STATCOM FOR MITIGATION OF FLICKER CAUSED BY AN ELECTRICAL ARC FURNACE

BY

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A Thesis submitted to
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In Partial Fulfillment of the Requirements for the Degree of

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Statcom for Mitigation of Flicker Caused by an Electrical Arc Furnace

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A Thesis/Practicum submitted to the Faculty of Graduate Studies of The University of Manitoba in partial fulfillment of the requirement of the degree

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ABSTRACT

Currently the power system is lagging behind the demands of the consumer. With the inability to build new transmission and generation due to social and economic pressures, the weakened power system tends to exhibit poor power quality. This problem gets dramatically worse if there is an Electric Arc Furnace (EAF) on the network due to it's chaotic highly non-linear load. The power quality issue mostly associated with the EAF is light flicker, where people working and living nearer the EAF notice the lights flickering due to the EAF demands on the power system

The utilities and the industrial community need to work together to design and apply new and novel ways to compensate this poor power quality.

This thesis developed a control strategy using the STATCOM to effectively compensate light flicker.

This thesis also develops a method to benchmark the level of compensation by modeling the UIE/IEC Flickermeter for use in and EMT-Type program.

Using the models developed above and a novel method of integrating real recorded data and an EMT-Type simulation, a method to successfully mitigate light flicker and to find the most cost effective size was developed.

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1 Introduction

1.1 The Problem

As industrial and consumer demands outgrow the present power system, one of the first items to suffer is the quality of power being delivered. The current deregulation of power systems is slowing down the necessary upgrades and maintenance of the system. This problem is only going to get worse as some of the main causes of power quality problems are just going to increase.

A cost effective solution to mitigate power quality issues is the use of active compensation to quickly and efficiently compensate any power/voltage deviations that might cause problems. In this thesis we will look at the specific problem of electric arc furnace compensation as this is one of the worst single point power polluters of the electric network. An electric arc furnace (EAF) is considered a chaotic load, with many deviations within a 1/2 cycle, which causes many power quality problems, including voltage flicker. In this study, a novel method to mitigate the flicker caused by an arc furnace was developed. As part of the study, a technique to simulate an EAF in an Electro-Magnetic Transient (EMT) Type program using measured data is developed. A simulation model of a flickermeter was also developed to measure the effect of the mitigation method.

1.2 Power Quality Causes

As mentioned above, some of the main causes of power quality issues are industrial and consumer loads, which is not to say that the utility is completely innocent as power system outages and un-maintained equipment all add to the problem.

Power quality actually encompasses many type of power system phenomenons, such as:

- Voltage Flicker
- Voltage Notching
- Harmonics
- voltage sags
- Voltage swells
- voltage unbalance
- System Phase jumps
- Power System Faults (weather, equipment failure, vandalism, etc.)

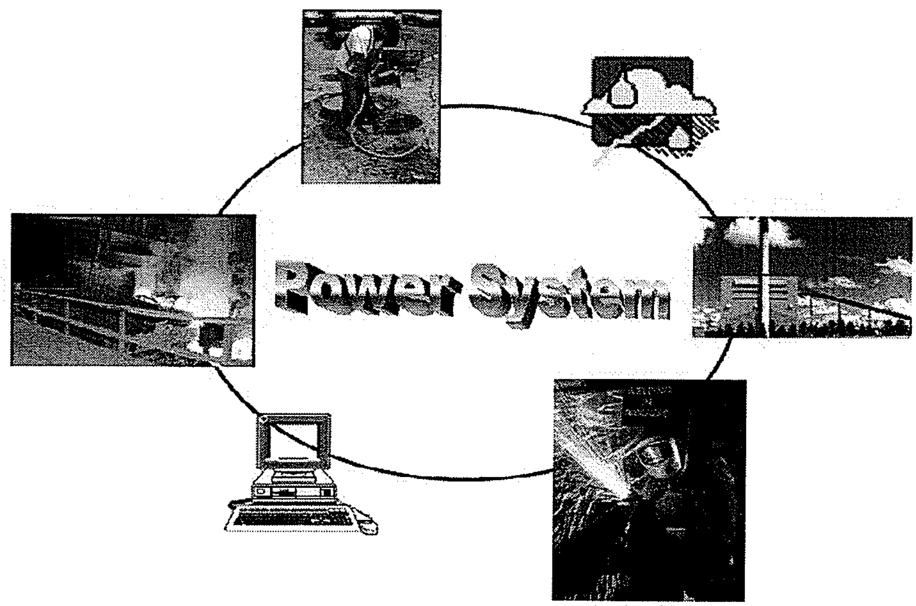

Figure 1-1. Power Quality Causes

Some of the main causes of power quality issues are shown in Figure 1-1. They are:

- Industrial process such as; Welding, compressor loads, Electric Arc Furnaces
- Consumer processes such as; computer loads (switched power supply), unbalanced farm agriculture loading, heat and cooling loads
- weather issues; lightning, wind, icing, etc.
- Power system degradation

1.3 Mitigation Methods

Since rebuilding the power system is unpractical and adding more transmission and generation capacity is getting harder and harder, engineers must come up with novel ways to solve these power quality problems. Some of these solutions include using fixed compensation such as ac filters and switched capacitor banks which may cause transient voltage quality issues of their own. In order to compensate for the more of the sporadic power quality issues, active compensation is needed. These include synchronous condensers, which by nature are slow and by newer type of power electronic devices such as static transfer switches, automatic voltage regulators, Static Var Compensators (SVC) and Static Synchronous Compensators (STATCOM). The more common of these are outlined in chapter 4.

For EAF compensation, the SVC have been the method of choice for many years, but the fact that the SVC needs to wait for a current zero limits its reduction capability. A STATCOM on the other hand, using the right control method, can compensate almost instantly as will be shown.

1.4 Thesis Outline

The Thesis is organized as follows:

In Chapter 2, we look at the history of flicker and flicker measurement. This is important as it gives an understanding of the depth of the problem

Chapter 3 looks at the 3 phase electric arc furnace. This chapter will review the components that make up an arc furnace and describe the melt sequence. The actual electric arc will be examined as well

In chapter 4, the procedure to develop an EMT-Type flickermeter will be presented. The flickermeter will also be tested and verified in this chapter.

In Chapter 5, different compensation techniques will be examined. These methods will lead to the thesis main objective, that of EAF compensation.

Chapter 6 describes the development of an VSC based compensation system for an EAF installation.

Chapter 7 will develop a means to apply recorded data in a EMT-Type program. After this is done, the compensation technique developed in Chapter 6 will be applied and improvements in flicker will be measured using the flickermeter developed in chapter 4.

Chapter 8 will conclude the thesis with a review of the tests completed and any results found. Future work will also be discussed.

2 What is Flicker?

2.1 Introduction

The definition of flicker is "The amplitude modulation of the fundamental frequency voltage waveform by one or more frequencies (typically in the 0 to 30Hz range)"[1], but practically flicker is much harder to define.

A flicker problem has two main causes, a voltage deviation in the circuit supplying the lighting circuits and a person being present to notice the light intensity variation due to these voltage deviations. This human factor significantly complicates the issue, as it is now a problem of perception. What bothers one person may not bother the next.

Cases of flicker damaging equipment are very rare, as the voltage deviations causing the flicker are small. To a human being though, a change of 1-2% is enough to cause annoying flicker.

2.2 History of Flicker in North America[1]

In 1891, the North American power industry chose 60Hz as the standard frequency for the electrical system, partly to reduce visible flickering in the open-type arc lamps. At around this same time, the European power industry selected 50Hz as the system frequency, as they were using a less flickering enclosed-type arc lamp. As the widespread use of the tungsten filament bulb started, flickering started to become a serious problem.

In 1921, General Electric engineers began to research the human response to the flicker phenomena in the 0-10Hz range of a 115V tungsten filament lamp as shown in Figure 2-1. In 1925, GE published these findings, which eventually becomes the flicker design standard for North America. Even so, there is no uniformity among utilities, companies and regions.

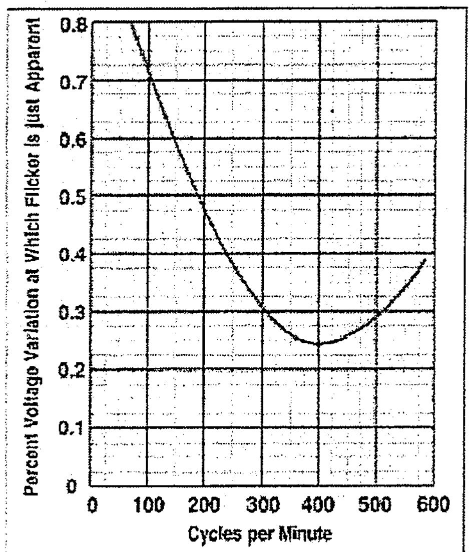

Figure 2-1. Original GE Flicker Curve

In 1937, Utilities Coordinated Research completed a comprehensive study on the human perception of flicker. This study validates the GE curve for cyclic flicker and recommends a voltage limit for non-cyclic flicker.

During the 1950's, the stroboscopic effect of fluorescent lights became a concern, but were found not to present significant annoyance to human beings. The 120V incandescent lamp still remained the most prone to flicker. This also proved that the incandescent light bulbs have an amplified response to voltage changes at low pulsation rates.

In 1964, IEEE published Standard 141 better known as the IEEE Red book which included a modified GE flicker curve covering both cyclic and non-cyclic pulsations. This curve can be seen in Figure 2-2.

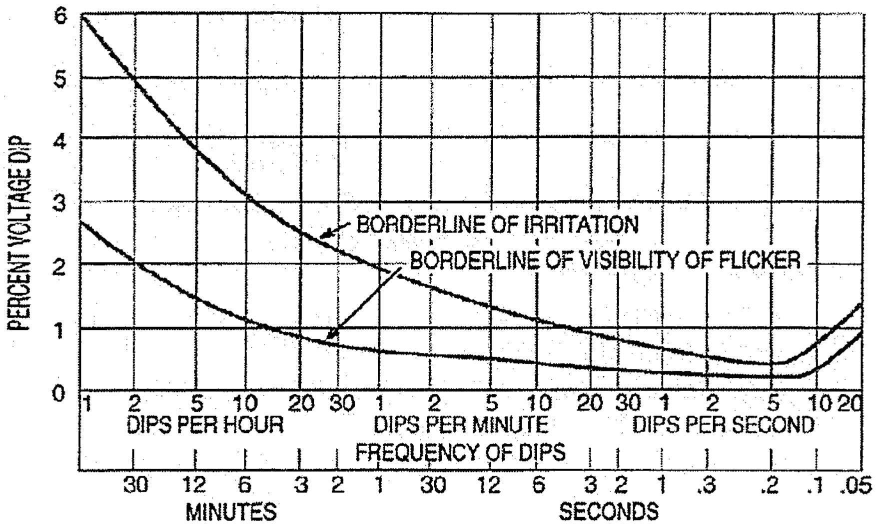

Figure 2-2. Modified GE Flicker Curve from IEEE Standard 141

In 1985, the IEEE conducted a survey and found that 69% of responding(85) utilities were using the modified GE Flicker Curve as their voltage standard.

2.3 Classification of Voltage and Light Flicker[2]

2.3.1 Voltage Flicker

To define light flicker, we first need to define voltage flicker. Voltage Flicker is the amplitude modulation of the fundamental frequency voltage by one or more frequencies, typically in the 0 to 30 Hz range. At some magnitude, this modulation causes a noticeable "flicker" in the lighting connected to this voltage.

The easiest way to understand the meaning of flicker is through a simple example. To define voltage flicker mathematically, refer to Figure 2-3.

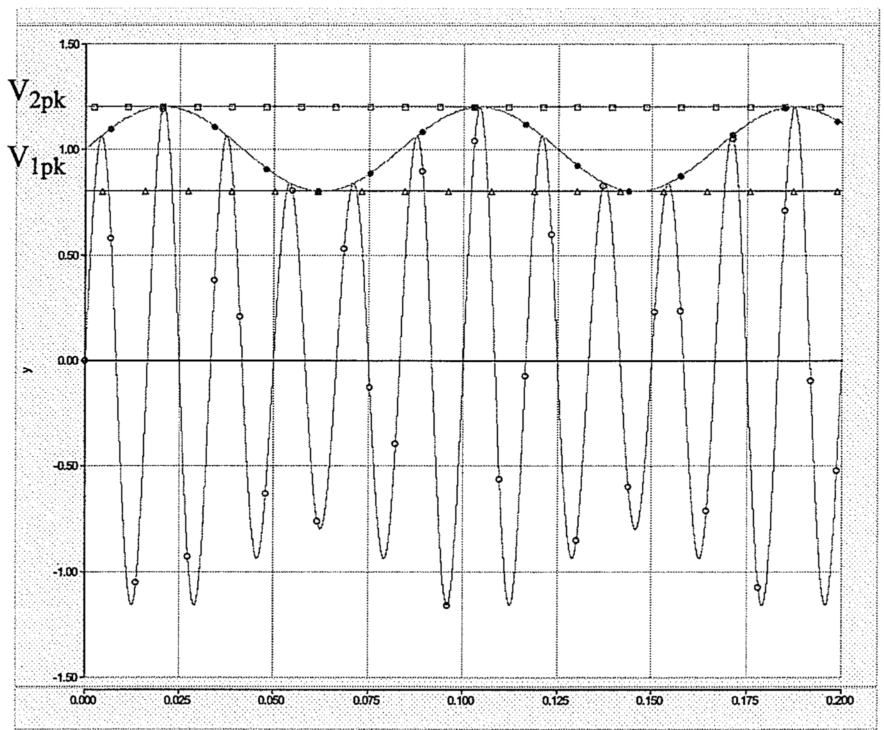

Figure 2-3. Single Frequency Flicker waveform: 20% flicker at 12Hz.

$$\text{Percent Voltage Flicker} = \frac{dV}{V} = \frac{V_{2pk} \angle V_{1pk}}{V_{2pk} + V_{1pk}} \cdot 100\%$$

$$\text{Percent Voltage Flicker} = \frac{1.2 \angle 0.8}{1.2 + 0.8} \cdot 100\% = 20\%$$

Percent Voltage Flicker **Equation 2-1.**

$$\text{Votlage Flicker Magnitude} = \frac{V_{ModulatingRMS}}{V_{FundamentalRMS}}$$

where,

$$V_{ModulatingRMS} = \frac{V_{2pk} \angle V_{1pk}}{2\sqrt{2}}$$

and

$$V_{FundamentalRMS} = \frac{V_{2pk} + V_{1pk}}{2\sqrt{2}}$$

Voltage Flicker Magnitude **Equation 2-2.**

An important point to recognize, is that voltage flicker is not equal to light flicker. The reason for this is that when different types of lighting is exposed to the same voltage flicker, different light flicker results, due to the individual dynamics of each light producing device.

When multiple frequencies are present, basic amplitude modulation theory is applicable, which states that the flicker (voltage or light) will be proportional to the RMS sum of the individual modulating components.

2.3.2 Light Flicker

To calculate light flicker, the gain factor for the particular type of light is required (i.e. a generic brand incandescent light bulb). In conjunction with this, a model of how the human eye/brain perceives this flicker must be used. Once this is done, a flicker weighting curve (see Figure 2-1) can be calculated.

Most of these "flicker weighting curves" are modeled assuming incandescent light bulbs. The average human eye is most sensitive to flicker frequencies in the 6 to 10Hz range. A modulation of 0.3 to 0.4% in this range is enough to be noticed.

Perhaps one of the most important factors of light flicker is the perceptibility factor. Not everyone will perceive flicker the same at any given time. For example, if some one is reading, they might notice it more than someone who is not visually focusing as intently. Another perception factor is the person's past awareness of the flicker. There are two major categories with perception; first where someone does not notice the flicker until they are told there is a problem; secondly, where there was a flicker problem that was mitigated, and then the population starts to complain. This indicates that there was never a perceived problem, and after the flicker was mitigated, the lighting had a different characteristic than what the public was used to.

2.4 Weighted Average and Statistical Analysis

As mentioned previously, GE has produced the first flicker weighting curve. The newest version, and the most widely used is the IEC weighting curve as 61000-4-5. It can be seen in Figure 2-4. This plot has two different curves, one for the North American 115V/60Hz system and one for the European 230V/50Hz system. The original curve is the European one, and the North American response is a modified response due to thicker bulb filament used in a 120V/60Hz system. These curves gives the perceptibility limits, anything above the curve is noticeable, anything below is not, according to the research using an "average person".

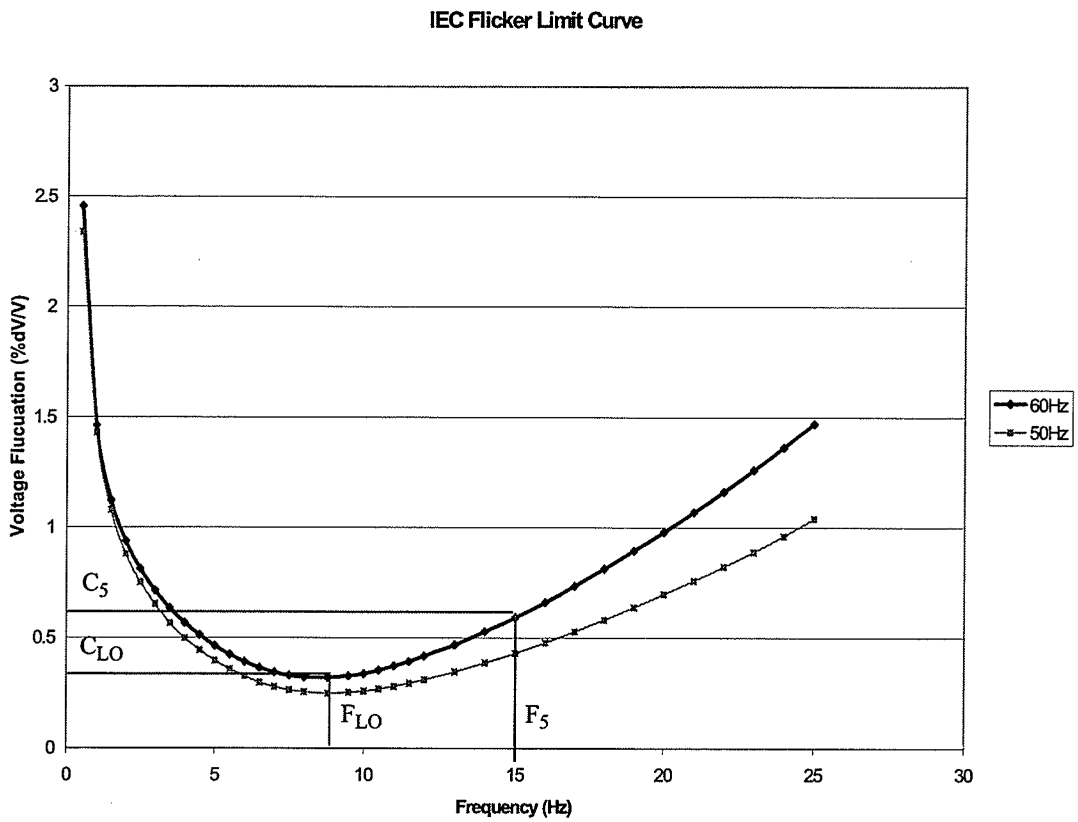

Figure 2-4. IEC Flicker Limit Curve

2.4.1 Weighted Flicker Average

The weighted flicker average is analogous to the total harmonic distortion. It represents the complete flicker spectrum and as a single number. This single number is then expressed relative to the specific perceptible flicker curve being used. The weighted average flicker may be expressed as:

$$W = \sqrt{\sum_n \left(\frac{F_n \cdot C_{LO}}{C_n}\right)^2} = C_{LO} \cdot \sqrt{\sum_n \left(\frac{F_n}{C_n}\right)^2}$$

Weighted Average Flicker **Equation 2-3.**

where,

W = weighted average flicker

n = frequency increment

F_n = measured flicker magnitude at the n^{th} frequency increment averaged over the sampling period.

C_{LO} = lowest flicker level on the perceptible flicker curve.

C_n = flicker value of the perceptible flicker curve at the n^{th} frequency increment.

The weighted flicker calculation normalizes the whole flicker spectrum to the lowest point on the flicker weighting scale. By using this equation, any weighted average that exceeds the minimum point on the flicker curve becomes visible. This method is effective for calculating the effect of multiple frequencies. A situation can easily occur where 2 frequencies by themselves will not cause flicker, but their additive effects will. For example, if we have a 0.45% voltage deviation at 5 Hz voltage flicker, a 0.45 voltage deviation at 15 Hz voltage, and then a voltage flicker the combines the 5 and 15 Hz components. Looking up the values from Figure 2-4:

Frequency	Min. point (8.8 Hz)	5 Hz	15 Hz
Curve Value	0.321	0.465	0.593

Table 2-1.

If we only consider the 5 Hz component:

$$WA = 0.321 \cdot \sqrt{\left(\frac{0.45}{0.465}\right)^2} = 0.3106$$

5Hz weighted average flicker example **Equation 2-4.**

$$WA = 0.321 \cdot \sqrt{\left(\frac{0.45}{0.593}\right)^2} = 0.2436$$

15 Hz weighted flicker example **Equation 2-5.**

$$WA = 0.321 \cdot \sqrt{\left(\frac{0.45}{0.465}\right)^2 + \left(\frac{0.45}{0.593}\right)^2} = 0.3948$$

5 Hz and 15 Hz combined weighted flicker example **Equation 2-6.**

From Equation 2-4 to Equation 2-6, we can see that when we only consider individual frequencies, we do not exceed the minimum flicker level (0.3106<0.321, 0.2436<0.321), and is therefore the flicker is imperceptible. However, in the combined frequency case, the weighted average is 0.3948 which means that the flicker will be perceptible.

2.4.2 Statistical Analysis of Flicker

The actual measurement of flicker as described above is just one part of the flicker problem. Another issue is how often does the flicker occur. Light flicker often occurs when a washing machine or air conditioner starts in a house, but the flicker will not be classified as an annoyance, as it only occurs a few times a day. However, if there is a residential area next to an industrial consumer with a motor starting load that occurs every hour, it may be conceived as an objectionable flicker.

To better visualize this occurrence, a distribution of the weighted flicker captured over a given time period can be used, as shown in Figure 2-5, which shows a 24 hour period at a steel mill with multiple furnaces and SVC systems. This curve was weighed on a 0.33 minimum flicker level, and as indicated on the graph, anything above this point is considered visible flicker.

An alternative view, which is also the more common one, can be seen in, is a cumulative distribution of the weighted flicker values. The graph can be interpreted as a percentage of time the weighted flicker exceeds the value on the horizontal axis.

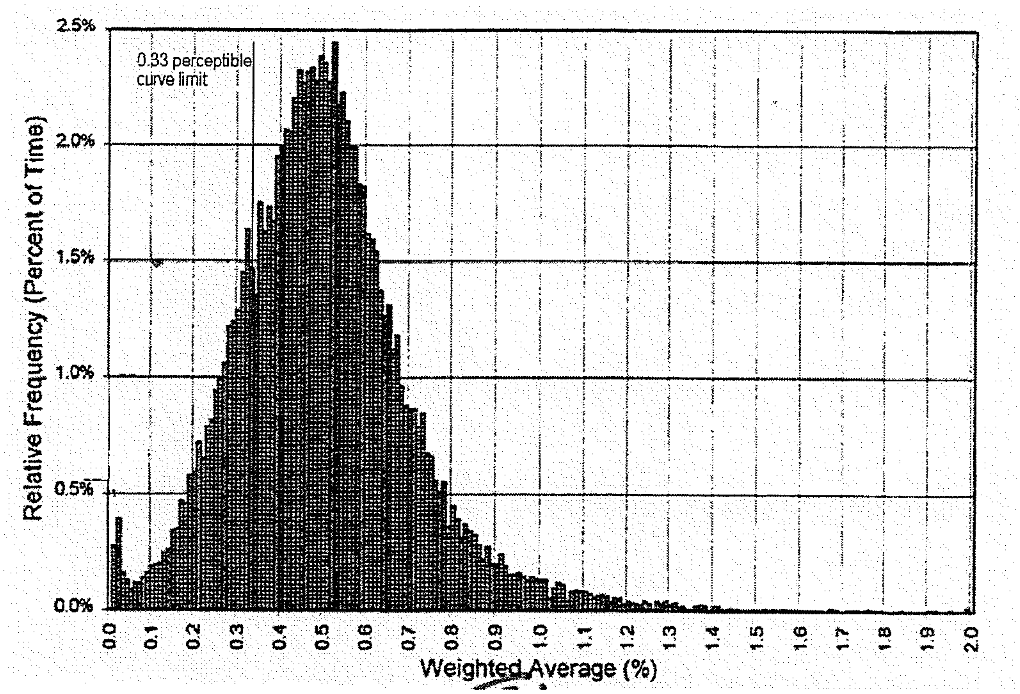

Figure 2-5. Distribution weighted Flicker Value Curve[2]

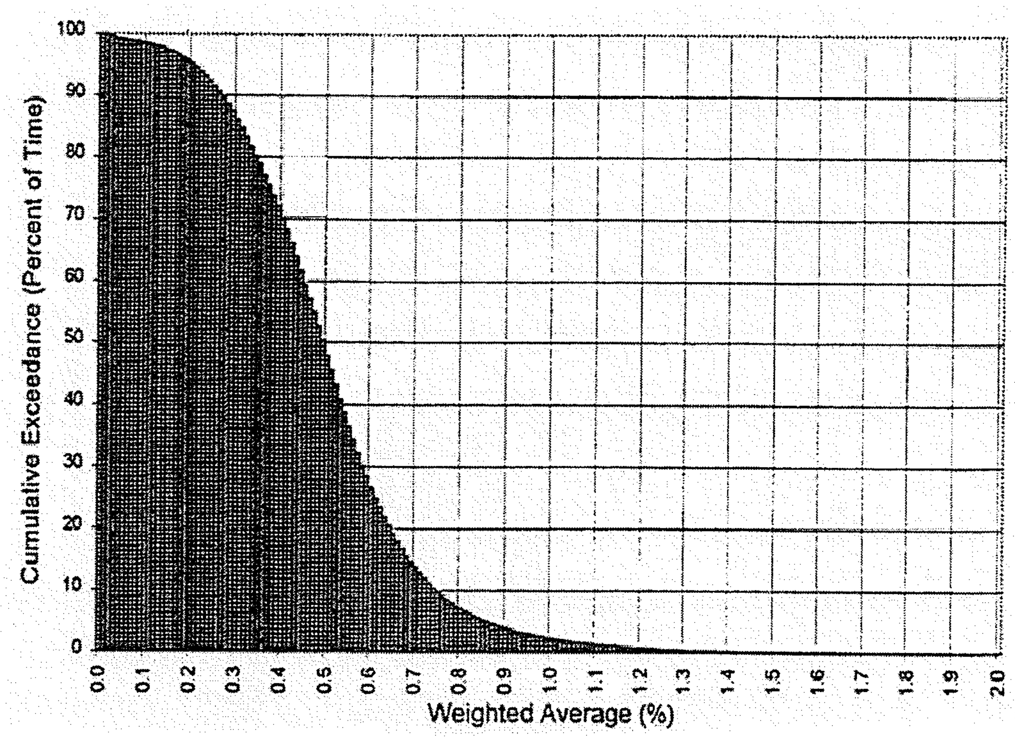

Figure 2-6. Cumulative Distribution of Weighted Flicker Values[2].

The International Electric Colloquium (IEC) introduced a term to take into account the statistical distribution. This is done by introducing a short-term severity term (Pst). The shape of the curve represents the build up to customer annoyance. High level of flicker for a short duration may not cause complaints, but if this level continues, more complaints may arise. An interesting point to note here is that if someone has been exposed to near objectionable flicker for long periods of time, they would be less likely to be annoyed should flicker levels rise to an objectionable limit.

The formula for calculating Pst is:

$$P_{ST} = \sqrt{0.0314 \cdot P_{0.1} + 0.0525 \cdot P_1 + 0.0657 \cdot P_3 + 0.28 \cdot P_{10} + 0.08 \cdot P_{50}}$$

Pst calculation **Equation 2-7.**

$P_{0.1}$, P_1, P_3, P_{10} and P_{50} represent the flicker level squared using the IEC methodology, to be described later, exceeded by 0.1%, 1%, 3%, 10% and 50% of the observation period. IEC recommends a 10 minute observation window, and if the Pst level exceeds 1.0, the flicker is said to be objectionable.

For the purposes of this study, though Pst is the industry standard, we did not use it to benchmark our results as will be shown in chapter 4.

3 Electric Arc Furnaces

3.1 Introduction

The 3-phase Electric Arc Furnace (EAF) is used in many steel mills around the world, typically operating at power levels in the 30-80MW range with a power factor of anywhere between 0.6-0.9 depending on the process. The EAF load also behaves very chaotically with the before mentioned power swings occurring inside of an electrical power systems operating frequency.

Due to the nature of an EAF loading, which are increasing every year and the fact that the electrical systems are already operating near the system limits, a study of the effects of the arc furnace load is required. This chapter will go through the various aspects of an EAF and the actual electric arc. Some case studies and some simulation techniques to mitigate the effects of the EAF will be described.

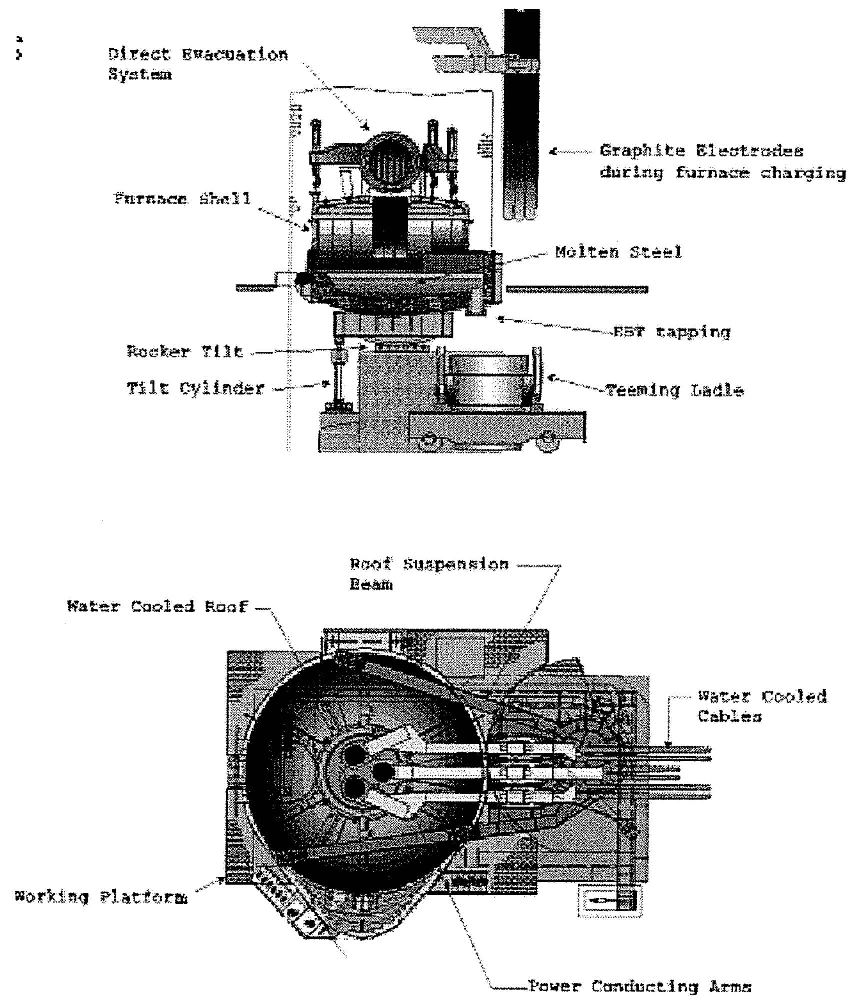

Figure 3-1. The Electric Arc Furnace[3]

3.2 The Electrical Arc Furnace Process[3]

Before the electrical description of the EAF, it is worthwhile to describe the process involved in EAF Steelmaking. There are 6 main steps in an EAF operating cycle (which is called the tap-to-tap cycle) are as follows:

- Furnace Charging
- Melting
- Refining

- De-Slagging
- Tapping
- Furnace Turn around

The tap-to-tap time of modern furnaces is approximately 60 minutes. Each of the above steps will now be explained briefly.

3.2.1 Furnace Charging

The furnace charging step consists of raising the electrodes and swinging the roof to the side, to allow the scrap crane to drop the steel scrap into the furnace. Once this is done, the roof swings back and the electrodes are lowered until an arc is struck on the scrap, which then commences the melting sequence of the cycle

3.2.2 Melting

The melting sequence is the main portion of the cycle, and is accomplished by supplying energy to the furnace. This energy can be electrical or chemical, but the main contributor is the electrical energy supplied through the graphite electrodes. When the electrodes are initially lowered, an intermediate voltage tap on the EAF transformer is selected until the electrodes bore into the scrap. During the initial bore in phase, in which the electrodes are placed into the scrap, 15% of the scrap is melted. After a few minutes, when the electrodes have bored deep enough into the scrap, the transformer taps to a higher voltage, thus creating a longer arc. The long arc maximizes the transfer of power to the scrap, and a liquid pool of metal will form. The main reason for not using a longer arc right away, is that more of the arc is outside of the scrap and could cause radiation damage to the roof of the furnace.

At the start of the electrical melting sequence, the arc is erratic with unstable and wide swings in the current. As the EAF atmosphere heats up, the arc stabilizes and eventually, as the molten pool is formed.

The chemical energy is supplied mainly via oxygen lances and oxy-fuel burners. Oxy-fuel burners burn natural gas using oxygen, or a blend of air and oxygen. The heat is transferred to the scrap by flame radiation. In some operations, the oxygen is injected by a pipe, or "lance" and is used to cut the scrap. The injected oxygen reacts with several components in the bath, which produce exothermic reactions, which then contribute more heat energy to the cycle.

Once enough scrap has been melted, a second furnace charging will occur. Some operations process up to 3 charges every melt cycle. Anymore than this, and too much heat is lost when the arc roof is opened.

After the final charge is melted, the furnace sidewalls are exposed to intense radiation from the arc, and as a result the voltage must be decreased. Alternatively, creation of a foam slag will allow the electrodes to buried and protect the furnace. This will also allow more energy to be transferred to the slag.

Once this is all completed, a sample will be taken and analyzed and from this more oxygen and/or alloys can be added during the refining stage.

3.2.3 Refining

The refining operation is done to remove impurities (phosphorus, sulphur, aluminum, silicon, manganese, and carbon) from the steel. This is done by blowing oxygen into the bath to lower the carbon content to the desired level for the tapping stage. Also, the above mentioned elements have a high affinity for the oxygen and form oxides which float out of the steel, and into the slag

3.2.4 De-Slagging

De-Slagging is carried out to remove impurities from the furnace. During the previous two operations, some of the undesirable materials within the bath are oxidized and enter the slag. During this step, the furnace is tipped backwards and the slag is poured out of the furnace

3.2.5 Tapping

Once the desired steel composition and temperature is reached, the tap-hole is opened, the furnace tilted and the steel pours into a ladle for transfer for the next batch operation

3.2.6 Furnace Turn-around

This is the period following the completion of the tapping, until the charging process starts again for the next heat. During this period, the roof is raised, and the furnace is inspected for damage. They also may change out the furnace bottom if required. This is the largest "dead-time" of the furnace, but new installations are limiting this time to 5-20 minutes

3.2.7 Electrical Systems of the Arc Furnace

The EAF electrical systems consist of a primary system which supplies the power from the utility, and a secondary system which steps down the voltage and supplies the EAF. The primary system consists of the following:

- Vacuum Switch
- Motorized Disconnect Switch
- EAF Transformer
- Water-Cooled Cables

Of these items, we will only look at the EAF transformer and water cooled cables.

3.2.8 EAF Transformer/Water Cooled Cables

The EAF transformers are specially designed to allow the operation of the arcs in the desired range of arc voltages and currents. Since there are different voltage levels as outlined in the previous section, the EAF transformers are equipped with on-line tap changers. Connected to the secondary of the EAF transformer are flexible water-cooled cables. These cables must be flexible to allow the movement of the electrodes up and down, and to allow the furnace roof to swing open and close. These cables usually account for a large part of the reactance of the circuit, but newer installations are using rubber centered cables which take advantage of the skin-effect to reduce cost, weight and reactance.

3.3 The Arc

The Arc developed in the EAF is a non-linear, time-varying load. There have even been studies performed that point to the arc being a chaotic load.[4] The following chapter will describe the mechanics of an arc, and how it is applied to an EAF[5].

3.3.1 What is an Arc

An arc, in the general sense of the word is a sustained flow of current across a gap (i.e. air). A simple example of an arc is a lightning bolt. In an EAF, the manufacturers make it a lot easier to for an arc to form by using techniques as described in Section 3.2.2. In an EAF, this arcing action is used to transfer substantial amounts of energy into the scrap metal (an arc can reach temperatures of up to 30,000F), and depending on the stage of melt as outlined in Section 3.2, the power delivered, and the stability of the arc is defined.

One of the fundamental features of an arc is that arc resistance increases with arc length, in a virtually proportional manner. Typically, the arc voltage gradient is about 15V/cm of arc length. Shown in Figure 3-2 is a snap shot of a simulated arc current and voltage.

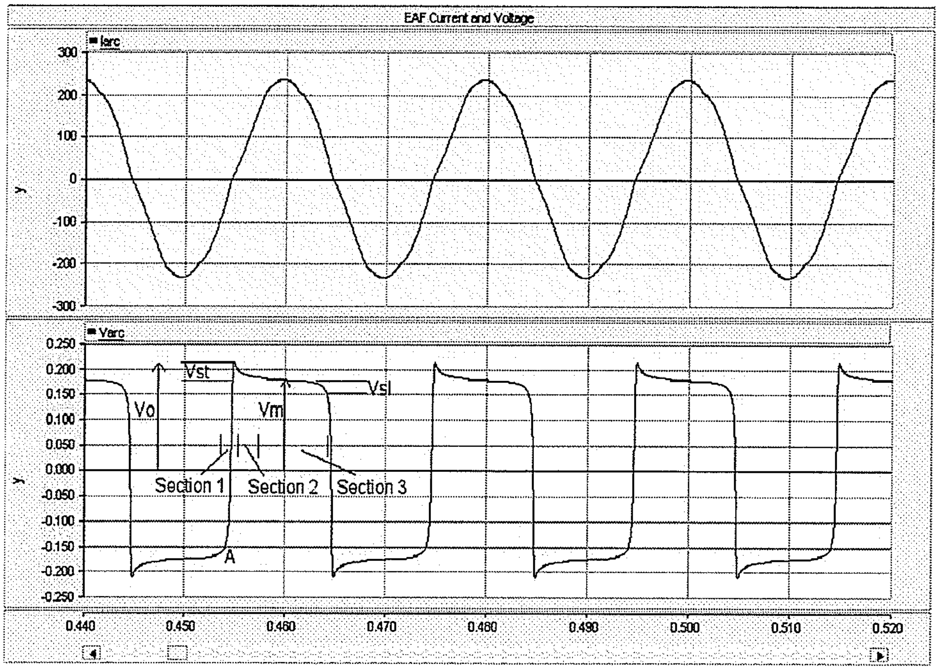

Figure 3-2. Arc Voltage and Currents

The easiest way to analyze the arc is to break it down into sections and look at the arc behavior for each section. Referring to Figure 3-2, there are three distinct sections:

3.3.1.1 Section 1

This part of the waveform is the voltage and current inversion cycle. At Point A, the arc has extinguished and the instantaneous electrode current has dropped to contain only the leakage current through the slag. The Voltage continues to rise, goes through zero, and increases to the arc firing voltage Vo. As can be seen in the Figure 3-2, during the period the equivalent circuit of the EAF is linear, as the slag can be considered a pure resistance.

3.3.1.2 Section 2

The next portion of the waveform is when the electrode tip to bath voltage has reached Vo. As soon as this occurs, an arc is formed and the tip to bath voltage drops. This drop is equal to the arc firing overvoltage, and is called the step voltage (Vst). The voltage falls to the initial arc sustaining value, Vm + Vsl/2, where Vm is the medium voltage and Vsl is the voltage reduction (slope) during section 3.

3.3.1.3 Section 3

During this period, the voltage depends on arc length and drops linearly an amount equal to the slope voltage Vsl, to a final value of Vm - Vsl/2. At this time, the arc extinguishes, and the whole process is repeated for the negative cycle. An other way of visualizing this is plotting the arc voltage versus current as shown in Figure 3-3. Figure 3-4 shows the arc

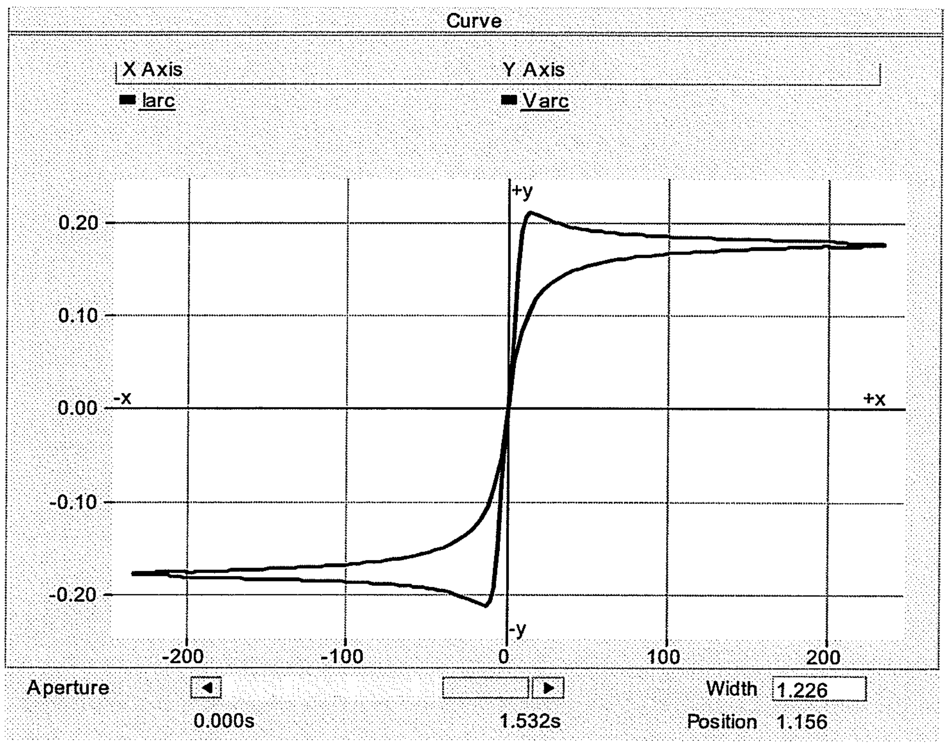

Figure 3-3. Voltage (x-axis) vs. Current (Y-axis) Characteristic of a simulated arc

voltage versus current of a real arc furnace, it quickly becomes apparent of the power quality issues a distorted load like this could cause.

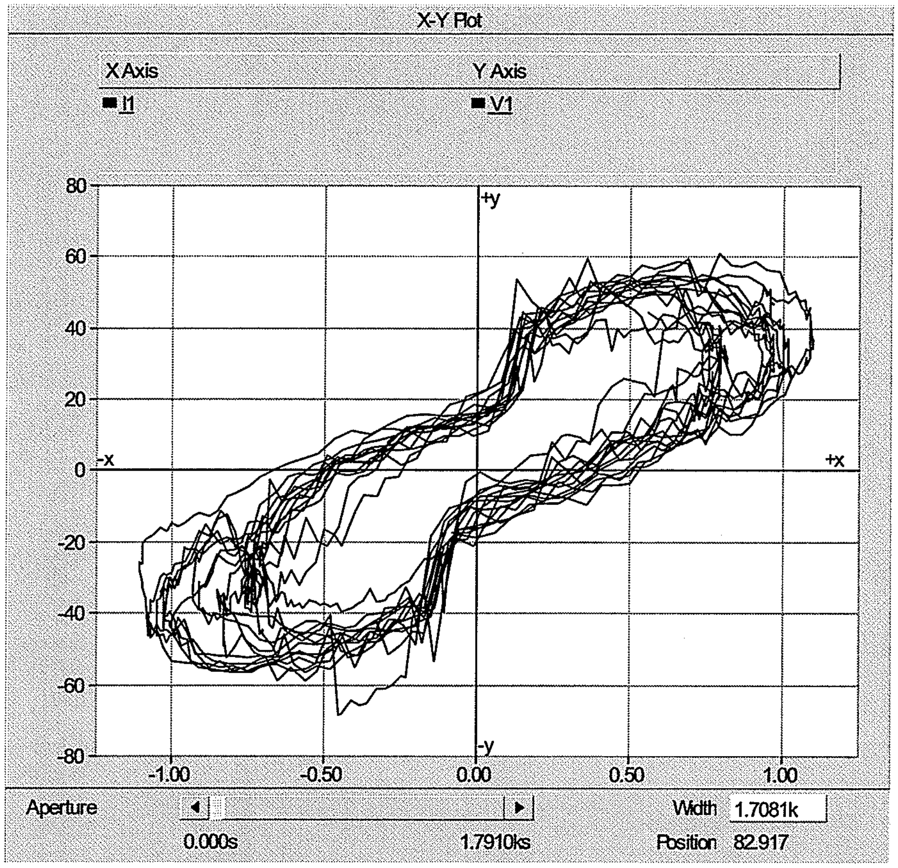

Figure 3-4. Voltage (x-axis) vs. Current (Y-axis) Characteristic of an actual arc (measured)

4 Development of an EMTP-Type Flickermeter

4.1 Flickermeter

Voltage flicker is caused by amplitude modulation of the fundamental frequency voltage waveform by one or more frequencies, typically in the 0 to 30 Hz range[2] and is considered a nuisance for many people who perceive them. Recently, utilities have been taking steps to reduce the flicker levels, but flicker is a hard quantity to measure, identify, and isolate. As stated earlier, and will be discussed in more detail in Chapter 5, there are many techniques available for flicker reduction such as the application of power electronics devices such as Static Var Compensators (SVC), Static Synchronous Compensators(STATCOM) and thyristor controlled series reactors. There is also the method of introducing additional transmission lines to the load. Trying to determine which of these methods will be most effective is very challenging, and requires much effort and time. Using an Electro-Magnetic Transients (EMT) Type simulation tool to simulate the power systems, the system can be simulated, with a variety of different types of compensation methods, included the ones mentioned above. This paper describes a flicker meter model that was developed in PSCAD/EMTDC to allow the simulation results from the different compensation topologies to be compared. The improvements to the flicker performance was then evaluated, allowing the best flicker mitigation method to be chosen.

4.2 Development of the Flickermeter Model

The EMT-Type flicker meter is based on the UIE/IEC flicker meter standard[6]. The flicker meter will only model instantaneous flicker, or up to block 4 of the standard IEC flicker meter as shown in Figure 4-1. The reason for this is that EMT-Type programs are time-domain simulation tools. To get a true flicker level, or a long-term flicker level, a minimum of 10 minutes of data is needed, which in simulation would take an extremely long time. It will be shown, that during system studies, one only needs to compare the instaneaous values of flicker to evaluate the impact of one mitigation method versus another. Below, a block diagram of the flickermeter is shown, as implemented in PSCAD. Each block will be described in detail. When a function is implemented, it will be noted be referring to it's specific label.

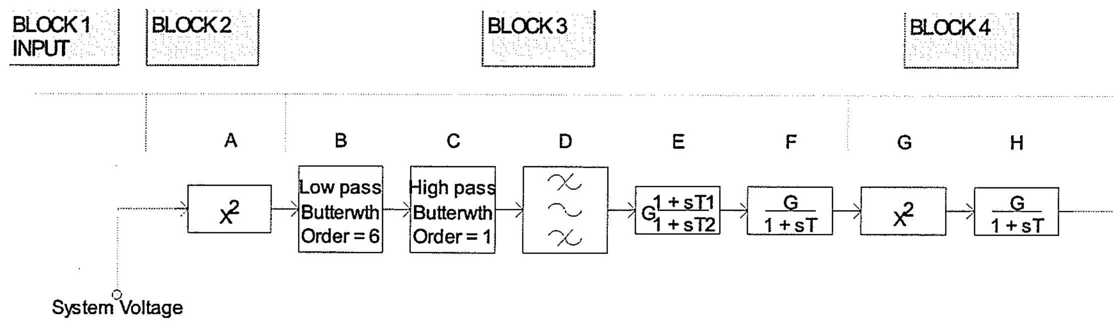

Figure 4-1. PSCAD Flickermeter

4.2.1 Block 1

Block 1 is responsible for scaling the line to line voltage down to a usable level. For the sake of convenience, one can assume that the block 1 output is a 1.0 pu signal.

4.2.2 Block 2

Block 2 is responsible for separating the flicker quantity from the voltage magnitude quantity. This is accomplished by squaring (A) the input voltage, as shown by the proof below.

$$V = A\cos(\omega t)(1 + m\cos(\Omega t))$$

Equation 4-1.

where,

- V = Supply Voltage
- A = Amplitude of Supply Voltage
- ω= Frequency of Supply Voltage
- m = Amplitude of Flicker
- Ω= Frequency of Flicker

By squaring Equation 4-1,

$$V^2 = \frac{A^2}{2}\left(1+\frac{m^2}{2}\right)+\frac{A^2}{2}\left(1+\frac{m^2}{2}\right)\cos(2\omega t)+\frac{m^2A^2}{8}\cos(2\omega+\Omega)t$$
$$+\frac{m^2A^2}{8}\cos(2(\omega\angle\Omega))t+$$
$$\frac{mA^2}{2}\cos((2\omega+\Omega))+\frac{mA^2}{2}\cos(2\omega\angle\Omega)t+mA^2\cos(\Omega t)+\frac{m^2A^2}{4}\cos(2\Omega t)$$

Equation 4-2.

By filtering out the DC component and the frequency components higher then ω we get a voltage whose magnitude is proportional to the flicker amplitude m:

$$V = mA^2\cos(\Omega t)+\frac{m^2A^2}{4}\cos(2\Omega t)$$

Equation 4-3.

$$V \approx mA^2\cos(\Omega t)$$

Equation 4-4.

The second term in Equation 4-3 is an error term, however the magnitude of the error is small since it is proportional to the square of the modulating magnitude (m).

4.2.3 Block 3

Block 3 is responsible for the filtering of the DC and the nω components mentioned above, and representing the lamp-eye-brain response. The first filter block (B) is 6^{th} order Butter-worth filter with its cut-off frequency at 35 Hz. The frequency response of this filter is shown below.

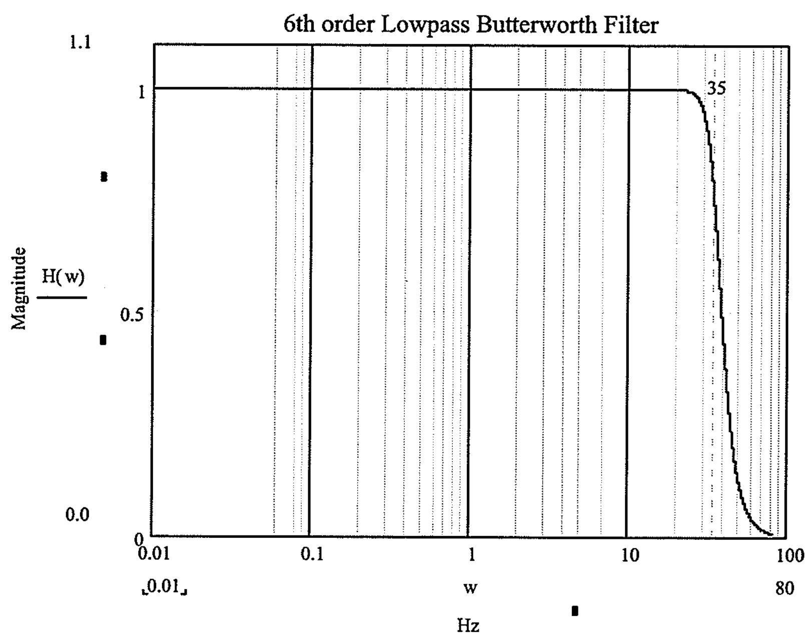

Figure 4-2. Freq Response for 6th order Butterworth Filter

The next filter(C) is needed to filter out the DC components and is achieved be a simple 1^{st} order high-pass filter, shown in Figure 4-3.

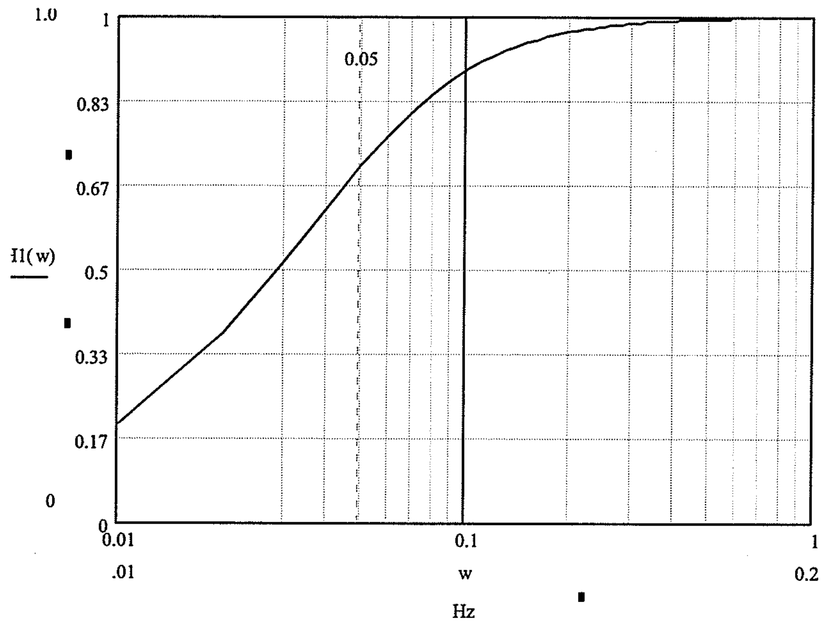

Figure 4-3. First Order High Pass Filter

The final component(D,E,F) of block 3 is the weighting filter. The human eye is frequency selective, exhibiting a peaked response, which must be taken into account. It must also be realized that the reference lamp, (a 230 V, 60W bulb) exhibits a low-pass response with a cut-off of around 6Hz. Based on past studies, it was accepted to use the resulting Laplace function to model the lamp – eye response.

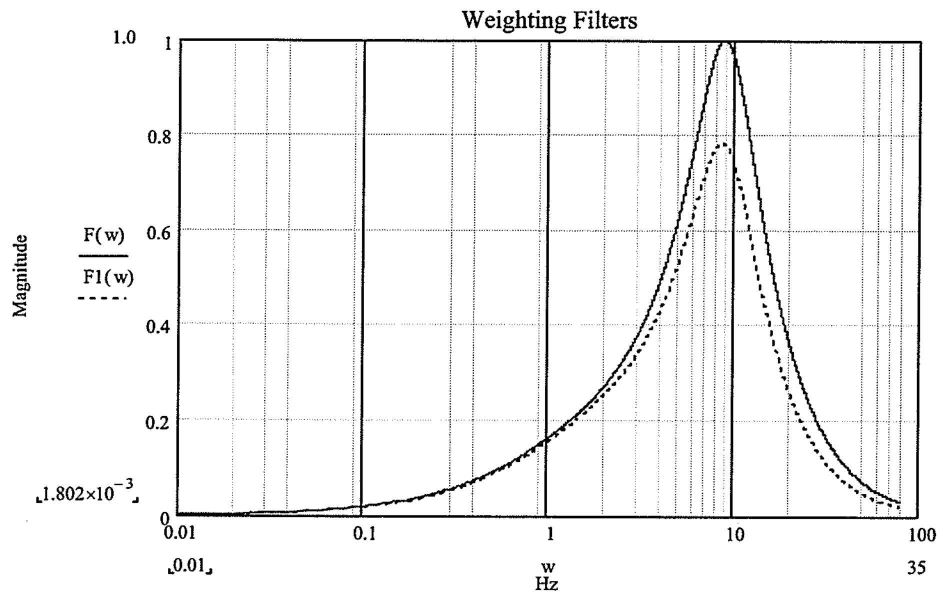

Figure 4-4. Weighting Filter Response (red plot is the 230V curve, blue plot is the 120V curve)

The reason that the peak of the 120 V curve magnitude is less than that of the 230V curve in Figure 4-4, is that a 120 V system is less susceptible to the voltage fluctuations causing flicker, due to the thicker filament used.

The weighting functions of Figure 4-4 can be expressed by the following equation

$$F(s) = \left(\frac{k\omega_1 s}{s^2 + 2\lambda s + \omega_1^2}\right)\left(\frac{1 + \frac{s}{\omega_2}}{\left(1 + \frac{s}{\omega_3}\right)\left(1 + \frac{s}{\omega_4}\right)}\right)$$

A B C

Equation 4-5.

Where:

Values for a 230V, 60W bulb

- $k = 1.74802$

- $\lambda = 2\pi 4.05981$
- $\omega_1 = 2\pi 9.15494$
- $\omega_2 = 2\pi 2.27979$
- $\omega_3 = 2\pi 1.22535$
- $\omega_4 = 2\pi 21.9$

Values for a 120V, 60W bulb

- $k = 1.6357$
- $\lambda = 2\pi 4.167375$
- $\omega_1 = 2\pi 9.077169$
- $\omega_2 = 2\pi 2.939902$
- $\omega_3 = 2\pi 1.394468$
- $\omega_4 = 2\pi 17.31512$

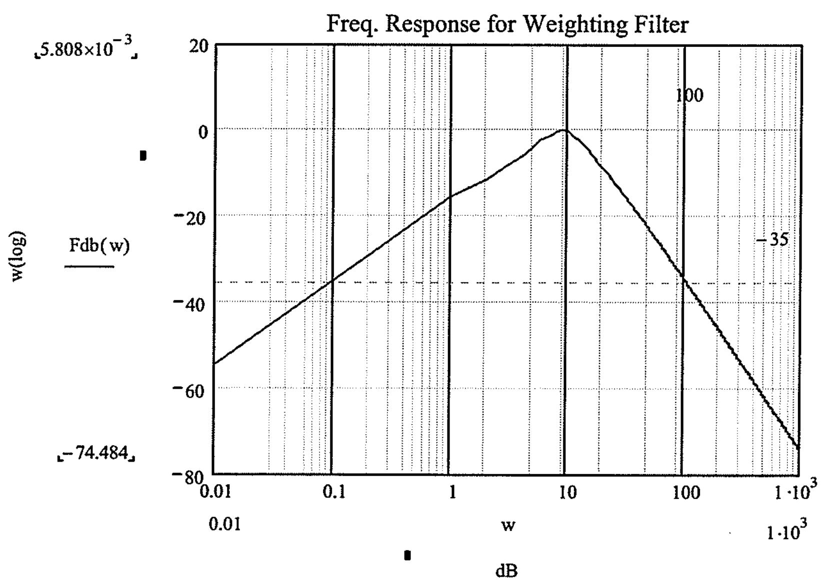

Figure 4-5. Bode plot for Weighting Filter

In order to be effective in measuring flicker, the above filters must be able to detect a 0.5% voltage deviation, and the resolution must be not less than 1% of this range. It follows that there needs to be an attenuation of 90dB at 100Hz, as shown in Figure 4-6.

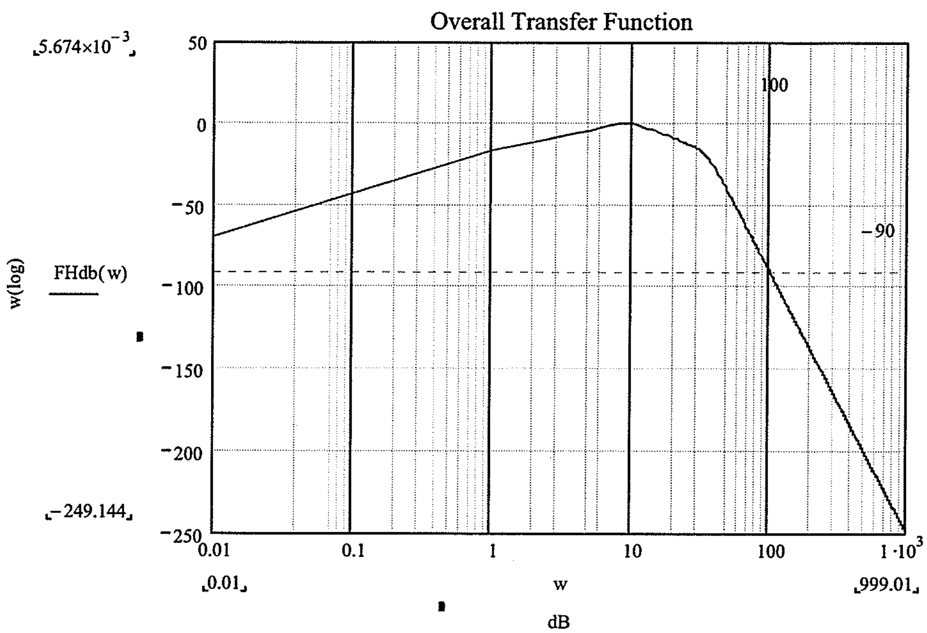

Figure 4-6. Overall Transfer Function

4.2.4 Block 4

Block 4 that is modeled in PSCAD is the Rashbass model. The Rashbass model is named after the scientist who developed it and represents the response of the human brain to the changes in light. This block takes the output of block 3 and squares and smooths it, realized by a square function and a low-pass filter. From a number of tests, Rashbass was able to determine the reaction of the human eye and brain to flashes of light. He was also able to determine that each type of light variation has a different effect. The weighting factor from block 3 represents the change of the light over time, to extend the duration of change due to a very brief flash. The squaring function is used to represent the fact that a light that gets brighter, is the same as a sudden dimming of the light. The last function is the low pass filter, with the time constant set to 300msec. This is represents the memory effect of the human system. The Gain of the output is used to tune the signal to unity.

In order to test the EMT-Type implementation of the flickermeter, the test outlined in [7]

Frequency (Hz)	Sinusoidal (%) deltaV/V	Rectangular (%) deltaV/V
3.125	0.662	0.356
4.16	0.48	0.33
5	0.398	0.292
6.25	0.32	0.25
7.14	0.28	0.21
8.3	0.25	0.2
10	0.26	0.206
12.5	0.334	0.26
16.6	0.51	0.41
25	1.042	0.768

Table 4-1. Test Values for calibrating PSCAD Flickermeter to give an instaneaous value of 1

describes a method to calibrate the output of block 4 (which is known as output 5). By inputting the values listed in Table 4-1, the output of the Flickermeter implemented here will be 1.

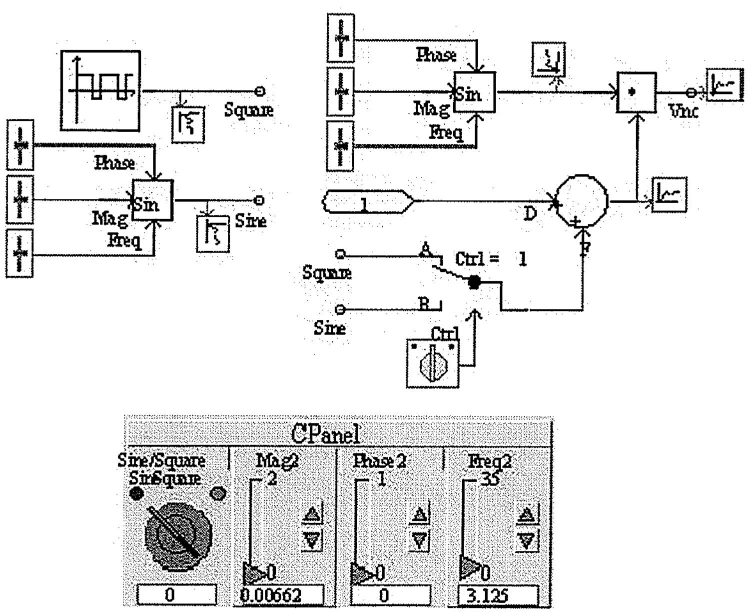

Figure 4-7. Controls for PSCAD Flickermeter tests

To test the flickermeter in PSCAD, the circuit in Figure 4-7 was designed. This circuit allows for the input of a square or sine wave at 50 or 60Hz with a modulated (or flicker) signal added to the peak.

Figure 4-8 consists of three tests, which are:

- Sinusoidal modulation of a sine wave at 0.662% at 3.125Hz
- Square wave modulation of sine wave at 0.356% at 3.125Hz
- Square wave modulation of a sine wave at 8.8% at 2Hz

The first two tests are from the tests laid out in Table 4-1, while the final test is for demonstration of flickermeter outputs as the values that are being imposed from Table 4-1 are barely visible on the graphs.

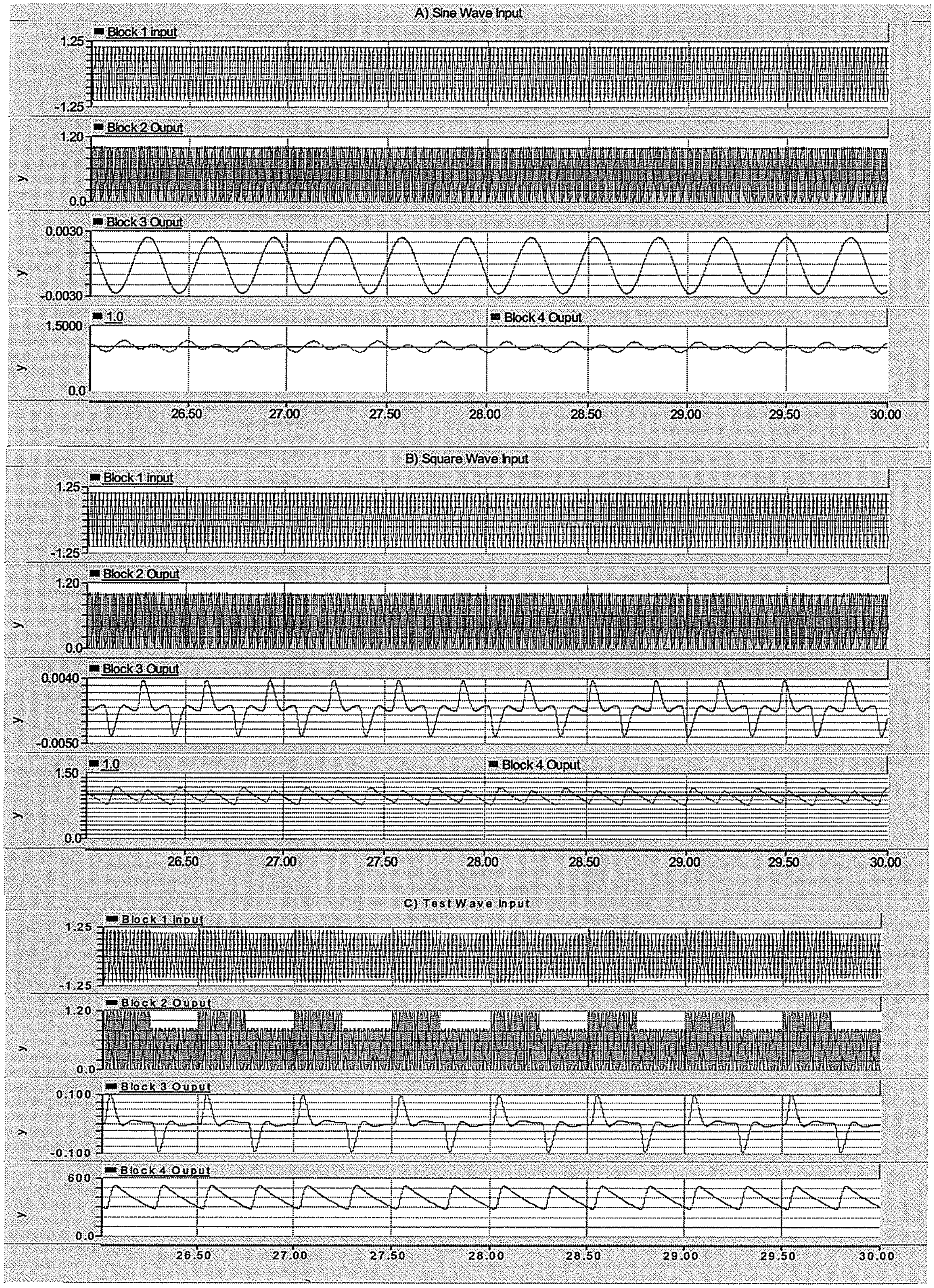

Figure 4-8. Output Plots for test Cases.

4.2.5 Block 5

Block 5 is the statistical component of the UIE flickermeter, which was briefly described in Chapter 2. It takes the output of Block 4 and calculates the Pst value, which is repeated for convenience as Equation 4-6. Due to the fact that time domain simulations are slow, it is not reasonable to run a 10 minute simulation to define the Pst value. It will be shown however, that using the specified tests as outlined in [8], we can obtain the correct Pst value, for our limited test cases. This will prove that for our studies which contain a uniformly dispersed flicker, that we can effectively use the output Block 4 for our tests.

$$P_{ST} = \sqrt{0.0314 \cdot P_{0.1} + 0.0525 \cdot P_1 + 0.0657 \cdot P_3 + 0.28 \cdot P_{10} + 0.08 \cdot P_{50}}$$

Equation 4-6.

If it is assumed that a uniform distribution of the flicker over all the probability classes, i.e.;

$$P01 = P1 = P3 = P10 = P50$$

Equation 4-7.

By using Equation 4-7 and Equation 4-6:

$$P_{ST} = \sqrt{0.0314 \cdot P + 0.0525 \cdot P + 0.0657 \cdot P + 0.28 \cdot P + 0.08 \cdot P}$$

Equation 4-8.

$$P_{ST} = 0.71386 \cdot \sqrt{P}$$

Equation 4-9.

and for a Pst = 1;

$$P = \left(\frac{P_{ST}}{0.71386}\right)^2$$

Therefore,

P = 1.96

From the preceding formula, and assuming that a uniform distribution of flicker, Pst and instantaneous flicker can be directly related.

The following table shows the Pst value for a number of validation points that are designed to test the flickermeter over a variety of values. The PSCAD flickermeter was compared to the MiniIQO flickermeter, designed by Hydro Quebec and the RTDS (Real Time Digital Simulator) flickermeter.

Frequency	deltaV/V	RTDS (Pst)	PSCAD (Pst)	MiniIQO (Pst)	System Frequency
13.5	0.547	1.01	0.99	0.99	60
13.5	0.2735	0.52	0.5	0.5	60
0.91667	0.841	1.0	0.98	0.99	60
3.958	0.5	0.95	0.935	0.94	50
15	0.45	0.95	0.935	0.94	50

Table 4-2. Flickermeter Comparison

The difference in the results between the three meters is due to slightly different implementation of the flickermeter transfer function and different techniques to measure the system voltage

4.2.6 Conclusions

To implement an EMT-Type Flickermeter in system cases, you must replace the input voltage with a measured voltage. The circuit below can be used to give you a stable pu voltage reference. It should also be noted that the longer the case is run, the longer averaging constant in the RMS meter can be set, producing better results. A good number to use is to set the RMS meter to 1 sec., and run for 10 seconds. By about 5 seconds, good results will be obtained. Also notice that phase to phase values are being used in this model.

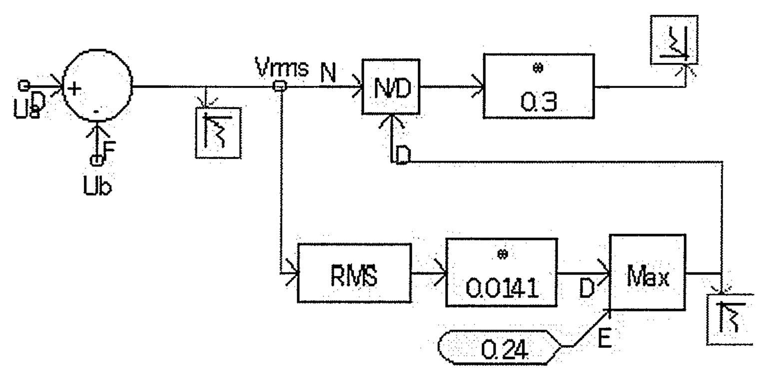

Figure 4-9. Sample Voltage Averaging Component

As will be seen in the next chapter, the EAF instantaneous flicker level is fairly quick, uniform deviation and the purpose of these studies is to bring this instantaneous baseline down. By establishing a base case and comparing this to different cases employing different compensation levels, a flicker reduction factor can be established.

5 Compensation Techniques

5.1 General Compensation Methods for Flicker Control

The following section will introduce some general compensation technologies.

5.1.1 Rotating Synchronous Compensator

The rotating synchronous compensator is an unloaded rotating synchronous machine as shown in Figure 5-1.

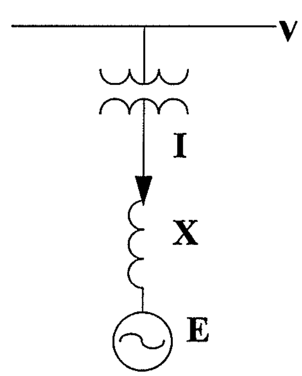

Figure 5-1. Rotating Synchronous Compensator

Where:

- **V** = System Voltage
- **X** = Machine and transformer leakage Reactance
- **E** = Machine Internal Voltage
- **I** = Current Entering Machine

To provide a purely reactive power flow, the three-phase machine voltage e_a, e_b, e_c are in phase with the system voltage v_a, v_b, v_c. Therefore the current I is determined by the following equation:

$$I = \frac{V \angle E}{jX}$$

Equation 5-1.

By controlling the excitation of the machine (E) and hence the current (I), the reactive power flow (Q) can be controlled. If E is greater than V, the resulting leading current is seen as a capacitance by the system. If E is less than V, the resulting lagging current is seen as an inductance by the system. There is a slight flow of real power to supply the machines mechanical and electrical losses. The phasor diagrams below show this.

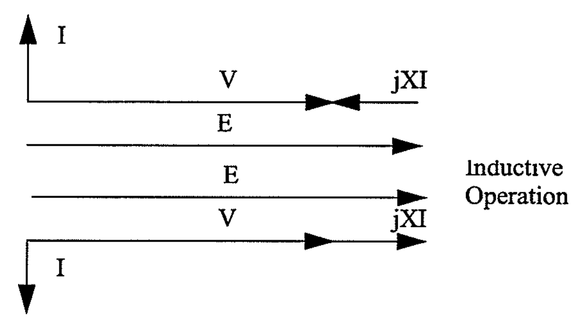

Figure 5-2. Phasor diagram for Capacitive/Inductive Operation

Where:

- **V** = System Voltage
- **X** = Machine and transformer leakage Reactance
- **E** = Machine Internal Voltage
- **I** = Current Entering Machine

By being able to control the reactive power in and out of a point on the power system we can effectively control the voltage as reactive power is directly influenced by voltage and vice versa.

5.1.2 Static Var Compensator[9]

The Static Var Compensator (SVC) as shown in Figure 5-3 was one of the first electronic type compensation

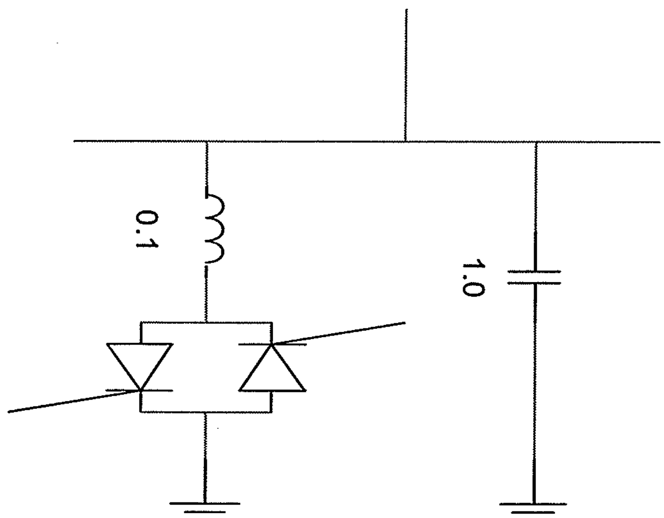

Figure 5-3. SVC Single Line Diagram

topologies to use power electronics. The inductor is connected to the power system by controlling the firing angles of the back to back thyristors, therefore controlling the amount of reactive current introduced. By adding fixed capacitance, the compensation range can be greatly increased, as shown below in the SVC V/I characteristics.

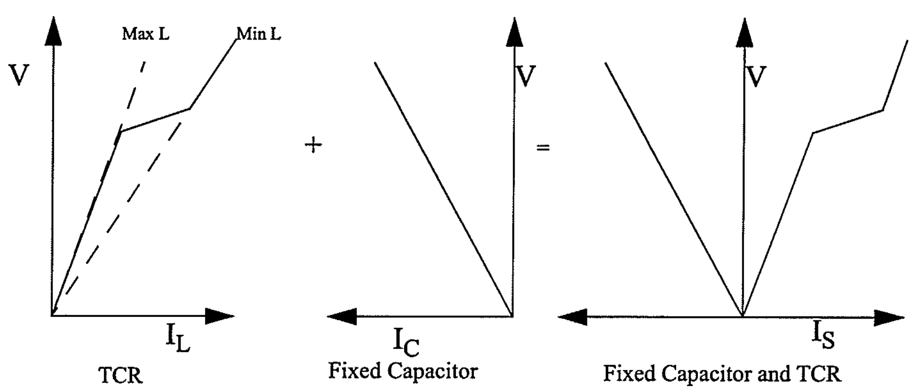

Figure 5-4. Composite Characteristics of an SVC

5.1.2.1 SVC For Flicker Compensation

Historically, the SVC has been the main technology in mitigating flicker from EAFs. Usually the TCR is used in combination with the fixed capacitance coming from the AC Filters. The size of the SVC needed to decrease the flicker by an order of two is of the same order of magnitude of the arc furnace. The limitations in using a SVC for flicker control are the inherent delays of the TCR and the dynamic interactions between the resonant AC filters of the SVC and the network[10].

5.1.3 Static Synchronous Compensators[9]

Static Synchronous Compensators (STATCOMs) in operation, are similar to the aforementioned synchronous compensator. Instead of a rotating machine, the STATCOM uses solid-state switching devices (IGBT, GTOs etc.) arranged in a converter. For the purpose of discussion, only a basic six-pulse two level converter is considered.

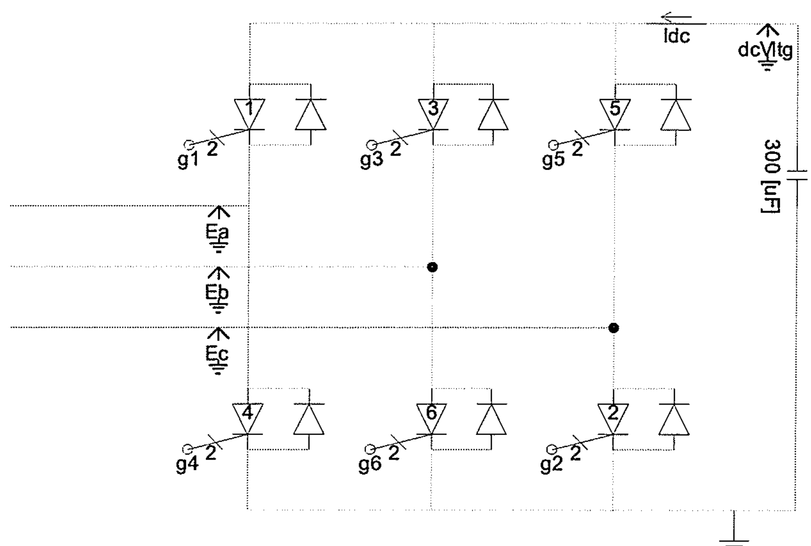

Figure 5-5. Six-pulse, two-level voltage sourced converter

Figure 5-5 shows a basic six-pulse voltage sourced converter. A charged DC capacitor provides the DC voltage used in producing the three phase voltage E. For the purpose of explanation of the basic fundamentals of STATCOM operation, the inverter can be replaced by a variable AC Voltage source as shown in Figure 5-6.

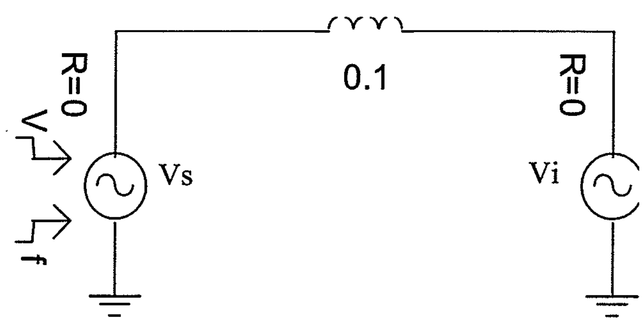

Figure 5-6. Equivalent circuit of STATCOM

When the STATCOM is not needed, the inverter voltage (Vi) is controlled to be in phase with the system voltage (Vs) as shown in Figure 5-7, and no reactive power is delivered.

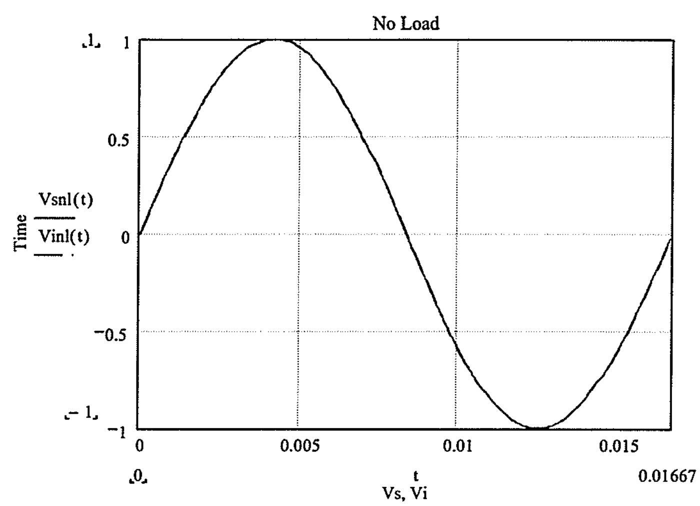

Figure 5-7. No Load

If capacitive power is needed, Vi is controlled to be greater than Vs, and a current of a leading phase angle of 90 degrees (with respect to Vs) begins to flow as shown in Figure 5-8.

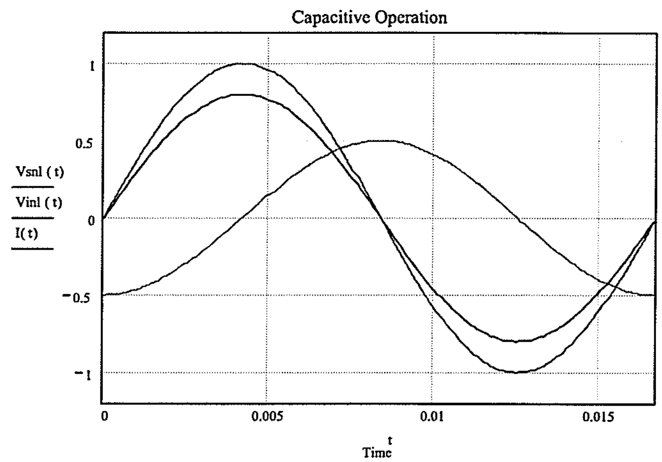

Figure 5-8. Capacitive Operation

If inductive power is need, Vi is now controlled to be less than Vs, and a current of a lagging phase angle of 90 degrees (with respect to Vs) begins to flow as shown in Figure 5-9.

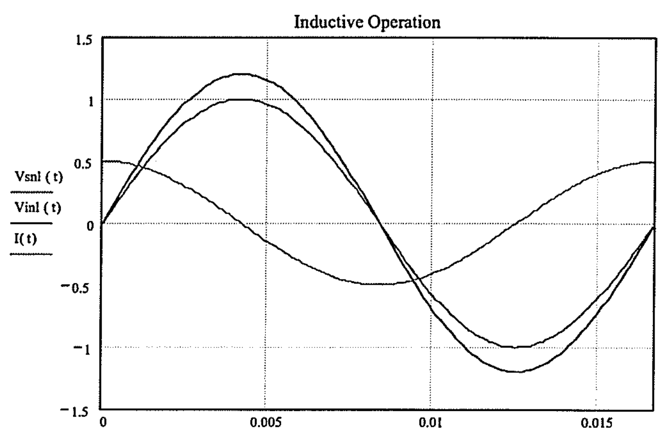

Figure 5-9. Inductive Operation

Figure 5-10 shows the V-I characteristics of the STATCOM. It controls V from V1 to V2, and if the system goes beyond a high or low voltage limit, the STATCOM becomes a constant current source.

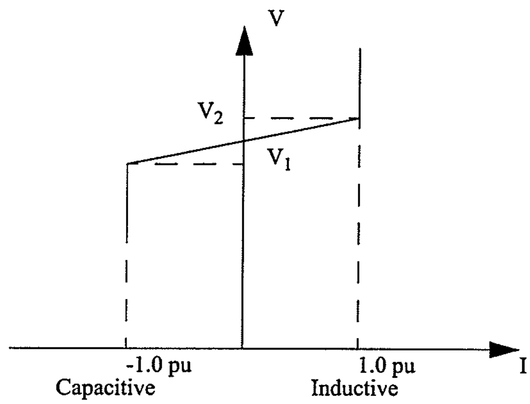

Figure 5-10. V-I characteristic of the STATCOM

In order to control flicker, the voltage needs to be controlled to a constant value, and referring to Figure 5-10, as long as the STATCOM is operating in range, it should be able to control the voltage by varying it's current output. The challenge of course is to do this with sufficient rapidity.

5.1.3.1 Six-Pulse Inverter

In Figure 5-11, which for simplicity uses constant current sources on the AC side, the current is seen leading the voltage in its capacitive operation. In Figure 5-12, it can be see that the diodes and the GTO each carry the current for 90 degrees. In the capacitive operation one can also from Figure 5-12 that the GTO has to be turned off at the peak of the current. Alternatively, if the STATCOM was running inductively, the current would commutate naturally. In this example, the output current of the converter is completely reactive. As the current approaches unity power factor, the conduction of the GTO's increase from 90 degrees to 180 degrees, while the diode decreases from 90 to 0 degrees.

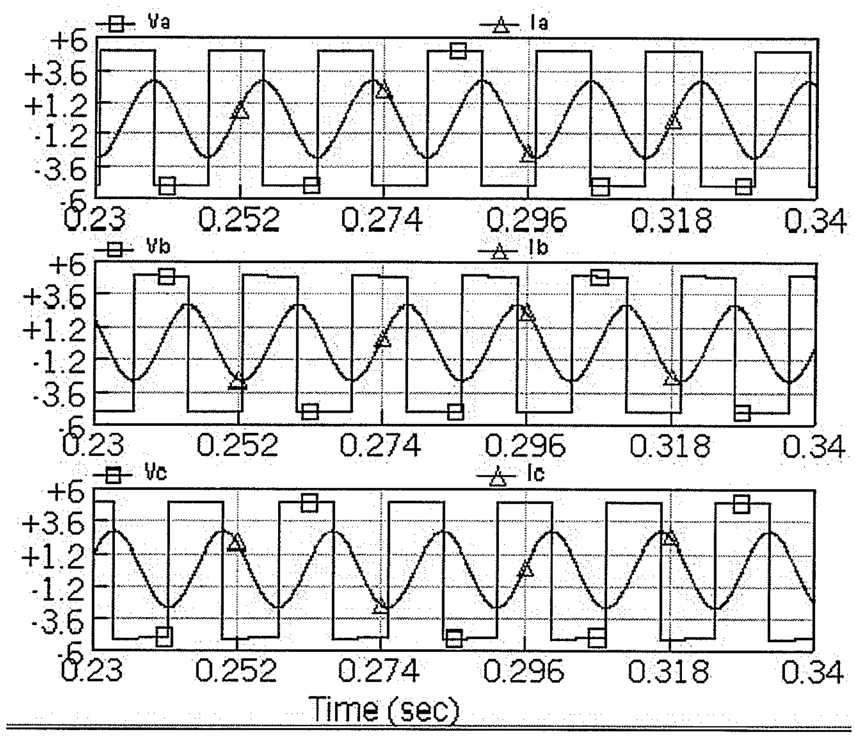

Figure 5-11. Six Pulse Waveforms

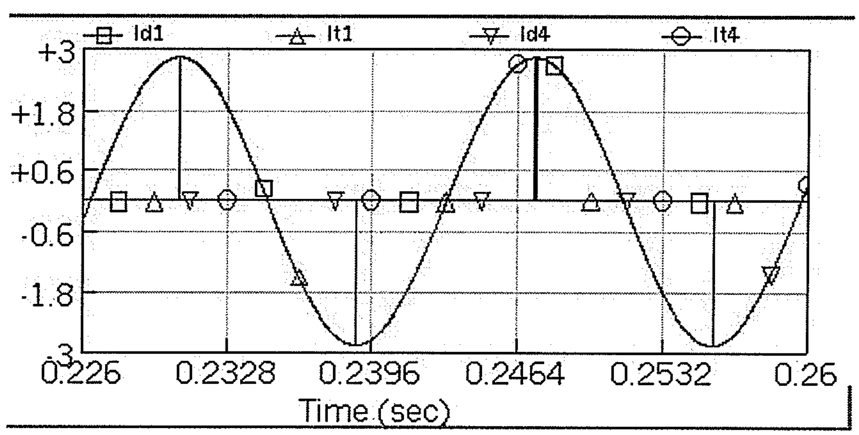

Figure 5-12. commutation intervals of A phase pole

It should also be noted that the STATCOM is capable of transiently suppling real power. The net instantaneous power exchange between the AC output terminals and the DC input terminals is always zero, neglecting converter losses. The DC capacitor helps maintain constant DC voltage thereby permitting the generation of the square wave type AC side voltages. The reason for the capacitor is that the output voltage waveform of the DC to AC converter is a quasi-square wave. For this reason the net instantaneous output power fluctuates, and in order not to violate the equality of instantaneous output/input powers, the converter must draw a fluctuating current from the DC capacitor[11].

In the above example, the control method of adjusting the phase angle and hence changing the DC voltage. If sufficiently large energy storage device is available, the STATCOM is capable of suppling large amounts of real power transiently which is a major component of the method to be further developed.

Figure 5-13 shows the actual current expected in a real STATCOM. The current is non-ideal, but can be improved using a variety of techniques such as filtering, pulse-width modulation (PWM) switching, multiple STATCOM levels and current reference PWM. Some of these will be discussed below.

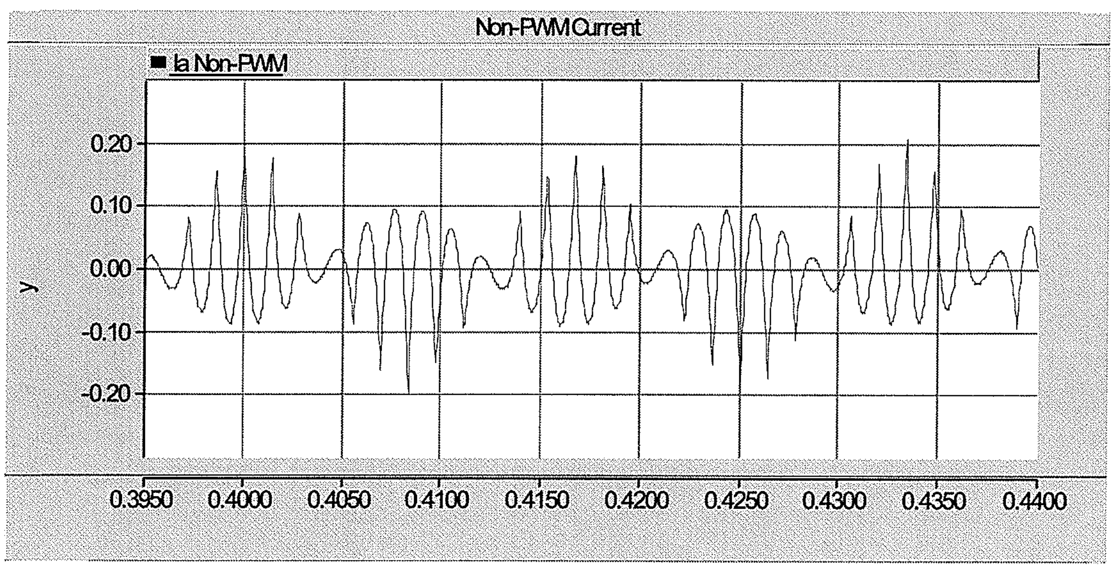

Figure 5-13. Non-PWM STATCOM Current

5.1.3.2 STATCOM For Flicker Control

The quick response of the STATCOM, and the high performance of the inverter makes it ideal for the compensation of flicker as will be seen in Section 5.2.2.

5.2 STACOM Control Techniques

There are many control techniques available for the control of the STATCOM, but only a few are fast enough to control flicker. The technique used for the method described in this thesis is based on Pulse-Width Modulation (PWM) techniques. First the method of Sinusoidal PWM (SPWM)[12] will be shown, and then the technique employed in this thesis of Current Reference PWM (CRPWM)[13].

5.2.1 Sinusoidal Pulse-Width Modulation

From the circuit in Figure 5-5, 3 AC voltages with variable magnitude and frequency can be generated. In order to produce the desired waveforms, 3 sinusoidal waveforms, each out of phase by 120 degrees are compared to a control generated triangular waveform as shown Figure 5-14.

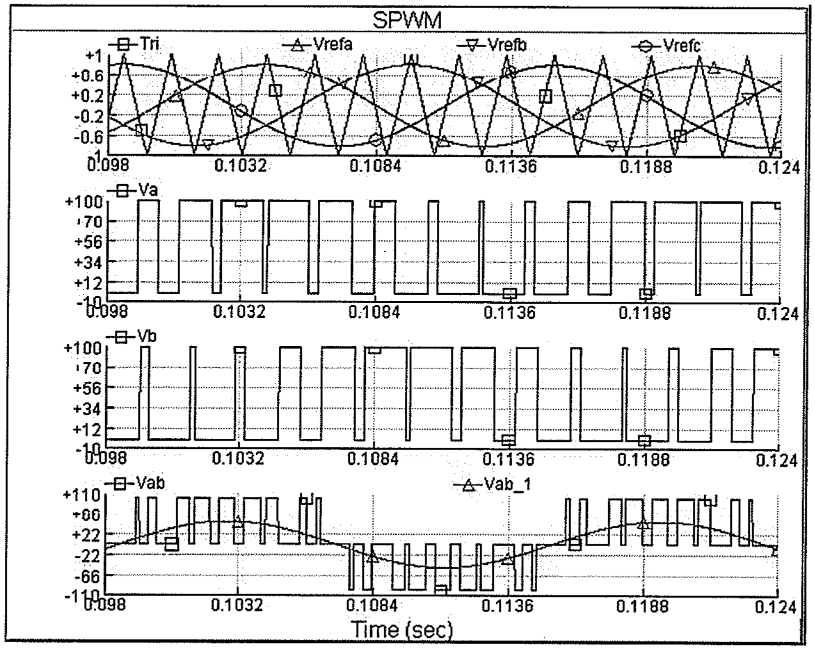

Figure 5-14. Sinusoidal Pulse-Width Modulation

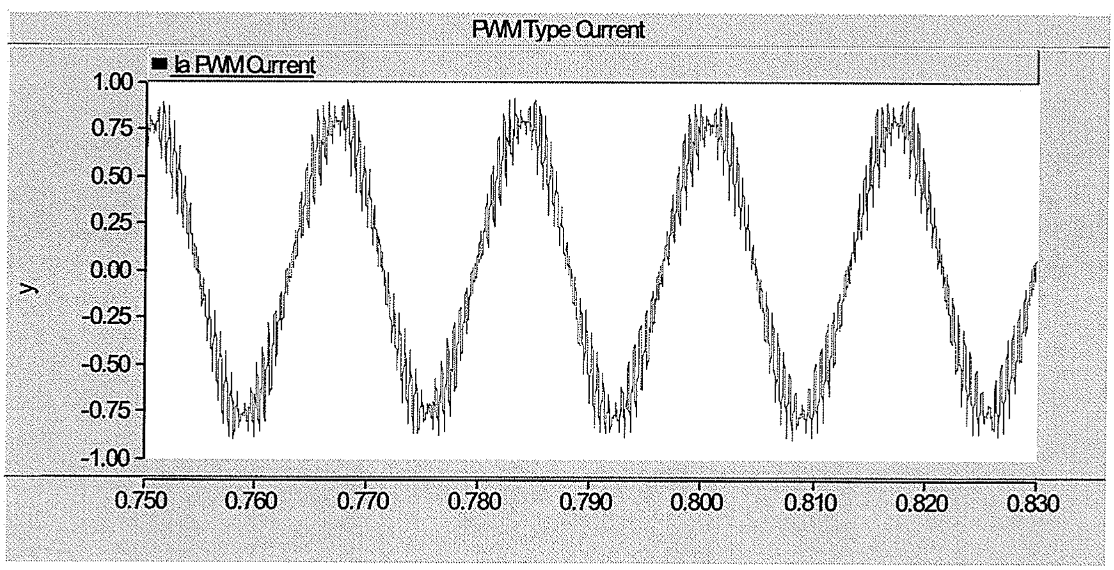

Figure 5-15. PWM Current

The triangular waveform has a frequency of an odd multiple of the fundamental frequency of the reference sine waves. In Figure 5-14, the sine waves are at 60 Hz, and the triangular reference wave is at 9x the sine wave frequency (540 Hz). The frequency of the triangle waveform establishes the inverter switching frequency. The sine reference waves are controllable in magnitude and frequency.

Table 1 outlines the switching order of the Converter.

Voltages	**Switch On**
Vref<Vtri	G1
Vrefa>Vtri	G4
Vrefb<Vtri	G3
Vrefb>Vtri	G6
Vrefc<Vtri	G5
Vrefc>Vtri	G2

TABLE 1. Switching Order

Using Table 1 above and Figure 5-14, it can be easily seen how the desired voltage can be obtained by changing the magnitude and frequency of the reference waves. The frequency of the generated voltage is the same as the fundamental frequency of the reference wave. The magnitude of the voltage is determined by the following equation.

$$V_{ll} = \frac{\sqrt{3}}{2\sqrt{2}} \cdot M_f \cdot V_d$$

Equation 5-2.

Where V_d is the DC Capacitor voltage and M_f is the modulation factor

SPWM is a very fast and effective control method but from Figure 5-14 it can be seen that it generates a substantial amount of harmonics. The harmonics in the inverter output appear as sidebands, centered around the switching frequency and it's multiples. For Mf less than or equal nine, (which is usually the case), the harmonics amplitudes are almost independent of Mf. The frequencies at which the voltage harmonics are produced are:

$$F_h = (j \cdot M_f + k) \cdot f_1$$

Where,

$$h = jM_f \pm k$$

Equation 5-3.

The harmonic order h corresponds to the kth sideband of j times Mf. For odd values of j, the harmonics only exist for even values of k and vice versa. Van and Vbn have a phase difference of (120*Mf) degrees. This phase difference will be equivalent to zero if Mf is an odd multiple of 3. This results in an odd symmetry and the even harmonics disappear, leaving only the odd ones. When we have over-modulation (Ma greater than 1), more sideband harmonics appear around the original sideband harmonics. However, the original harmonics may not be as large, so harmonic losses still may not be factors as one would think, and in some instances may actually give better performance. Techniques such as optimal PWM may help alleviate some of these harmonic issues.

5.2.2 Current Reference Pulse-Width Modulation

By using Current Reference Pulse-Width Modulation[13] (CPWM), it is possible to shape the currents to almost what is needed extremely quickly. The basic idea behind CRPWM is to feed in what currents is desired into a controller and have the STATCOM match these as closely as possible. The current reference is inputted into a current sensing controller, that is capable of detecting the current at every instant. For simplicity we will consider the single phase example as shown in Figure 5-16.

The reference is then compared to the actual value, and the inverter switching is altered to correct any error. To realize this, a hysteresis type controller is used as shown in Figure 5-16

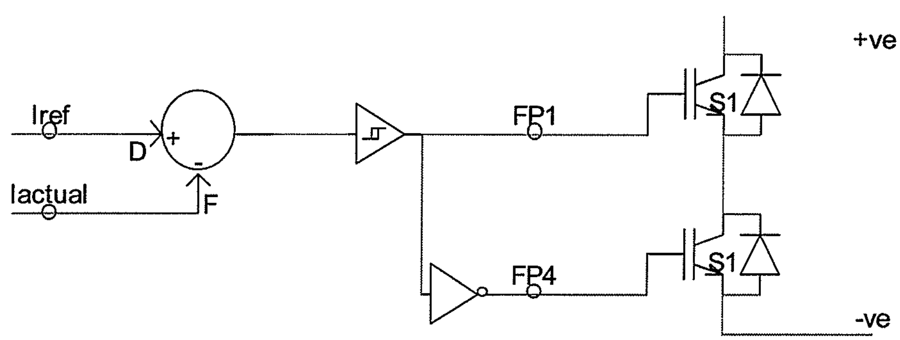

Figure 5-16. CRPWM Firing Pulse Circuit

The difference between Iref and Iactual is considered the error and is inputted into a hysteresis controller of a set bandwidth +/-BW. If the current error at a given time is positive, the Iactual is less than Iref, and if this positive value is greater than the lower bandwidth limit, the current controller will turn off S4, and turn on S1. This will connect the load to the positive DC voltage bus, and cause the current to rise. When the current passes Iref, the error becomes negative, and as soon as this negative value becomes more negative than the negative bandwidth limit, S4 turns on, S1 turns off connecting the load to the negative DC voltage bus causing the current to decrease. This is shown below in Figure 5-17.

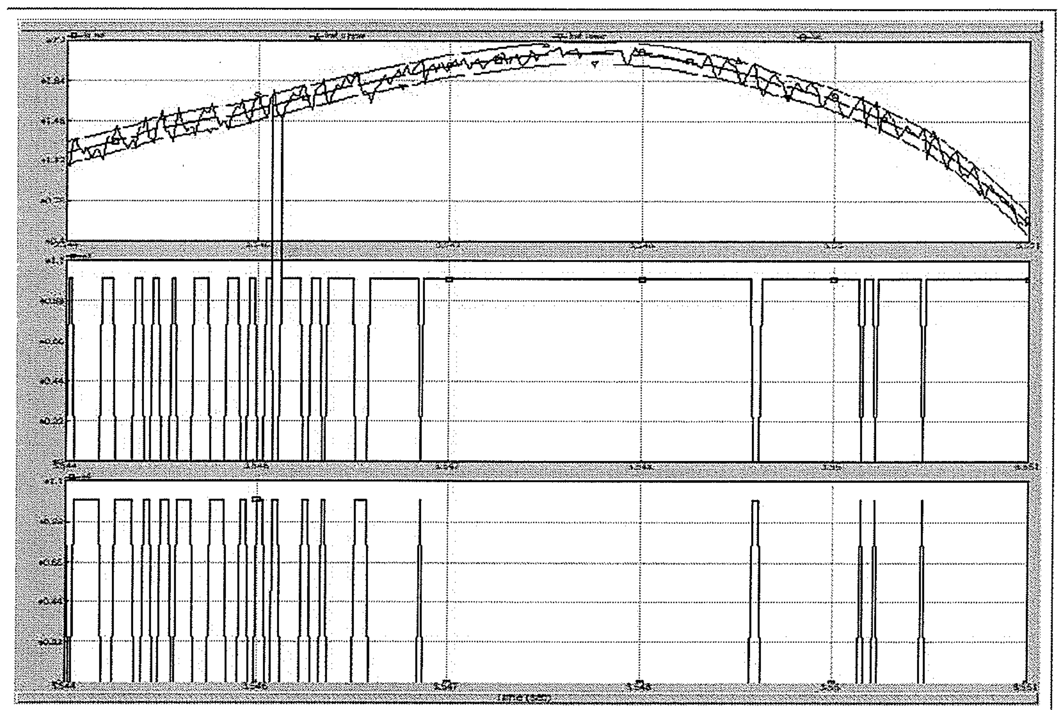

Figure 5-17. CRPWM Waveform and firing pulses

From Figure 5-17, it can be seen that if the bandwidth is made smaller, the actual current will more closely follow the reference current. The disadvantage of this, is that the switching frequency of the inverter increases. This switching frequency is not fixed as in SPWM, but depends on the rate of growth and decay of the currents. In fact, in an unbalanced load, the switching frequency of each of the phases could be drastically different, because this type control tries to match the desired current at every instant, if the measurement circuitry is precise enough and the bandwidth is of sufficient resolution, the CRPWM can be considered as phase independent current source. The following chapter develops the control methodology for flicker compensation

6 Development of a Control Strategy for Flicker Mitigation

Note: This Chapter refers extensively to ref. [10] of which the thesis author and his supervisor were contributing members.

6.1 Basic Concepts

As seen in previous chapters, flicker mitigation requires very fast acting compensation, with the ability to move in both the reactive and active power bands, which the STATCOM, with the proper control strategy, is perfectly suited for. Since the STATCOM can move in all 4 quadrants of control (positive, negative/real and reactive power) in less than a cycle, it can react very quickly and compensate to the instantaneous changes in voltage which cause flicker.

6.2 Flicker Control Circuit

Shown in Figure 6-1 is the equivalent circuit used in the simulation to test the controls. The basic approach is to determine the long term average values of the real and reactive currents and to compensate any instaneous deviations around these averages.

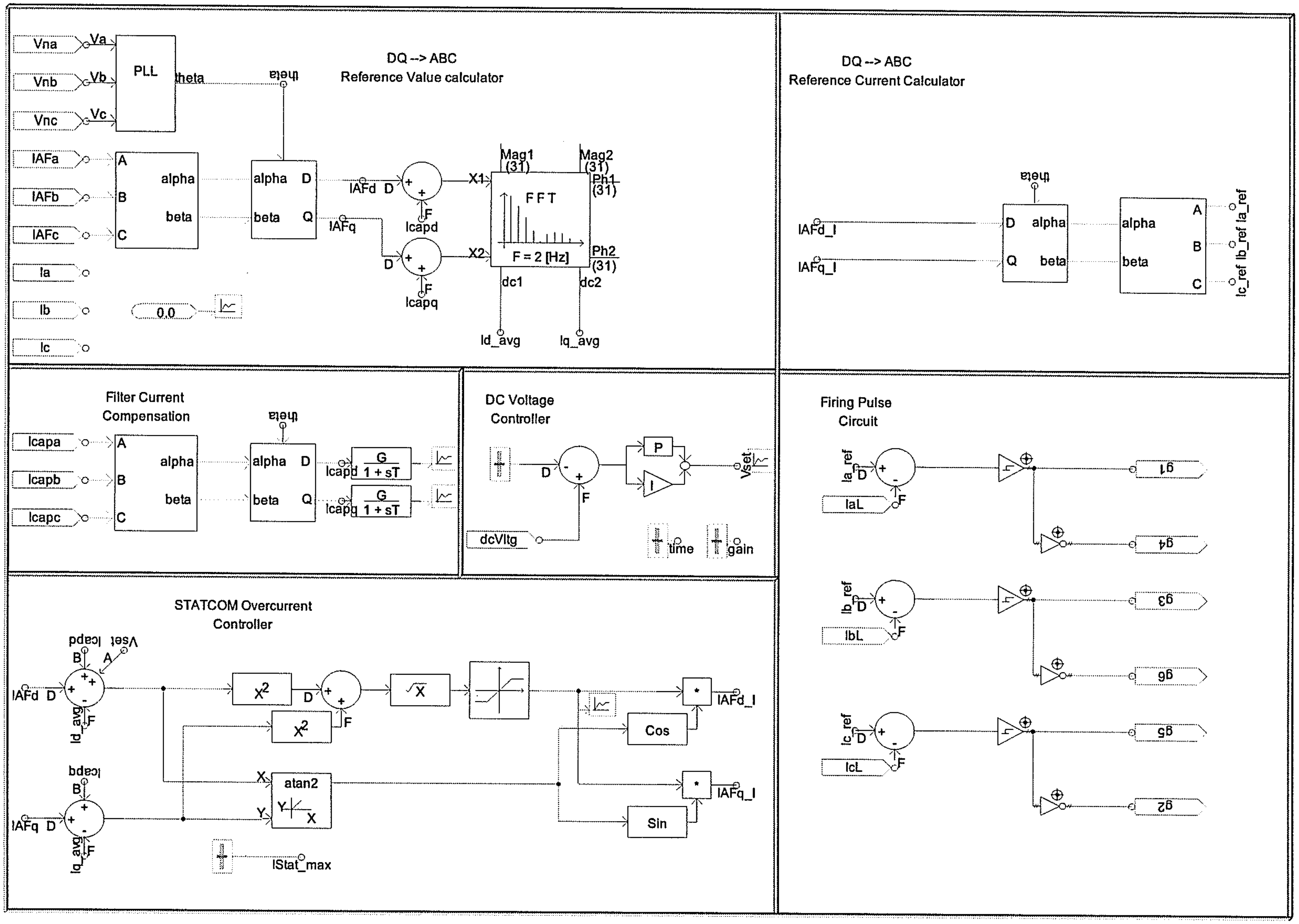

Figure 6-1. STATCOM Control Circuit

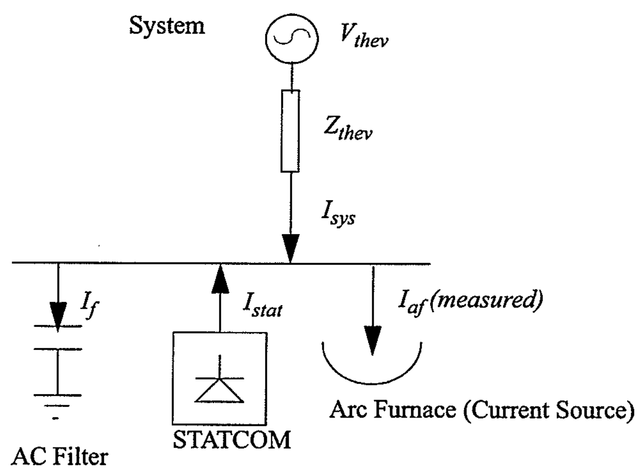

Figure 6-2. Equivalent Circuit of Study System

Each major control section will be developed individually in the following sections

6.2.1 ABC to DQ Arc Furnace Current Reference Current Calculator

The basic control approach consists of deriving I_D and I_Q which are the current components for the real and reactive powers respectively. This is a step process, where the intermediate Clarke Transform (Equation 6-1.) is first used to reduce the 3 phases to 2 phases, and subsequently a commutator transformer (Equation 6-2.) is needed to get the D-Q DC components

The Arc Furnace currents are inputted into the 3 to 2 transform block to decompose the three phase values into its real and reactive values using the following equation:

$$\begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & \angle\frac{1}{2} & \angle\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \angle\frac{\sqrt{3}}{2} \end{bmatrix} \cdot \begin{bmatrix} Ia \\ Ib \\ Ic \end{bmatrix}$$

Equation 6-1.

where,

Ia, Ib, Ic are the phase currents on the high side of the arc furnace transformer.

Figure 6-3 shows the result of applying Equation 6-1.

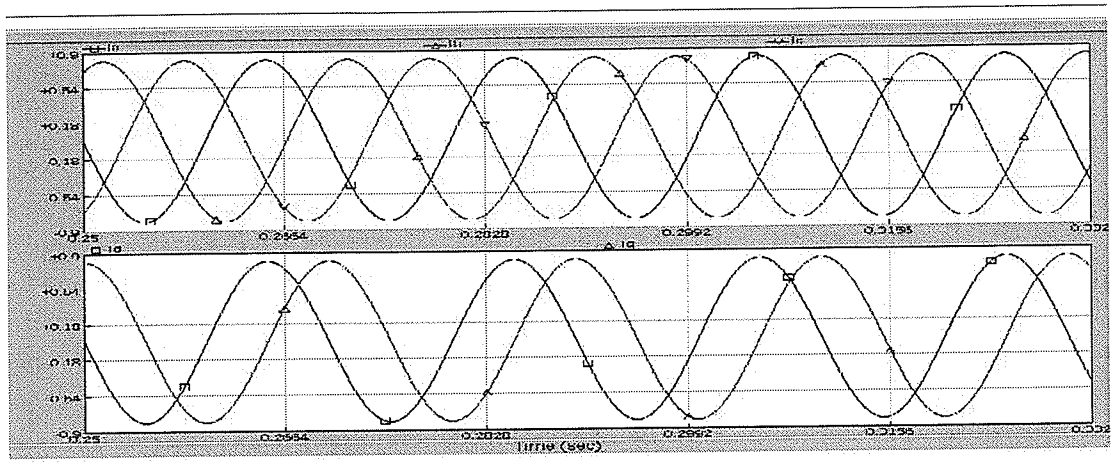

Figure 6-3. ABC to alpha beta transform

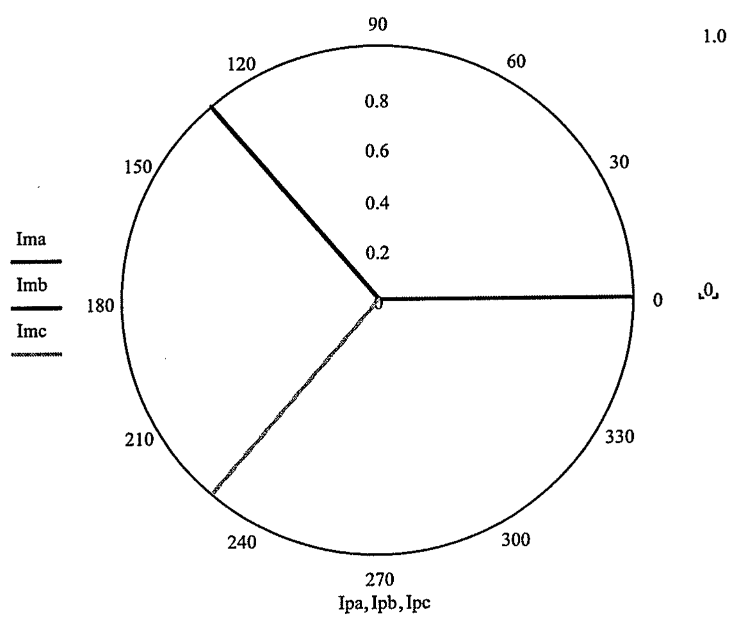

Figure 6-4. ABC Phasor Diagram

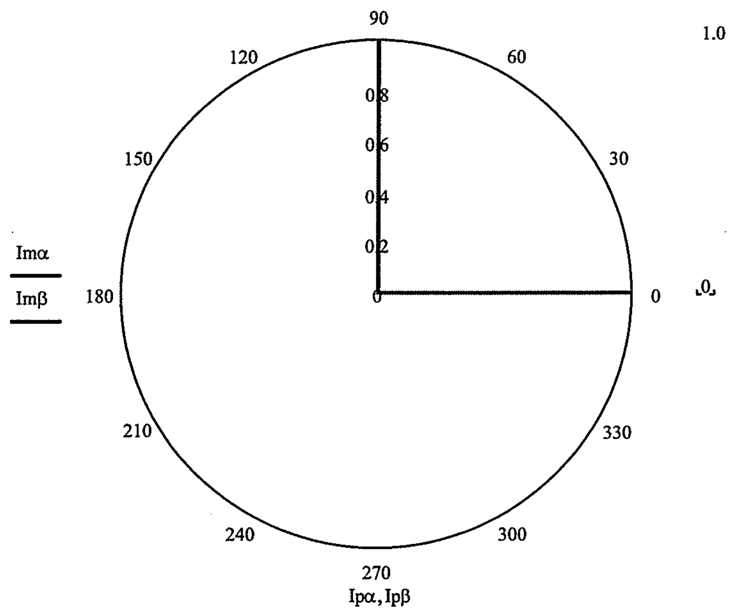

Figure 6-5. Alpha Beta transformed Values

The alpha beta values contain all of the positive and negative sequence information.

The alpha and beta currents are then rotated into a synchronous rotating reference frame. These quantities are easier to use as they are near DC in the steady state

$$\begin{bmatrix} I_D \\ I_Q \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ \angle \sin(\theta) & \cos(\theta) \end{bmatrix} \cdot \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix}$$

Equation 6-2.

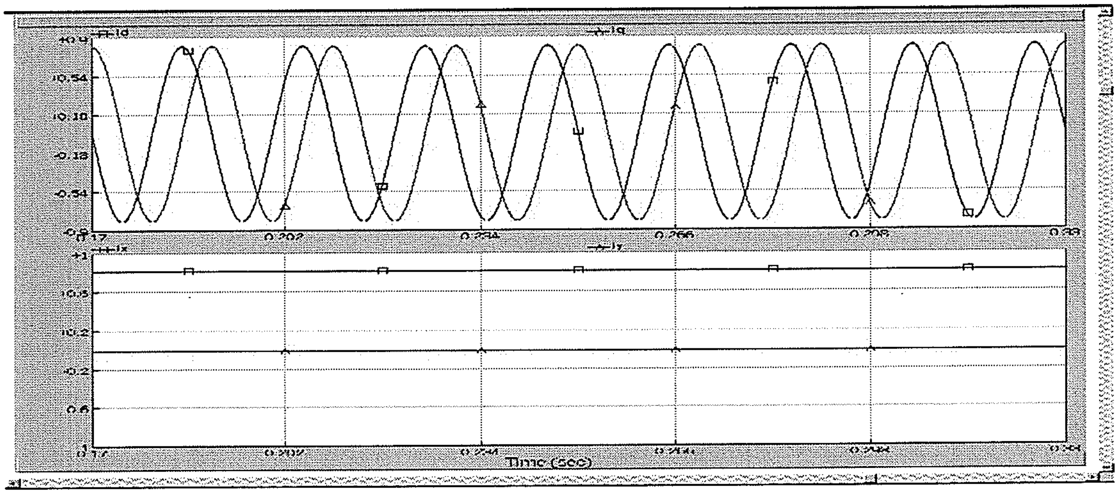

Figure 6-6. DQ to DC (x,y) values

The same is done to the filter currents and summed with the Arc Furnace currents, giving the total system current needing to be compensated. This is developed further in the next section.

The next step of this controller is to generate the long-term average values of I_D and I_Q. This is done by processing current signals through a Fourier transform block, from the standard library block of PSCAD/EMTDC, and reading the DC level over a period of 0.5 seconds. Since I_D and I_Q are DC values with some noise, the average level is derived from the Fourier analysis. The Fourier transform is set to sample 31 times per cycle (1 cycle = 2Hz = 0.5 seconds). This in effect, provides the average value of I_D and I_Q over the 0.5 second sliding window as seen in Figure 6-7. The limitation of this method is that there is added delay of 0.5 seconds before the controls reach steady-state. Half a second was selected by trial and error, as it does not take that long to reach steady-state, yet it is short enough to react to system wide changes. A low-pass filter was tried, but it was found that with the FFT, a DC value was found every cycle, where as the low-pass filter took the full 0.5 seconds to up date which tended to cause the start up sequence to be very slow, and also smoothed the value too much.

$$Iavg = \frac{\sum_{i=1}^{32} Ii}{N}$$

Equation 6-3.

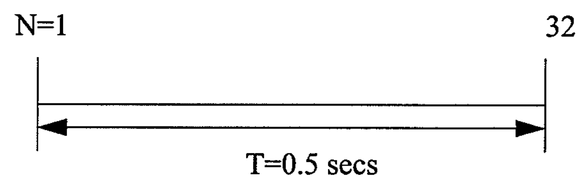

Figure 6-7. Sliding Window

These averaged values represent the "Flicker-Free" real and reactive values.

6.2.2 Filter Current Compensation

As will be seen later, our circuit includes a filter. By using the same transformer used to calculate the arc furnace I_D and I_Q, the filter I_D (which is ideally zero) and I_Q are calculated and add to the from the input of the FFT averaging circuit.

6.2.3 STATCOM Current Controller

Again referring to Figure 6-1, you will see the STATCOM Current Controller. This section of the controls is responsible for the formation of the current order. The summation node performs the following function:

Without the STATCOM in the system, the currents supplied from the system are:

$$Isys = Iaf + If$$

Equation 6-4.

and,

$$Isys = Iaf + \Delta Iaf + If + \Delta If$$

Equation 6-5.

where,

- Iaf is the arc furnace current
- If is filter current
- Δ(Iaf+If) are the flicker causing components of the system, which is what the STATCOM needs to compensate

therefore when we add the STATCOM, it will supply current to the arc furnace busbar.

$$Isys = Iaf + If + \Delta Iaf + \Delta If \angle Istat$$

Equation 6-6.

If the STATCOM was operating ideally and was compensating for all current deviations:

$$0 = \Delta(If + Iaf) \angle Istat$$

Equation 6-7.

Then,

$$Isys = If + Iaf$$

Equation 6-8.

and,

$$Istat = \Delta(Iaf + If)$$

Equation 6-9.

From these equations, the STATCOM would be responsible for all of the current deviations only, and leave the system to take care of the steady-state currents

The reference currents are then fed to a current limit circuit which is used to provide over current protection for the transformer and STATCOM, otherwise it could potentially be operating outside of the limits. This is implemented as follows:

$$\mathrm{Imag} = \sqrt{I_D^2 + I_Q^2}\Big|\begin{pmatrix}\mathrm{Imax}\\ 0\end{pmatrix}$$

Equation 6-10.

$$\theta = \mathrm{atan}\left(\frac{I_Q}{I_D}\right)$$

Equation 6-11.

where,

- Imag is the Current magnitude
- θ is the current phase
- Imax is the maximum current the transformer/STATCOM can handle

By converting the $I_D + j^*I_Q$ values into polar notation, we can accurately limit only the magnitude and not influence the phase of the compensating current.

In Equation 6-10. the matrix consisting of Imax and zero limits the current between these values.

We then reconstruct the I_D and I_Q values as follows:

$$I_D = \mathrm{Im}\cos(\theta)$$

$$I_Q = \mathrm{Im}\sin(\theta)$$

Equation 6-12.

These are now the I_D and I_Q reference values that will be used for the STATCOM firing circuit.

6.2.4 DC Voltage Controller

When a STATCOM needs to supply or receive real power it needs to draw or add to the energy stored in the DC bus capacitor. To ensure that the capacitor does not become overloaded, a simple Proportional Integral controller is used to maintain the bus voltage at 7kV, and this error signal is also added to the input of the current controller. If it was added at the output of the limited value, there is a potential for the transformer to become overloaded.

If desired, an AC voltage controller can be implemented in the same manner as the DC voltage controller by taking a rms measurement of the AC voltage, comparing to a voltage setpoint and interfacing with Iq quantity.

In practice, these controllers are slow acting to ensure that they do not interfere with STATCOMs main purpose of flicker compensation

6.2.5 DQ to ABC Reference Current Calculator

This part of the circuit does two things. First the DC Voltage controller is added to the Id reference value to maintain the DC voltage level. Next Id and Iq values are converted back into its 3 phase equivalent using the following equations:

$$\begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \angle\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix} \begin{bmatrix} Id \\ Iq \end{bmatrix}$$

Equation 6-13.

$$\begin{bmatrix} Ia \\ Ib \\ Ic \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & 0 \\ \angle\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \angle\frac{1}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix}$$

Equation 6-14.

6.2.6 Firing Pulse Circuit

The current values calculated in Section 6.2.5 are now used as reference to a CRPWM controller to calculate the firing pulses. Referring to section 5.2.2, given an actual current and an ordered current, the firing pulses can be generated to provide the current, which in this application is equal to Equation 6-9.

7 System Tests of the Flicker Control Strategy

Note: This Chapter refers extensively to ref.[10] of which the thesis author was a contributing member

7.1 A System model for Arc Furnace Flicker Studies

One way to include an arc furnace in a transient simulation is to develop a detailed model for the furnace. This model should respond to changes of the AC bus voltage and inject a current with the appropriate statistical properties back into the network. There are number of linear models.[14][15][16]. There are also a few models that are based on the non-linear arc equations that show great promise.[17][18] Unfortunately such models are still in the domain of research and it was felt that at present it would be more appropriate to use a model based on measured data. In this model, the arc furnace is represented by a current source and these currents are the actual measured currents. It is important that these currents be injected in the proper phase relationship to the bus voltage so that the real and reactive powers drawn from the system are correct.

Figure 7-1 shows a schematic indicating the arc furnace and the appropriate thevenin equivalent that represents the ac network at the connection point. As discussed above, it is important to have the correct arc furnace currents and also the correct thevenin voltage (magnitude as well as phase).

In order to obtain the proper relationship between the current and voltage, one approach which appears to be viable is to model the arc furnace as a current source of measured data and also to model the system Thevenin voltage as the fundamental component of the measured system voltages. This fundamental component can be obtained from an on-line Fast Fourier Transform (FFT) of the measured voltage.

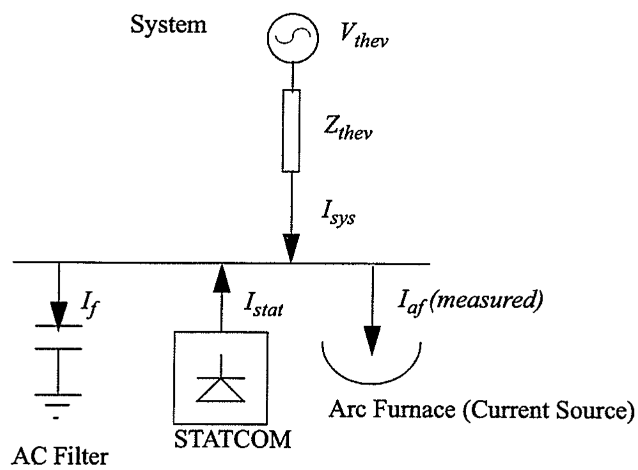

Figure 7-1. Equivalent Circuit of Study System

Vthev = 14.2kV

Zthev: Rp = 10ohms

Lp = 3.06mH

Rs = 0.04ohms

STATCOM Rating: Varying

Filter Rating: 40MVA, 3rd Harmonic

An instantaneous measurement of flicker is used for making comparisons between the simulated and measured data. The instantaneous flicker is measured using the first four blocks of the IEC Flicker meter algorithm. This gives a flicker index. The final block (Block 5) of the IEC standard is to produce long-term statistics over a period of ten minutes and is not suitable for the short-term behavior being discussed here. When the base case is simulated with this modeling, the observed flicker on the arc-furnace bus voltage appears to be considerably larger (an average index of 30 as opposed to 22 for the measured data). This is due to the FFT updating the estimate for the Thevenin voltage too frequently.

In order to overcome this shortcoming, the Thevenin equivalent source was modeled as a constant magnitude fundamental frequency source. The flicker produced on the bus is thus

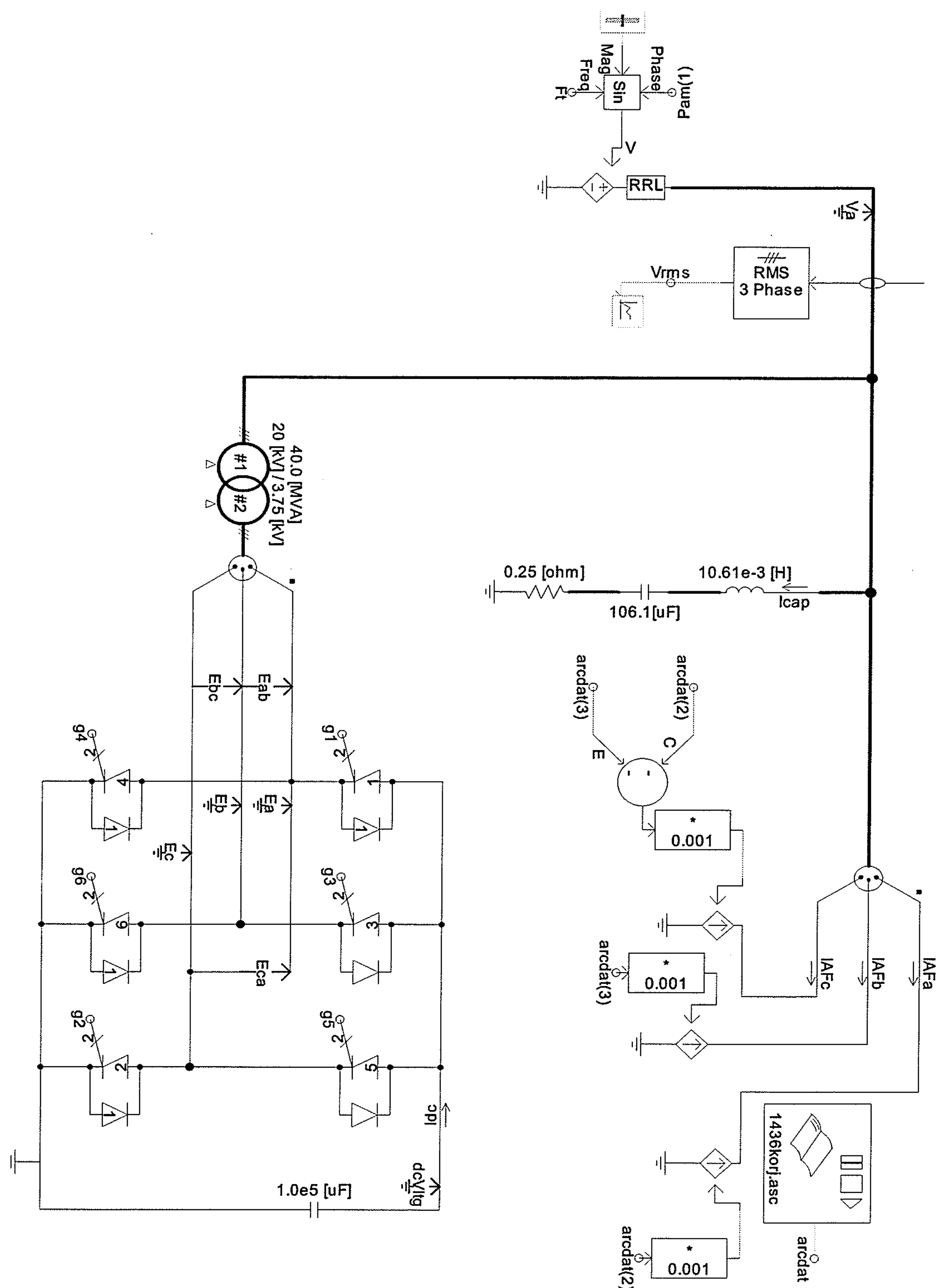

Figure 7-2. PSCAD Implementation of the Study System

due to the voltage drop of the arc-furnace currents across the system's Thevenin impedance, which is the major contributor of the measured flicker in the real system. As seen from Figure 7-3, the flicker index is now more in agreement with the measured value (approximately 23). This approach does have a serious drawback, as in the real system on which the recordings were taken from, there are slight deviations in system frequency which over a period of time create a phase difference between the observed and simulated bus voltage as seen in Figure 7-4. This implies that the real and reactive powers taken from the network are no longer correct.

The above shortcoming can be overcome by using a phase-locked loop to synchronize the phase of the measured bus voltage to the thevenin equivalent. The phase angle used was the positive sequence deviation from the measured data, which was then applied to all three phases. The magnitude and initial phase of the Thevenin equivalent is kept constant at a value which generates the appropriate fundamental voltage on the arc-furnace bus, as seen from the second graph in Figure 7-4, which also shows that the simulated system has very good correlation with the measured system. This method does provide the correct value of the flicker index while maintaining the correct phase relationship.

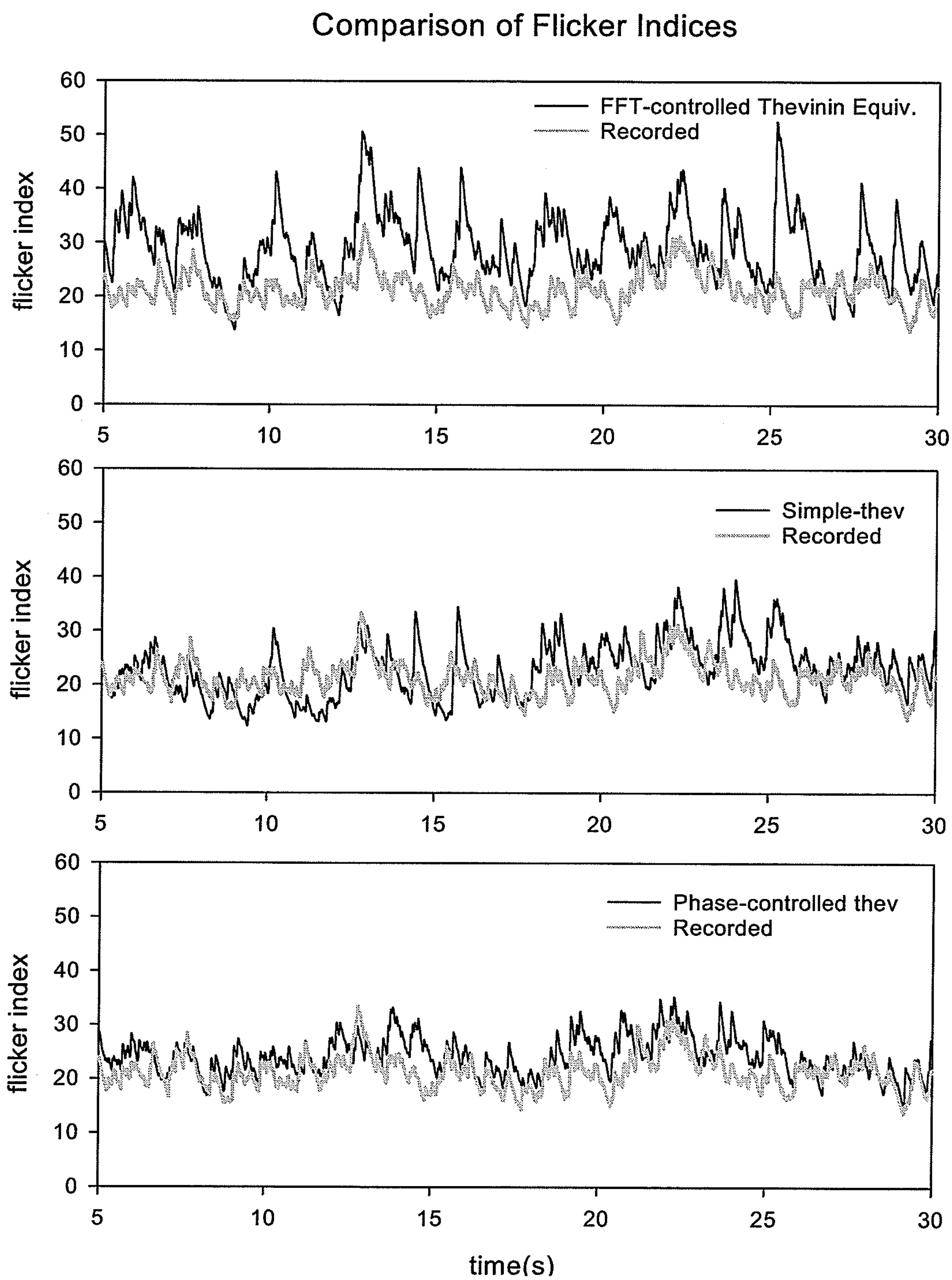

Figure 7-3. Comparison of Flicker Indices

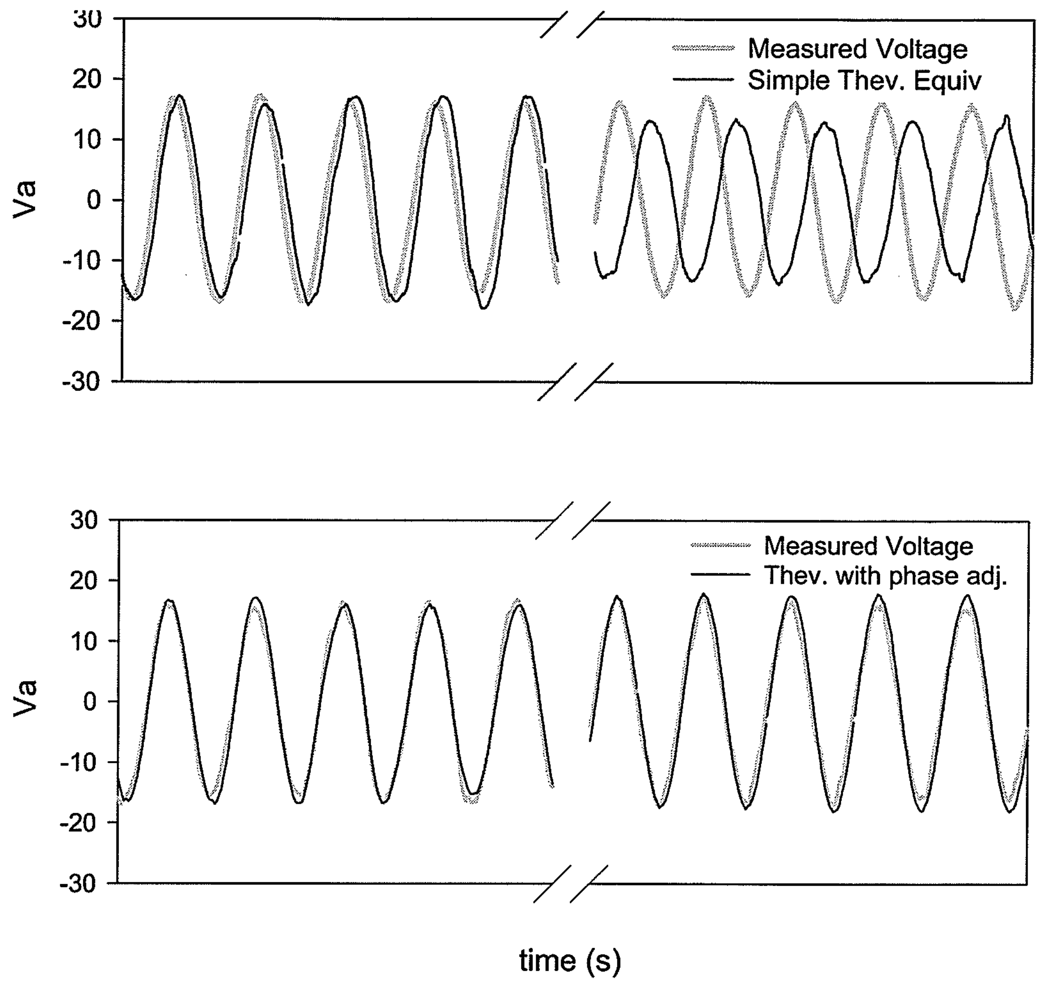

Figure 7-4. Arc Furnace Bus Voltage Waveforms (Voltage in kV)

7.2 STATCOM Configuration for Flicker Control

The STATCOM used for flicker compensation is controlled in a different manner from one used for voltage support. In the flicker control application, each phase of the STATCOM is controlled to produce the desired current waveform. There is thus the possibility of a temporary unbalance between the phases which results in a partial charging (or discharging) of the DC capacitor. In order to make the process work, a somewhat larger DC capacitance is required. The STATCOM circuit topology used in this study is shown in Figure 7-5.

The controls for the STATCOM are shown in Figure 6-1, and will be briefly discussed again for completion. The (instantaneous) direct and quadrature components of the AC currents are first extracted. The direct component is the one in phase with the positive sequence (fundamental component) phasor of the AC bus voltage, and the quadrature component is the one at right angles to this phasor. The reference angle for calculating the D and Q components is obtained from a phase-locked loop which tracks the AC voltage. These instantaneous components are then subtracted from their respective long-term averages; which are calculated using an on-line FFT based filter. This type of filter guarantees a maximum measurement delay of 1-cycle. The results are the D and Q components of the compensator current. The current orders to each phase are then calculated using an inverse D-Q transform. Actual compensator currents corresponding to these orders are then produced using a hysteresis type current-reference Pulse Width Modulation algorithm.

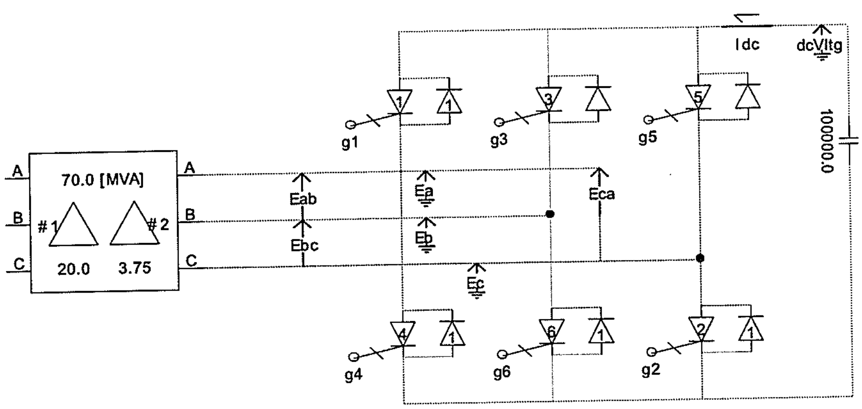

Figure 7-5. Flicker Control STATCOM (Electrical Circuit)

The above STATCOM is connected into the network as shown in Figure 7-6. The installation has 40Mvar of fixed capacitance in the form of a third harmonic filter in addition to the

STATCOM rating of 80Mvar. This allows a total compensation rating from -40Mvar (inductive) to +120 Mvar (Capacitive).

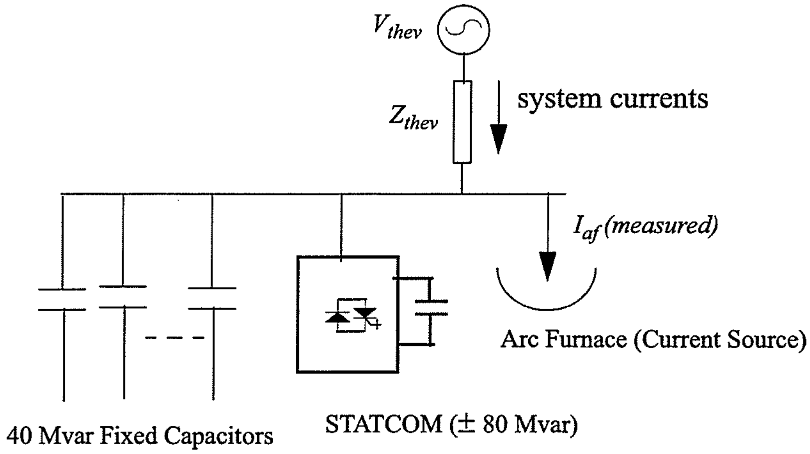

Figure 7-6. Arc Furnace and Compensator

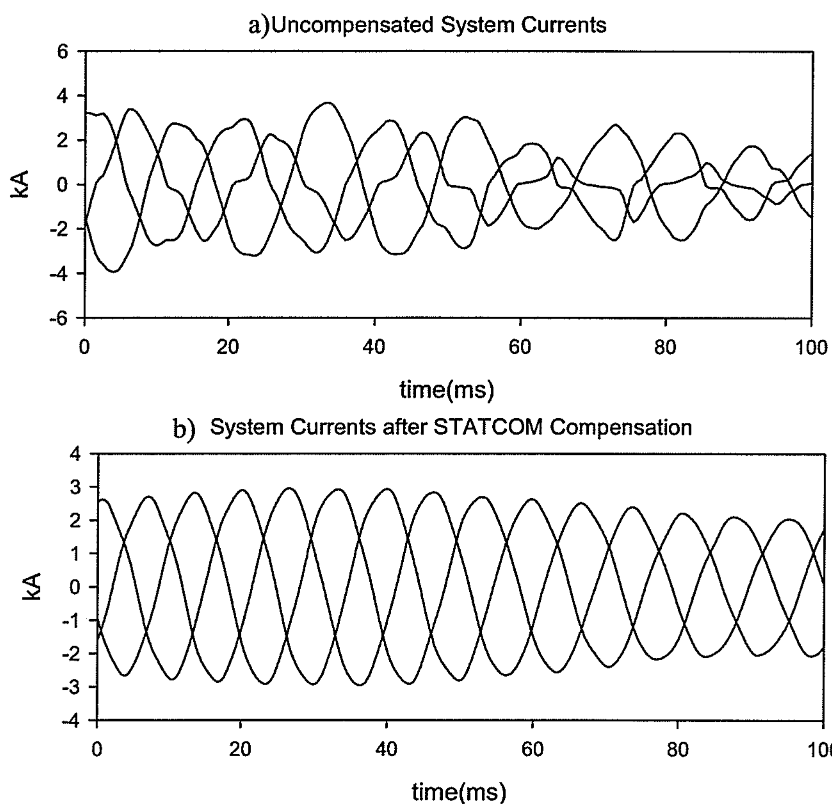

Figure 7-7. Arc Furnace and Ac-system currents with STATCOM Flicker Compensator

Typical current waveforms entering the ac network before/after such compensation are shown in Figure 7-7. The high-frequency ripple due to the PWM switching action is hardly visible as the shunt capacitance largely absorbs them. The effectiveness of the STATCOM in cleaning up the currents is apparent. Figure 7-9 shows the ac busbar voltages in the uncompensated and compensated systems respectively.

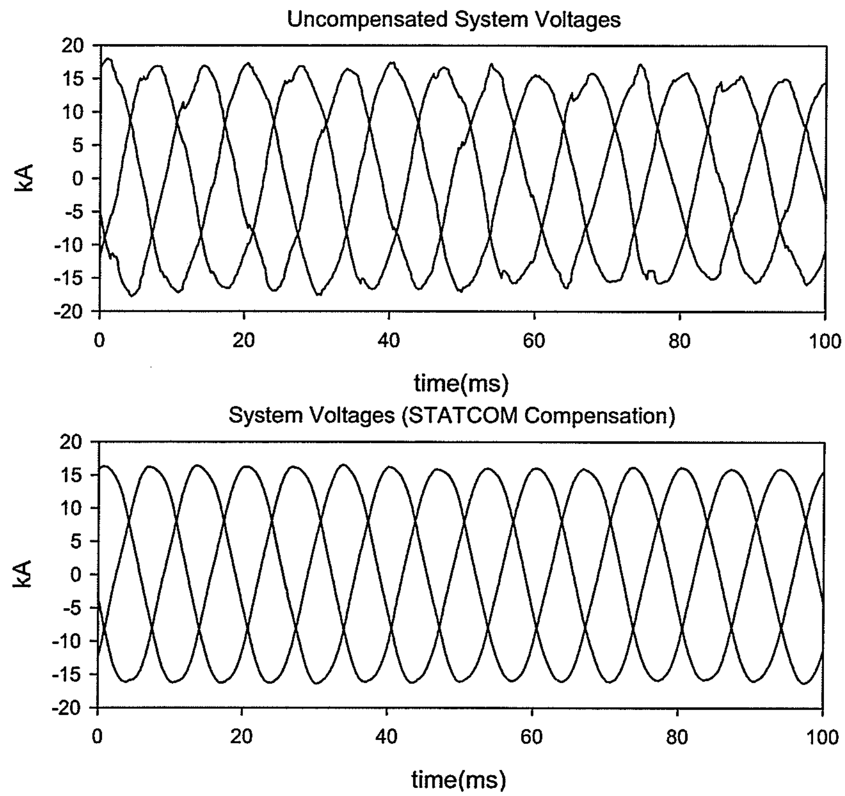

Figure 7-8. Arc Furnace and Ac-system voltages with STATCOM Flicker Compensator

7.2.1 Impact of STATCOM on Flicker Indices

Figure 7-9 shows the impact of the STATCOM flicker control system on the actual flicker index over a 25 second period. The flicker index is reduced from an average value of about 23 to about 5.6. A figure of merit called the flicker reduction index which is the ratio of flicker index after compensation to the uncompensated flicker index is shown in Figure 7-9 (second graph). Notice that this index has an average value of about 0.267, i.e. a reduction in flicker of about 73%.

In addition to the compensator's performance, Figure 7-9 also shows what would happen with an ideal compensator, i.e., one which completely eliminates all harmonics and unbalances from the ac voltage. Ideally, this index should be zero for perfect compensation. In our case however, it has a value of approximately 1.5. This is because although the injected currents are harmonic free and balanced, there is still some contribution to the flicker from the phase correction discussed in earlier. However, this contribution can be considered to be negligible.

Table 7-1 presents the flicker reduction for a variety of STATCOM sizes. This data is presented graphically in Figure 7-10. It can be seen that the greatest improvements in flicker mitigation occur with a STATCOM with a 50MVA rating. After this, the improvement is minimal and in some cases worse due to over-compensation.

This type of analysis is important when deciding on the ratings of the STATCOM as if the pricing data for different sizes of STATCOMS was available, it could be compared to the flicker reduction level and the most cost effective rating could be selected as shown in Figure 7-10.

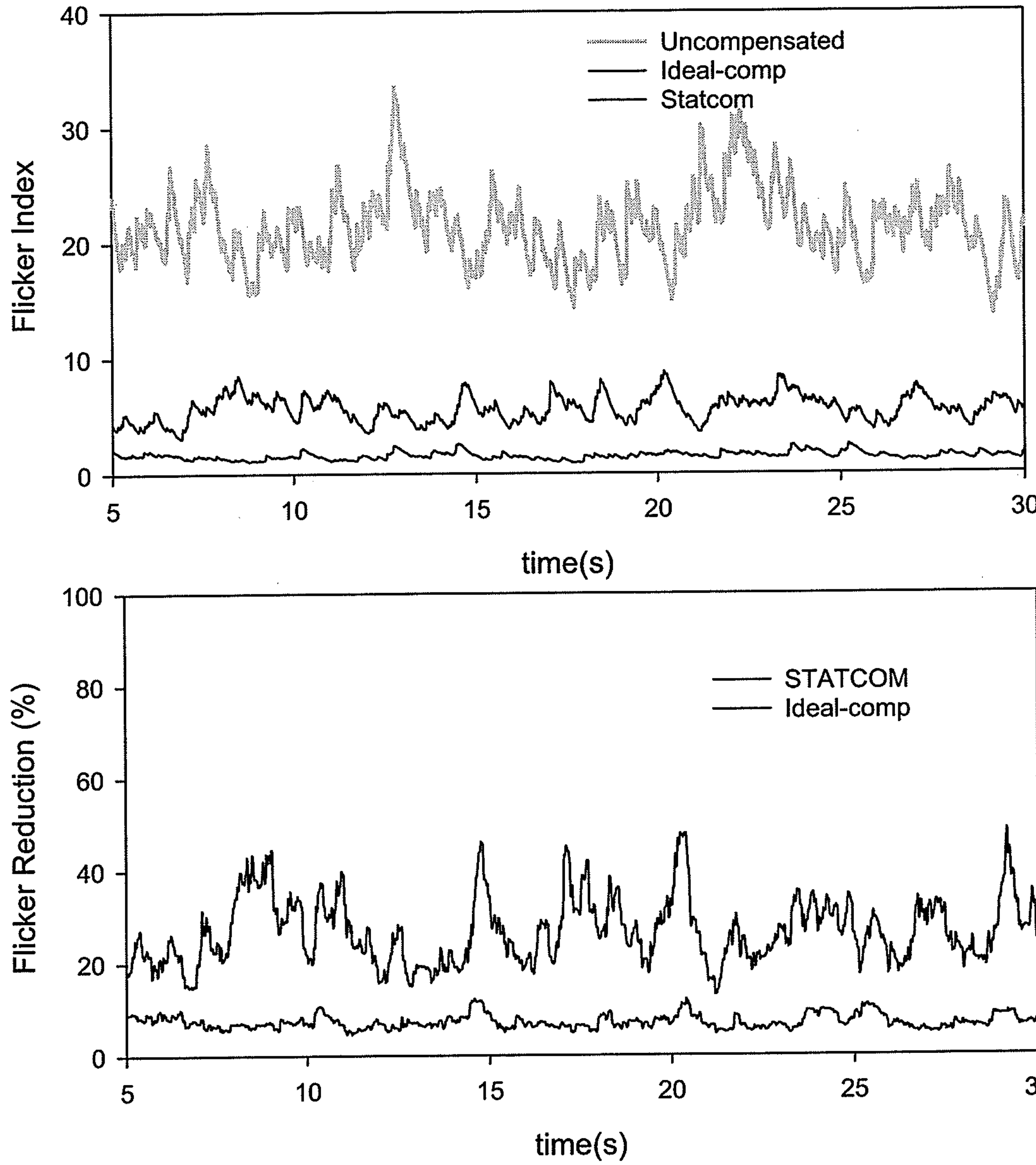

Figure 7-9. Flicker Reduction due to STATCOM Compensation

Table 7-1. Flicker Reduction

STATCOM Rating (MVA)	Filter Rating (MVA)	Flicker Reduction (%)
0	40	0
5	40	5.75
10	40	21.84
20	40	48.28
30	40	66.9
40	40	79.31
50	40	88.75
60	40	86.67
70	40	87.36
80	40	88.05

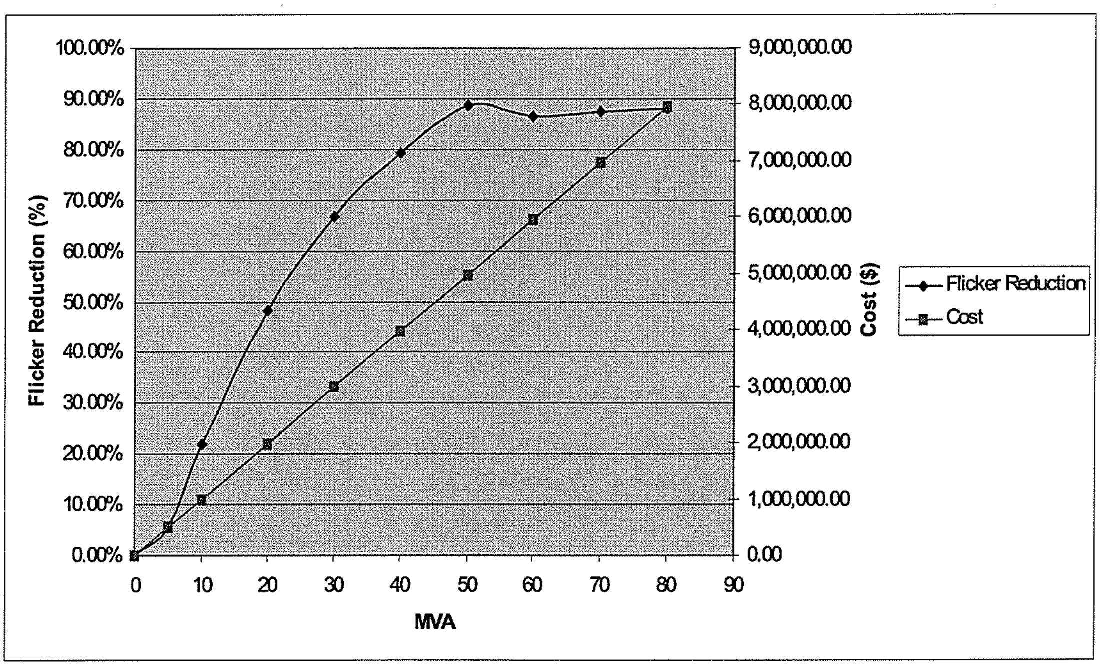

Figure 7-10. Flicker reduction graph

8 Conclusions

8.1 Conclusions

This thesis has provided an:

- Introduction to flicker and it's measurement. This included a detailed look at the history of flicker and the events leading up to the current definition of it. The IEC/UIE flickermeter was also presented in great detail, and from this background a flickermeter was developed and tested for an EMT-Type tool. A method to use the instantaneous flicker measurement as opposed to the Pst measurement was implemented. This was done to overcome the problem of running and EMT-type program for an extended period of time, which is needed to calculate the Pst number.
- A review of Electric Arc Furnaces and their impact on the power system. This included a detailed look at the arc furnace, the power system components of the arc furnace and the process used by the owners of these furnaces. The actual electric arc was also dissected and presented to give an overview of what is actually happening inside the furnace. A brief review of the available EMT-Type models for EAF simulation was reviewed. Since the main focus of this thesis was the development of the controls and not the validation of and EAF model, the decision was made to model the EAF using real data interfaced with an EMT-Type tool. To implement this, a method to interface real data and an EMT-Type program was implemented. This included developing and benchmarking the simulation to ensure that the real data and the simulation were running in-sync.
- A review of Static compensation techniques and their application to flicker control was reviewed. From this review, it was decided to use a STATCOM for the flicker compensation as the other techniques were either too slow or would be cost prohibitive in reality.
- A novel method of compensating flicker caused by an Electric Arc Furnace using a Current Reference Pulse-Width Modulated based STATCOM was developed. This technique was rigorously tested to give the optimum control and STATCOM sizing for flicker mitigation.

It was shown that using the above methods, a significant reduction of flicker can be obtained. Along side the flicker reduction, this thesis introduced a method to adequately size the STATCOM based on incremental improvement in flicker for different sizes of STATCOMs.

8.2 Future Work

There are two main items of future work that can be done using this work as a starting point:

The first one is to develop a method to measure the 10 minute Pst value using the relatively short time (30sec) available in a time-domain simulation. This would be fairly straight forward using some assumptions as outlined in Chapter 4. This technique would not work for other industrial process such as machine starts, as this would occur over a span of time which would exceed the practical limits of time-based simulation.

It is also evident that a detailed model of an arc furnace needs to be developed. This model could be based on differential modelling and include the chaotic load pattern found in present day arc furnaces.

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