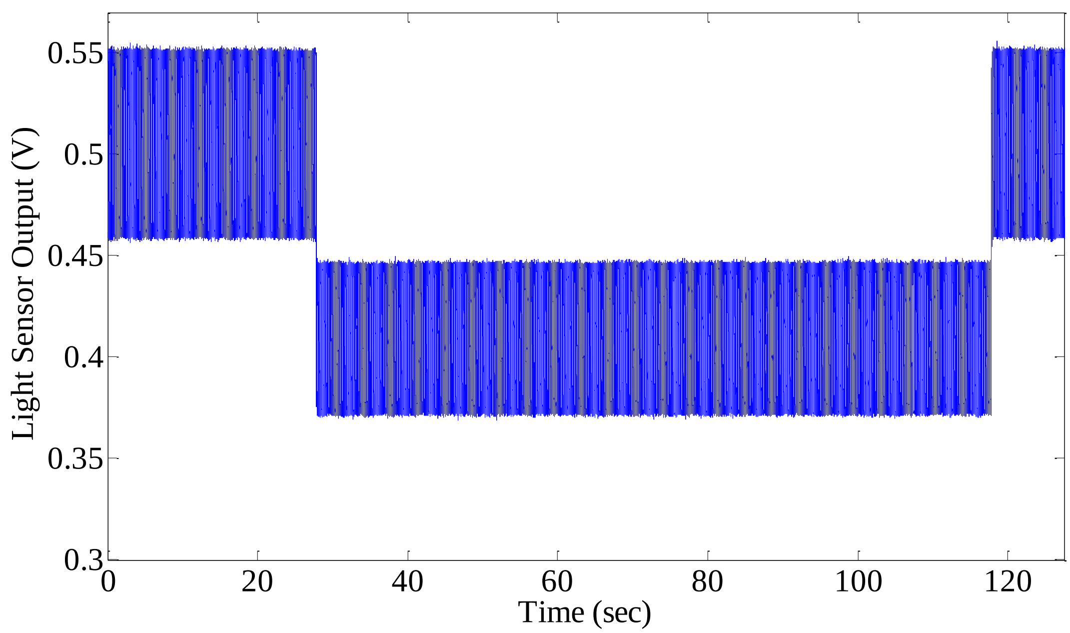

Figure 3.2: Light Sensor Output for a Voltage Sag of 4.834% on Incandescent Lamp B

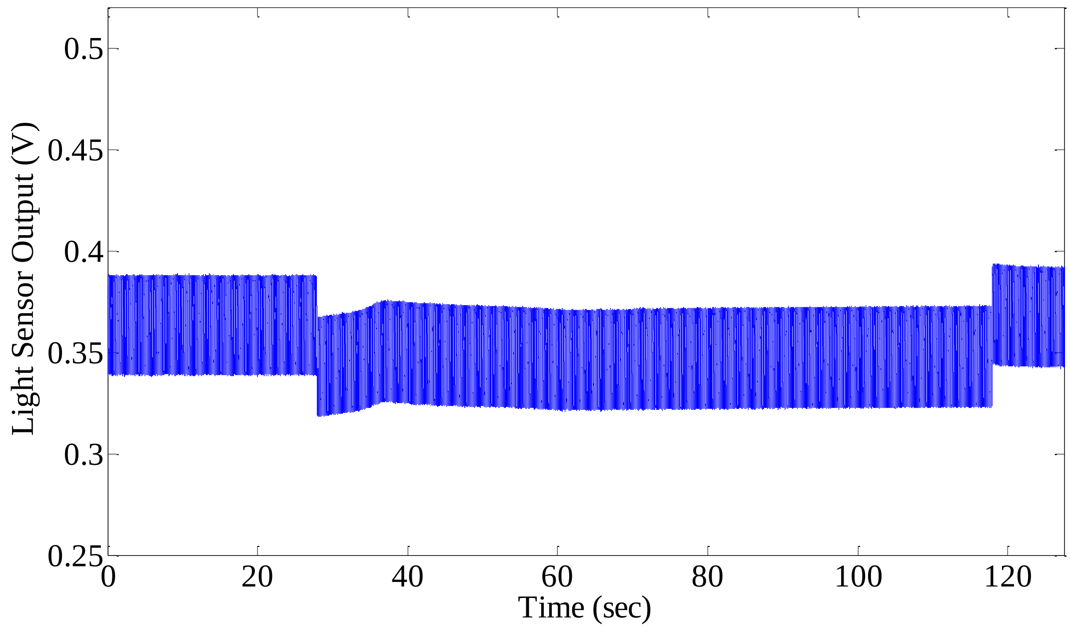

Figure 3.3: Light Sensor Output for a Voltage Sag of 4.834% on CFL Lamp E

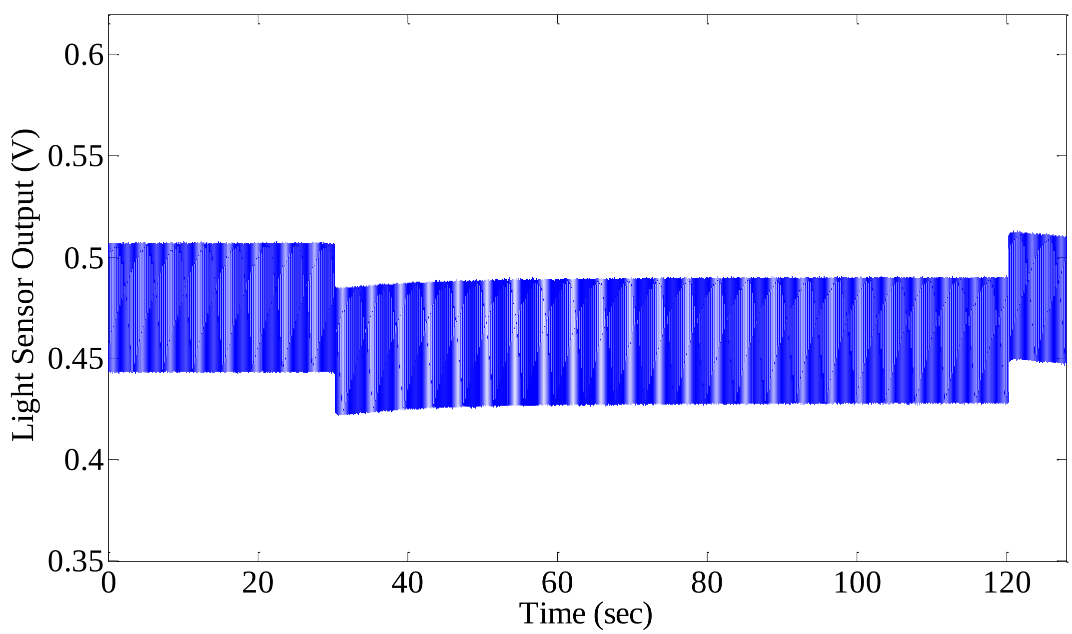

Figure 3.4: Light Sensor Output for a Voltage Sag of 4.834% on CFL Lamp F

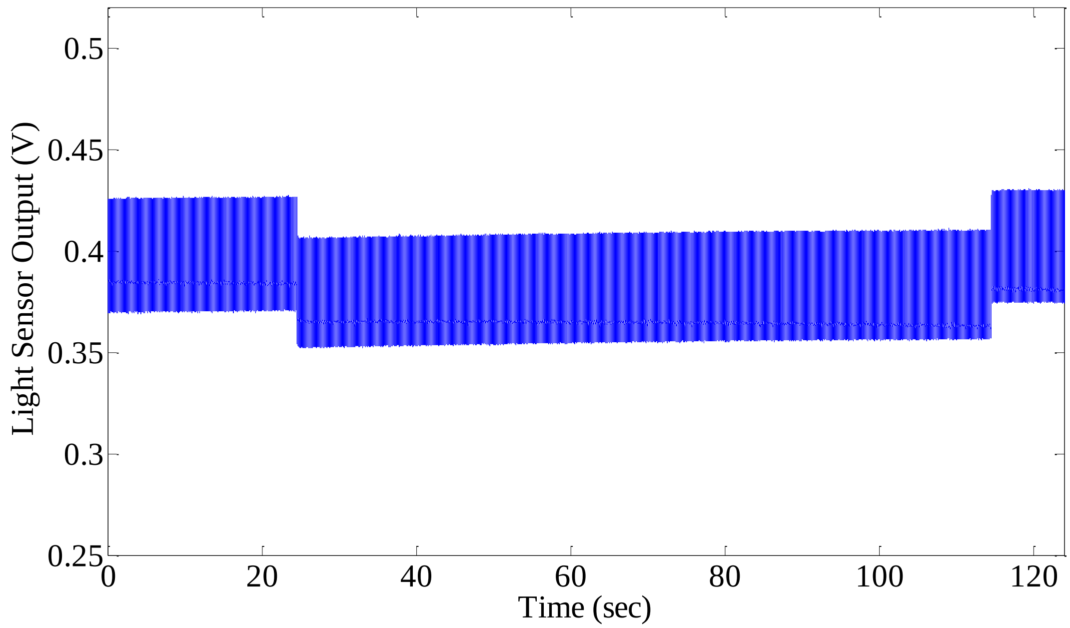

Figure 3.5: Light Sensor Output for a Voltage Sag of 4.834% on CFL Lamp H

Through observation of Figure 3.1 through Figure 3.5, it is obvious that the incandescent lamps settle almost instantaneously whereas the compact fluorescent lamps take some time once the voltage fluctuation has occurred to reach a new steady state. This observation is not surprising since it was mentioned that CFL bulbs have a run-up period at start-up whereas incandescent bulbs start nearly instantly. It would make sense that voltage fluctuations could cause similar results. Studies of these plots and similar plots for the remaining bulbs dictated the necessary length of time for the applied voltage sag.

Short Duration Tests

The short duration tests were performed in order to determine how an incandescent lamp and a compact fluorescent lamp would respond to a voltage fluctuation that lasted only a few electrical cycles. The lamps were fed a rectangular voltage fluctuation that would quickly recover. In testing Lamps A, B, E, F, and H, tests were performed with both 4.834% and 1.044% voltage sags lasting 1, 3 and 10 electrical cycles. For the remaining lamps, the 10 cycle tests were omitted.

Non-Rectangular Tests

In a real system, the great majority of voltage fluctuations are not the perfectly rectangular fluctuations that have been assumed in both the steady state and short duration tests performed. As a result, it is desired that a comparison between an incandescent lamp and a CFL also be performed with voltage fluctuations that are more indicative of fluctuations that may be observed on a real system. In order to perform this task, new voltage fluctuations were applied to the lamps. These fluctuations were obtained from [23]. In this paper, a design is proposed for a device that is able to suppress the voltage sag caused by air conditioners and heat pumps. Included in the paper are voltage sags that were measured at startup of a 2.5 ton heat pump, a 4 ton air conditioner, and a 5 ton air conditioner in a laboratory environment. These sags are presented in Figures 3.6 through 3.8 (reproduced from [23]) [23]. Of interest in these graphs is the fact that the largest unit (the 5 ton air conditioner) has the shortest duration voltage fluctuation. This is due to the fact that this particular unit contained a torque assist [23]. In each of these figures, the baseline voltage fluctuation, which was acquired without any compensation, is presented. This is the fluctuation that would be present if no action was taken to alleviate the sag. Also presented are the compensated voltage fluctuations [23]. In the tests performed here, the waveforms of interest were the baseline waveforms.

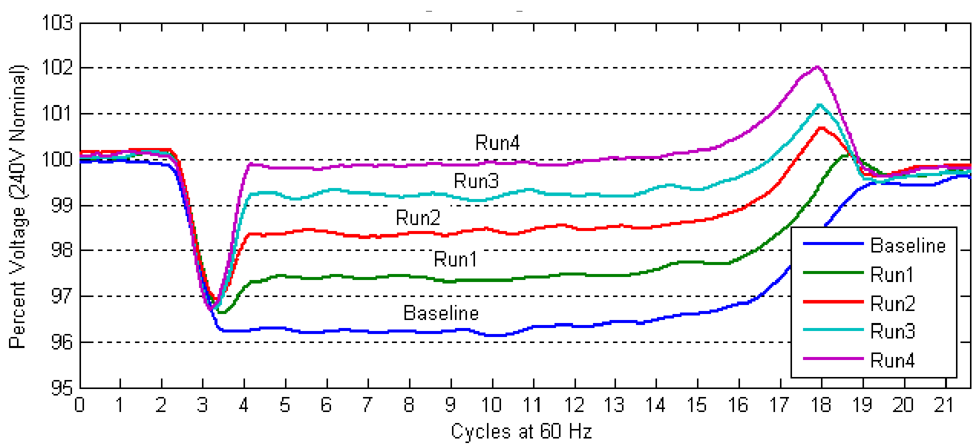

Figure 3.6: Voltage Fluctuation Due to a 2.5 Ton Heat Pump

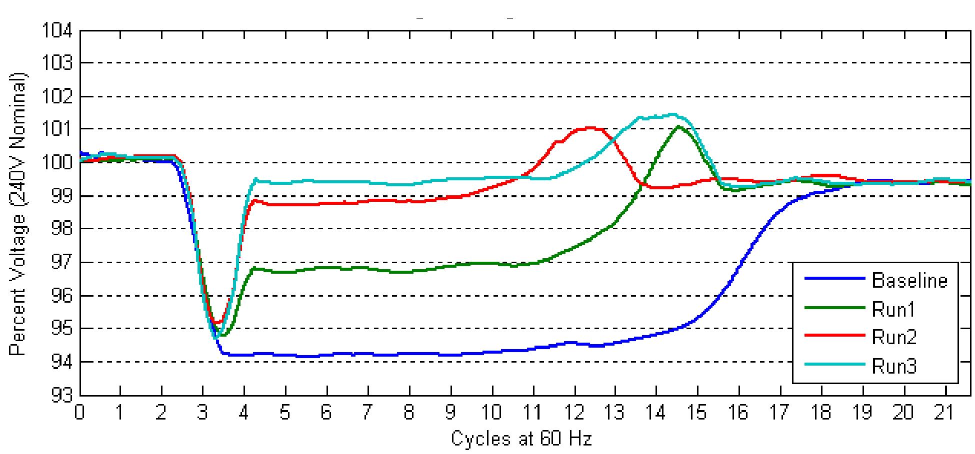

Figure 3.7: Voltage Fluctuation Due to a 4 Ton Air Conditioner

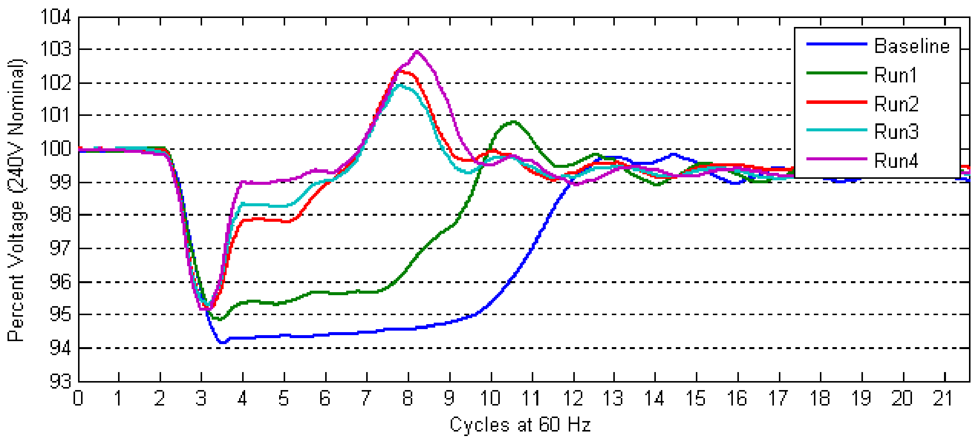

Figure 3.8: Voltage Fluctuation Due to a 5 Ton Air Conditioner

In order to ease the process of simulating these fluctuations using the ELGAR, the fluctuations were first linearized. They were then programmed into the ELGAR and applied to the lamps. The linearized fluctuations for the 2.5 ton heat pump, the 4 ton air conditioner, and the 5 ton air conditioner are shown in Figures 3.9 through 3.11 respectively. These waveforms present actual data taken from the ELGAR and analyzed in MATLAB. In order to perform this analysis, an rms value of each cycle was calculated and plotted, thus giving the points of change in the graph a sharper appearance than would actually be expected.

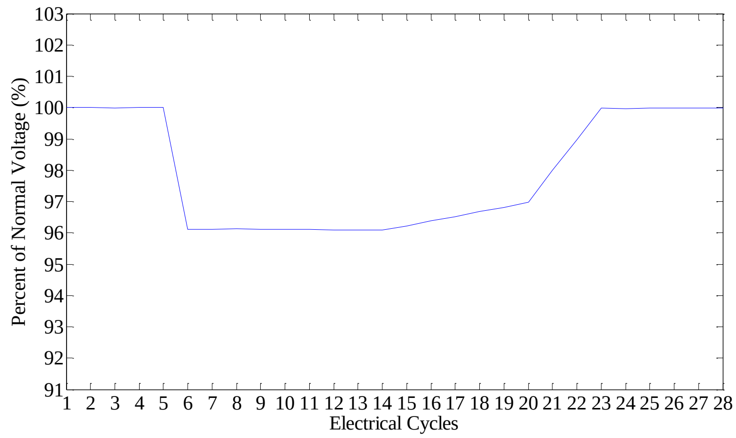

Figure 3.9: Simulated Voltage Fluctuation for a 2.5 Ton Heat Pump

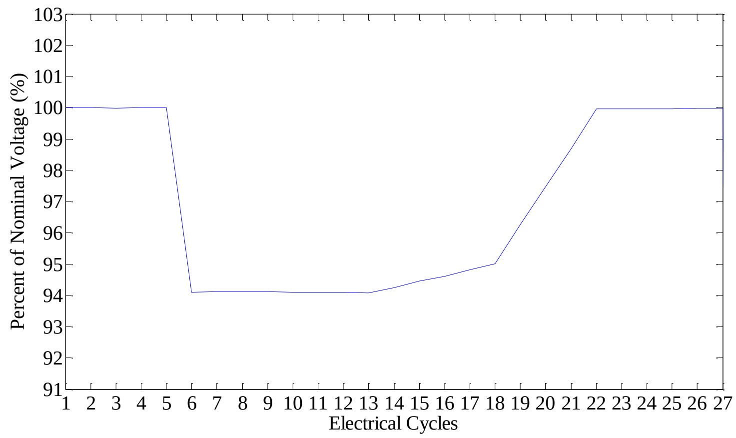

Figure 3.10: Simulated Voltage Fluctuation for a 4 Ton Air Conditioner

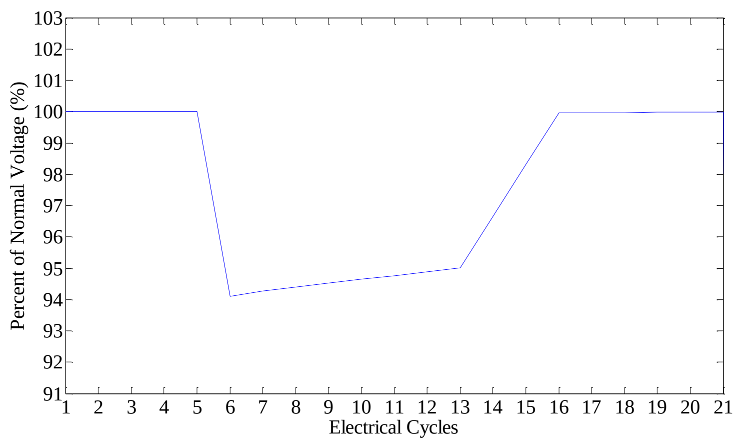

Figure 3.11: Simulated Voltage Fluctuation for a 5 Ton Air Conditioner

In the non-rectangular tests, results from all three voltage fluctuations were collected for Lamps A, B, E, F, and H. The remaining bulbs were tested only with the 4 ton air conditioner.

Analytical Procedure

The light that is output from both an incandescent lamp and a compact fluorescent lamp inherently contains oscillations. Current flows through the incandescent lamp filament during both the positive and negative half cycles of the voltage waveform, thus heating the filament to its maximum temperature and causing a maximum light output two times for each electrical cycle. When the supply voltage approaches 0V, the filament cools slightly, thus causing the light output to decrease. Therefore, the light output of an incandescent bulb oscillates at twice the system frequency.

The light output from a compact fluorescent lamp also oscillates at twice the system frequency, but for a different reason. The CFL light output follows the DC bus of the rectifier. Since the rectifiers in a CFL ballast use a full bridge topology, the DC bus peaks for both the positive and negative half cycles of the system voltage. When the voltage of the DC bus increases, the output voltage of the inverter increases and pushes a larger current through the tube of the bulb, thus causing a higher light output. Characteristic light outputs from an incandescent lamp and a compact fluorescent lamp are given in Figure 3.12 and Figure 3.13, respectively.

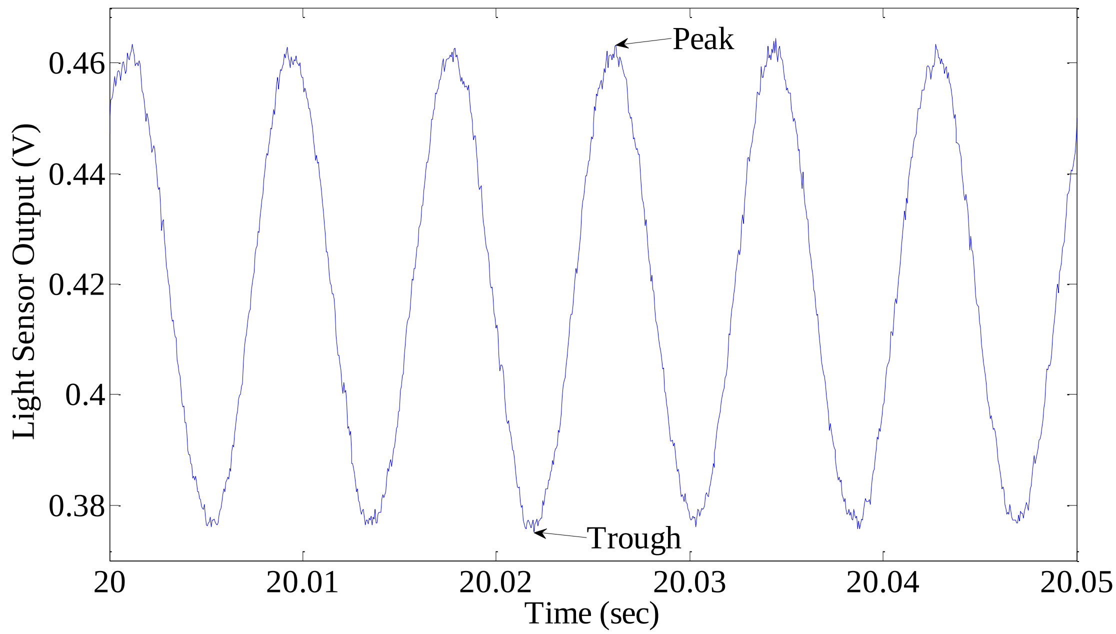

Figure 3.12: Characteristic Light Output from an Incandescent Lamp (Lamp A)

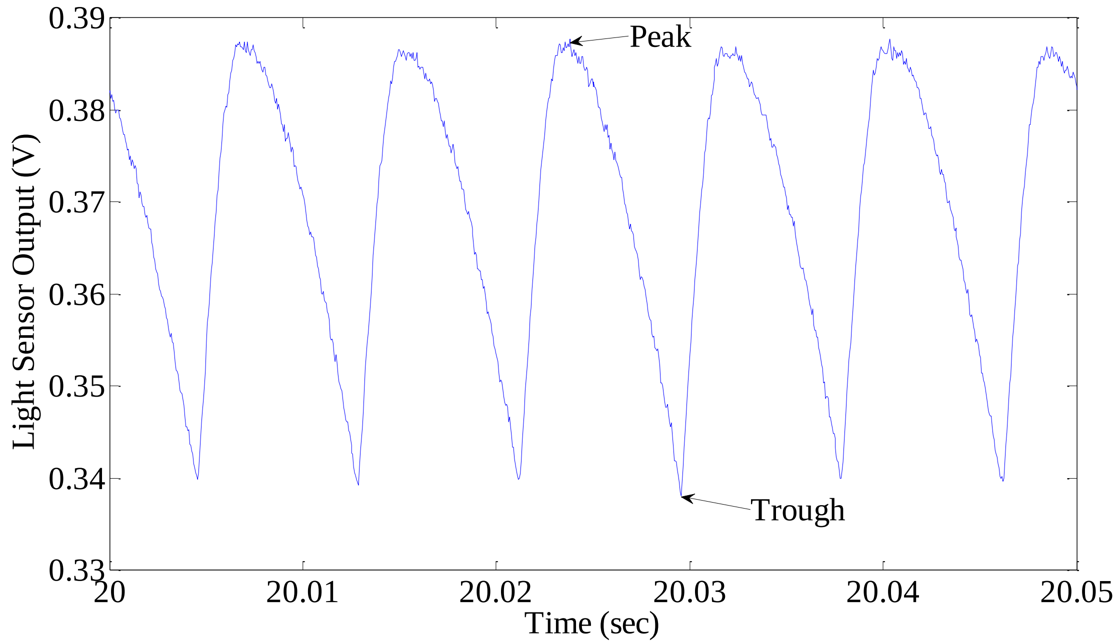

Figure 3.13: Characteristic Light Output from a Compact Fluorescent Lamp (Lamp C)

In the description of the IEC Flickermeter, it was shown that the human eye-brain response can be modeled as a low pass filter. Therefore, the eye perceives the average of a fluctuating light waveform. In order to simulate this response in the analysis of the data, each waveform was analyzed to find its average value. In order to simplify this procedure, the light output from an incandescent lamp was approximated as a sine wave. Therefore, the average could be simply found using Equation 3.1 below. The CFL light output was approximated as a rectified sine wave, and so could be found using Equation 3.2 below. In each case, the definitions of peak and trough are given in Figures 3.12 and 3.13.

$$AveLight_{inc} = \frac{Peak + Trough}{2} \qquad (3.1)$$

$$AveLight_{CFL} = Trough + \left(\frac{2Peak}{\pi} \right) \qquad (3.2)$$

Since the incandescent lamp is not a perfect sine wave and the compact fluorescent lamp is not a perfect rectified wave, these equations provide approximations as to the average light output. Initially, analysis was performed that determined the fluctuation of the peak value of light and the trough value of light for the lighting waveforms of the lamp. Since the peak and trough values were readily available, the method described above lent itself well to the purposes of the research.

When the fluctuation of the average value of light was compared to the earlier fluctuations of the peak and trough values of light, it was found that they were very similar. This redundancy of results led to the conclusion that this method would provide accurate results. Therefore, it was determined that this method was an accurate and quick way of analyzing the light data.

No incandescent bulb or compact fluorescent bulb is perfectly consistent, meaning that each cycle results in slightly different light output. In an effort to ensure that results were not skewed by taking a single point, which could potentially represent an outlier not indicative of the typical light output, averages of the light output were calculated. For each test, data was acquired for 30 seconds prior to the application of the voltage fluctuation. At three points in this 30 second period, specifically at 6 seconds, 15 seconds, and 30 seconds, the peaks of 10 light cycles were averaged together and the troughs of 10 light cycles were averaged together.

The three values for each the peak and the trough were then compared to one another to be sure that no trend could be observed. If the peak or trough averages showed a dramatic trend up or down, it could indicate that the lamp output was fluctuating for unintended reasons and the test would have to be re-run. This was an especially important requirement for the compact fluorescent lamps, which seemed to occasionally exhibit an unpredictable light oscillation. If it was found that no trend existed, the three values for the peak were averaged together and the three values for the trough were averaged together. These values could be used in Equation 3.1 or 3.2 to find the average value of the light prior to the voltage fluctuation. The process of finding the light output prior to the voltage fluctuation was the same for every test run. The method for finding the light output during the voltage fluctuation differed for the different types of tests.

Steady State Analysis during Voltage Fluctuation

The method for finding the light output during the voltage fluctuation used for the steady state tests was much the same as the method used to find the light output prior to the fluctuation. Ten cycles of light output were averaged at both the peak and the trough at three specific times during the steady state portion of the light dip. Again, the three peaks and the three troughs were checked for potential trends. If none were found, the three peaks were averaged together and the three troughs were averaged together. These values could then be used in Equation 3.1 or 3.2 to determine the average light.

Once the values prior to the fluctuation and after the fluctuation were obtained, percentage change between the two was found. This percentage was the given as the final result for the steady state light fluctuation.

Short Duration Analysis during Voltage Fluctuation

The analysis during the voltage fluctuation for the short duration tests was performed in a slightly different manner. Due to the nature of the test, many times the light did not reach a steady state value. Therefore, the maximum light drop would be identified and the peak and trough of that cycle was recorded. These values were then used in Equation 3.1 or 3.2 to find the average value during the dip.

In some of the short duration tests, a steady light output was observed. In these cases, the point at which the light output became steady was identified and the average light output was taken. This value was then used to determine the percent change due to the voltage fluctuation.

Another piece of data that was recorded from the short duration tests was the length of time it took for the light output to drop after the fluctuation occurred and how long it took to recover once the proper voltage was re-applied. Figure 3.14 and Figure 3.15 indicate what was considered a drop time and a recovery time for an incandescent lamp and a CFL, respectively.

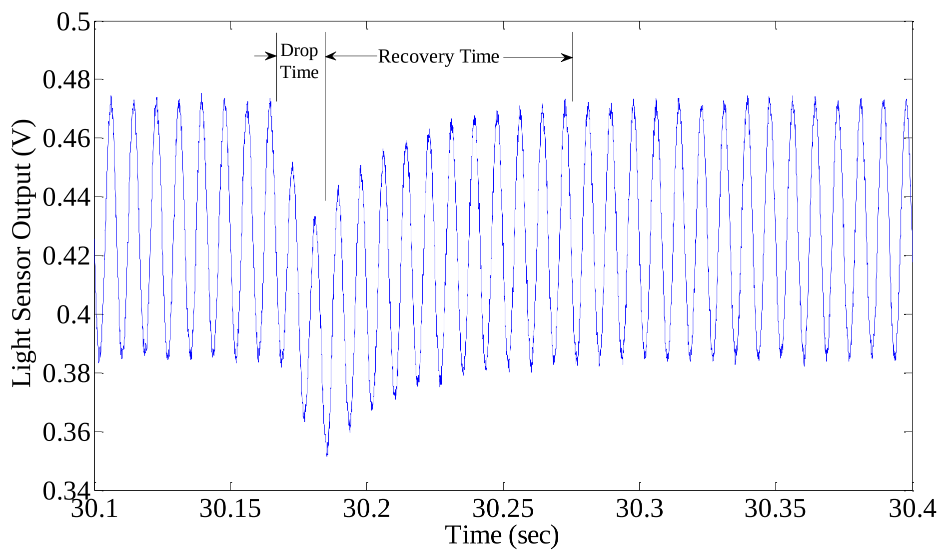

Figure 3.14: Drop Time and Recovery Time for an Incandescent Lamp (Lamp A)

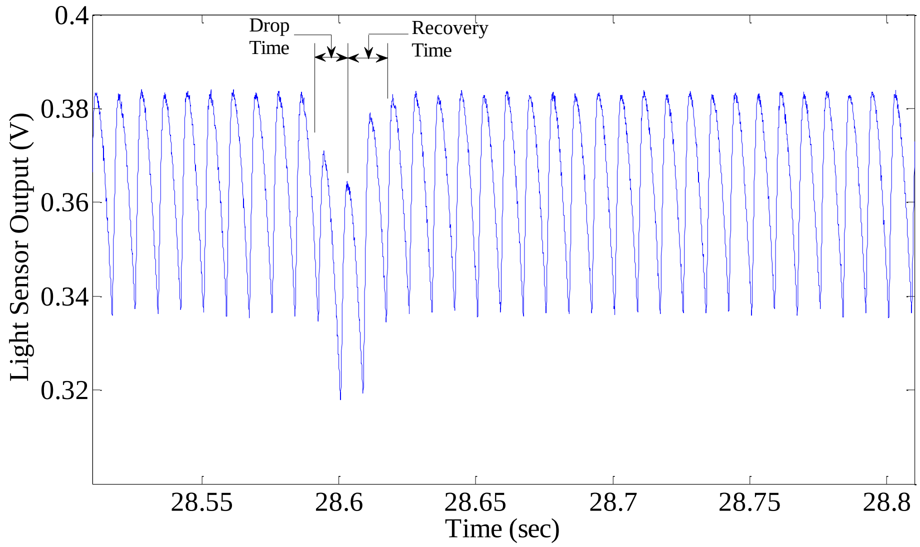

Figure 3.15: Drop Time and Recovery Time for a Compact Fluorescent Lamp (Lamp E)

Non-Rectangular Analysis during Voltage Fluctuation

The non-rectangular test analysis proceeded in much the same way as the short duration test analysis. A point of minimum light output was found, the average value of the light at that point was calculated, and the percentage drop from nominal was recorded. Also of interest in the non-rectangular testing was the duration of the light dip. In the non-rectangular tests, though, instead of finding the drop time and recovery time, the entire light dip duration was recorded. Representations of the length of time used in this analysis for an incandescent lamp and a CFL are shown in Figures 3.16 and 3.17 below. This value could then be compared to the duration of the voltage dip in order to determine the extent to which the lighting technology in question extended the voltage dip.

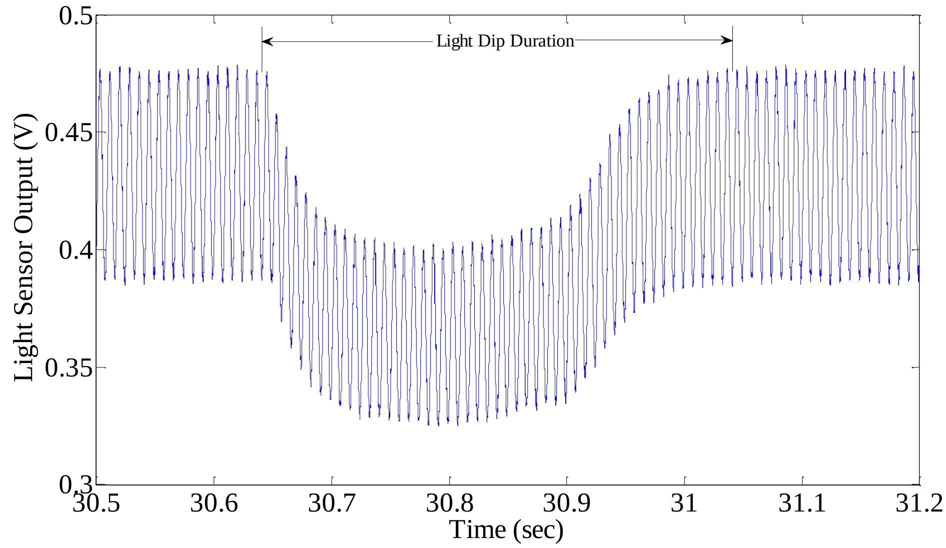

Figure 3.16: Light Dip Duration for an Incandescent Lamp (Lamp A) due to a 2.5 Ton Heat Pump

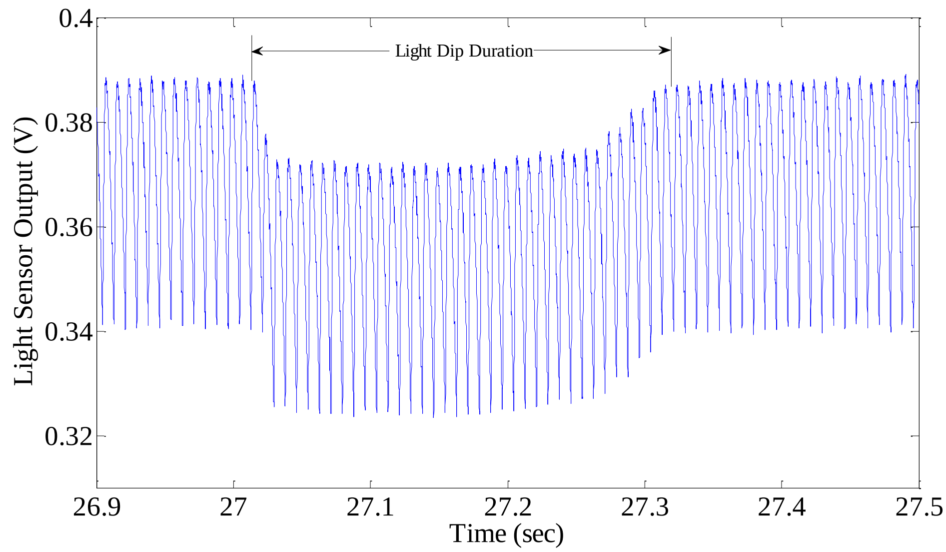

Figure 3.17: Light Dip Duration for a Compact Fluorescent Lamp (Lamp E) due to a 2.5 Ton Heat Pump

Procedure Used to Create New Flicker Curve

The final goal of this research was to propose a new flicker curve that would be based on the compact fluorescent lamp. In order to create this curve, specific points on the GE flicker curve were chosen and programmed into the ELGAR. These points are shown in Table 3.3 below.

Table 3.3: GE Flicker Curve Points Used to Establish CFL Flicker Curve

Frequency of Dip	Percent Voltage Drop
10 dips/second	0.75%
5 dips/second	0.46%
2 dips/second	0.54%
1 dip/second	0.67%
10 dips/min	1.13%
5 dips/min	1.33%
30 dips/hour	2.21%
20 dips/hour	2.50%

Once the points shown in Table 3.3 were programmed into the ELGAR, two incandescent lamps (Lamps A and B) were subjected to each voltage fluctuation. The acquired data was analyzed to determine the severity of the resulting light fluctuation. In order to analyze the data, the average value of the light output was calculated prior to the voltage dip using the same method as has been used in every test up to this point. Also calculated was the average value for every cycle within the light dip. This is shown graphically in Figure 3.18 below for a 0.54% 2 dip/second voltage fluctuation on Lamp A. In this figure, the red line represents the average light value prior to the dip and the green line represents the average light value at each cycle within the dip. The final data taken was the area between these two lines. A MATLAB program was written to perform this calculation. The final result was taken to be the area between the average value prior to the dip and the average value during the dip.

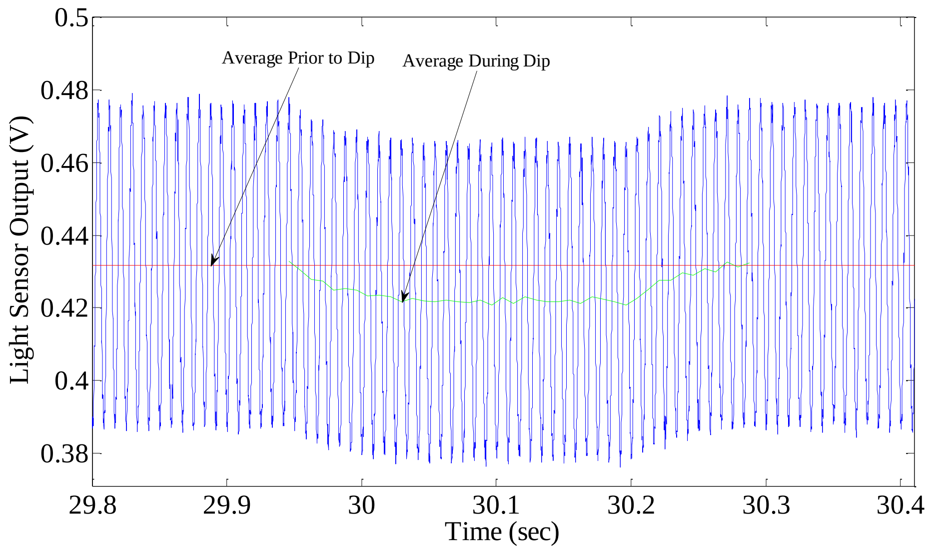

Figure 3.18: Flicker Curve Analysis for a 0.54% Voltage Dip at a Frequency of 2 dips/sec on Lamp A

The reason this calculation was taken this way was for two reasons. First, as will be discussed thoroughly later, the two different lighting sources have been shown to have two separate time constants. The incandescent lamp takes longer to respond to a voltage fluctuation than does a compact fluorescent lamp. This means that the shape of the light fluctuation is different for the different lighting technologies. An incandescent lamp will have a ramp down into the dip and out of the dip while a CFL will look more rectangular. Furthermore, as has been shown in Figures 3.3, 3.4, and 3.5, when a long duration voltage fluctuation of large enough magnitude is applied to a compact fluorescent lamp, the light output tends to overshoot its final value and then move toward a final value whereas an incandescent lamp seems to reach and then stay at its final value. When attempting to perform a one to one comparison of these lamps, these differences in the lighting technologies need to be taken into account. One way to do this was to calculate the area of the light dip.

In calculating the area of a light dip, non-rectangular qualities in the light can be taken into account. Consider two methods of analysis for a perfectly rectangular light fluctuation, i.e. merely taking the percent drop in the average value of the light at its lowest point and also calculating the area of the light drop. Since the light drop is rectangular both methods of analysis will result in the same value. Now consider two separate light drops. The two are of the same duration, but one is perfectly rectangular whereas the other ramps into the drop and also ramps out of the drop. The lowest point of each light drop is exactly the same. If the ramp is of long enough duration, it is intuitive that the severity of this light drop will be less than that of the rectangular light drop. Now, consider again the two methods of analysis. The first method uses just the percentage of the average light drop at the lowest point. In this case, since each fluctuation reaches the same lowest point, the analysis of the two results in the same value. The analysis using the area, however, results in a smaller value for the ramped light drop, which would be more accurate. In taking the area of the light drop, the ramps were weighted accordingly to provide a more accurate solution. For this reason, the analysis method using areas was used in this research.

Once the area of the light dip for each incandescent lamp was found, the same duration tests were performed on two compact fluorescent lamps (Lamps E and F). This time, the magnitudes of the dips were altered in order to find the magnitude that would most closely result in an area similar to that which had been created by the incandescent lamp. The magnitude found was determined to be the new magnitude for that particular fluctuation frequency to place on the new proposed flicker curve.

CHAPTER 4: EXPERIMENTAL RESULTS

Steady State Test Results

Numerical Results

In this section, the results of the steady state tests are presented. Figures 4.1 through 4.9 show the results of each test that was run. Each of these figures shows the percentage of average light drop caused by the corresponding voltage fluctuation. Table 4.1, which is located below the figures, presents some overall statistics. This table presents the averages of the percent changes in light output for all bulbs of the same technology. Also shown in this table is the factor by which the average incandescent percent light change was found to be larger than the average compact fluorescent percent light change. These tables provide analysis of only Lamps A, B, E, F, and H since these were the only lamps that underwent exhaustive testing. It should be noted that the number of significant digits presented throughout the analyses in this research are a little optimistic. By the nature of lighting, each time these tests are run, slight differences in these values will result. Even so, the values give a very good indication as to how these lamps are reacting to the voltage fluctuations presented to them.

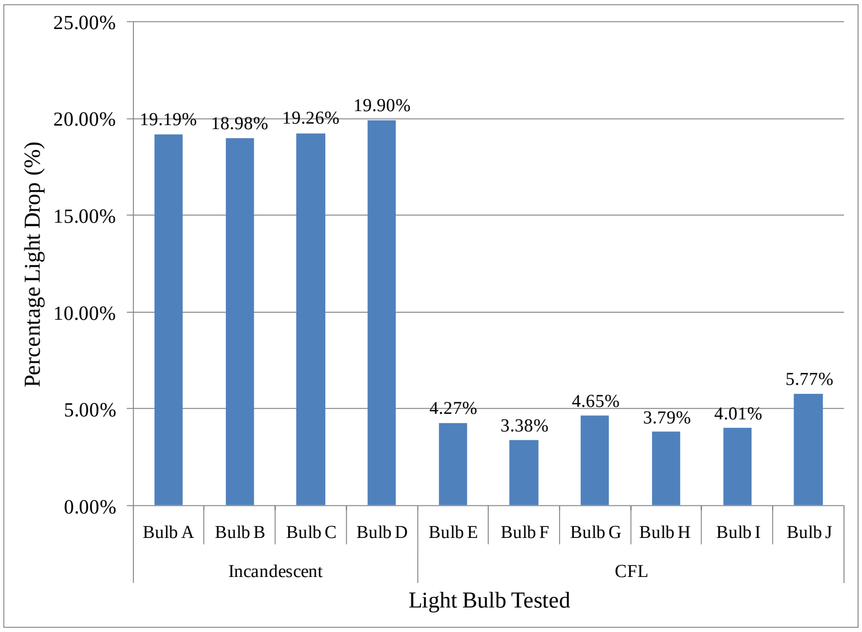

Figure 4.1: Percent Drop in Light from Soft White Bulbs for Voltage Dip of 4.834%

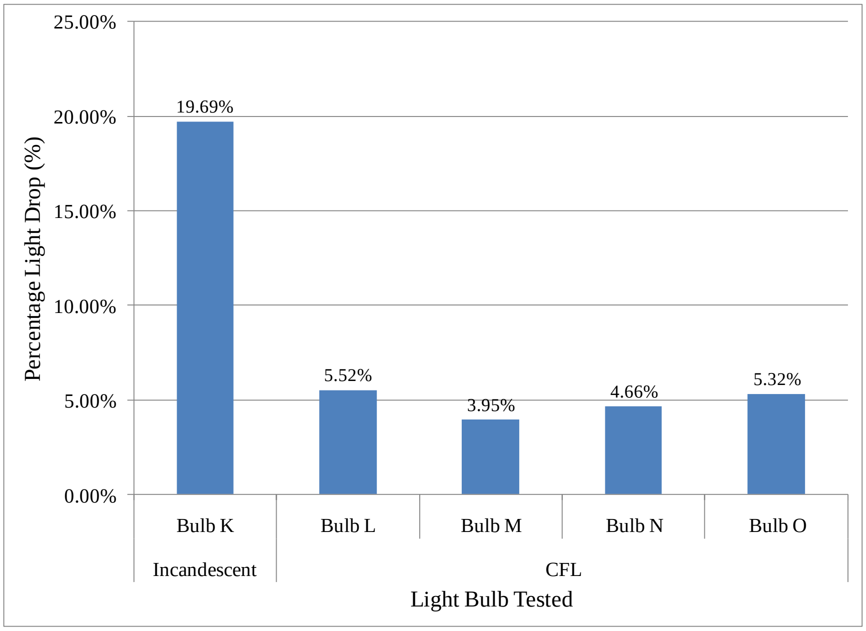

Figure 4.2: Percent Drop in Light from Alternate Color Bulbs for Voltage Dip of 4.834%

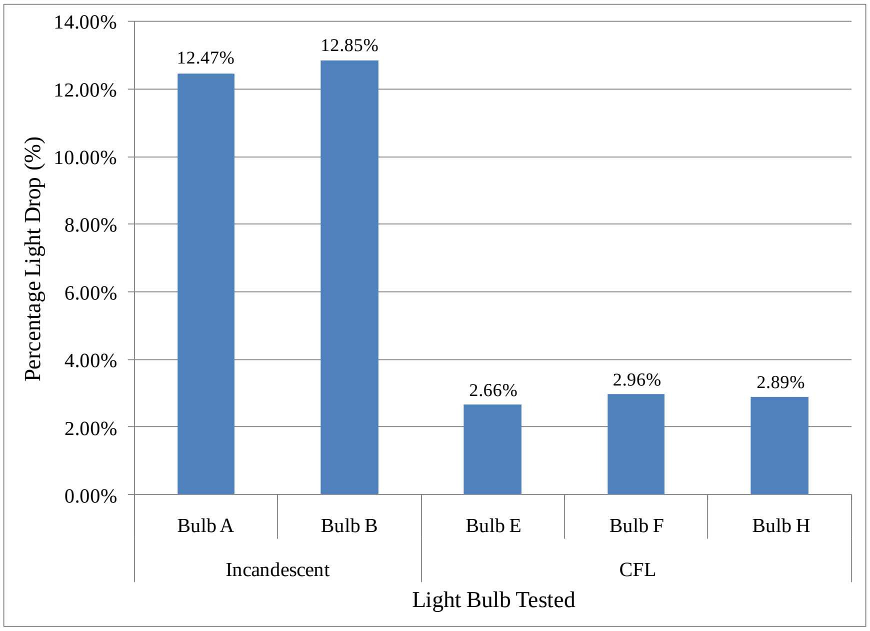

Figure 4.3: Percent Drop in Light from Selected Soft White Bulbs for Voltage Dip of 3.166%

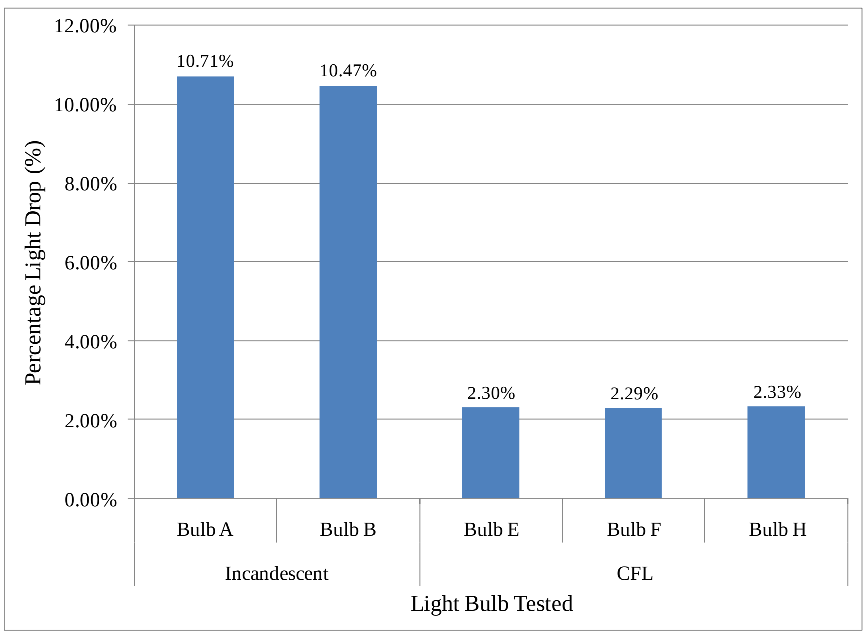

Figure 4.4: Percent Drop in Light from Selected Soft White Bulbs for Voltage Dip of 2.568%

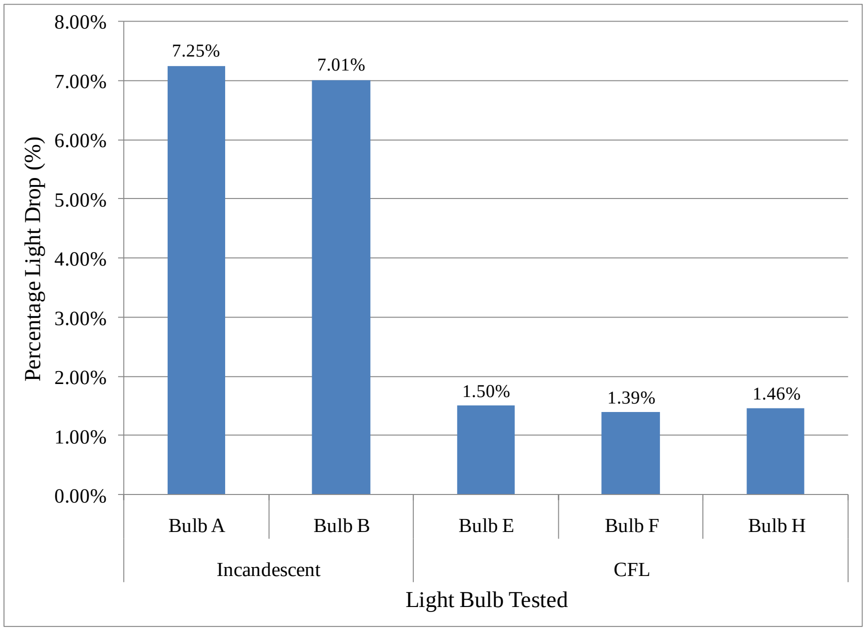

Figure 4.5: Percent Drop in Light from Selected Soft White Bulbs for Voltage Dip of 1.695%

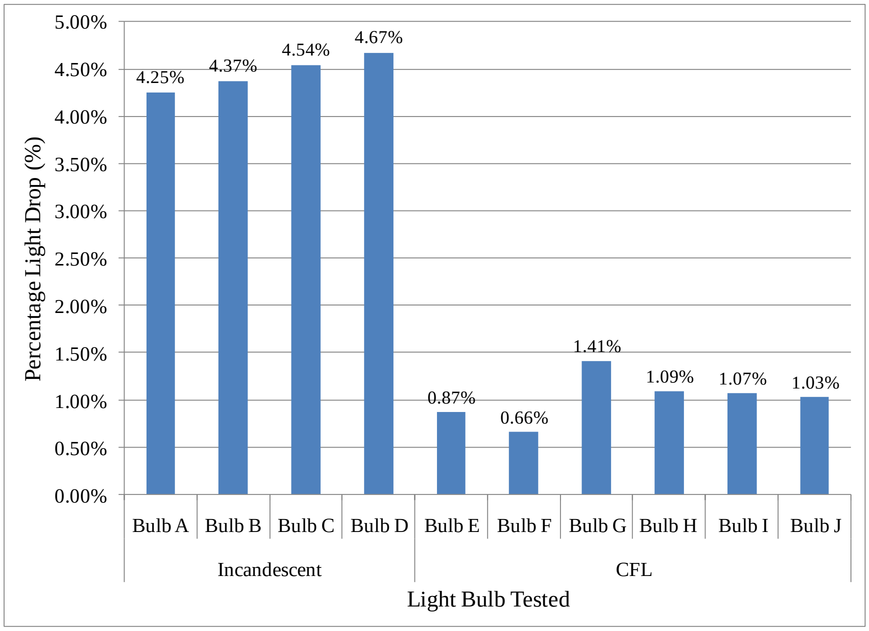

Figure 4.6: Percent Drop in Light from Soft White Bulbs for Voltage Drop of 1.044%

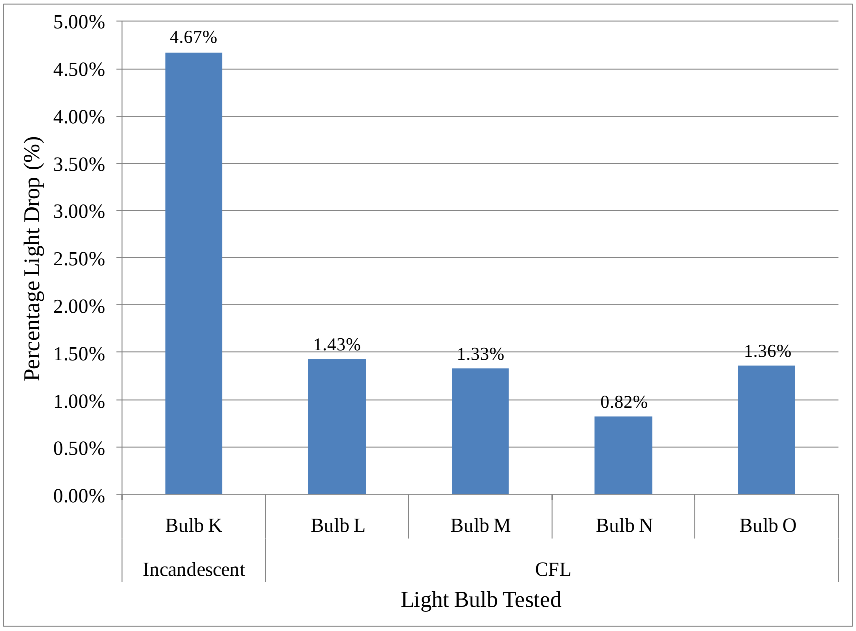

Figure 4.7: Percent Drop in Light from Alternate Color Bulbs for Voltage Drop of 1.044%

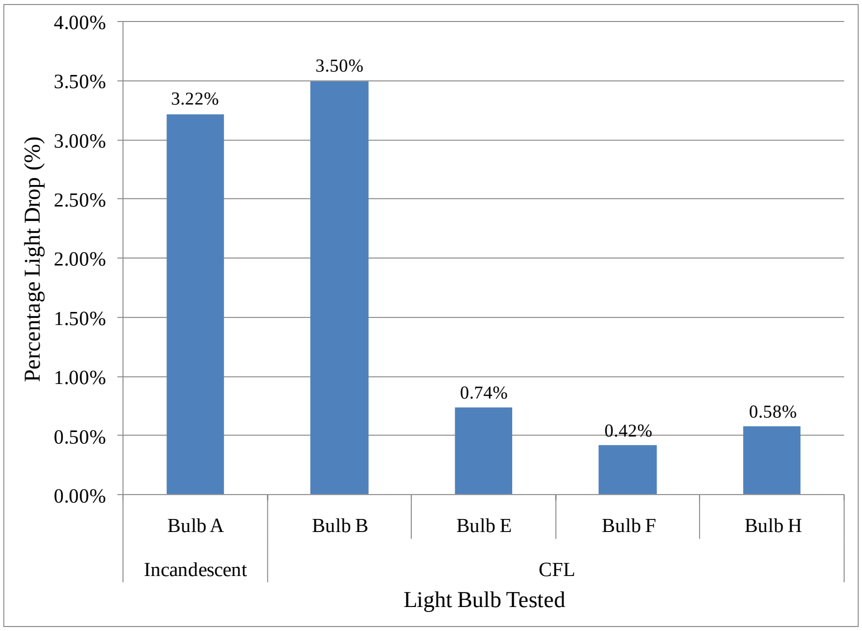

Figure 4.8: Percent Drop in Light from Selected Soft White Bulbs for Voltage Dip of 0.841%

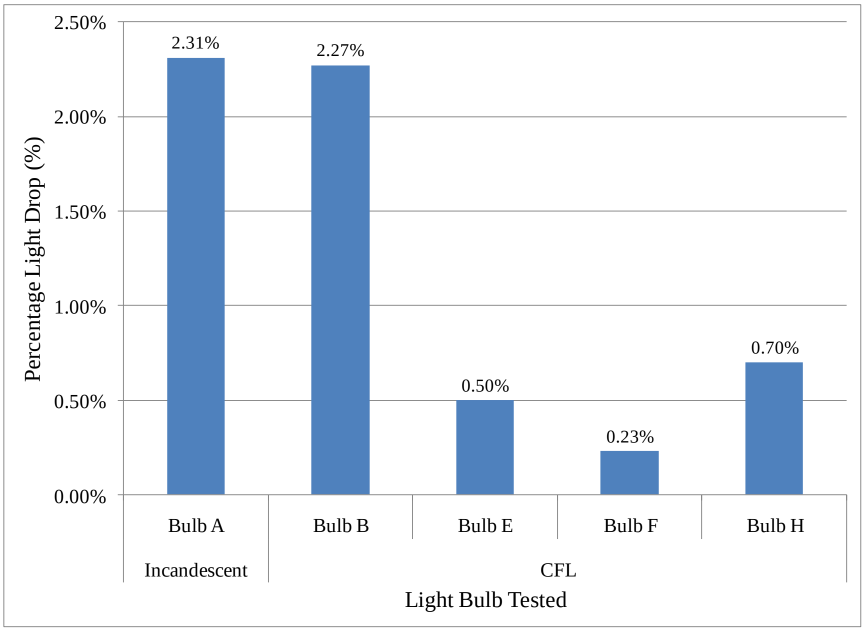

Figure 4.9: Percent Drop in Light from Selected Soft White Bulbs for Voltage Dip of 0.547%

Table 4.1: Overall Average Values for Steady State Tests

Voltage Dip (%)	**4.834**	**3.166**	**2.568**	**1.695**	**1.044**	**0.871**	**0.547**
Incandescent Light Drop (%)	19.09%	12.66%	10.59%	7.13%	4.31%	3.36%	2.29%
CFL Light Drop (%)	3.81%	2.84%	2.31%	1.45%	0.87%	0.58%	0.48%
Light Drop Factor*	5.04	4.46	4.58	4.92	4.95	5.79	4.77

*Light Drop Factor = Incandescent Light Drop/CFL Light Drop

Discussion of Steady State Test Results

Through observation of Figures 4.1 through 4.9, it becomes clear that the compact fluorescent lamp light output is much less susceptible to voltage fluctuations than the incandescent lamp light output. In every case tested, the compact fluorescent lamps had a much smaller variation in their light output than did the incandescent lamps. For example, with a voltage fluctuation of 4.834%, the best performing incandescent lamp had a steady state light dip of 18.98% while the worst performing CFL had a light dip of 5.77%. This trend continued for every test. In fact, as is shown in Table 4.1, when taken over all tested samples, the average light fluctuation observed from the incandescent lamp is consistently 4 to 6 times greater than the average light fluctuation observed from the compact fluorescent lamp. These tests indicate that if the voltage on a power system dips down for a significant period of time, both lighting technologies will be affected, but the observed lighting change from a compact fluorescent lamp will be 4 to 6 times less than that of an incandescent lamp.

Figures 4.1 and 4.6 summarize the results from the tests that were performed on every soft white lamp. It can be observed from these figures that all soft white lamps in question followed the same trend. For each test, the CFL performed remarkably better than the incandescent lamp. Also noteworthy is the fact that the color of the lamp did not affect the steady state response. Figures 4.2 and 4.7 display the results from tests performed on the lamps that were not of the soft white color. It is clear that there is no significant difference between the response of these lamps to voltage fluctuations and the response of the soft white lamps.

Short Duration Test Results

Numerical Results

In this section, the results of the short duration tests are given. Figures 4.10 through 4.19 provide the data graphically. Each figure contains two separate graphs. The first graph shows the percent light drop from the initial steady state value to the lowest point in the light drop. The second graph shows the time required by the lamp in question to both drop from the initial steady state value to the lowest point and also to recover from the lowest point back to steady state once the voltage has been returned to normal. As a reminder, Figures 3.14 and 3.15 show the definition used for drop time and recovery time. Tables 4.2 and 4.3, which are located below the graphs, provide the overall average light change, drop times, and recovery times of the two separate technologies. Again, these tables only consider Lamps A, B, E, F, and H since these were the lamps that underwent exhaustive testing.

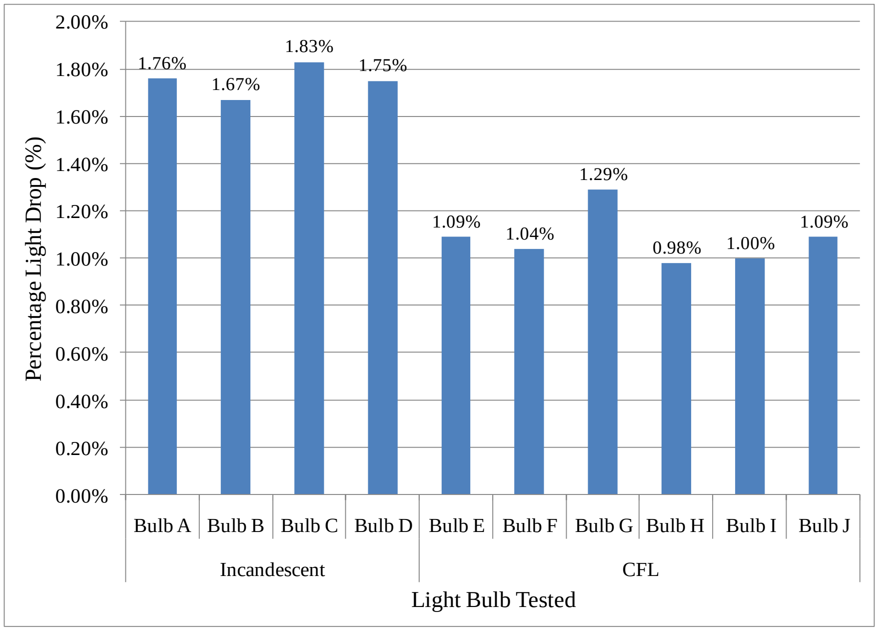

Figure 4.10a: Percent Drop in Light

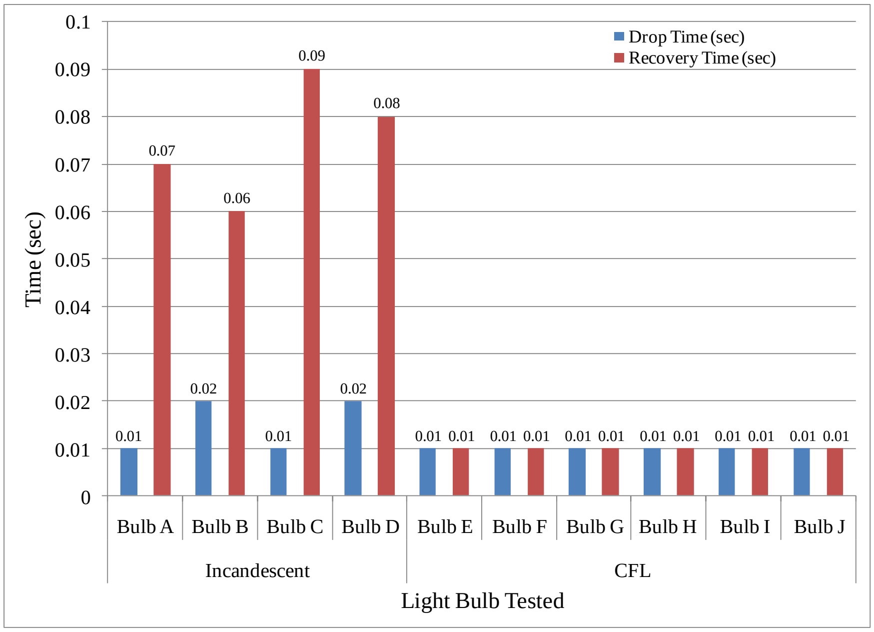

Figure 4.10b: Time Analysis

Figure 4.10: Response of Soft White Bulbs to a 1.044% Voltage Dip Lasting 1 Electrical Cycle

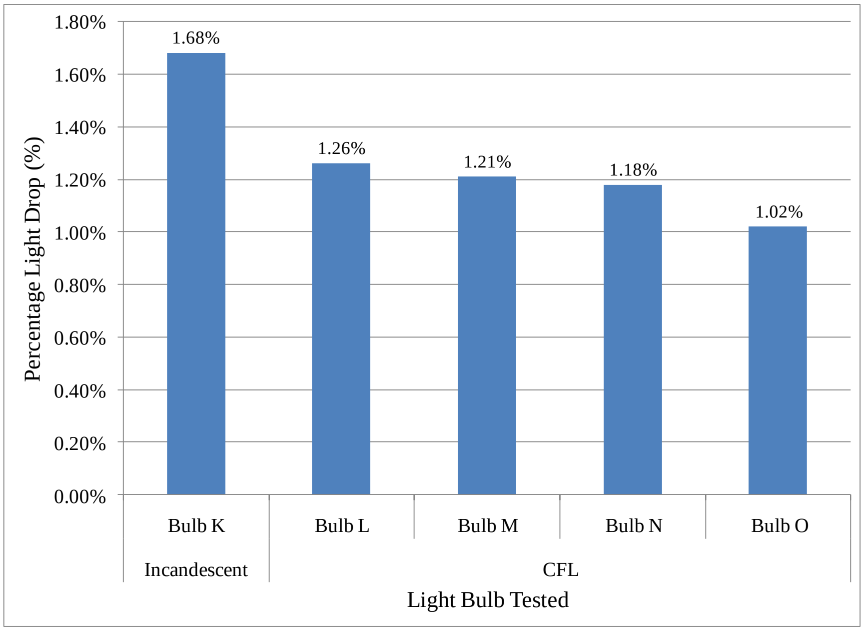

Figure 4.11a: Percent Drop in Light

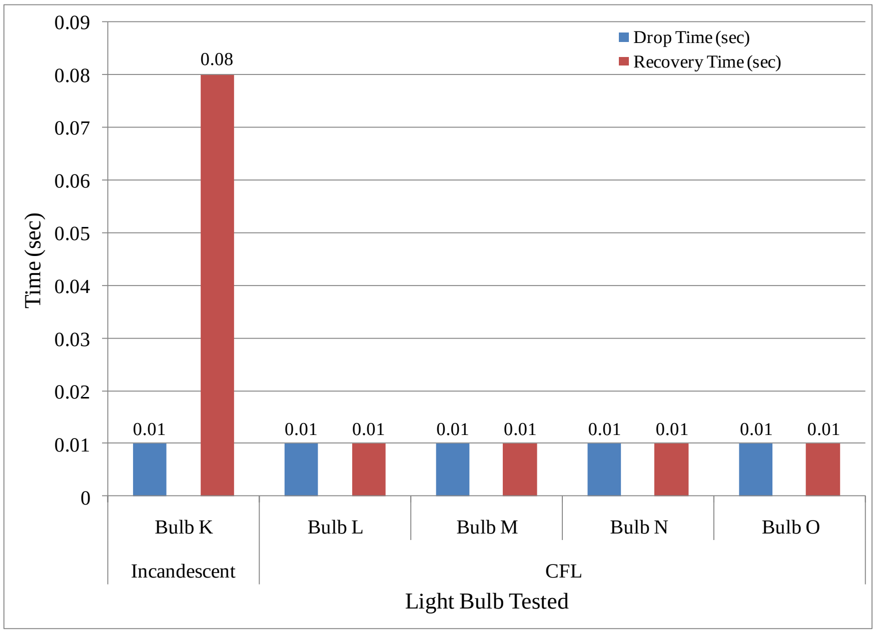

Figure 4.11b: Time Analysis

Figure 4.11: Response of Alternate Color Bulbs to a 1.044% Voltage Dip Lasting 1 Electrical Cycle

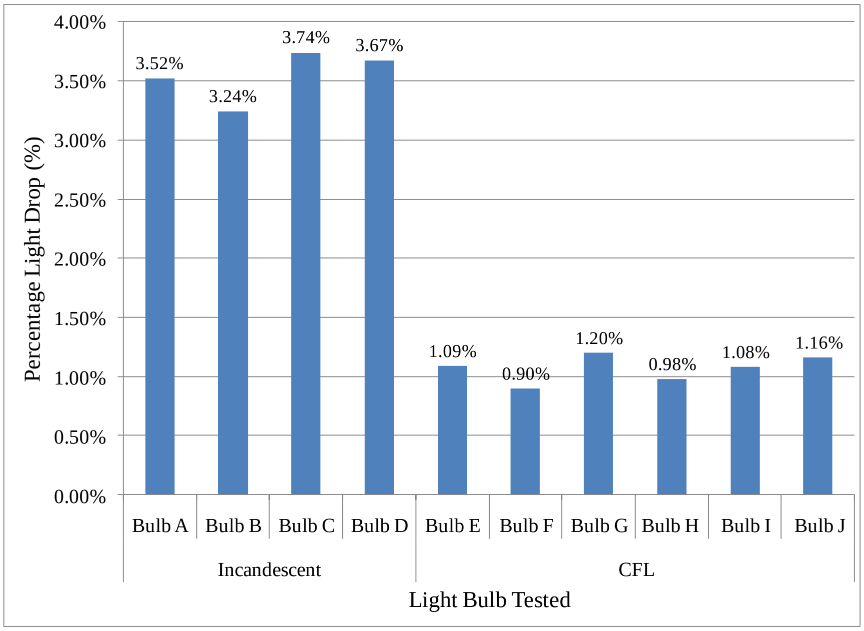

Figure 4.12a: Percent Drop in Light

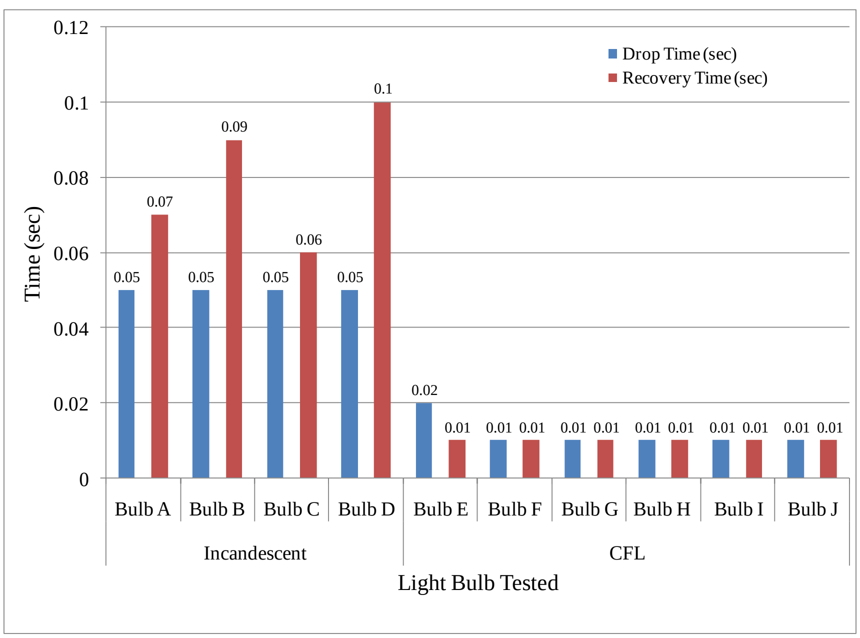

Figure 4.12b: Time Analysis

Figure 4.12: Response of Soft White Bulbs to a 1.044% Voltage Dip Lasting 3 Electrical Cycles

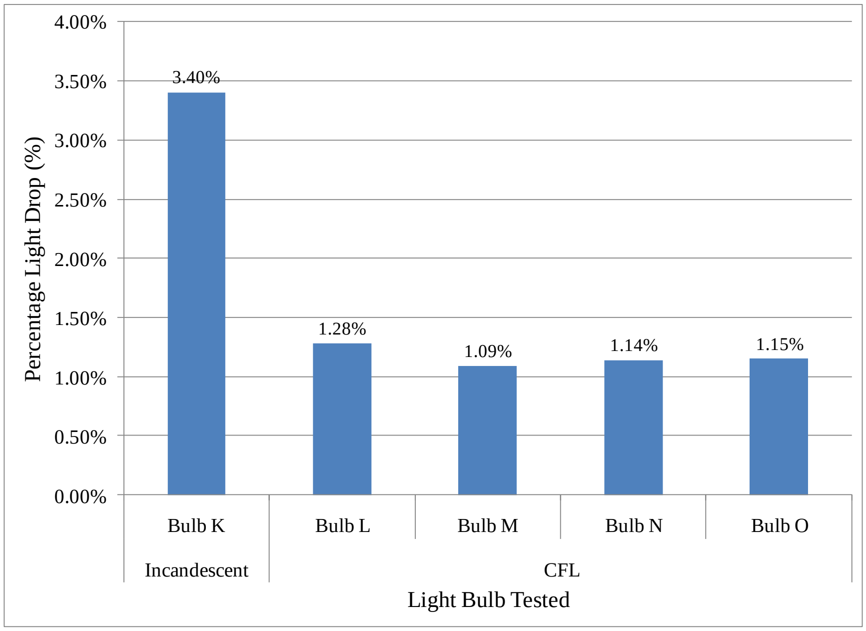

Figure 4.13a: Percent Light Drop

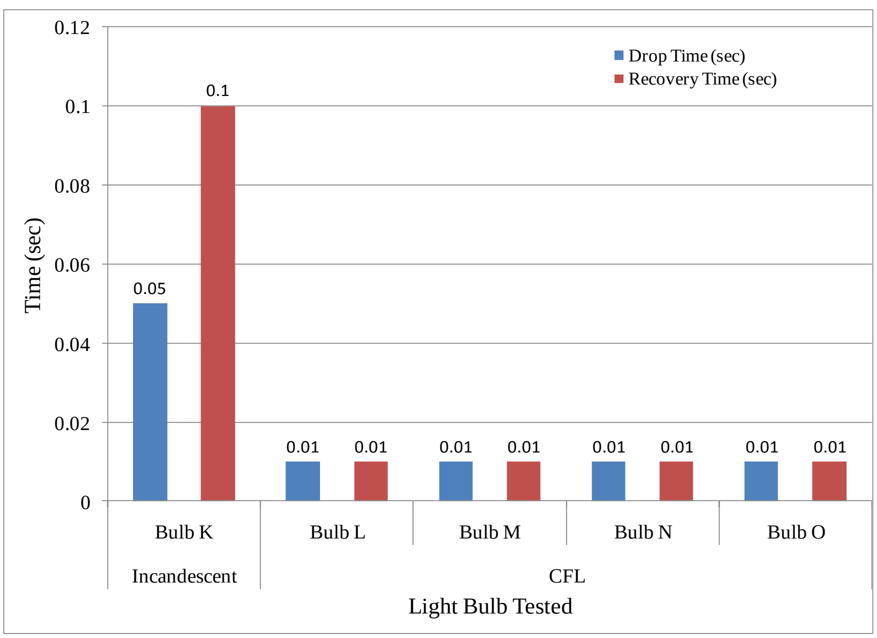

Figure 4.13b: Time Analysis

Figure 4.13: Response of Alternate Color Bulbs to a 1.044% Voltage Dip Lasting 3 Electrical Cycles

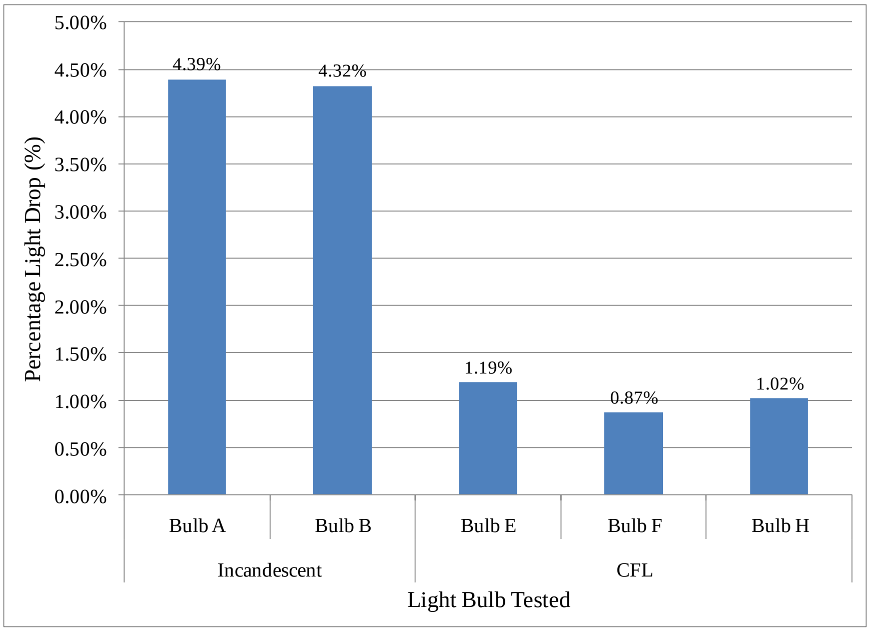

Figure 4.14a: Percent Light Drop

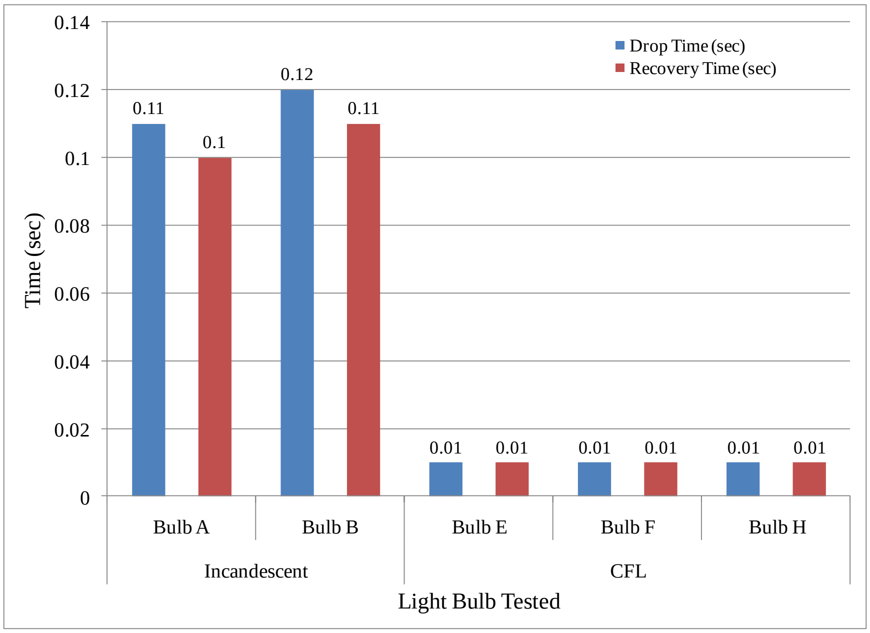

Figure 4.14b: Time Analysis

Figure 4.14: Response of Selected Soft White Bulbs to a 1.044% Voltage Dip Lasting 10 Electrical Cycles

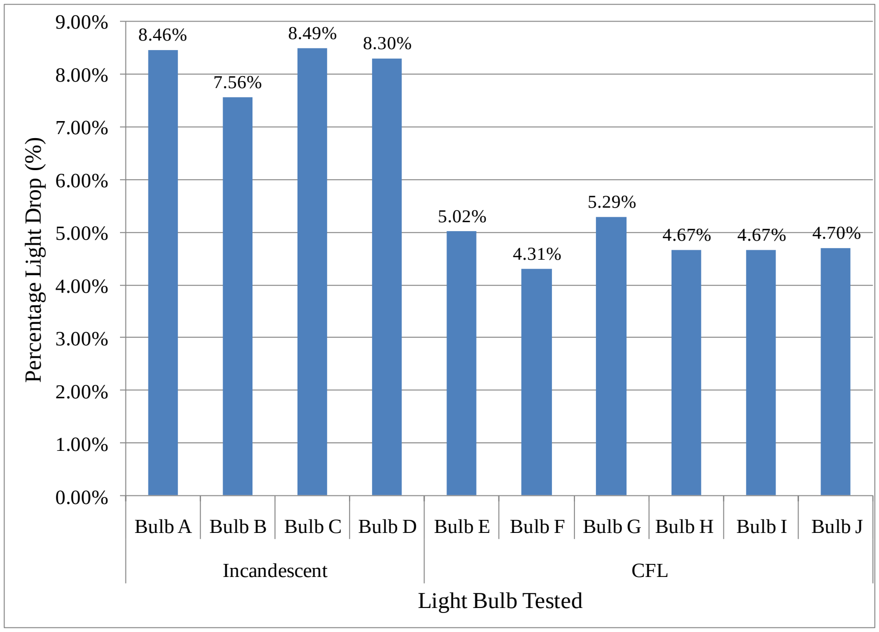

Figure 4.15a: Percent Light Drop

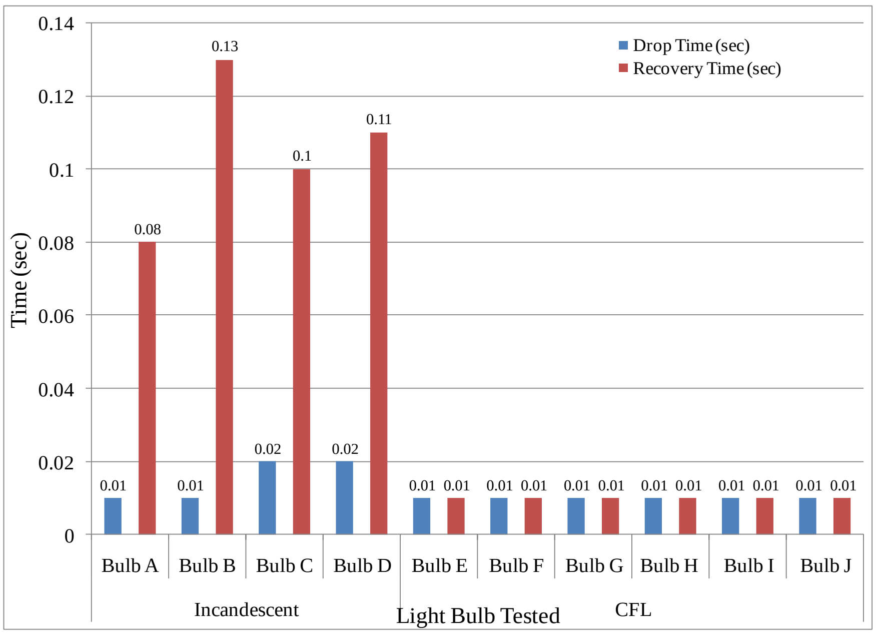

Figure 4.15b: Time Analysis

Figure 4.15: Response of Soft White Bulbs to a 4.834% Voltage Dip Lasting 1 Electrical Cycle

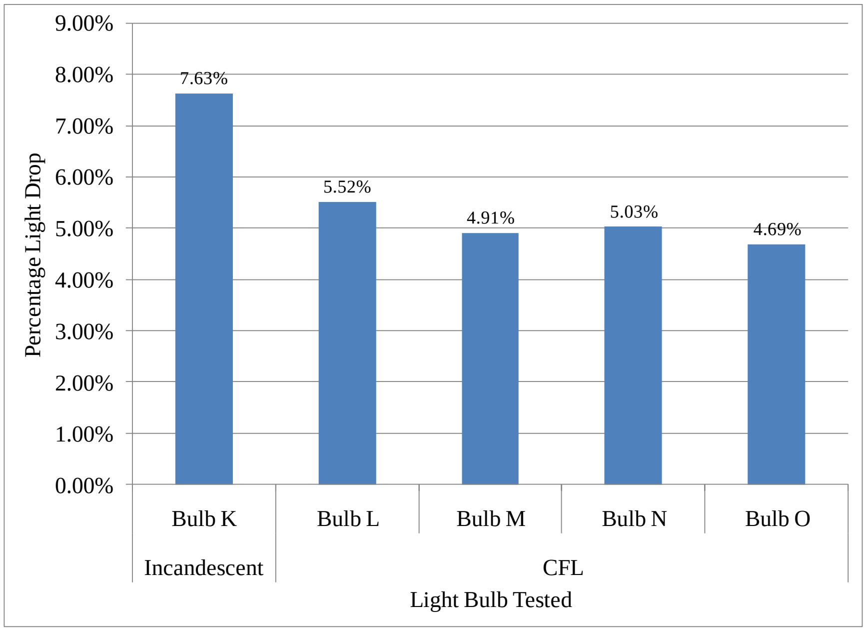

Figure 4.16a: Percent Light Drop

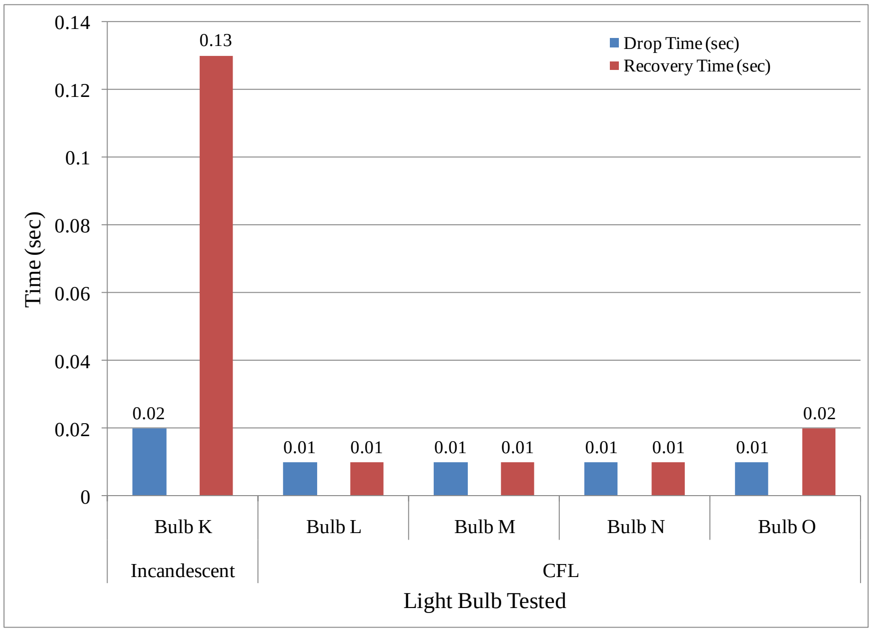

Figure 4.16b: Time Analysis

Figure 4.16: Response of Alternate Color Bulbs to a 4.834% Voltage Dip Lasting 1 Electrical Cycle

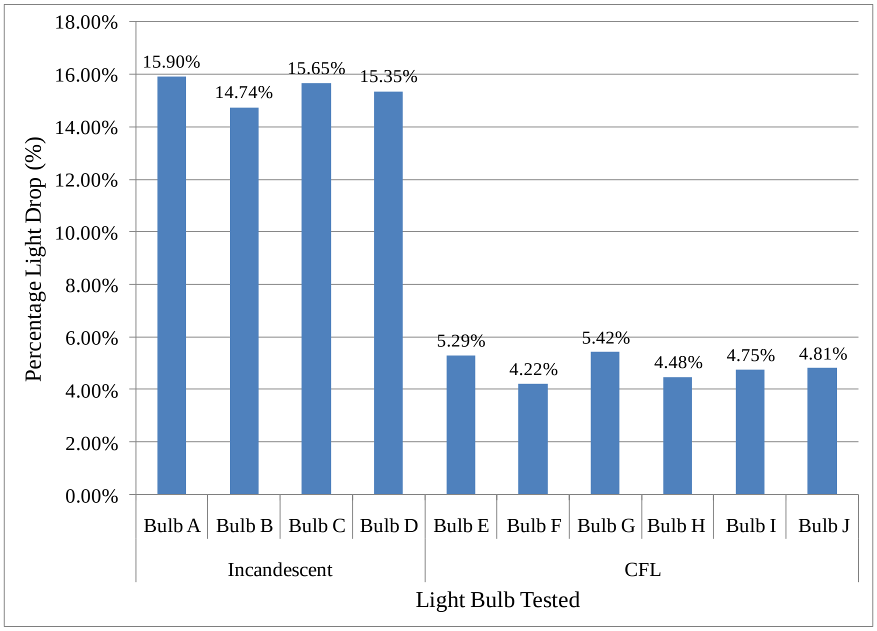

Figure 4.17a: Percent Light Drop

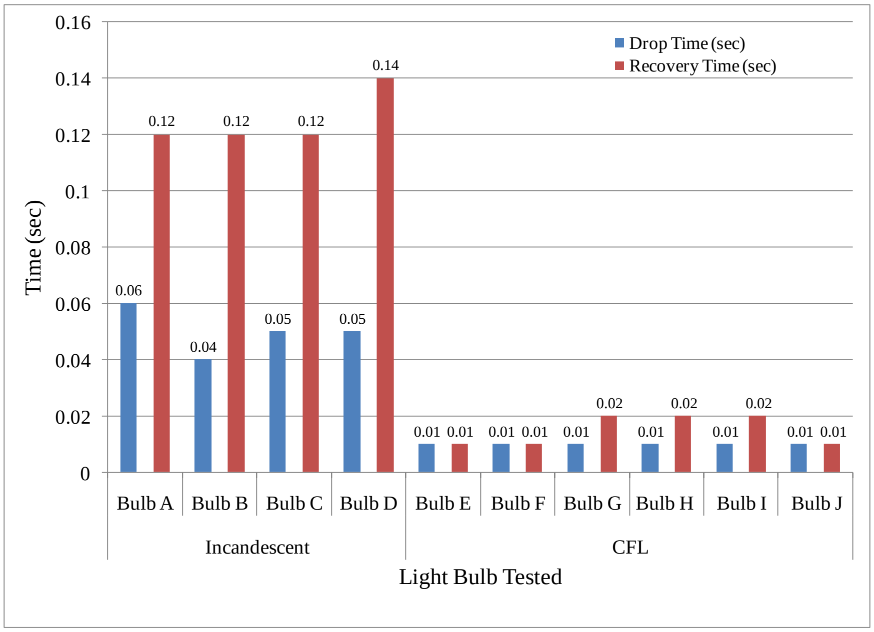

Figure 4.17b: Time Analysis

Figure 4.17: Response of Soft White Bulbs to a 4.834% Voltage Dip Lasting 3 Electrical Cycles

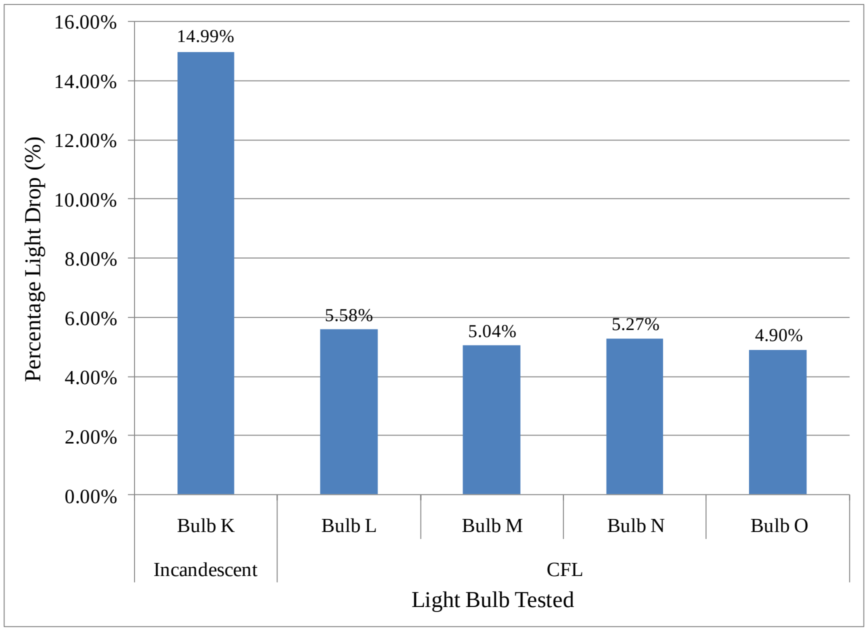

Figure 4.18a: Percent Light Drop

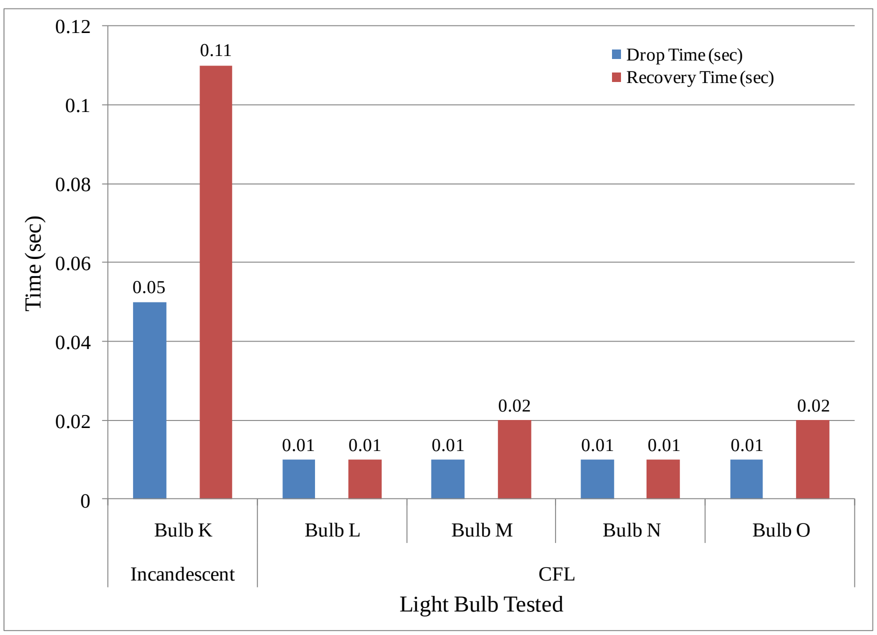

Figure 4.18b: Time Analysis

Figure 4.18: Response of Alternate Color Bulbs to a 4.834% Voltage Dip Lasting 3 Electrical Cycles

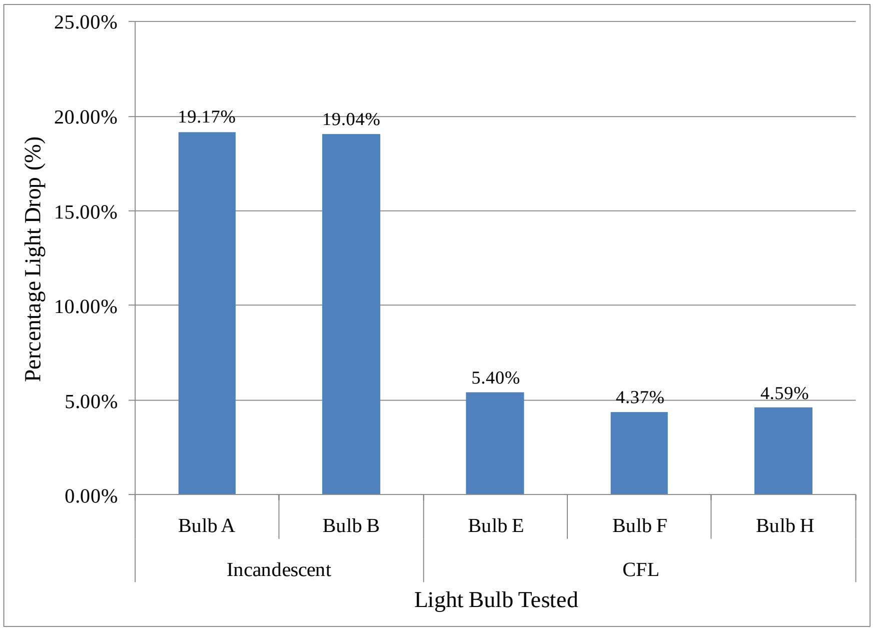

Figure 4.19a: Percent Light Drop

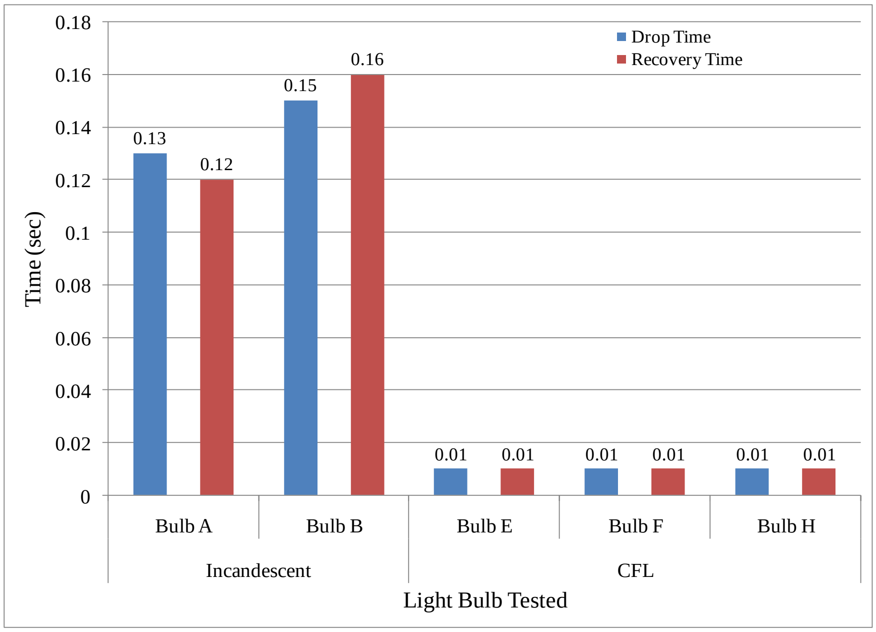

Figure 4.19b: Time Analysis

Figure 4.19: Response of Selected Soft White Bulbs on a 4.834% Voltage Dip Lasting 10 Electrical Cycles

Table 4.2: Overall Average Light Dips for Short Duration Tests

Voltage Dip (%)	1.044			4.834		
Number of Cycles	**1**	**3**	**10**	**1**	**3**	**10**
Incandescent Light Drop (%)	1.72%	3.38%	4.36%	8.01%	15.32%	19.11%
CFL Light Drop (%)	1.03%	0.99%	1.03%	4.67%	4.66%	4.79%
Light Drop Factor+	1.67	3.41	4.23	1.72	3.29	3.99

+Light Drop Factor = Incandescent Light Drop/CFL Light Drop

Table 4.3: Overall Average Drop and Recovery Times for Short Duration Tests

Voltage Dip (%)	1.044			4.834		
Number of Cycles	**1**	**3**	**10**	**1**	**3**	**10**
Incandescent Drop Time (sec)	0.02	0.05	0.12	0.01	0.05	0.14
CFL Drop Time (sec)	0.01	0.01	0.01	0.01	0.01	0.01
Drop Time Factor**	2	5	12	1	5	14
Incandescent Recovery Time (sec)	0.07	0.08	0.11	0.11	0.12	0.14
CFL Recovery Time (sec)	0.01	0.01	0.01	0.01	0.01	0.01
Recovery Time Factor++	7	8	11	11	12	14

**Drop Time Factor = Incandescent Drop Time/CFL Drop Time

++Recovery Time Factor = Incandescent Recovery Time/CFL Recovery Time

Discussion of Short Duration Test Results

The results of the short duration tests provide some interesting insight into the differences between the incandescent bulbs and the compact fluorescent bulbs. One of the most noticeable differences between the incandescent lamps and the compact fluorescent lamps is the time constant that is associated with their light output, which is related to the time it takes for the light output of the lamp to drop once a voltage dip is applied and also the time it takes for the light output to recover once the voltage recovers. This difference in the time constant is due to the fact that the two light sources use two separate phenomena to create light. In the incandescent lamp, there is an inherent thermal time constant associated with the filament of the bulb. Once an excitation has been removed, it takes some time for the filament to cool and thus reduce its light output. In the fluorescent lamp, on the other hand, the light time constant is provided by the capacitive time constant associated with the DC bus capacitor.

It becomes obvious through observation of the presented data that the time constant associated with the incandescent lamp is much greater than the time constant associated with the compact fluorescent lamp. This is especially noticeable when looking at the recovery times of the lamps. In almost every situation tested, the compact fluorescent lamp had a recovery time of 0.01 seconds, and the few tests that deviated from that produced a recovery time of only 0.02 seconds. The incandescent lamps, however, generally produced a recovery time on the order of 0.1 seconds. This recovery time did vary depending on the magnitude and duration of the voltage fluctuation. The larger magnitude and longer duration voltage fluctuations tended to produce a longer recovery time, which makes sense since these fluctuations caused the greatest light deviations from nominal. Even in the best case scenario, though, the average recovery time of the incandescent lamp was seven times longer than the recovery time of the CFL.

The times that are provided for the light drop times for each of these tests can be a bit deceiving. In the shortest test, the drop time of the incandescent lamp seems to be consistent with the drop time of the CFL. As the tests get longer, the incandescent drop time appears to get larger while CFL drop time remains consistent for each test. Obviously, the time constant of the incandescent lamp has no dependence upon the duration of the voltage dip. The apparent deviation actually comes from the fact that the incandescent lamp does not have the time to reach a steady value before the voltage recovers for the one cycle and three cycle tests. Therefore, the drop time for the light coincides with the duration of the voltage fluctuation. This can be verified by noticing that for the one cycle and three cycle voltage dips, the light output of the incandescent lamp takes about one electrical cycle and three electrical cycles, respectively, to drop to its lowest value. This is analogous to removing the excitation voltage from a resistor/capacitor (RC) circuit for a shorter period of time than it would take for the capacitor to discharge (approximately five time constants). The voltage across the capacitor would appear to continue to decrease regardless of the time the voltage was set to 0V (so long as the time never reached five time constants). The 10 cycle drop time on the incandescent lamp is long enough for the lamp to reach a steady value that is comparable to the results of the steady state tests, which is why the drop time for the light output of the incandescent lamp was less than the 10 cycle sag time. This is analogous to removing the voltage across the RC circuit for more than five time constants.

Initially, it may seem reasonable that the long time constant of the incandescent lamp will provide a better short duration ride-through of a voltage dip than will a compact fluorescent lamp with a much smaller time constant. Through observation of the results, however, it becomes clear that this is not the case. Even in the test performed that would most readily serve this theory (the test involving a 1 cycle 1.044% dip), the performance of the CFL was superior to that of the incandescent lamp. According to Table 4.2, in this situation, the light output variation of the CFL was a factor of 1.67 smaller than the variation of the incandescent lamp. While this does present a large improvement over the factor of 4 to 6 observed in the steady state tests, it still shows the superiority of the CFL's performance during a voltage sag. As the time of the sag increases and the light from the incandescent lamp is allowed to fall even further, the difference between the CFL and the incandescent lamp increases. This is due to the fact that, while the minimum incandescent light output is partially dependent upon the duration of the sag, the CFL minimum light output has shown to be fairly independent of the duration of the sag. This is because the time constant governing the CFL light output is small enough that it can reach a steady value within one cycle whereas an incandescent lamp requires more time. One interesting point to note is that the factor by which the CFL light output outperformed the incandescent light output during a voltage fluctuation was highly dependent upon the duration of the voltage dip and less dependent upon the magnitude of the dip. This can be noted from Table 4.2.

The failure of the incandescent lamp's long time constant to maintain the light output is related to the poor response of the incandescent lamp observed through the steady state tests. Here again, the analogy of the RC circuit is helpful. Consider two RC circuits with vastly different time constants running with the same initial conditions. If both circuits are subjected to the same disturbance (in this case, say a voltage sag of short duration), the voltage across the capacitor in the circuit with the smaller time constant will decrease to a lower value than the circuit with the larger time constant. However, if a sufficiently large voltage sag is applied to the circuit with the large time constant and a sufficiently small voltage sag is applied to the circuit with the small time constant, the voltage across the capacitor in the former circuit will reach a lower value than the voltage across the capacitor in the latter. This is simply due to the fact that the final voltage of the former circuit is so much lower than the final voltage of the latter circuit.

The lamps in question can be viewed in much the same way. It became obvious with the steady state tests that the incandescent lamp reaches a much lower light output than the CFL lamp when subjected to the same disturbance. Therefore, even though it has a much larger time constant, the mere fact that the incandescent lamp is attempting to reach a much lower value than the CFL forces the light output to approach a lower value even in a short period of time.

Since the long time constant of the incandescent lamp is unable to maintain the light output, this long time constant actually hurts the operation of the incandescent lamp. As has been shown, this long time constant forces the lamp to have a long recovery time.

This means that once the light output of the incandescent lamp decreases, it takes a relatively long time to recover. The CFL, by contrast, has a much lower time constant and, therefore, a much shorter recovery time. This makes the light drop from the incandescent lamp even more perceptible to the human eye. The human eye works as a low-pass filter, meaning that it tends to blend images that occur too close to one another in time. Since the long time constant of the incandescent lamp forces such a long recovery time, it becomes much more perceptible to the low-pass filter of the human eye than does the fast reacting light output of the CFL.

As was the case with the steady state tests, it was observed that all lamps of the same technology reacted similarly to the short duration tests. There was no significant difference between lamps of similar technology when varying lamp colors were observed.

The results of the short duration tests point to a reason, or possibly more accurately, away from a theory, for the robustness of the CFL. From these tests, it has become obvious that the robustness of the CFL is not due to the DC bus capacitor of its ballast. The fast response rate of the light output to the voltage sag implies that the time constant associated with the capacitor of the ballast is very small. Therefore, this capacitor is unable to maintain the voltage applied to the lamp and, therefore, unable to maintain the light output.

One possible source of confusion that warrants discussion is the fact that, while presenting the results of the short duration tests, the response time of the CFL bulbs was shown to be faster than the incandescent bulbs while, when discussing run-up times, the incandescent bulbs appeared to be faster. The reason behind this apparent inconsistency is the reasoning behind each of these phenomena. As has been mentioned, the run-up time in a CFL is due to the time required to vaporize the mercury in the tube of the bulb. The incandescent bulb requires no such task. Therefore, the incandescent bulb reaches full light output quicker than does the CFL. In the short duration tests discussed in this section, the duration of the fluctuation is short enough that no changes occur in the chemistry of the mercury of the CFL. Therefore, only the time constant of the ballast effects the response time of the lamp. The apparent inconsistency is really due to the fact that each outcome is caused by a separate sequence of events.

Results of Non-Rectangular Tests

Numerical Results

The numerical results of the non-rectangular tests are presented in Figures 4.20 through 4.23. Once again, each figure contains two graphs. The first graph in each figure provides the percentage light drop at the point of lowest light output. The second graph in each figure provides the total length of time of the light dip. The data that is presented in the graphs is summarized in Tables 4.4 and 4.5. Table 4.4 gives the average light drop of each lighting technology for each test conducted. Table 4.5 displays the average light drop duration of each lighting technology for each test conducted. Once again, these tables only consider Lamps A, B, E, F, and H since these were the tests that underwent exhaustive study.

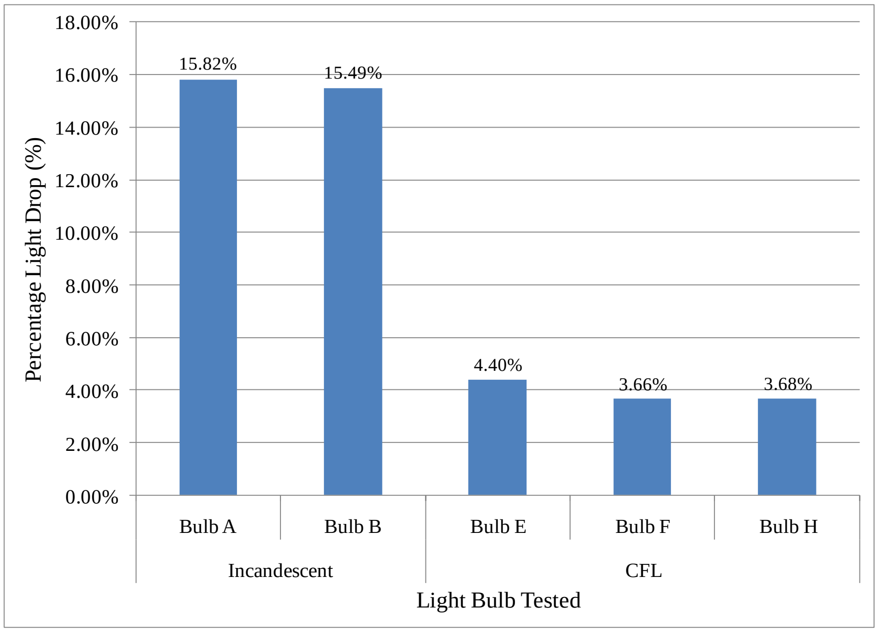

Figure 4.20a: Percent Light Drop

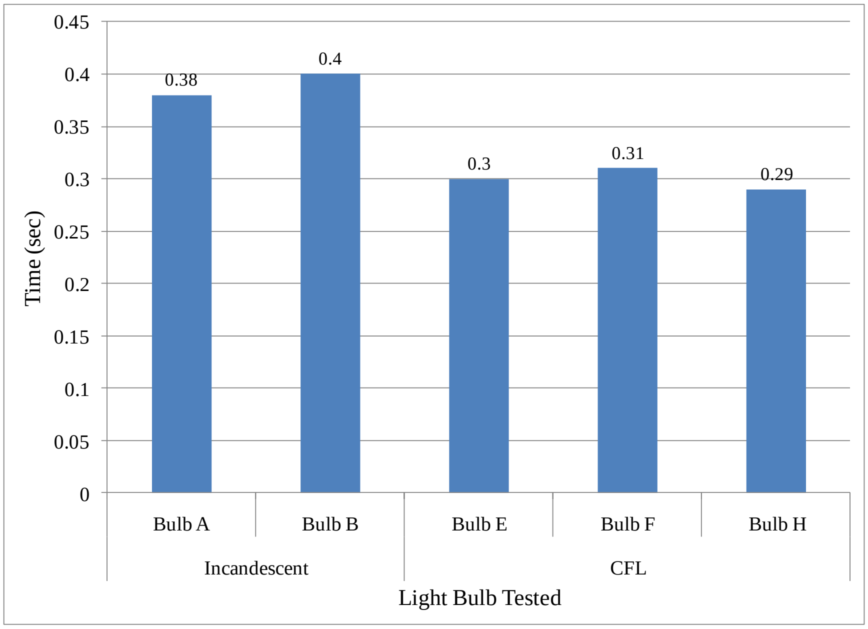

Figure 4.20b: Time Analysis

Figure 4.20: Response of Selected Soft White Bulbs to a Voltage Dip Caused by a 2.5 Ton Heat Pump

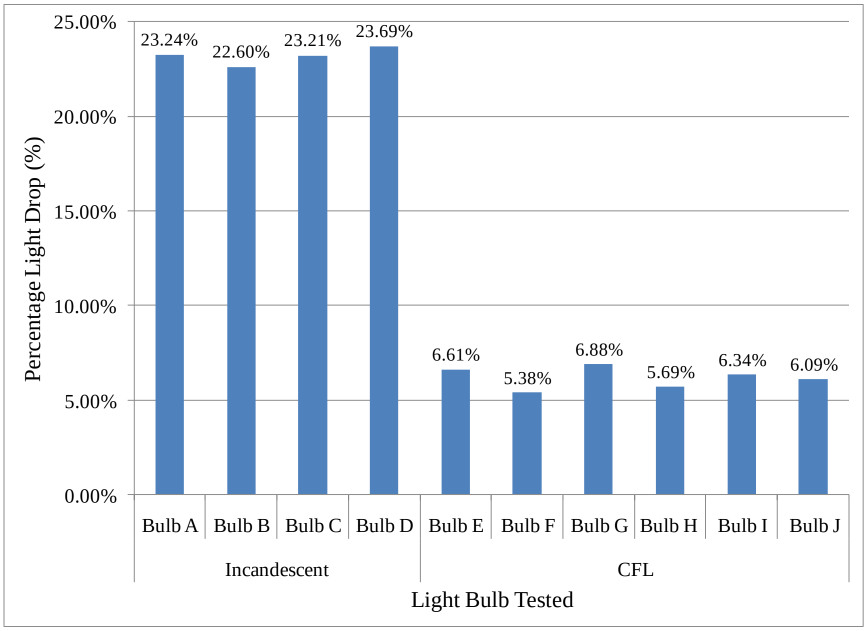

Figure 4.21a: Percent Light Drop

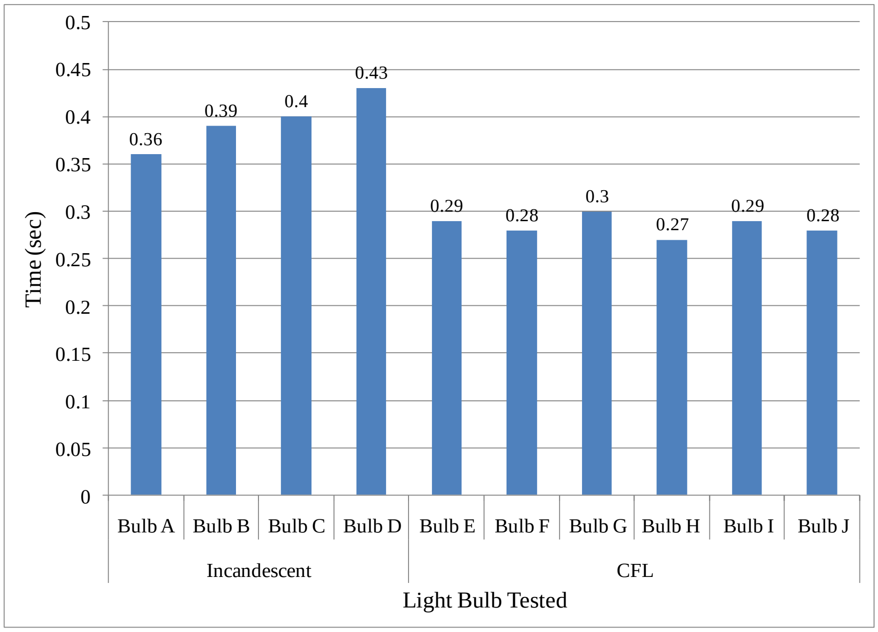

Figure 4.21b: Time Analysis

Figure 4.21: Response of Soft White Bulbs to a Voltage Dip Caused by a 4 Ton Air Conditioner

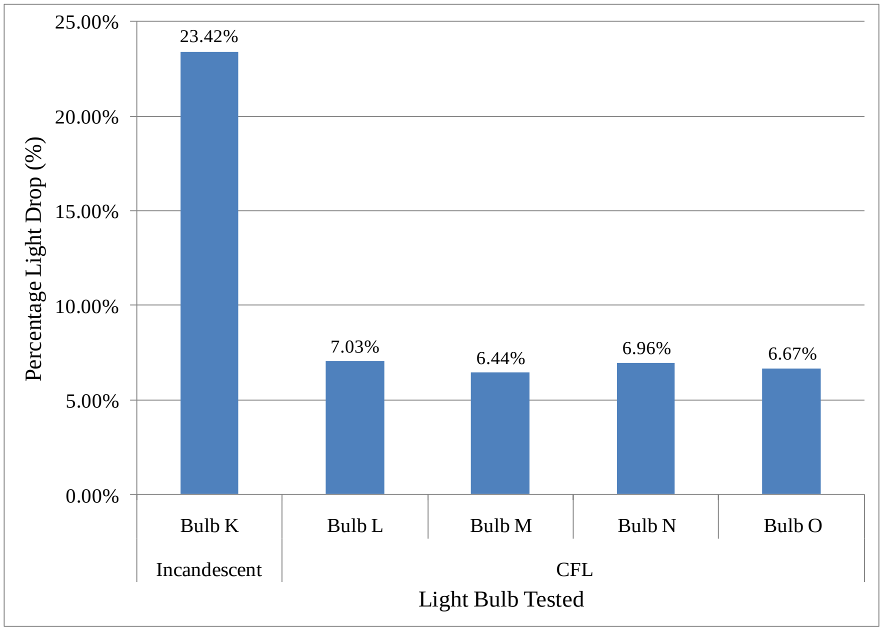

Figure 4.22a: Percent Light Drop

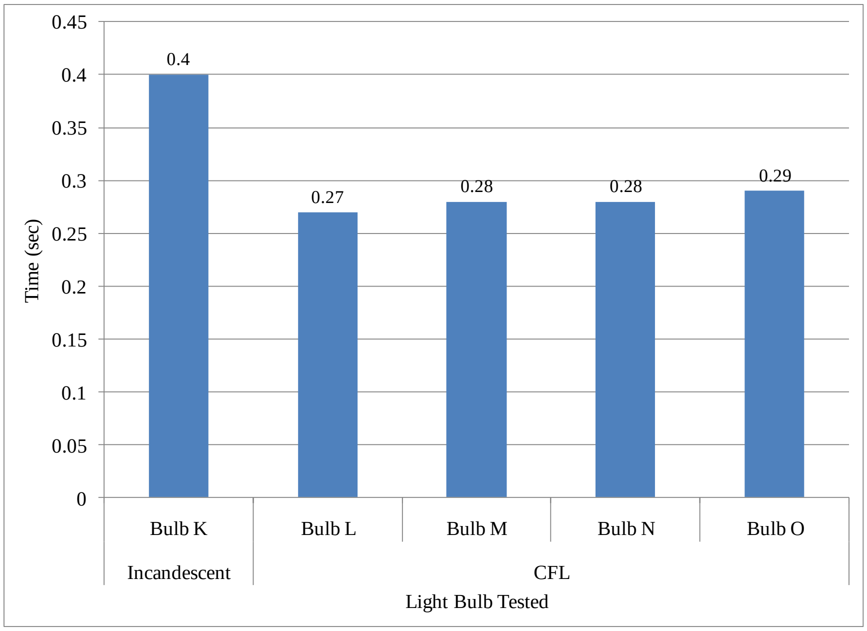

Figure 4.22b: Time Analysis

Figure 4.22: Response of Alternate Color Bulbs to a Voltage Dip Caused by a 4 Ton Air Conditioner

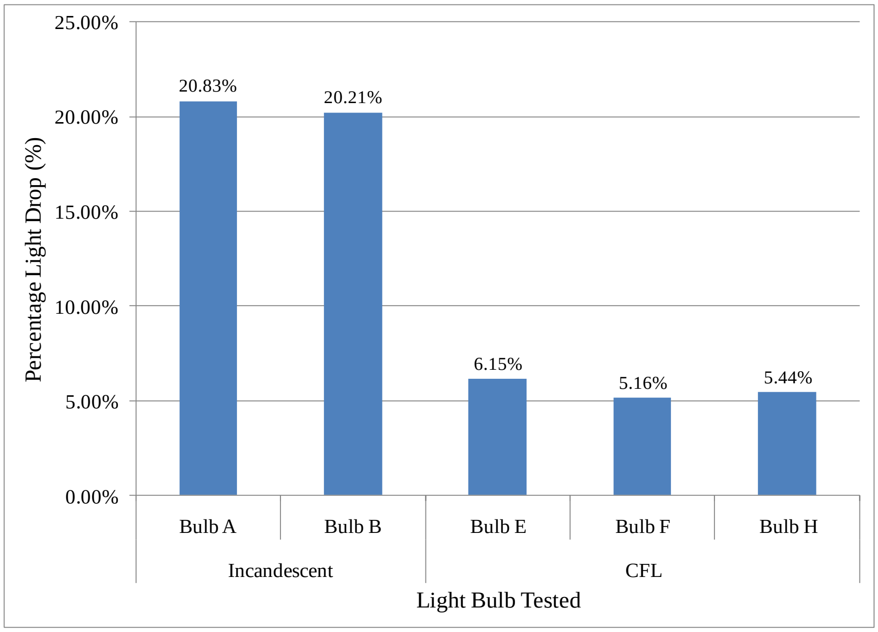

Figure 4.23a: Percent Light Drop

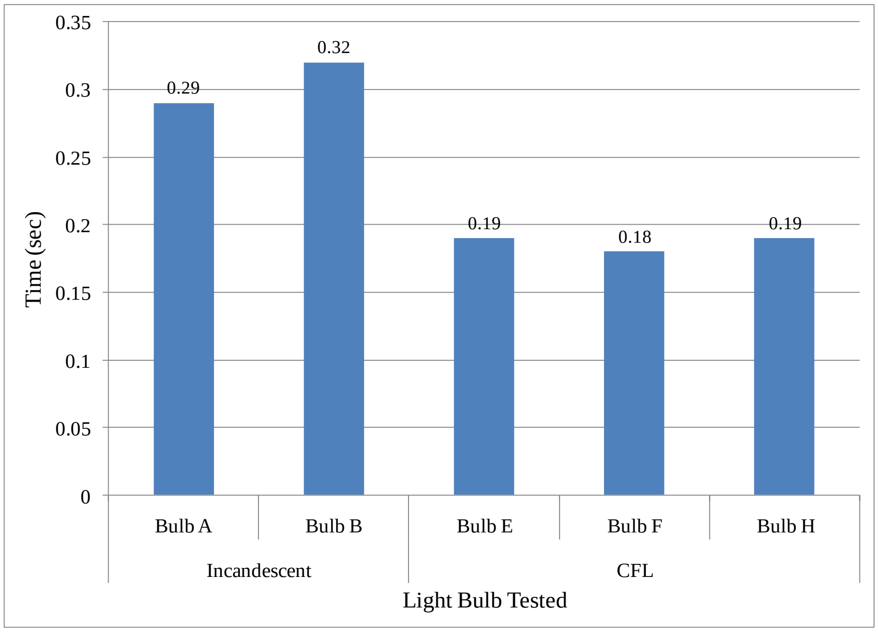

Figure 4.23b: Time Analysis

Figure 4.23: Response of Selected Soft White Bulbs to a Voltage Dip Cause by a 5 Ton Air Conditioner

Table 4.4: Overall Average Light Dips for Non-Rectangular Tests

	2.5 Ton Heat Pump	**4 Ton Air Conditioner**	**5 Ton Air Conditioner**
Incandescent Light Drop (%)	15.66%	22.92%	20.52%
CFL Light Drop (%)	3.91%	5.89%	5.58%
Light Drop Factor***	4.01	3.89	3.68

***Light Drop Factor = Incandescent Drop (%)/CFL Light Drop (%)

Table 4.5: Overall Average Time Analysis for Non-Rectangular Tests

	2.5 Ton Heat Pump	**4 Ton Air Conditioner**	**5 Ton Air Conditioner**
Incandescent Light Drop Duration (sec)	0.39	0.38	0.31
CFL Light Drop Duration (sec)	0.30	0.28	0.19
Light Drop Duration Factor+++	1.30	1.36	1.63

+++Light Drop Duration Factor = Incandescent Light Drop Duration (sec)/CFL Light Drop Duration (sec)

Discussion of Non-Rectangular Tests

The results presented for the non-rectangular tests confirm that the conclusions found for the steady state tests and the short duration tests are applicable in a real system. In each case tested, the light output of the compact fluorescent lamp was less affected by the voltage fluctuation than that of the incandescent lamp. In fact, as is shown in Table 4.4, the light fluctuation from the incandescent was on the order of 3.5 to 4 times worse than that of the CFL.

This result is to be expected when considering the results of the steady state tests and the short duration tests. The results of the steady state tests showed that the light fluctuation of the compact fluorescent lamp was 4 to 6 times less severe than that of the incandescent lamp. The results of the short duration tests showed that for a voltage drop of 4.834%, the drop time of the incandescent lamp was around 0.14 seconds. Effectively, the non-rectangular tests combine the results of the steady state tests and the short duration tests. The 2.5 ton heat pump, for example, has a voltage drop of 3.9% and stays at that level for eight cycles, or approximately 0.13 seconds. Therefore, it would be expected that the resulting light fluctuation from the incandescent lamp would be approaching a point where it is four to six times more severe than the light fluctuation from the CFL. As is shown in Table 4.4, this is, in fact, the case. The 4 ton air conditioner and the 5 ton air conditioner are of larger voltage drops and shorter duration, so it would be expected that they are approaching the factor of four to six range but would not quite hit it. As is shown in Table 4.4, this is the case.

It is also expected that since the incandescent lamp has a longer time constant than the CFL, the duration of the light drop from the incandescent lamp would be greater than that from the CFL. It is shown in Table 4.5 that this is true. The differences in the length of the light drop for the incandescent and the compact fluorescent lamp may seem to be less severe in these non-rectangular tests than they did in the previous tests. In the previous tests, it was shown that the drop and recovery times for the incandescent was on the order of 0.1 seconds, whereas the drop and recovery times for the CFL was on the order of 0.01 seconds. Therefore, it may seem as though the incandescent light dip duration should be on the order of 0.18 seconds longer than the CFL. Table 4.5 shows that this is not true. The reason for this is due to the fact that the non-rectangular tests are not sharp rectangular waveforms and, in actuality, ramp into and out of the voltage dip.

Once again, the results of this test stayed consistent when the tests were performed on all bulbs. The color of the lamp did not affect the response of the lamp to voltage fluctuation.

Proposed New Flicker Curve Based on Compact Fluorescent Lamps

Numerical Results

As has been discussed, the new flicker curve that is proposed here has been based on areas of light dips due to voltage fluctuations. The areas of light dips found in incandescent lamps were found first for specific points on the GE flicker curve. The results of these tests are given in Table 4.6 below. The results presented are the average areas from Lamps A and B.

Table 4.6: Results from Incandescent Lamps to GE Flicker Curve Fluctuations

Test Performed	Average Area (Vsec)
10dips/sec @ 0.75% voltage drop	6.83×10^{-4}
5dips/sec @ 0.46% voltage drop	8.67×10^{-4}
2dips/sec @ 0.54% voltage drop	0.0026
1dip/sec @ 0.67% voltage drop	0.0066
10dips/min @ 1.13% voltage drop	0.0668
5dips/min @ 1.33% voltage drop	0.1578
30dips/hour @ 2.21% voltage drop	2.5690
20dips/hour @ 2.50% voltage drop	4.3460

Next, data was collected from compact fluorescent lamps E and F. Since the results from the steady state test showed that the light fluctuation from the compact fluorescent lamp was consistently 4 to 6 times better than that from an incandescent lamp, data was taken for each compact fluorescent lamp at each of 4 times, 5 times and 6 times the fluctuation magnitude presented in the GE flicker curve at the corresponding fluctuation frequency. The results of this analysis are given in Table 4.7 below. The average area given here is the average of Lamps E and F.

Table 4.7: Results from Compact Fluorescent Lamps to Determine CFL Flicker Curve

Test Performed	Average Area (Vsec)
10dips/sec @ 3.00% voltage drop (x4)	6.04×10^{-4}
10dips/sec @ 3.75% voltage drop (x5)	7.60×10^{-4}
10dips/sec @ 4.50% voltage drop (x6)	9.14×10^{-4}
5dips/sec @ 1.84% voltage drop (x4)	7.41×10^{-4}
5dips/sec @ 2.30% voltage drop (x5)	9.55×10^{-4}
5dips/sec @ 2.76% voltage drop (x6)	0.0011
2dips/sec @ 2.16% voltage drop (x4)	0.0022
2dips/sec @ 2.70% voltage drop (x5)	0.0028
2dips/sec @ 3.24% voltage drop (x6)	0.0033
1dip/sec @ 2.68% voltage drop (x4)	0.0055
1dip/sec @ 3.35% voltage drop (x5)	0.0069
1dip/sec @ 4.02% voltage drop (x6)	0.0084
10dips/min @ 4.52% voltage drop (x4)	0.0561
10dips/min @ 5.65% voltage drop (x5)	0.0709
10dips/min @ 6.78% voltage drop (x6)	0.0857
5dips/min @ 5.32% voltage drop (x4)	0.1318
5dips/min @ 6.65% voltage drop (x5)	0.1634
5dips/min @ 7.98% voltage drop (x6)	0.2004
30dips/hour @ 8.84% voltage drop (x4)	1.7862
30dips/hour @ 11.05% voltage drop (x5)	2.300
30dips/hour @ 13.26% voltage drop (x6)	2.8069
20dips/hour @ 10.00% voltage drop	2.9377
20dips/hour @ 12.50% voltage drop	3.7717
20dips/hour @ 15.00% voltage drop	4.6266

The two tables above were compared to determine which value from each set of CFL tests had the closest area to the corresponding incandescent lamp test. This would be set as the new voltage fluctuation magnitude for that particular voltage fluctuation frequency in the new CFL flicker curve. If the value fell between two test points, then a voltage fluctuation magnitude somewhere between the two was chosen. The chosen values for the new flicker curve are given in Table 4.8 below.

Table 4.8: Data Points for Proposed CFL Flicker Curve

Voltage Fluctuation Frequency	Voltage Fluctuation
10dips/sec	3.50%
5dips/sec	2.00%
2dips/sec	2.50%
1dip/sec	3.30%
10dips/min	5.60%
5dips/min	6.50%
30dips/hour	12.00%
20dips/hour	14.00%

In order to show the relationship between this proposed CFL flicker curve and the GE flicker curve based on incandescent lamps, the two are plotted on the same set of axes in Figure 4.24 below.

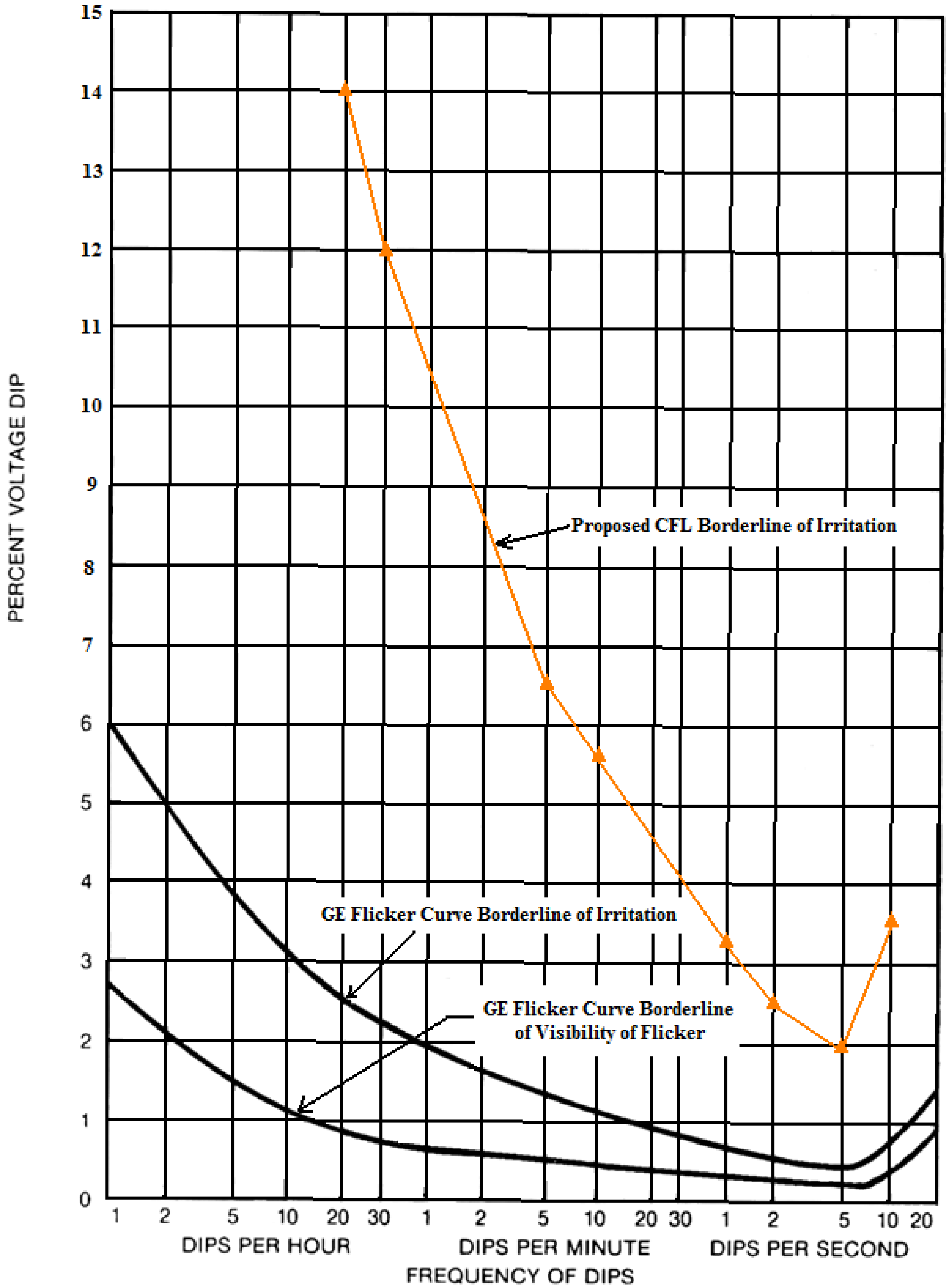

Figure 4.24: Proposed CFL Flicker Curve Compared to GE Flicker Curve

Discussion of Proposed CFL Flicker Curve Results

The results that are shown in Figure 4.24 provide a flicker curve for compact fluorescent lamps. As has been noted throughout this research, compact fluorescent lamps exhibit a higher tolerance for voltage fluctuations. Due to this robustness, as CFLs become increasingly prominent in the lighting load, utilities may find it desirable to alter their voltage fluctuation regulations to allow for higher voltage fluctuations should it be found that nothing but lighting is affected. The results of this testing has provided a frame of reference which can indicate to utilities the extent to which they can alter their regulations.

One interesting point to note on this proposed flicker curve is that the factor of 5 rule works fairly well for the entire curve. This was a surprising result. The factor of 5 that was found earlier was determined for steady state fluctuations. The short duration tests showed that, for short voltage fluctuations, the difference in response between CFLs and incandescent lamps was based on the time constant of each lamp. As the duration of the voltage dip decreased, so too did the factor by which the CFL outperformed the incandescent lamp. It was therefore expected that this factor of 5 rule would begin to fall apart as the shorter dips were found. In reality, though, it was found that this held up even through a fluctuation frequency occurring at 10dips/second. The reasoning behind this is that the recovery time of incandescent lamp extends the dip out long enough that any gain made on the CFL due to the magnitude of the light dip is canceled out by its duration. It is interesting that the CFL consistently outperforms the incandescent lamp by approximately a factor of 5.

The results that are presented here are a good basis for a CFL flicker curve, but some additional testing would be beneficial. One desired test would be a human test similar to the one used to build the original GE flicker curve. It has also been noted that when a large voltage change is applied to a CFL, the light output tends to overshoot its final value before settling down completely. In this testing, the overshoot was accounted for during the dip, but the overshoot that occurred as the lamp came out of the dip was ignored. While it is doubtful that it would cause any significant changes to the results of this test, it would be an interesting exercise.

It also needs to be noted that the testing used in order to create this proposed curve analyzed relatively few data points. The curve was created using straight line approximations between these points, which can result in some inaccuracies. For example, in the proposed curve, the most sensitive point is shown to be at 5dips/second whereas the GE curve shows the most sensitive point at about 8dips/second. It is unlikely that changing the lamp technology will actually alter this point, since this is based on the sensitivity of the human eye to certain fluctuations frequencies. The real reason for this discrepancy is simply due to the fact that there are not any data points taken between 5 and 10 dips per second. More testing using the same method at more points along the GE flicker curve would result in a curve that is more accurate for the entire range of fluctuation frequencies. This type of research could provide some beneficial results in the future.

Even though some more testing would be beneficial, the flicker curve presented here could become very useful to utilities in the future. As CFLs become a larger portion of the lighting load, regulation shifts will need to be made. This curve provides the utility with a reference as to how this shift can be made.

CHAPTER 5: CONCLUSIONS AND CONTINUING RESEARCH

Conclusions

The results of this research confirm the idea that the light output of the compact fluorescent lamp is less sensitive to voltage fluctuation than that of the incandescent lamp. As has been shown, during a long voltage sag that allows the lamp output to achieve steady state under a lower voltage, the CFL consistently provides a light fluctuation that is 4 to 6 times less severe than the light fluctuation of the incandescent lamp. The short duration tests provided similar conclusions where the light fluctuation from the compact fluorescent lamp was less severe than that from the incandescent lamp. In the short duration testing, the factor by which the CFL was superior to the incandescent depended upon the duration of the fluctuation. When a 1 cycle voltage drop was applied to the lamps, the CFL lamp fluctuation was only 1.5 to 2 times better than the light output of the incandescent lamp. When a 10 cycle voltage drop was applied, this factor increased to approximately 4. One interesting observation that came from this was that the factor by which the CFL was superior to the incandescent seemed to be independent of the magnitude of the sag, much like with the steady state tests. This shows that when comparing the compact fluorescent lamp to the incandescent lamp, the main focus has to be put on the duration of the sag and not so much on the magnitude.

Also of interest in the results obtained from the short duration tests is the response time of the compact fluorescent lamp in comparison to the incandescent lamp. The results show that the compact fluorescent lamp responds to a voltage fluctuation in a much shorter time period than does the incandescent lamp. This result shows that the robustness of a CFL during a voltage flicker does not come from the DC capacitor within the ballast of the lamp. It is obvious from the short duration results that the time constant associated with the ballast is much smaller than the thermal time constant of the incandescent lamp.

The non-rectangular tests that were performed confirm that the trends that are observed in the steady state tests and short duration tests are applicable to actual systems. The results of the non-rectangular tests followed trends that could be predicted by the short duration tests and the steady state tests, thus proving that it can be expected that a CFL will perform better than an incandescent lamp in a real situation.

Finally, a new flicker curve for compact fluorescent lamps was proposed. This flicker curve was based on finding the voltage fluctuations that cause compact fluorescent lamps to act in a way that is similar to incandescent lamps on the GE flicker curve. This can prove to be very useful as CFLs become more abundant.

These results can help utilities predict what sort of alterations will be needed in their voltage standards should CFLs become more prominent in the United States. From the results shown here, it is clear that the utilities will be able to relax some their standards so long as the only effect of such a relaxation is on lighting. Since CFLs are more robust than incandescent lamps when it comes to voltage fluctuation, a larger magnitude of voltage fluctuation will be allowable before customer complaints are expected. In fact, according to the proposed CFL flicker curve, the magnitudes of voltage fluctuations that are allowed by utilities can be increased by a factor of five before adverse effects become visible. At this point, it is very possible that voltage fluctuation regulations will no longer be completely dependent upon lighting. Voltage fluctuation regulations will need to be made to accommodate loads that were able to take the fluctuations allowed by incandescent lamps, but can no longer take the fluctuations allowed by CFLs.

Compact fluorescent lamps are providing an economical and robust form of electrical lighting. Because of this, they are becoming more prominent in the electric power system. While there are issues with CFLs that need to be dealt with, such as mercury content and harmonic content, these light sources are proving to be very beneficial to humans. It has been known that they provide light with less of a power demand than their incandescent counterparts. It has also been found that they are much more robust to voltage fluctuations than are incandescent lamps. These compact fluorescent lamps have found a niche in the lighting market and will only become more prominent as time goes on.

Suggestions for Continuing Research

As has been mentioned, some continuing research on the presented CFL flicker curve would be beneficial to its acceptance. A human test would be helpful to prove that humans react to these fluctuations as has been proposed. More data points along the GE curve could also be analyzed to get more accuracy along the entire range of fluctuation frequencies.

It will also become important in the future for the IEC flickermeter to have the ability to analyze light fluctuations from compact fluorescent lamps. An alteration to the blocks within the flickermeter to account for compact fluorescent lamp light output will be necessary to keep the device up to date.

Finally, LEDs have the potential to become the next generation of lighting technology. Therefore, this sort of study will soon be needed for LED lighting sources. A new flicker curve based on the LED will be beneficial to utilities as will further alterations to the flickermeter to account for LEDs.

APPENDICES

Appendix A: ELGAR Interface Program

In order to make the use of the ELGAR SW 5250A arbitrary waveform generator easier, a program has been written in Microsoft Visual Basic 6.0 to allow the user to easily interface with the device. In this appendix, a description of this program and instructions on how it is used are provided.

When the program is started, the user is presented with a startup screen. This startup screen is shown in Figure A.1 below. Here, the user clicks the "Click To Begin" button, which enables the options available in the program.

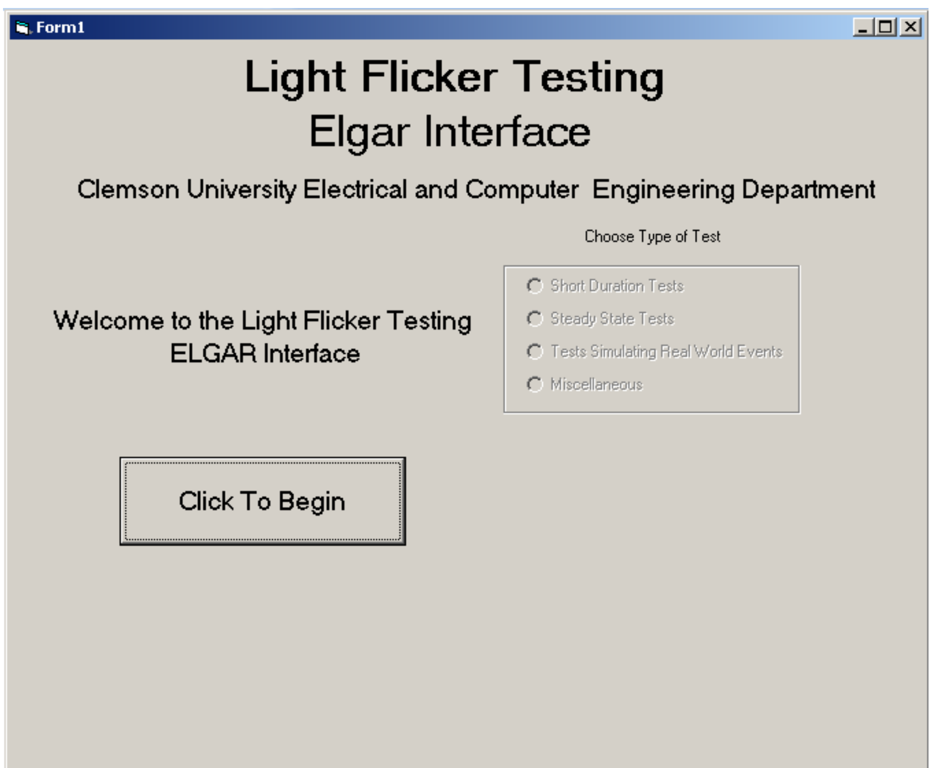

Figure A.1: Interface Startup Screen

After the user clicks the "Click To Begin" button, the "Choose Type of Test" options that had been disabled become available. The next screen presented to the user is shown in Figure A.2. On this screen, the option of "Short Duration Tests" is already selected. The user has the option to either use this screen or select another test.

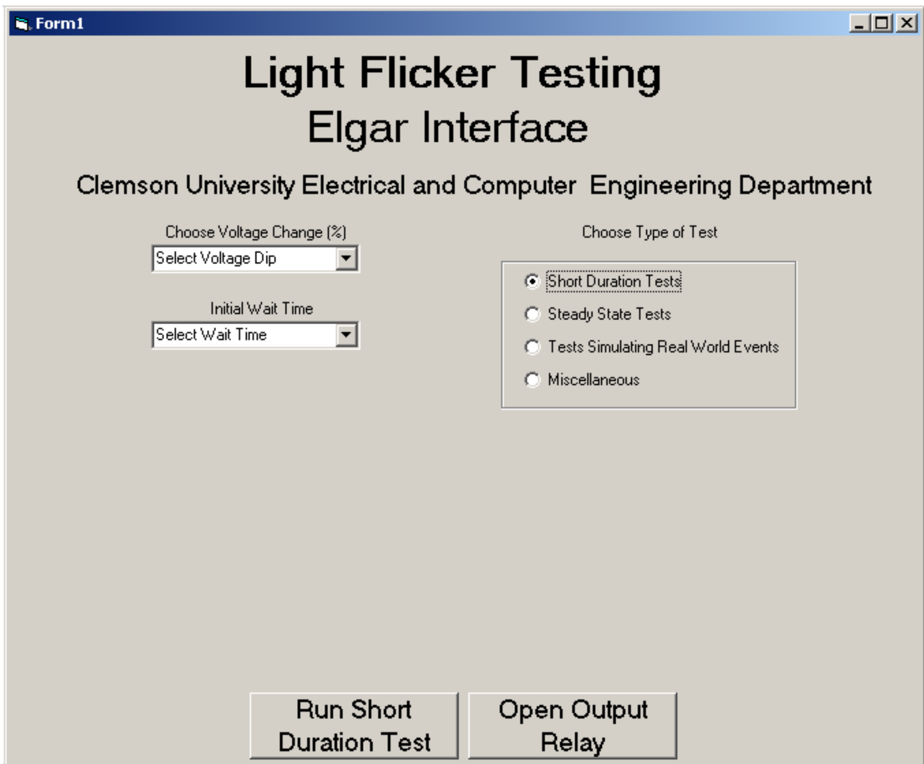

Figure A.2: Short Duration Testing Screen

If the user decides that a short duration test is desired, they are presented with two options presented as drop down menus. These are "Choose Voltage Change (%)" and "Initial Wait Time." The drop down menu for "Choose Voltage Change (%)" presents the user with the choices of 3.166%, 2.568%, 1.695%, 1.044%, 0.841%, 0.547%, and 4.834%. These values represent the percentage by which the voltage in the test will drop, with the nominal voltage being 120Vrms. For example, if 3.166% is chosen, each drop run during this test will be at a magnitude of 116.2Vrms.

The "Initial Wait Time" option presents the choices of 5mins, 15mins, 25mins, and 35mins. This is the time the ELGAR will apply the nominal 120Vrms before beginning the voltage dips. The purpose for this option is to account for the run-up time for the compact fluorescent lamp and then the time it takes for the lamp to reach a steady output. CFLs will generally reach a maximum light value within a minute of being turned on, but then the light output will decrease for a significant period of time before reaching a true steady value. Some initial tests may be required before selecting an "Initial Wait Time" and it is likely that each CFL tested will require a different time. Most incandescent lamps provide nearly instantaneous steady light output and can use the 5min option.

Once the user selects the two desired options, the test can be run by clicking the "Run Short Duration Test" button. The test will apply an rms voltage of 120V for the initial period of time selected and then will apply a 1 cycle voltage dip at the drop specified. It will then wait two minutes and apply a 3 cycle voltage dip. Finally, it will wait two more minutes and then apply a 10 cycle voltage dip. At the end, 30 seconds of 120Vrms will be applied and then the output will turn off. If at any time during the run it becomes desired to turn off the output, the "Open Output Relay" button can be clicked and the output from the ELGAR will be turned off.

If the “Steady State Tests” option is selected, the program presents the screen shown in Figure A.3 below.

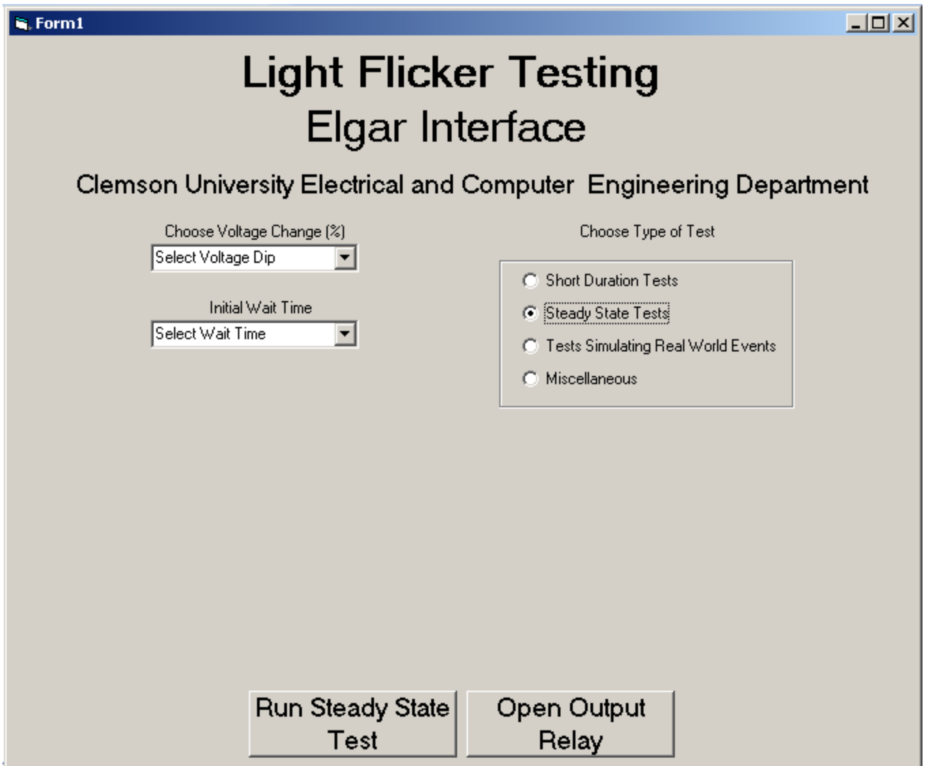

Figure A.3: Steady State Testing Screen

Once again, the same options of “Choose Voltage (%)” and “Initial Wait Time” are presented and perform the same tasks as described for the short duration tests. When the options are selected, the “Run Steady State Test” button can be clicked to begin the testing. The ELGAR will provide 120Vrms for the selected wait time and then will provide a the selected voltage dip for 90 seconds. At the end of this 90 second period, the voltage will recover to 120Vrms for 30 seconds before the output turns off. Once again, the test can be stopped at any time by clicking the “Open Output Relay” button.

If the “Non-Rectangular Tests” option is selected, the user is presented with the screen shown in Figure A.4.

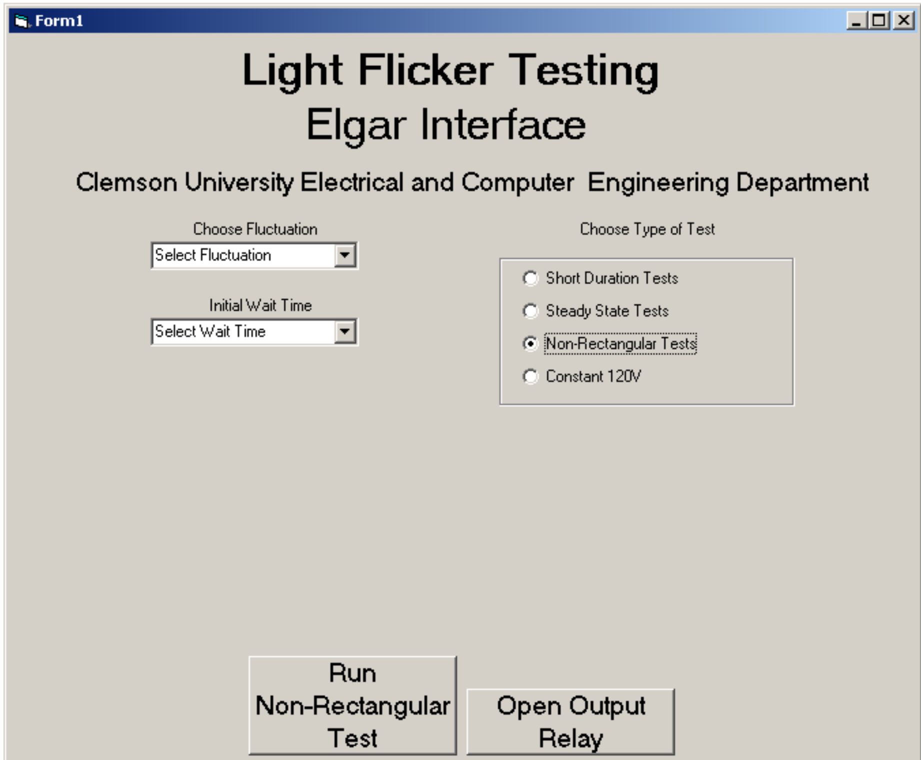

Figure A.4: Non-Rectangular Testing Screen

At this screen, the user is asked to choose a waveform. The options for this waveform are “2.5 Ton Heat Pump,” “4 Ton Air Conditioner,” and “5 Ton Air Conditioner.” These waveforms correspond to the waveforms shown in Figures 3.9 – 3.11 in Chapter 3. Once again, the “Initial Wait Time” is presented. The user clicks the “Run Non-Rectangular Test” button to start the test. Again, the ELGAR outputs 120Vrms for the selected initial time and then runs the selected fluctuation. After the fluctuation is run, 120Vrms is applied for 30 seconds and then the output is turned off.

Once again, the output can be manually turned off at any time by clicking the "Open Output Relay" button.

If the "Constant 120V" option is selected, the screen shown in Figure A.5 is presented to the user.

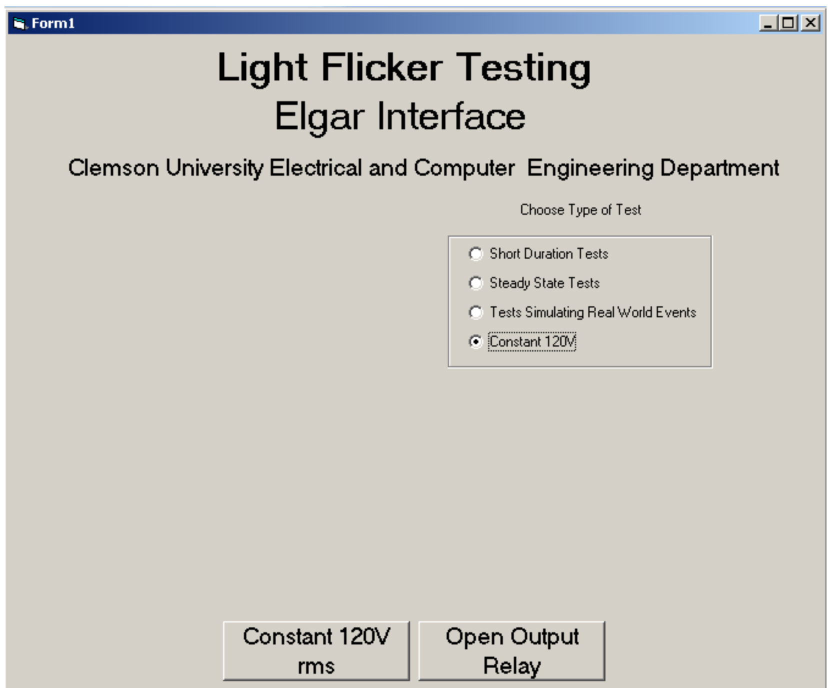

Figure A.5: Constant 120V Test Screen

Here, very simply, by clicking the "Constant 120Vrms" button, the user can apply a 120Vrms voltage to the lamp for an indefinite period of time. The output only stops when the user clicks the "Open Output Relay" button. This test is very useful when determining the necessary wait time when testing a lamp in the above mentioned tests.

Appendix B: Experimental Setup Pictures

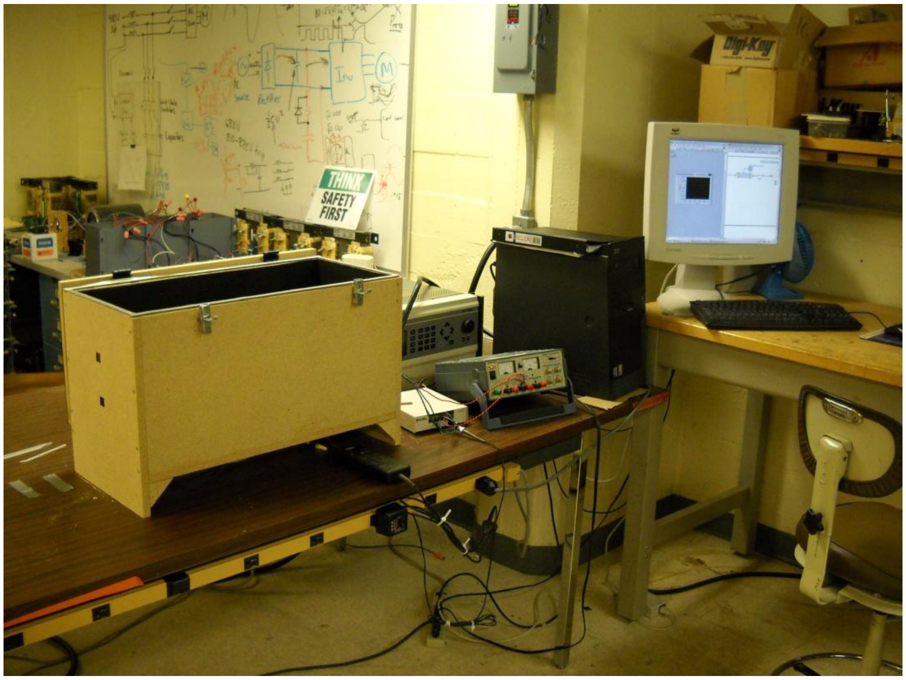

Figure B.1: Complete Experimental Setup

Figure B.2: Experimental Setup

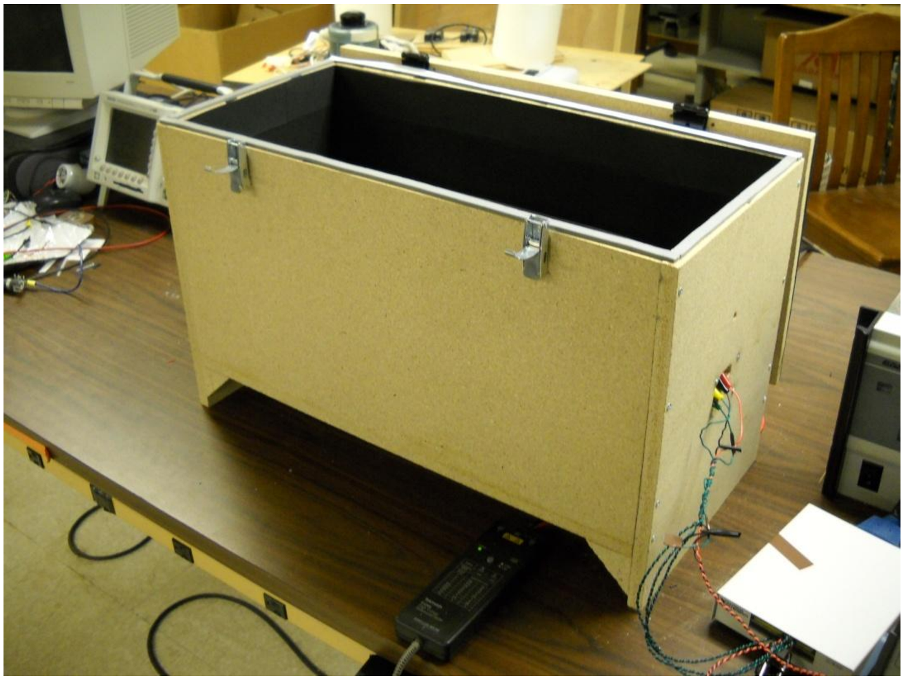

Figure B.3: Enclosure in Open Position

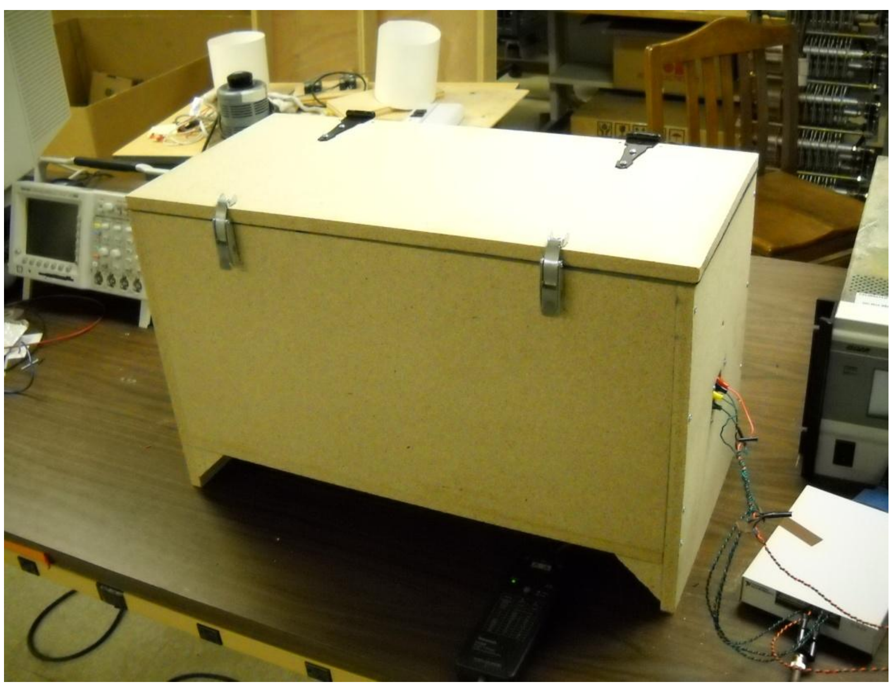

Figure B.4: Enclosure in Closed Position

Figure B.5: Inside Enclosure

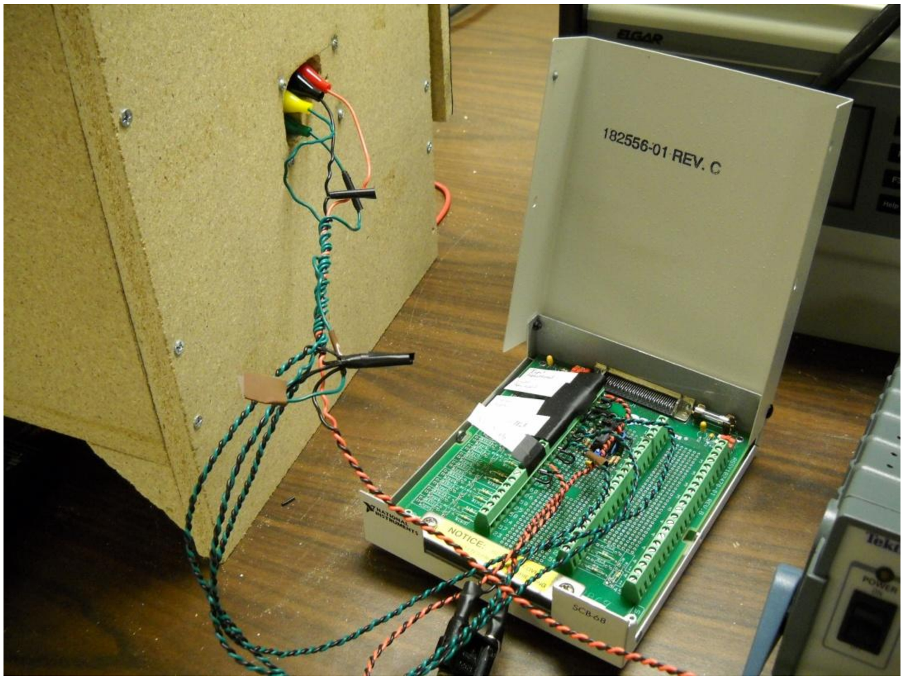

Figure B.6: NI Connector Block with Sensor Connections

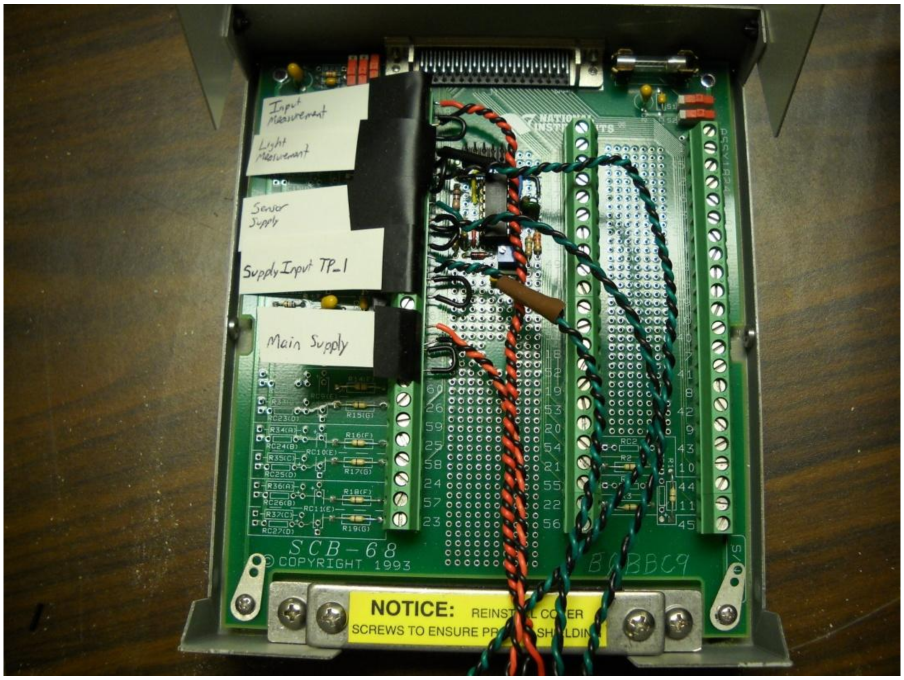

Figure B.7: Wiring of NI Connector Block

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