A Study on Power Factor Improvement and Its Relationship With Harmonics

by

Nur Azra binti Azmi

Dissertation submitted in partial fulfilment of
the requirements for the
Bachelor of Engineering (Hons)
(Electrical & Electronic Engineering)

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CERTIFICATION OF APPROVAL

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Electrical & Electronics Engineering Programme
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Approved by,

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Project Supervisor

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

December 2004

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons

Nur Azra bt. Azmi

Abstract

This is a report written for a research project on Power Factor Correction and The Interaction with Harmonics. These two issues are the major concerns in power quality analysis. Power quality is defined as a set of electrical boundaries that allows equipment to function in its intended manner without significant loss of performance or life expectancy.

The aim of this project is to understand power factor as a part of power quality concern and how it relates to harmonics problems by developing a simulation to justify the issue. Prior to this, there is a need to understand the overall concept of power factor and harmonics. Literature reviews on the relevant topics are carried out. This will further explained in Chapter 2.

The project methodology is discussed in chapter 3. Basically the project involves the research of relevant topics and analysis of the finding. The main concern here is the study on the effect of improving power factor to harmonic in the harmonic impedance network. The finding will be further verified by simulation using the power system software (ERACS).

The results and finding are discussed in the chapter 4. Here, the student has briefly discussed the findings from the research done on related topic. This chapter describes the analysis that has been done on harmonic effect in a distribution network and the resonance phenomena in the system. A few case studies are conducted .The effect of power factor improvement using capacitor bank is shown.

Chapter 5 discusses the conclusion of this project in relevancy of the project's objectives. It can be concluded that even though power factor is an old and at first glance uninteresting concept, it is worthy of being re-visited because it has, in a relatively simple way, the potential of being very useful in limiting the harmonics produced by modern day distorting loads.

Acknowledgement

First and foremost, I would like to thank the Almighty Allah for giving me the strength, wisdom and good health throughout this project.

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Chapter 1

Introduction

1.1 Background of Study

Today, electrical utilities are no longer independently operated entities; they are part of large network of utilities tied together in a complex grid. The combination of these factors has created electrical system requiring power quality. Power quality is defined as a set of electrical boundaries that allows equipment to function in its intended manner without significance loss of performance or life expectancy. Any power related problem that compromises either attribute is a power quality concern. The project is attempted to explain how power quality factors in particular power factor and harmonics interact in an electrical system. Understanding of power quality issues is a good starting point for solving any power quality problem.

Power factor is one of the major concerns in power quality as it is an economic issue in the operation of a power system. As utilities are increasingly faced with power factor demands that exceed generation capability, the penalty for low power factor is expected to increase. An understanding of power factor and how to remedy low power factor conditions is not any less important than understanding other factors that determine the health of a power system.

In addition the remedy of low power factor by applying capacitor may create parallel or series resonance problems which increase the harmonic distortion of the voltage and current waveforms. Power system harmonics are low frequency phenomenon characterized by waveform distortion, which introduces harmonic frequency components. Voltage and current harmonics have undesirable effects on power system operation and power system component. This project describes the design of power factor correction to avoid harmonic problems.

Prior to installing a capacitor bank it is important to perform a harmonic analysis to ensure that resonance frequencies not coincide with any of the characteristic harmonic frequencies of the power system. The subject of power quality is one of cause and effect.

Power quality is the cause, and the ability of the electrical equipment to function in the power quality is the effect.

1.2 Problem Statement

For most conventional analyses, the power system is essentially modeled as a linear system with passive elements excited by constant-magnitude and constant-frequency sinusoidal voltage sources. However, with the widespread proliferation of power electronics loads nowadays, significant amounts of harmonic currents are being injected into power systems. Harmonic currents not only disturb loads that are sensitive to waveform distortion, but also cause many undesirable effects on power system elements. As a result, harmonic studies are becoming a growing concern.

In the presence of harmonics producing load, capacitors for power factor correction can cause parallel or series resonance problems which tend to increase the total harmonic distortion of the voltage and current waveform. There is a need to do the harmonic analysis to verify the phenomenon and to further understand the interaction between power factor and harmonics problems as a whole.

1.3 Problem Identification

This study will emphasize on understanding the overall concept of power factor to as a part of power quality concern and how it relates to harmonics problems. There is a need to do a harmonic analysis before any power factor correction capacitor is applied to minimize the effect of harmonics that can be lived with indefinitely but in other cases they should be minimized or eliminated. Either of these approaches requires a clear understanding of the theory behind them. Literature reviews on book and journals are accomplished through this early stage. Apart from that the student has also done a site visit and obtain information from the industrial area for a better understanding on these two issues concern on power system in real world. Next step is simulating computer analysis using appropriate power analysis software. The simulation part is for the harmonic analysis to verify the relation with power factor correction.

1.4 Objectives

1. to obtain further understanding on overall concept of power factor including power factor improvement
2. to better appreciate the overall concept of harmonics and its effects on power system
3. to analyze the relation between power factor and harmonics
4. to develop a simulation program using power system software to verify the relation between power factor correction and harmonics

1.5 Feasibility of the Project within the Scope and Time Frame

The scope of study covered the following:

1. A thorough literature research is required to gather all the information regarding power factor and harmonic problems. The important part is to analyze the interaction between them.
2. Development of simulation program using the power system software to verify the findings from the literature review on the contribution of power factor correction in harmonic problems

The project is scheduled and planned such that it is feasibly within the scope and time frame in order to ensure the success of it. Since this is a two semester's project, the research and data gathering will be completed in the first semester and the simulation part are continued in the second semester.

CHAPTER 2

Literature review

2.1 For this project the author, has done a lot of literature review on the related topics. The matter has been extensively studied and is summarized in IEEE Std 519 that is Recommended Practice for Harmonic Control in Electric Power System. (Appendix 1). The recommended practices involve a number of considerations of feeder voltage and capacity, sensitivity of connected equipment, in plant versus system interference potential and other related matters.

2.2 Power Factor Correction

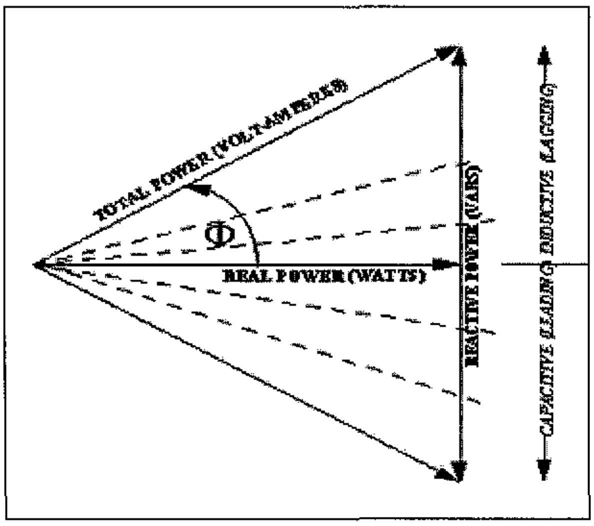


Figure 1: Power Triangle

The power triangle shown in figure 1 is the simplest way to understand the effects of reactive power. The figure illustrates the relationship of active (real) and reactive (imaginary or magnetizing) power. The active power (represented by the horizontal leg) is the actual power, or watts that produce real work. This component is the energy transfer component, which represents fuel burned at the power plant. The reactive power or magnetizing power, (represented by the vertical leg of the upper or lower triangle) is the power required to produce the magnetic fields to enable the real work to be done.

Without magnetizing power, transformers, conductors, motors, and even resistors and capacitors would not be able to operate. Reactive power is normally supplied by generators, capacitors and synchronous motors. The longest leg of the triangle (on the upper or lower triangle), labeled total power, represents the vector sum of the reactive power and real power components. Mathematically, this is equal to:

$$\text{TOTAL POWER} = \sqrt{(\text{REAL POWER})^2 + (\text{REACTIVE POWER})^2}$$ ---Equation 1

The angle "phi" in the power triangle is called the power factor angle and is mathematically equal to:

$$\cos\Phi = \frac{\text{REAL POWER (KWATTS)}}{\text{TOTAL POWER (KVA)}}$$ --------Equation 2

2.3 Definition of Power System Harmonics

In the power system, the definition of a harmonic can be stated as: A sinusoidal component of a periodic wave having a frequency that is an integral multiple of the fundamental frequency. Thus for a power system with f_0 fundamental frequency, the frequency of the h-th order of harmonic is hf_0 . Harmonics are often used to define distorted sine waves associated with currents and voltages of different amplitudes and frequencies.

One can compose a distorted periodic wave shape of any conceivable shape by using different harmonic frequencies with different amplitudes. Conversely, one can also decompose any distorted periodic wave shape into a fundamental wave and a set of harmonics. This decomposition process is called Fourier analysis. With this technique, we can systematically analyze the effects of nonlinear elements in power systems.

Most elements and loads in a power system respond the same in both positive and negative half-cycles. The produced voltages and currents have half-wave symmetry. Therefore, harmonics of even orders are not characteristic. Also, triplens (multiples of third harmonic) always can be blocked by using three-phase ungrounded-wye or delta transformer connections in a balanced system, because triplens are entirely zero sequence. For these reasons, even-ordered and triplens are often ignored in harmonic analysis. Generally, the frequencies of interests for harmonic analysis are limited to the 50th multiple.

One major source of harmonics in the power system is the static power converter. Under ideal operating conditions, the current harmonics generated by a *p*-pulse line-commutated converter can be characterized by $I_h = I_1 / h$ and $h = pn \pm 1$ (characteristic harmonics) where n = 1, 2, and p is an integral multiples of six. If 1) the converter input voltages are unbalanced or 2) unequal commutating reactance exist between phases or 3) unequally spaced firing pulses are present in the converter bridge, then the converter will produce non-characteristic harmonics in addition to the characteristic harmonics. Non-characteristic harmonics are those that are not integer multiples of the fundamental power frequency.

2.4 IEEE 519-1992 STANDARD

Location ISC/IL	**IEEE Allowed TDD (%)**
<20	5.0
20<50	8.0
50<100	12.0
100<1000	15.0
>1000	20.0

Bus voltage at PCC	Individual voltage distortion (%)	Total voltage distortion (THD %)
69 kV and below	3	5
69.001 kV – 161 kV	1.5	2.5
161 kV and above	1	1.5

2.5 Harmonic Distortion

2.5.1 Calculation of current distortion

Total current distortion, in general defines the relationship between the total harmonic current & fundamental current.

Total current distortion is the total harmonic distortion given by,

Total harmonic distortion, $THD = \frac{IH}{IL}$

Where, IL = The maximum load current

(Fundamental frequency component)

$IH = (I2^2 + I3^2 + \ldots + I25^2)^{1/2}$

$$THD\ (CURRENT) = \frac{(I2^2 + I3^2 + \ldots + I25^2)^{1/2}}{IL} \times 100\% \quad \text{------------------Equation 3}$$

The upper summation limit of H = 25 is chosen for practical purpose.

2.5.2 Calculation of voltage distortion

Total voltage distortion, in general defines the relationship between the total harmonic voltage & fundamental voltage.

Total voltage distortion is the total harmonic distortion given by,

Total harmonic distortion, $THD\ (voltage) = \frac{VH}{V1}$

Where, VI = Fundamental AC line – to – neutral voltage

$VH = (V2^2 + V3^2 + \ldots + V25^2)^{1/2}$

(Total line – to – neutral harmonic voltage)

I.e. $$THD\ (VOLTAGE) = \frac{(V2^2 + V3^2 + \ldots + V25^2)^{1/2}}{V1} \times 100\% \ldots\ldots\ldots\ldots \text{Equation 4}$$

2.6 Resonance circuit

To get the overall view on the effect of resonance in capacitor (power factor correction) that produces harmonic problems, the student should have some basic understanding on resonance circuit. In a series resonant circuit, the inductive and capacitive reactances are equal and the impedance is just the resistance, R. In the parallel resonant circuit, X L is approximately equal to X C and Q is defined in the same fashion as with the series circuit as X L /R or X C /R. The impedance of the parallel resonant circuit is then Q*X L or Q*X C, and the current circulating within the resonant circuit is Q times the current in the external circuit. If the Q is high, the impedance is much higher than either the inductive or capacitive reactance and the current multiplication is correspondingly high.

The phenomena which known as the parallel resonance leading to an amplification of harmonic currents. In the presence of the power factor correction capacitors the total impedance since by the harmonic currents is the parallel combination of the normal power system impedance and the impedance of capacitors. Based on figure 1, the parallel resonance frequency reduces as the capacitor kVAr rating increases.

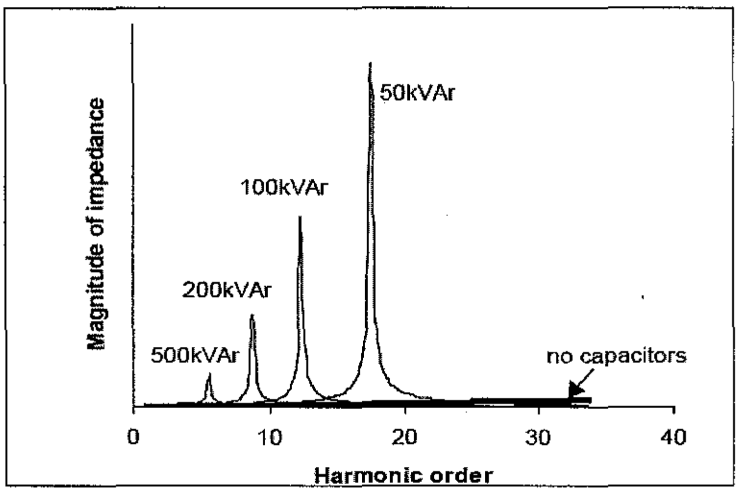


Figure 2: Variation of the impedance with harmonic order for dif ferent capacitor banks

2.7 Detuning the power factor correction capacitors

It is important to avoid parallel resonance at frequency which is close to a frequency of a harmonic current of distorting load. This is achieved by adding an inductor in series with the power factor correction capacitors leading a situation commonly known as series resonance. At the frequency where series resonance takes place the impedance seen by the harmonic current is small. If parallel resonance takes place and it happen at frequency which does not correspond to the lowest frequency of the current harmonic that is present in the load current and hence there will be no serious voltage distortion.

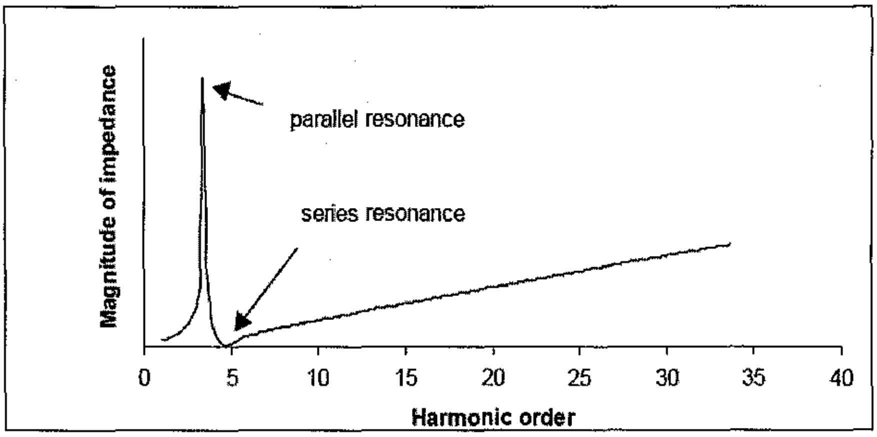
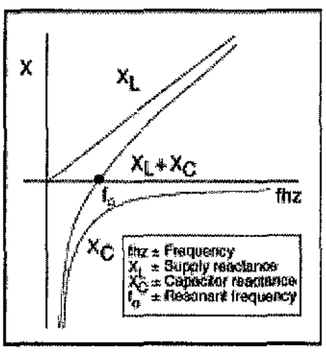


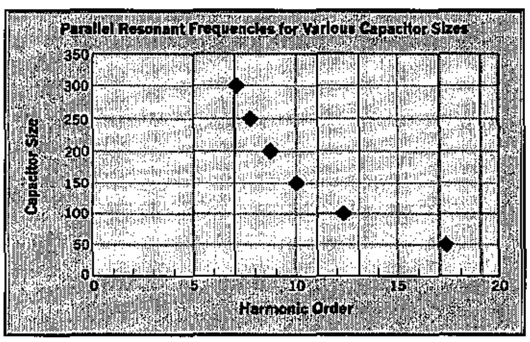
Figure 3: Variation of the impedance with detuning inductor

Generally, harmonic resonance is a steady-state phenomenon triggered by an event in which the harmonic source changes or the source impedance or capacitor size changes, such as if capacitors are switched on or off in steps. The resulting parallel resonant frequency or harmonic order can be estimated, by using the following equation:

$$h_R = \sqrt{\frac{MVA_{SC}}{MVAR_{CAP}}} \quad \text{------------------Equation 5}$$

Where h_R is the parallel resonant frequency harmonic order, such as the 5th or 7th, MVA_{SC} is the source impedance in MVA at the bus of interest, and $MVAR^{CAP}$ is the 3-phase rating in MVA of the capacitor bank.





IEEE Standard 18-2002, Standard for shunt Power Capacitors, states that power capacitors must withstand a maximum continuous rms over voltage of 110% and an over current of 180%, based on the nameplate rating. This over voltage and over current includes both the fundamental frequency and any harmonic contributions. The standard also states that the VA rating of the capacitor can't exceed 135%.

Chapter 3

Project Flow and Methodology

3.1

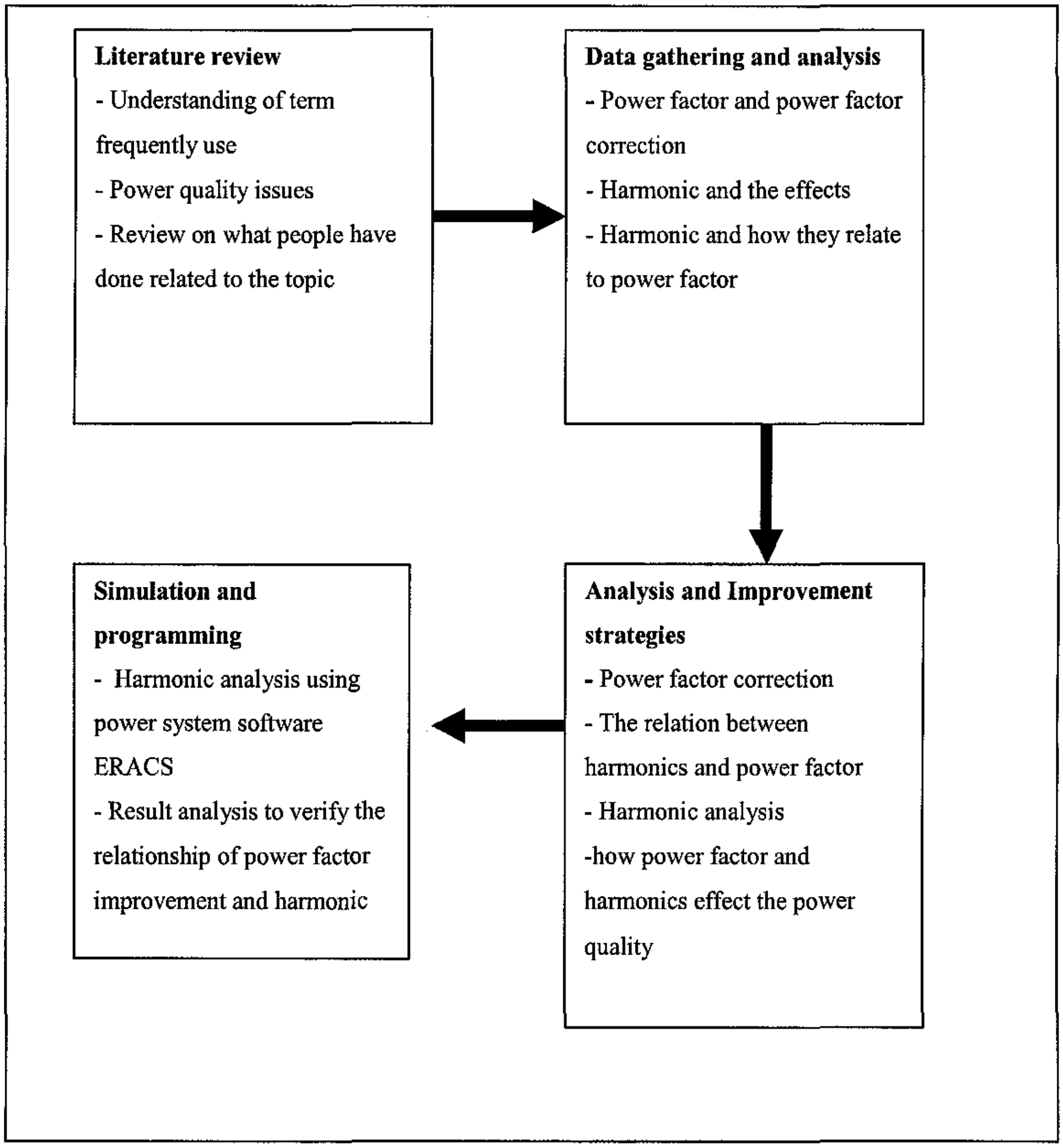


Figure 4: Project Flow Diagram

3.2 Data gathering and analysis

1. Power factor improvement
   - o Calculation
   - o Practical limit of correction
   - ➢ Potential drawback
   - o Investment cost
   - o Voltage rise
   - o Increased harmonic problems
   - ➢ Location of the capacitor bank
   - o Primary vs secondary bank
   - ➢ Maintenance/ harmonic effect
2. Harmonics
   - ➢ Definition of harmonic
   - ➢ Individual an total harmonic distortion
   - ➢ Cause of voltage and current harmonics
   - ➢ Effect of harmonic on Power System Devices
   - o Capacitor Banks
3. Power Factor and Harmonic
   - ➢ Power Factor and Harmonics Interaction
   - ➢ Power Factor Capacitor Resonance
   - ➢ Power Factor Transient

3.3 Simulation and programming

1. Harmonic Analysis on interaction between harmonic and power factor
   - ➢ ERACS

   The program calculates total harmonic voltage and current distortion across the system as well as the individual harmonic voltage and current values. They are aimed at detecting resonance and calculating harmonic currents, voltages and distortion levels/ factor.

3.3.1 Harmonic Impedance calculation procedure

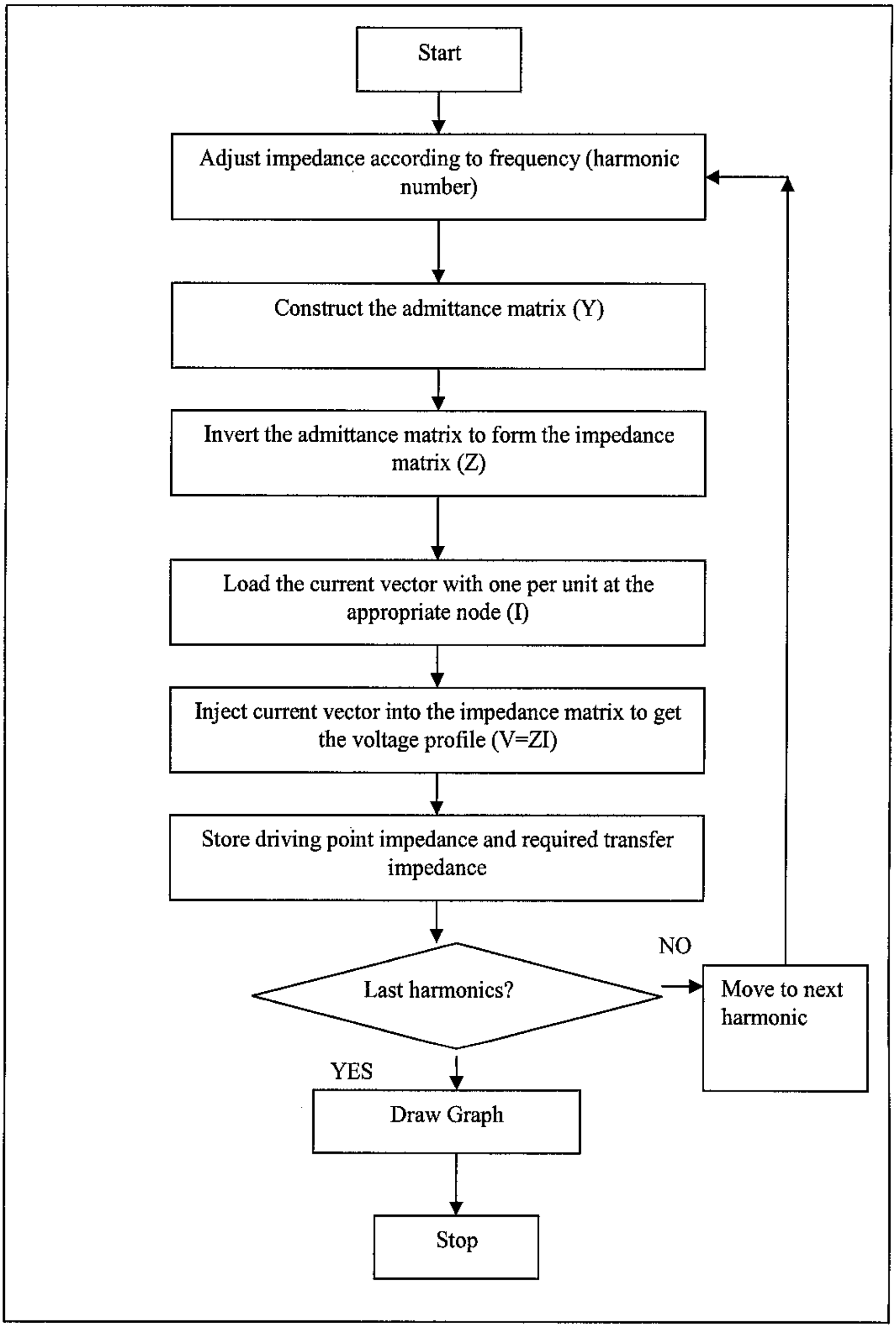


Figure 5: Harmonic Impedance Simulation Flow Chart

3.3.2 Calculation Parameters

1. Injection busbar- at which the 1 per unit harmonic current is to be injected
2. Transfer busbar- to plot the transfer impedance
3. Lowest/ highest harmonic- the range of harmonics over which study is to be conducted
4. Harmonic interval- the interval between the harmonics
5. Harmonic offset- allows the fundamental frequency to be offset by a fixed amount. The harmonic frequencies then satisfy the following equation:

$F_h = (100- h_{offset} / 100) x f_1 x h$-- **Equation 6**

3.3.4 Develop Base Case Harmonics Model

The first step in the harmonic study is to develop a system model to be used for the analysis. The model is developed from the one line diagrams, the electrical equipment data (transformers, cables, machines, etc.), the utility system characteristics, and the loading information. The result is a database that should include the following elements:

- Representation of the utility system supplying the facility. This system can be represented as a simple equivalent as long as there are no switched capacitors.
- Step down transformers (ratings and name plate impedances).
- Important low voltage circuits (specifically ASDs).
- Load data for each bus (kW, kVAr, kVA).
- Capacitor data (level of compensation, kVAr).

The electrical database developed at this stage is used for the development of both the transient model and the harmonic analysis model of the system. The model must include important connected capacitors, cable capacitances, transformer characteristics, reactor values, motor representations, and an equivalent representation for the utility supply system

Chapter 4
Result and Discussion

4.1 Power Factor

Power factor is the relationship between working (active) power and total power consumed (apparent power). Essentially power factor is a measurement of how effectively electrical power is being used. A higher power factor represents more effective use of electrical power. The term cos θ is called power factor. As the phase angle between applied voltage and total current increases, the power factor decreases, indicating an increasingly reactive circuit. The smaller the power factor the smaller the power dissipation.

Power Factor = Actual Power/ Apparent Power

= kW/ KVA

4.1.1 Power Factor Correction

Power factor correction means reduction of lagging reactive power (Q) or lagging reactive current (I_Q). For the project, the student focuses on power factor improvement using capacitor.

4.1.2 The advantages of an improved power factor

Higher power factors result in–

a) Reduced system losses, and the losses in the cables, lines, and feeder circuits and hence lower sizes could be opted.
b) Improved system voltages, thus enable maintaining rated voltage to motors, pumps and other equipment. The voltage drop in supply conductors is a resistive loss, and wastes power heating the conductors. A 5% drop in voltage means that 5% of your power is wasted as heat before it even reaches the motor. Improving the power factor, especially at the motor terminals, can improve your efficiency by reducing the line current and the line losses.
c) Improved voltage regulation.

d) Increased system capacity, by release of kVA capacity of transformers and cables for the same kw, thus permitting additional loading without immediate augmentation.

4.2 Power Factor and Harmonics Interaction

When a source of harmonic currents is connected to a feeder, two related but distinctly different effects arise. First, the currents flow into the electric utility system through the point of common connection. Their potential effects within the utility system will be examined later. Second, the utility supply has some source impedance and, in flowing through this source impedance, the harmonic currents will produce distortion in the feeder voltage. Commutation notching is one aspect of this phenomenon. Connected loads may be affected by these harmonics in the line voltage, particularly those which are sensitive to zero crossings in the voltage waveform or which have potential internal resonances. Computer disk drives, fluorescent lamp ballasts, telephone circuits, PA and paging systems, lamp dimmers and radios are just a few of the many connected devices which may experience interference from harmonics

4.3 Types of loads cause harmonic currents

A linear load is a load that opposes the applied voltage with constant impedance resulting in current waveforms that change in direct proportion to the change in the applied voltage. Examples of these loads are resistance heating, incandescent lighting, motors, etc. If the impedance is constant, then the applied voltage is sinusoidal, and the current waveform will also be sinusoidal.

A nonlinear load, on the other hand, is a load that does not oppose the applied voltage with constant impedance. The result is a non sinusoidal current waveform that does not conform to the waveform of the applied voltage. Nonlinear loads have high impedance during part of the voltage waveform, and when the voltage is at or near the peak the impedance is suddenly reduced. The reduced impedance at the peak voltage results in a large, sudden, rise in current flow until the impedance is suddenly increased resulting in a sudden drop in current.

Because the voltage and current waveforms are no longer related, they are said to be "nonlinear." Nonlinear loads are loads that have diode-capacitor power supplies such as: computers; laser printers; welders; variable frequency drives; UPS systems; fluorescent lighting; etc., which draw current in short pulses during the peak of the line voltage. These non sinusoidal current pulses introduce unanticipated reflective currents back into the power distribution system, and the currents operate at frequencies other than the fundamental 50 Hz.

4.4 Effect of Harmonic Distortion on Power System

1. Inductive heating of transformers, generators, and other electromagnetic devices such as motors, relays, and coils (due to the inductive heating effects of eddy currents, skin effect, and hysteresis).
2. Inductive heating of conductors, breakers, fuses, and all other devices that carry current (because of eddy currents, skin effect, and hysteresis). The harmonic current is a continuous overload and causes the fuse to be exceeded and it blows.
3. Inductive heating of metal parts such as raceways, metal enclosures, and other ferrous (iron or steel) metal parts (because of eddy currents and hysteresis).
4. Voltage distortion resulting in unpredictable equipment operation because of harmonics. Excessive neutral current resulting in equipment overheating or failure because of additive harmonic currents, excessive voltage drop, and distortion

4.4.1 Mitigation of power system harmonic

Solutions to harmonic problems are categorized as preventive and remedial.

Precautionary (preventive) solutions are those policies sought for at discretion to avoid harmonic and their consequences. These include:

- Phase cancellation or harmonic control in power converters
- Developing procedures and methods to control, reduce or eliminate harmonics in power system equipment mainly capacitors, transformers and generators

Corrective (remedial) solutions are those techniques recoursed to aiming at overcoming existing harmonic problems

- The use of filters and detuned of capacitor bank
- Circuit detuning which involves the configuration of feeders or relocation of capacitor bank to overcome resonance

4.5 Harmonic Resonance

The operation of nonlinear loads in a power distribution system creates harmonic currents that flow throughout the power system. The inductive reactance of that power system increases and the capacitive reactance decreases as the frequency increases, or as the harmonic order increases. At a given harmonic frequency in any system where a capacitor exists, there will be a crossover point where the inductive and capacitive reactances are equal. This crossover point, called the parallel resonant point, is where the power system has coincidental similarity of system impedances. Every system with a capacitor has a parallel resonant point.

Parallel resonance causes problems only if a source of harmonics exists at the frequency where the impedances match. This is typically called harmonic resonance. Harmonic resonance results in very high harmonic currents and voltages at the resonant frequency. It's extremely unlikely that these two impedances are exactly identical, but near resonance can be very damaging as well. If, for example, the parallel resonant point is at the 5.3rd harmonic and a source of 5th harmonic current exists on the system, problems are likely to occur

4.6 Harmonic Analysis Modeling

The power system harmonic studies are use to analyze the harmonic situation. They are aimed at detecting resonance cause by the power factor improvement capacitor and calculating harmonic currents, voltages and distortion level factor. In simple terms, the programs:

- build the bus admittance matrix for each harmonic
- given the harmonic source current spectrum I(h), find the bus voltage
- calculate the line currents
- calculate the voltage and current distortion factors

4.61 Harmonic Injection Simulation

- The program calculates total harmonic voltage and current distortion across the system as well as the individual harmonic voltage and current values
- For any given study multiple injection points may be specified at different voltages and locations across the network

4.6.2 Harmonic Impedance Simulation

- The harmonic impedance calculation provides the facility to determine the impedance at selected busbar over a range of definable harmonic frequencies.
- The resultant harmonic voltage is calculated for the injected busbar (3.3 kV) and any other specified busbar known as the transfer busbar (11 kV)
- The voltage to current ratio gives the harmonic impedance
-

4.6.3 System Description

Table 1: System Description

System	Description	
Medium Voltage Network	11 kV	
Transformer 1 & 2	T1 & T2	11/ 3.3 kV (6 MVA)
Transformer 3	T3	3.3/ 0.415 kV (2 MVA)
Motor 1 and 2	M1 & M2	3.3 kV
Motor 3	M3	0.415 kV
Harmonic Source	6- pulse variable speed drive	Result in harmonic number 5, 7,11,13
Power Factor Correction Capacitor 1	11 kV	* switch on and off alternately to see the effect on harmonic resonance
Power Factor Correction Capacitor 2	3.3 kV	

4.6.4 Power System Network Diagram

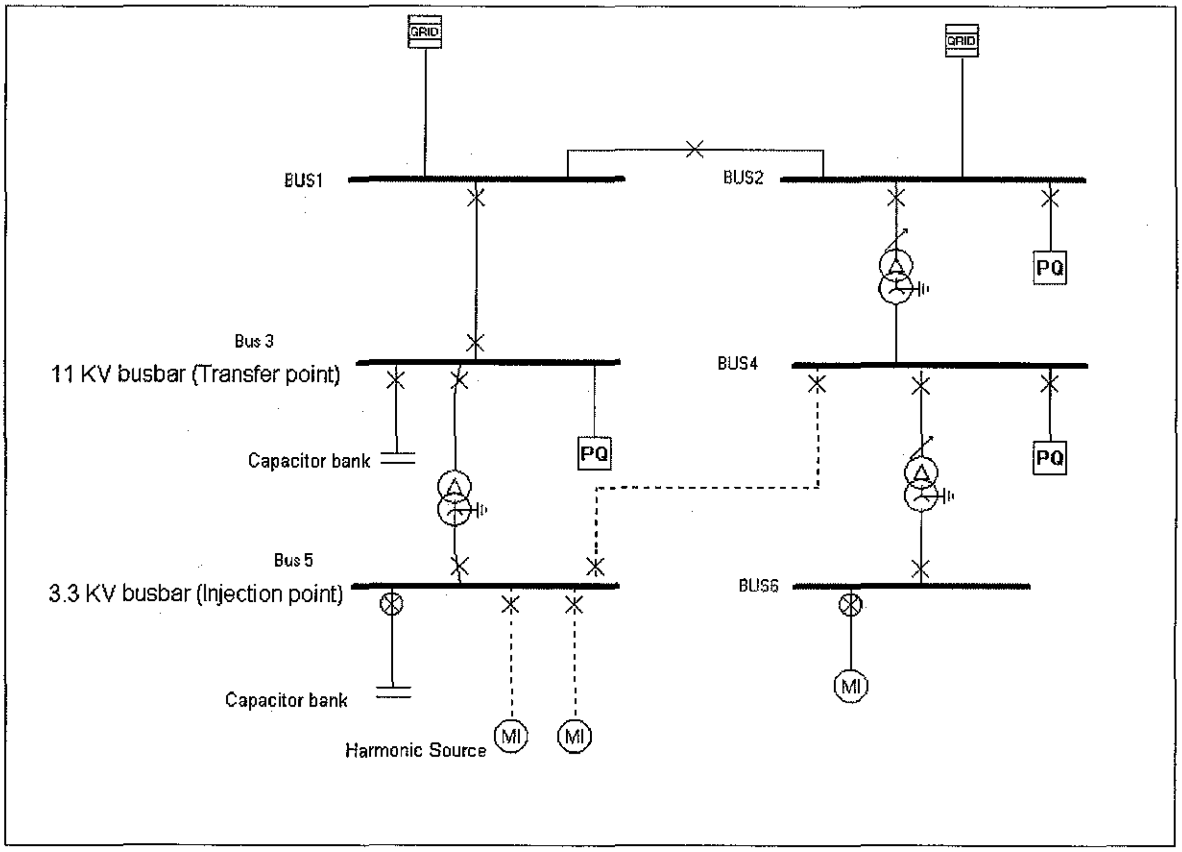


Figure 6: Power System Network Diagram (Appendix 3)

Initial Condition
No capacitor bank installed

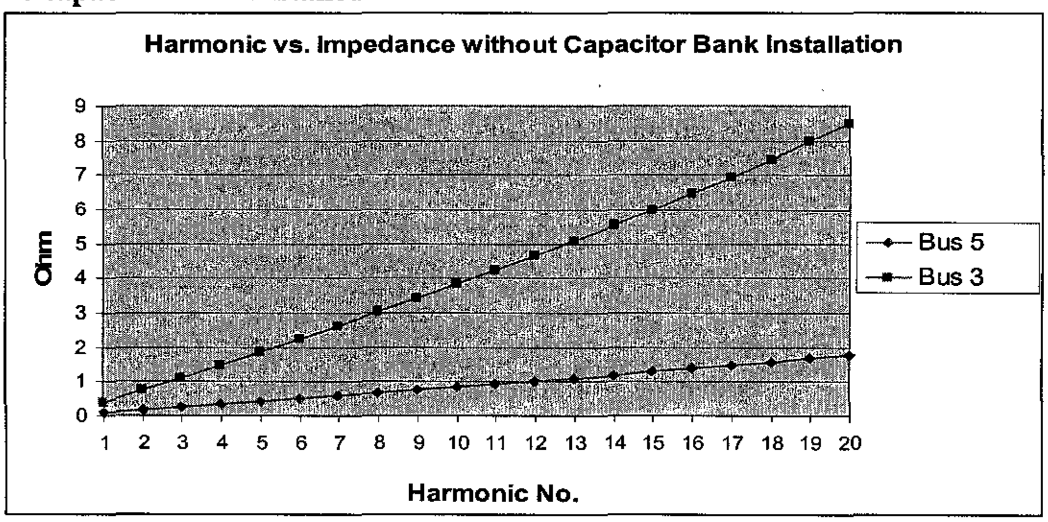


Figure 7: Harmonic No. vs. Impedance without Capacitor Bank Installation

From figure 7 "Harmonic Impedance vs. Harmonic number" graph, it can be verified that without capacitor bank installation there will be no harmonic resonance detected in the power system.

Harmonic distortion result (THD %)

Busbar	Distortion %
11 kV (B3)	0.19740
3.3 kV (B5)	0.46958

Table 2: Total Harmonic Distortion without Capacitor

Power Factor Improvement (initial P.F =0.77)

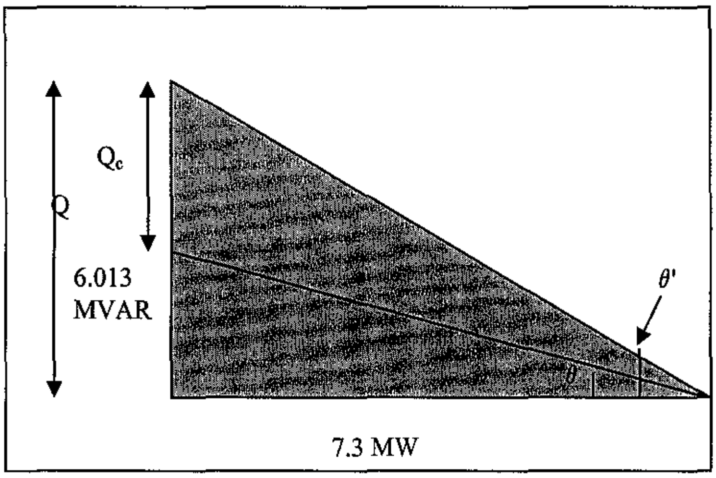


Figure 8: Power Factor Improvement

Initial power factor = 0.77
To improve power factor to 0.85
$\theta' = \cos^{-1} 0.85$
$= 31.78^{\circ}$
$Q' = P \tan \theta'$
$= 7.3\text{MW} \tan 31.78^{\circ}$
$= 4.52$ MVAR
$\therefore Q_c = Q - Q'$
$= 6.013 - 4.52$
$= 1.5$ MVAR
$\therefore$ Additional of 1.5 MVAR
= **2.5 MVAR** (new capacitor rating)

The initial power factor of the power distribution system in figure 6 is 0.77. The aim of the study is to improve the power factor to above 0.85 and analyze the effect of the addition of power factor correction capacitor bank to the harmonic contents in the system corresponding with the theory. Calculation has been carried out to identify the additional values of capacitor to be added in the system as in figure 8. The resonance phenomena produced by the capacitor bank are to be observed and verified how its contributed to the higher harmonic distortions

4.7 Case study 1: Capacitor Installed at 11 KV bus

Capacitor (KVAR)	Power Factor	Resonance Frequency Hn	System Impedance at Resonance Ohm	Total Harmonic Distortion (THD %) 11 KV bus-bar	3.3 KV bus bar
1000	0.77	16.97	181.88	0.295	0.553
2000	0.82	11.95	188.76	0.61	0.723
2500	0.85	10.98	174.61	1.238	1.184
3000	0.87	9.95	250.13	0.38	0.525
3500	0.9	8.94	54.61	0.346	0.54
4000	0.92	9.02	45.27	0.383	0.5589
4500	0.94	7.94	53.45	0.468	0.672
5000	0.96	7.94	55.54	0.645	0.836
5500	0.98	6.99	21.24	1.139	1.294
6000	0.99	6.94	56.22	4.883	4.831

Table 3: Resonance and Harmonic Distortion for Capacitor installed at 11 kV busbar

4.7.1 Harmonic Resonance Calculation

Fault level = 302.24MVA (11kV busbar fault level)

Harmonic resonance = $\sqrt{302.24MVA/2500kVAR}$

= 10.99 ≈ 11th harmonic (verify by the simulation result in table 3)

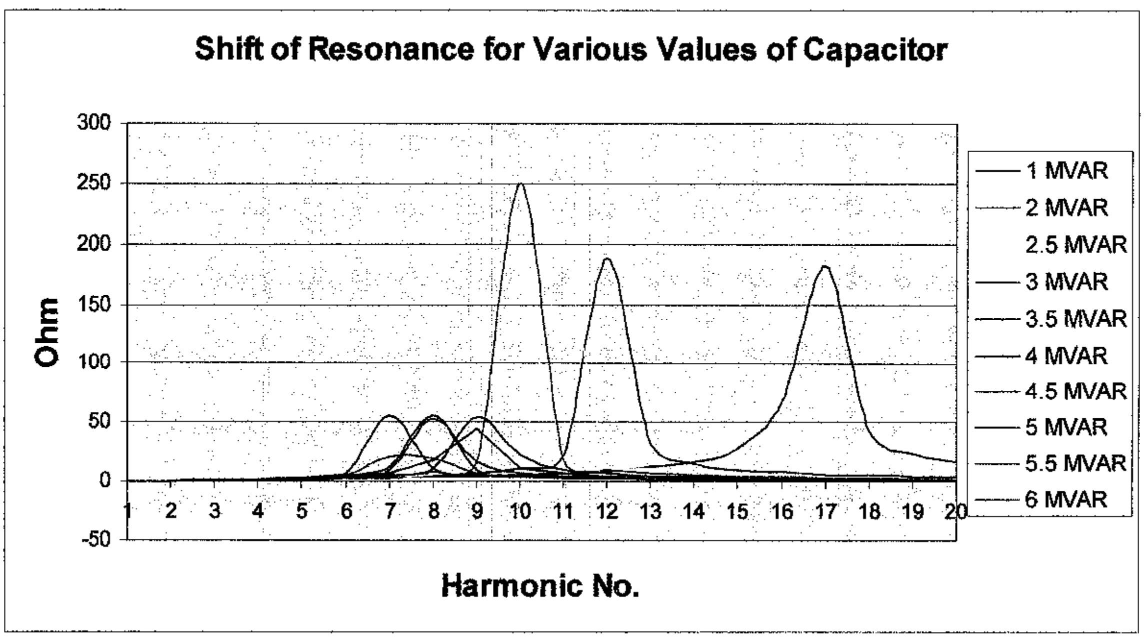


Figure 9: Harmonic Resonance shifting for capacitor installed at 11 kV busbar (see appendix 3)

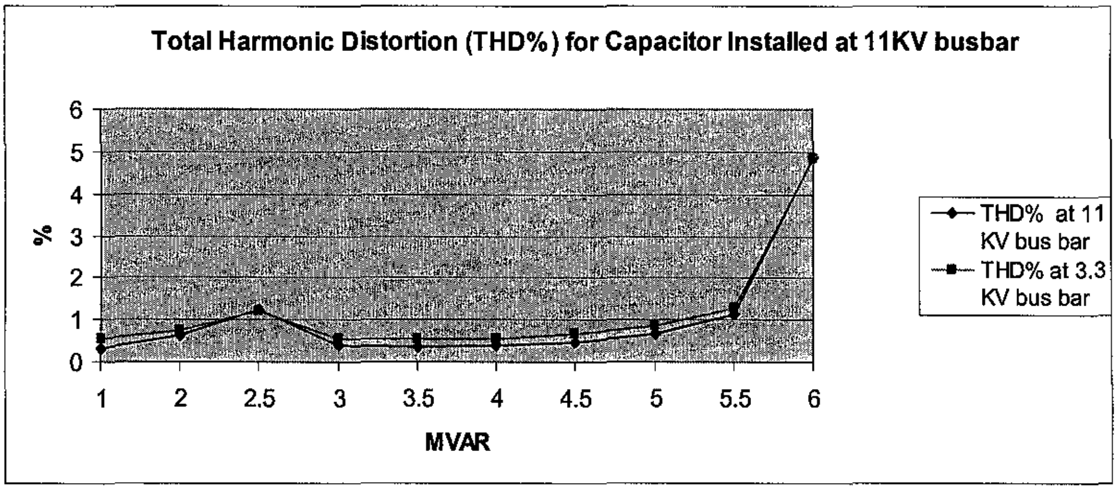


Figure 10: Total Harmonic Distortion for Capacitor Installed at 11 kV busbar

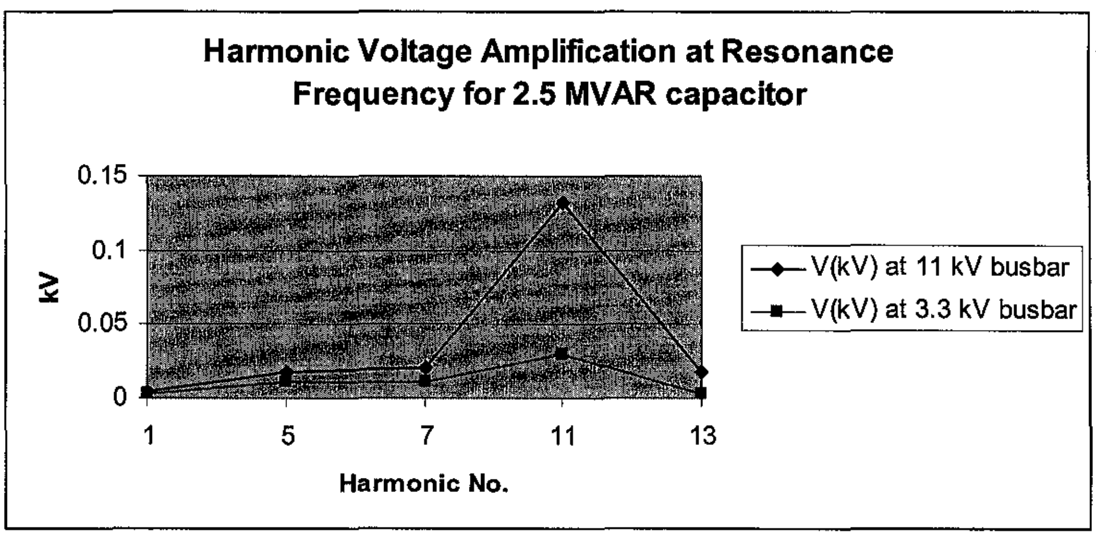


Figure 11: Harmonic Voltage Amplification at 11^{th} Harmonic (see appendix 4)

The result for the simulation using various values of capacitor installed at 11 kV busbar is summarized in table 3 and can clearly be seen as illustrated in the graphs. As the capacitor's value is varies, it can be observed from figure 9 that,

- An increased capacitor size that increased power factor of the system shift resonance to a lower value

- There is an intermediate range of frequencies where the capacitive and inductive effect can combine to give very high impedance. A small harmonic current within this frequency range can give a very high and undesirable harmonic voltage.

There is risk of harmonic resonance if this number is close to a harmonic order present in one of the harmonic loads. From figure 8, the effect of harmonic resonance can clearly be observed. The total harmonic distortion increased significantly when the capacitor is detuned to 2.5 MVAR. 2.5 MVAR capacitor size gives harmonic resonance at 11th order which is coincide with the harmonic order produce by 6 pulse variable speed drive in the system.

Form figure 11, it verified that at 11th harmonic, the busbar voltage V_{11} and $V_{3.3}$ are amplified. This is because a parallel resonance occurred at this frequency of a harmonic current of the distorting load. It is clear that if there is a load current harmonic which is close to the peaky section of the resonance curve in figure 9, a substantial voltage can be developed causing serious voltage distortion.

4.8 Case Study 2: Capacitor Installed at 3.3 kV bus bar

Capacitor (KVAR)	Power Factor	Resonance Frequency Hn	System Impedance at Resonance Ohm	Total Harmonic Distortion (THD %)	
				11 KV bus bar	3.3KV bus bar
1000	0.77	10.97	21.19	0.418	0.99
2000	0.83	7.97	17.45	0.475	1.124
2500	0.86	6.9	14.9	0.653	1.546
3000	0.88	6.68	12.77	0.49	1.157
3500	0.91	6.01	13.76	0.451	1.065
4000	0.92	5.6	12.29	0.538	1.269
4500	0.94	5.01	4.74	0.699	1.647
5000	0.98	4.93	11.62	0.773	1.819
5500	0.99	4.9	12.11	0.624	1.466

Table 4: Resonance and Harmonic Distortion for Capacitor installed at 3.3 kV busbar

4.8.1 Harmonic Resonance Calculation

Fault level = 134.42 MVA (3.3 kV busbar fault level)

Harmonic resonance = $\sqrt{134.42\ \text{MVA}/\ 2500\text{kVAR}}$

= 7.33

≈ 7th harmonic (verify by the simulation result in table 4)

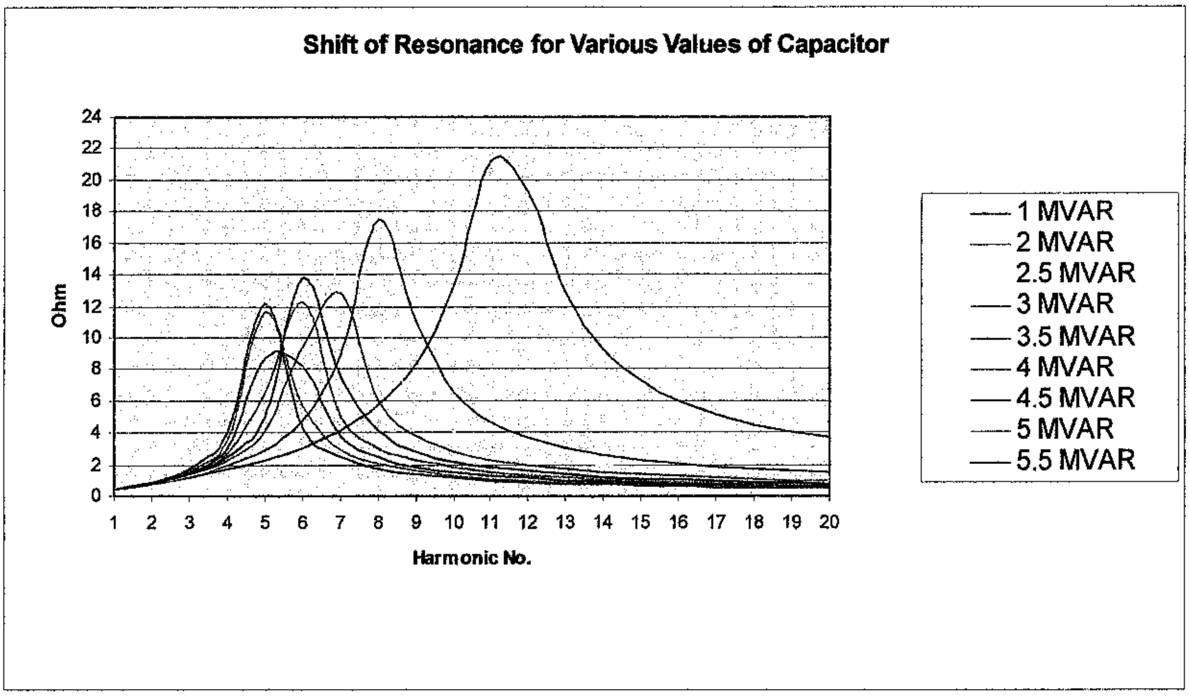


Figure 12: Harmonic Resonance shifting for capacitor installed at 3.3 kV busbar (see appendix 3)

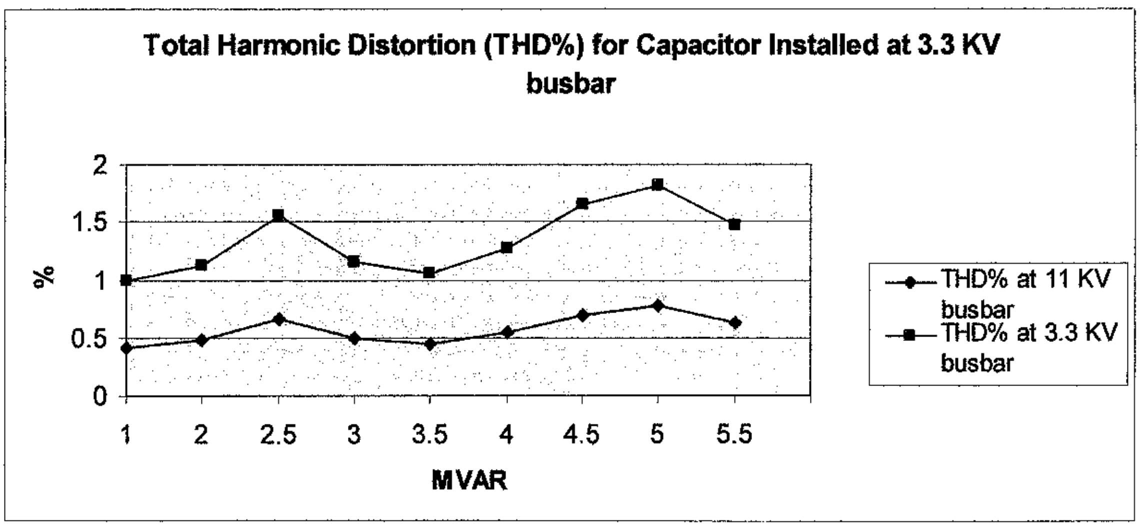


Figure 13: Total Harmonic Distortion for Capacitor Installed at 3.3 kV busbar

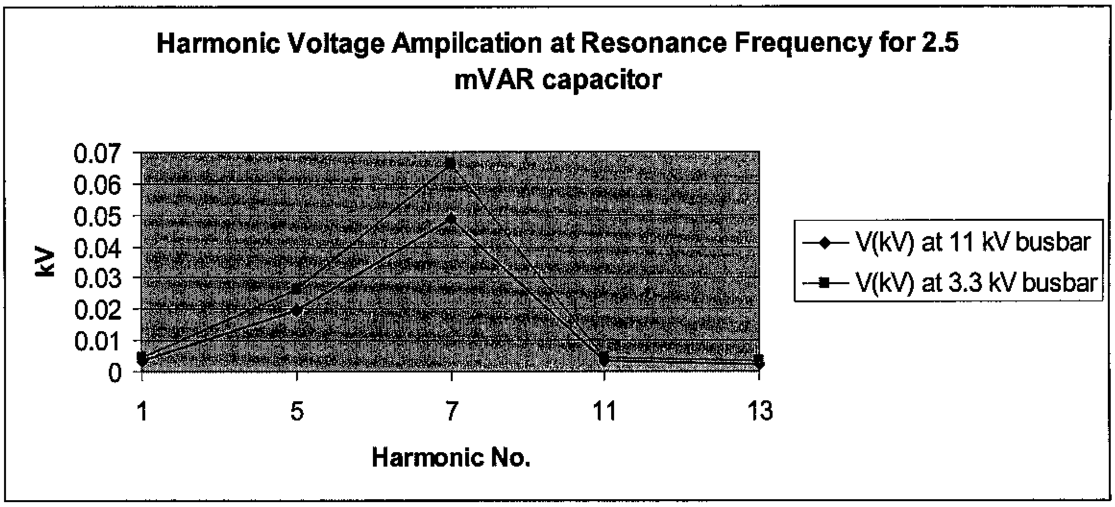


Figure 14: Harmonic Voltage Amplification at 7th Harmonic (see appendix 4)

For capacitor installed at 3.3 kV busbar, the same observation can be made as in when the capacitor is installed at 11 kV busbar. An increased capacitor size shift resonance to a lower value (*figure 12*). However at the same capacitor size, the harmonic resonance frequency is lower. This is because, the short circuit capacity at 3.3 kV busbar (134.42 MVA) obtained from the load flow study is less compared with 11 kV busbar (302.24 MVA). This agreed with $h_R = \sqrt{\frac{MVA_{SC}}{MVAR_{CAP}}}$ ---------------**Equation 4**

The decreased in short circuit capacity shift resonance to a lower value. The harmonic voltage distortion (THD %) is amplify at 7th harmonic for 2.5 MVAR capacitor size as shown in figure 11 and 12. It can be observed that at this 2.5 MVAR capacitor bank the harmonic voltage at bus bar 3 and bus bar 5 is amplified. This support that the harmonic distortion at this particular size of capacitor will contribute a higher harmonic distortion as the 7th harmonic resonance frequency coincide with the harmonic produce by the harmonic pollution load in the power system (6-pulse converter)

4.9 Effect of the Location of Capacitor Bank on Total Harmonic Distortion on Specific Bus Bar

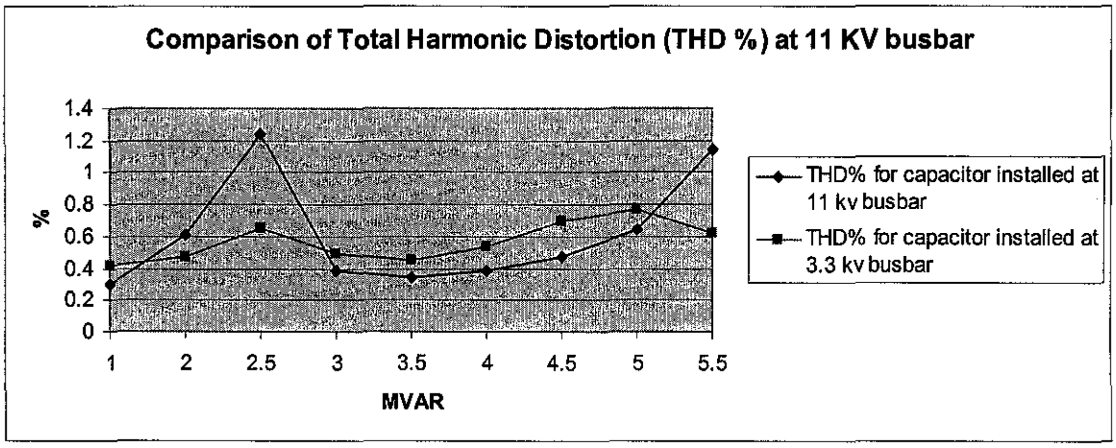


Figure 15: Comparison of Total Harmonic Distortion at 11 kV busbar for Different point of Capacitor Installation

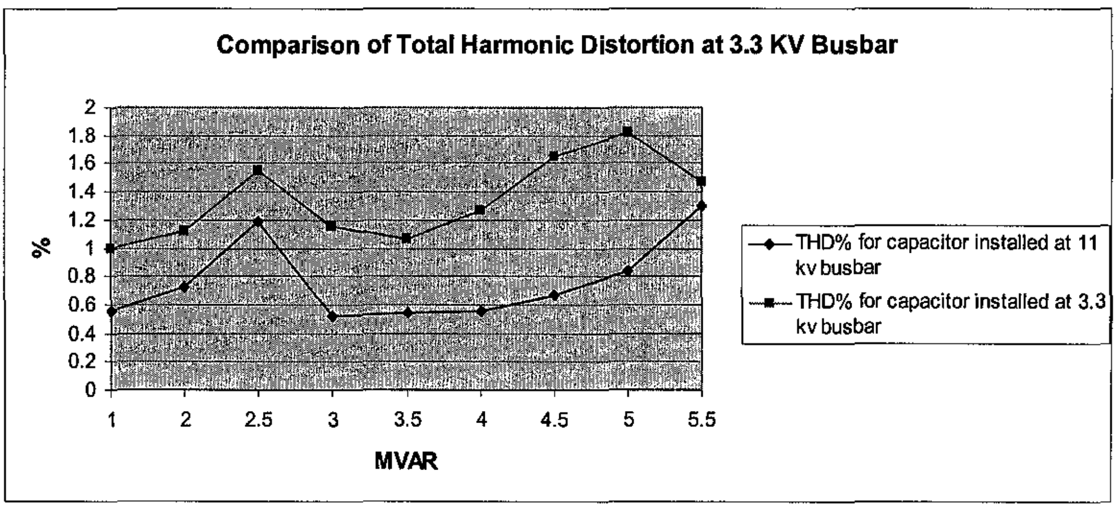


Figure 16: Comparison of Total Harmonic Distortion at 3.3 kV busbar for Different point of Capacitor Installation

From table 3 and 4, the power factor is improved to almost the same value regardless of where the capacitor is being installed. However, the total harmonic distortion produced when the capacitor is installed at 3.3 kV busbar is higher than the installation at 11 kV busbar. This variation is shown in figure 13 and 14. The THD% differences are higher for total harmonic distortion at 3.3 kV busbar. These are most likely because the harmonic load (6-pulse variable speed drive) is located at 3.3 kV busbar thus the capacitor is electrically near the harmonic source. The harmonic currents can become quite large at this point. This brings us to the conclusion that, installing the capacitor away from the harmonic source can reduced the harmonic distortion in the power system.

4.10 Effect of Harmonic Distortion on Power Factor

Power factor is always measured as the ratio between real power in kilowatts (kW) and apparent power in kilovolt amperes (kVA). For linear loads, the apparent power in kVA ($S = V \cdot I$) is the vector sum of the reactive power in kVAR (Q) and the real power in kW (P). The power factor is $P/S = \cos\Phi$, where Φ is the angle between S and P. This angle is the same as the displacement angle between the voltage and the current for linear loads. For a given amount of current, increasing the displacement angle will increase Q, decrease P, and lower the PF. Inductive loads such as induction motors cause their current to lag the voltage, capacitors cause their current to lead the voltage, and purely resistive loads draw their current in-phase with the voltage.

For circuits with strictly linear loads (a rare situation) simple capacitor banks may be added to the system to improve a lagging power factor due to induction motors or other lagging loads. For non-linear loads, the harmonic currents they draw produce no useful work and therefore are reactive in nature. The power vector relationship becomes 3 dimensional with distortion reactive power, H, combining with both Q and P to produce the apparent power which the power system must deliver. Power factor remains the ratio of kW to kVA but the kVA now has a harmonic component as well. (*refer to appendix 3*)

True power factor becomes the combination of displacement power factor and distortion power factor. For most typical non-linear loads, the displacement power factor will be near unity. True power factor however, is normally very low because of the distortion component. For example, the displacement power factor of a 6-Pulse VFD without a reactor will be near unity but its total power factor is often in the 0.65 – 0.7 range. The best way to improve a poor power factor caused by non-linear loads is to remove the harmonic currents.

Displacement factor (DF)

$$\cos \Phi = \frac{\text{REAL POWER (KWATTS)}}{\text{TOTAL POWER (KVA)}}$$ --Equation 2

True power factor (TPF)

$$pf_{true} \approx \frac{P_{avg1}}{V_{1rms} I_{1rms}} \bullet \frac{1}{\sqrt{1 + (THD_I / 100)^2}} = pf_{disp} \bullet pf_{dist}.$$

-----------------Equation 6

$$pf_{true} \leq pf_{dist} = \frac{1}{\sqrt{1 + (THD_I / 100)^2}}.$$ --Equation 7

$\therefore$

TPF ≤DF

4.10.1 Case Study 3: True Power Factor of Non-Linear Load

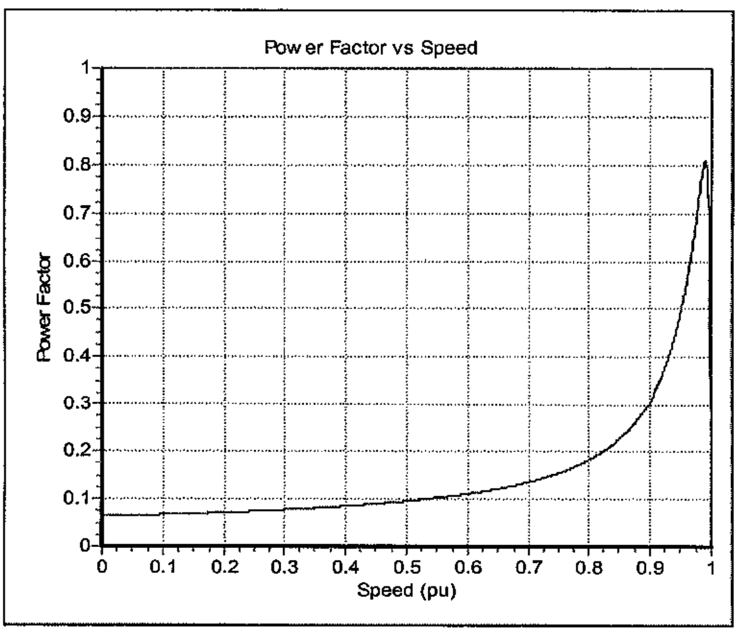


Figure 17: Power Factor VS Speed

Capacitor size MVAR	Total Harmonic Distortion (Current %)	Displacement Power Factor	True Power Factor
1	0.648	0.807	0.83
2	0.845	0.801	0.76
2.5	1.086	0.8	0.68
3	0.925	0.8	0.73
3.5	0.946	0.8	0.72
4	1.15	0.799	0.66
4.5	1.479	0.799	0.56
5	1.637	0.798	0.52
5.5	1.346	0.798	0.59

Table 5: Total Harmonic Distortion and True Power Factor of Induction Motor (M1)

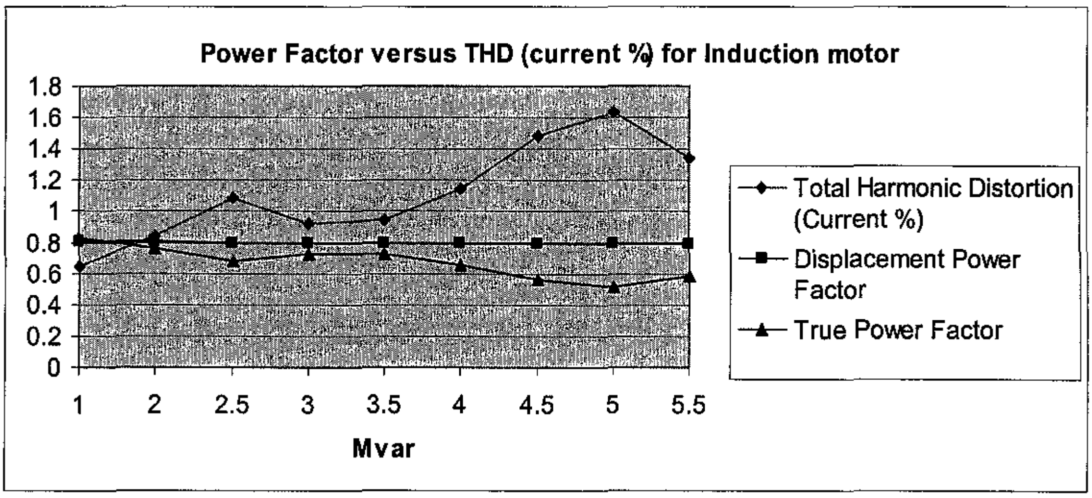


Figure 18: Power Factor VS THD (current %) for Induction Motor

Theoretically in the presence of high harmonic distortion, the true power factor is lower. From the simulation it can be observed that the higher the total harmonic distortion the lower the true power factor. It is important to point out that in general, that only displacement power can be improved with capacitor. For true power factor, the power factor is linearly affected by the content of total harmonic distortion. In these instances, the addition of shunt capacitor will likely worsen the power factor by including resonances and higher harmonic levels. A better solution is to add passive or active filters to remove the harmonics produced by the nonlinear loads, or to utilize low distortion power electronic loads.

Chapter 5
Conclusion and Recommendations

5.1 Well established concept of power factor does provide some measure of the relationship with harmonics. Studies on the theory have been carried out and with this clearer view on this Power factor improvement and it relationship with harmonic. As the use of power electronic devices grows, so will the need to understand the effect of harmonics. Studies on the theory have been carried out and with this clearer view on the power factor and harmonics problems is achieved. Good power factor is not necessary critical for most equipment to function in a normal manner. Operating in high power factor is important for the overall health of the power system.

Harmonics and power factor are closely related. The simulation of harmonic analysis is conducted and has successfully certified the relation between them. The presence of power factor correction capacitor in the system contributed to resonance phenomena. It is important to determine the suitable capacitor size to avoid resonance frequency that will coincide with the system frequency. From the modeling it can clearly be observed and realized how the resonance phenomena in the presence of capacitor bank gave impact on total harmonic distortion in a power system. If the power system contains distortion at resonance frequency, the entire system can oscillate resulting in large harmonic currents. The student is able to better understand the overall concept of harmonics and its effects on power system.

The harmonic analysis modeling enables the student to detect and investigate total harmonic distortion (THD) variations and resonance shifting in a power system. The resonance frequency is lowered as the size of the capacitor increased. Beside the harmonic distortion gave possible consequences in lowering the true power factor especially for non linear load. The addition of shunt capacitor will likely worsen the power factor by including resonances and higher harmonic levels. The results of the simulation is analyzed and organized in a simple way to gave further understanding and clear view of the theory.

5.2 Recommendations

Based on this project, harmonics and power factor are closely related. In fact they are tightly coupled that one can place limitations on the current harmonics produced by nonlinear load using the widely-accepted concept of power factor, providing that true power factor is used rather than displacement power factor. Efforts should be underway to develop new power factor definitions, such as harmonic adjusted power factor, that take into account the frequency dependent impact of voltage and current harmonics.

Apart from demonstrating the relation between power factor improvement and harmonics using the harmonic analysis modeling, one can do the field measurement especially in the industrial plant that harmonics are becoming a major issue nowadays. The results can be compared with the simulation values to identify other factor that might contribute in increasing total harmonic distortion.

Further study can be done to determine and design harmonic filtering requirement in reducing the harmonic distortion and eliminating the potential harmonic resonance that may coincide with any of the characteristic harmonic frequencies of the power system.

References

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Appendices

Appendix 1: Typical examples of harmonics generating equipment

Appendix 2: Influence of harmonics

Appendix 3: Power Triangle

Appendix 4Single Line Diagram

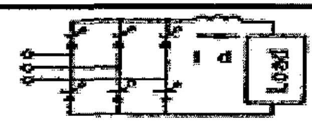
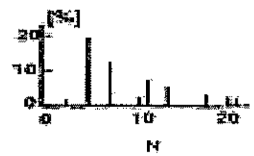
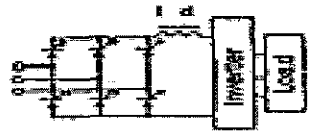
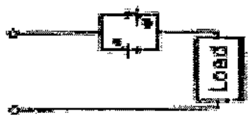
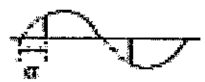
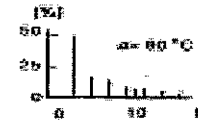
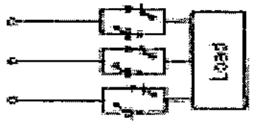
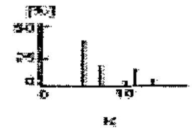
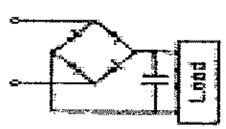
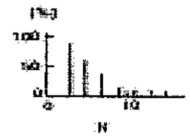
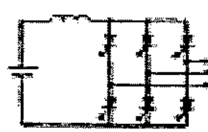
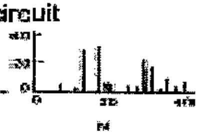
Appendix 5: Harmonic Impedance Result

Appendix 6: Harmonic Distortion Result

Appendix 7: Project's Gantt chart

Appendix 1: Typical examples of harmonics generating equipment

Appendix 1:Typical examples of harmonics generating equipment

	Source circuit types	Example input current waveforms on AC side	Example harmonic components of input current (100% for fundamental-wave component)	Typical example applications
3 Phase rectifier circuits	① 		Control delay angle 0° Commutation lap angle 20°C 	· Electrolysis rectifiers · Electric railroads · Chargers · General DC source
	② 			· AC speed control driving · CVCF unit · High-frequency heating unit
Power regulation circuits	③ 			· Dimmers · Temperature regulators for thermal equipment
	④ 			· AC speed control driving (primary voltage conlrol) · Heating controls for electric furnaces
Single-phase rectifier capacitors smoothing circuit	⑤ 			· TV receivers · Audio equipment · Personal computers · Electromagnetic cookers · Room air-conditioners
Inverter circuits	⑥  To AC systems	 Externally excited type  PWM type	Same as for 3-phase rectifier circuit Pulse frequency / fundamental frequency = 15% 	· AC interlinkages for solar power generation, fuel-cell power generation, etc.

Appendix 2: Influence of harmonics

Appendix 2: Influence of harmonics

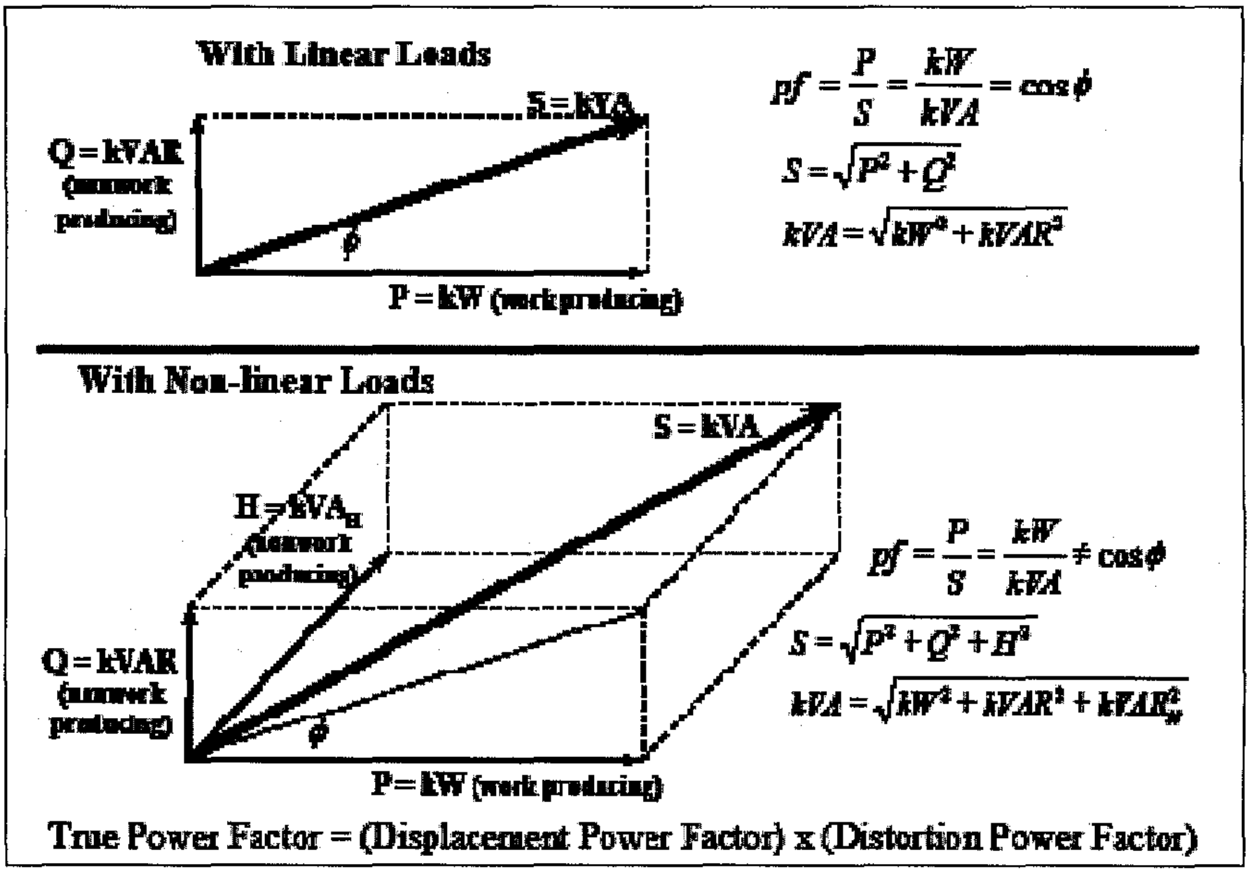
Equipment	Influence
Capacitors and reactors	Overheating, burnout, or generation of vibration and beat noise due to inflow of excessive current or reduction of circuit impedance against harmonic currents resulting from resonance phenomena
Neutral cables	Overheating of neutral lines in 3-phase-4-wire system due to flow of harmonic current
Rectifier controller	Faulty control due to phase shifting of control signals
Relays	Faulty operations due to excess of setting level or phase variation caused by harmonic current or voltage
MCCBs	Faulty operations due to excessive harmonic current
Generators	Overheating in coils and cores
Communication line	Generation of noise voltage due to electromagnetic induction

Equipment	Influence
Audio equipment and home appliances	Defects, influence on life and influence on performance of components such as diodes, transistors and capacitors, caused by harmonic current and voltage Noise and flickering of video image
Computer	Adverse influence on performance
Watt-hour meter	Measuring error due to non-linear characteristics of effective voltage and current flux Burnout of current coils due to inflow of excessive harmonic current
Power fuses	Blowing out due to excessive harmonic current
Transformer	Generation of beat noise due to core's magnetostriction phenomena caused by harmonic current Reduction of capacity due to increase of core and copper loss caused by harmonic voltage and current

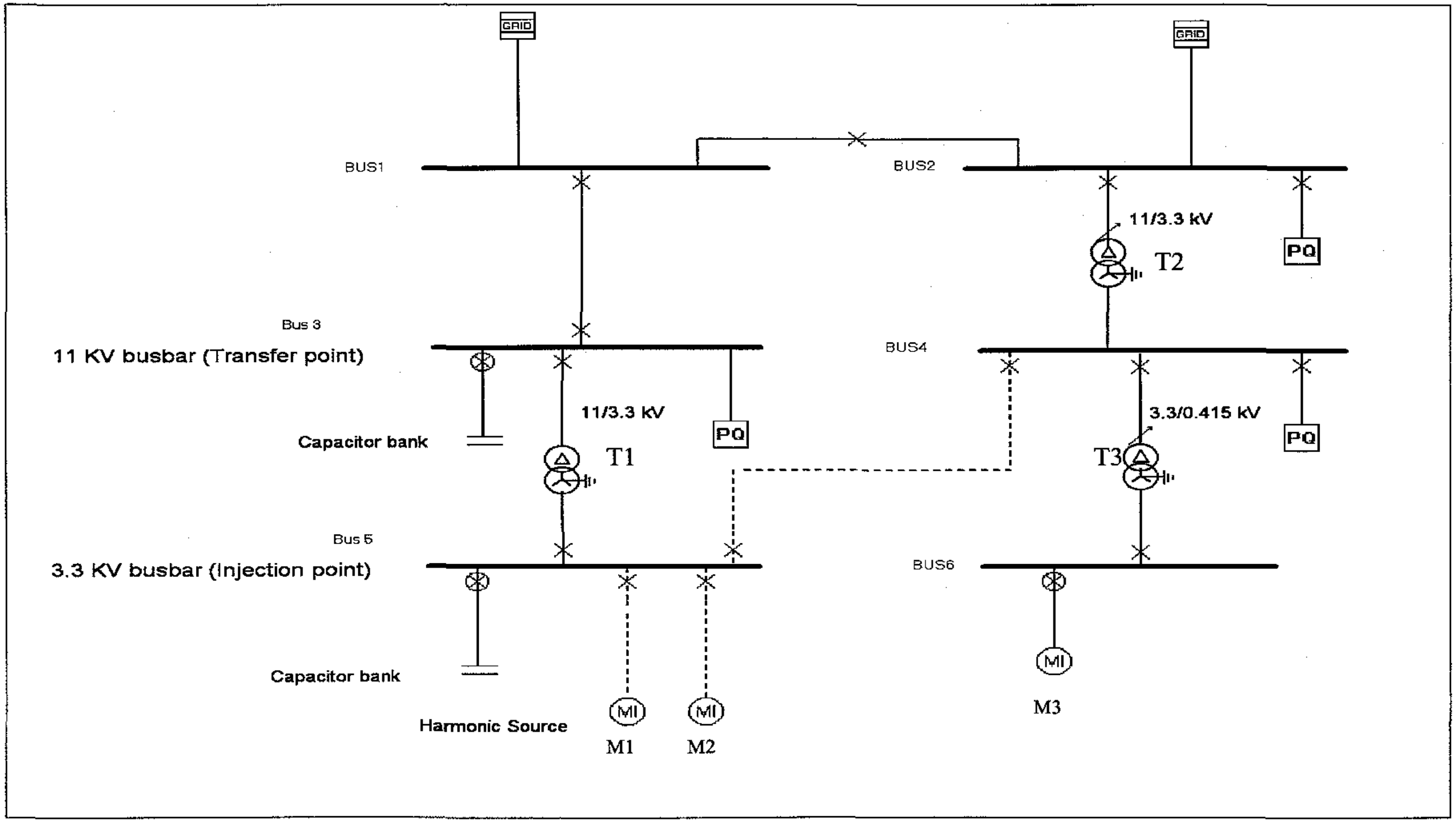
Appendix 3: Power Triangle

Appendices

Appendix 3: Power Triangle



Appendix 4: Single Line Diagram



Appendix 4: Single Line Diagram

Appendix 5: Harmonic Impedance Result

Appendix 5 (3.3 kV busbar)

2.5 MVAR

HARMONIC NO.	INJECTION BUSBAR BUS5 MAGNITUDE	ANG-DEG	TRANSFER BUSBARS BUS3 MAGNITUDE	ANG-DEG
1	0.084	82.598	0.38	84.121
2	0.176	82.429	0.798	86.926
3	0.292	81.153	1.327	87.298
4	0.462	78.807	2.095	86.185
5	0.754	74.348	3.42	82.747
6	1.412	63.547	6.403	72.831
7	3.284	20.875	14.903	30.947
8	2.319	-52.856	10.532	-42.071
9	1.274	-72.127	5.794	-60.69
10	0.879	-78.62	4.002	-66.582
11	0.678	-81.788	3.095	-69.193
12	0.557	-83.652	2.548	-70.54
13	0.476	-84.878	2.182	-71.284
14	0.417	-85.745	1.918	-71.7
15	0.372	-86.389	1.719	-71.924
16	0.337	-86.886	1.563	-72.03
17	0.308	-87.28	1.437	-72.061
18	0.284	-87.602	1.334	-72.043
19	0.264	-87.868	1.248	-71.996
20	0.247	-88.092	1.174	-71.931

3 MVAR

HARMONIC NO.	INJECTION BUSBAR BUS5 MAGNITUDE	ANG-DEG	TRANSFER BUSBARS BUS3 MAGNITUDE	ANG-DEG
1	0.084	82.573	0.381	84.1
2	0.179	82.305	0.81	86.807
3	0.304	80.782	1.38	86.933
4	0.503	77.777	2.28	85.161
5	0.902	71.143	4.088	79.549
6	2.088	48.716	9.463	58.007
7	2.816	-36.653	12.766	-26.573
8	1.322	-69.843	5.996	-59.05
9	0.845	-78.249	3.835	-66.804
10	0.629	-81.871	2.861	-69.823
11	0.506	-83.87	2.308	-71.265
12	0.427	-85.134	1.95	-72.011
13	0.371	-86.004	1.699	-72.398
14	0.329	-86.638	1.512	-72.582
15	0.296	-87.12	1.368	-72.644
16	0.27	-87.499	1.252	-72.631
17	0.248	-87.804	1.158	-72.571
18	0.23	-88.055	1.079	-72.483
19	0.215	-88.264	1.013	-72.379
20	0.201	-88.442	0.956	-72.267

3.5 MVAR

HARMONIC NO.	INJECTION BUSBAR BUS5 MAGNITUDE	ANG-DEG	TRANSFER BUSBARS BUS3 MAGNITUDE	ANG-DEG
1	0.084	82.516	0.382	84.061
2	0.181	82.154	0.821	86.671
3	0.317	80.361	1.435	86.526
4	0.551	76.533	2.496	83.931
5	1.113	66.415	5.038	74.833
6	3.04	15.483	13.764	24.787
7	1.66	-61.681	7.518	-51.588
8	0.904	-76.324	4.097	-65.517
9	0.629	-81.241	2.856	-69.781
10	0.489	-83.663	2.224	-71.601
11	0.404	-85.098	1.84	-72.478
12	0.346	-86.045	1.58	-72.906
13	0.304	-86.716	1.391	-73.094
14	0.272	-87.215	1.248	-73.142
15	0.246	-87.6	1.136	-73.106
16	0.225	-87.906	1.044	-73.02
17	0.208	-88.154	0.969	-72.903
18	0.194	-88.36	0.906	-72.769
19	0.181	-88.533	0.852	-72.628
20	0.17	-88.681	0.806	-72.485

4 MVAR

HARMONIC NO.	INJECTION BUSBAR BUS5 MAGNITUDE	ANG-DEG	TRANSFER BUSBARS BUS3 MAGNITUDE	ANG-DEG
1	0.085	82.49	0.382	84.04
2	0.184	82.022	0.833	86.544
3	0.331	79.923	1.497	86.093
4	0.61	75.035	2.762	82.44
5	1.437	58.842	6.501	67.268
6	2.716	-30.441	12.285	-21.129
7	1.114	-71.41	5.041	-61.308
8	0.683	-79.702	3.091	-68.886
9	0.501	-83.034	2.27	-71.565
10	0.4	-84.816	1.816	-72.744
11	0.336	-85.922	1.527	-73.291
12	0.291	-86.673	1.326	-73.523
13	0.257	-87.215	1.177	-73.582
14	0.231	-87.625	1.062	-73.54
15	0.211	-87.944	0.97	-73.439
16	0.193	-88.2	0.895	-73.302
17	0.179	-88.41	0.833	-73.145
18	0.167	-88.584	0.78	-72.979
19	0.156	-88.731	0.735	-72.812
20	0.147	-88.857	0.697	-72.647

4.5 MVAR

HARMONIC NO.	INJECTION BUSBAR BUS5 MAGNITUDE	ANG-DEG	TRANSFER BUSBARS BUS3 MAGNITUDE	ANG-DEG
1	0.085	82.433	0.383	84.001
2	0.187	81.861	0.845	86.399
3	0.345	79.425	1.562	85.61
4	0.682	73.173	3.082	80.591
5	1.934	45.68	8.74	54.119
6	1.791	-55.217	8.095	-45.891
7	0.831	-76.203	3.755	-66.088
8	0.548	-81.723	2.479	-70.893
9	0.416	-84.203	1.883	-72.719
10	0.338	-85.603	1.535	-73.516
11	0.287	-86.5	1.306	-73.854
12	0.251	-87.122	1.143	-73.957
13	0.223	-87.577	1.02	-73.928
14	0.201	-87.925	0.924	-73.824
15	0.184	-88.198	0.847	-73.675
16	0.169	-88.419	0.783	-73.503
17	0.157	-88.6	0.73	-73.317
18	0.147	-88.751	0.685	-73.128
19	0.138	-88.88	0.647	-72.941
20	0.13	-88.99	0.613	-72.759

2 MVAR

HARMONIC NO.	INJECTION BUSBAR BUS5 MAGNITUDE	ANG-DEG	TRANSFER BUSBARS BUS3 MAGNITUDE	ANG-DEG
1	0.084	82.655	0.38	84.159
2	0.173	82.573	0.787	87.054
3	0.282	81.514	1.28	87.645
4	0.427	79.694	1.939	87.059
5	0.648	76.651	2.939	85.036
6	1.043	70.863	4.732	80.133
7	1.951	56.409	8.86	66.467
8	3.841	4.629	17.455	15.4
9	2.422	-54.447	11.021	-43.025
10	1.438	-71.226	6.553	-59.203
11	1.022	-77.615	4.666	-65.035
12	0.8	-80.897	3.661	-67.801
13	0.662	-82.885	3.039	-69.306
14	0.568	-84.214	2.616	-70.187
15	0.499	-85.165	2.309	-70.718
16	0.447	-85.879	2.076	-71.041
17	0.405	-86.433	1.892	-71.232
18	0.371	-86.877	1.744	-71.337
19	0.343	-87.239	1.622	-71.387
20	0.32	-87.541	1.519	-71.4

1 MVAR

HARMONIC NO.	INJECTION BUSBAR BUS5 MAGNITUDE	ANG-DEG	TRANSFER BUSBARS BUS3 MAGNITUDE	ANG-DEG
1	0.083	82.706	0.378	84.201
2	0.168	82.802	0.766	87.273
3	0.262	82.128	1.192	88.248
4	0.37	81.094	1.685	88.447
5	0.502	79.708	2.284	88.08
6	0.672	77.833	3.056	87.089
7	0.905	75.166	4.119	85.208
8	1.254	71.055	5.712	81.809
9	1.836	63.923	8.372	75.327
10	2.928	49.205	13.368	61.209
11	4.631	14.217	21.19	26.776
12	4.196	-34.149	19.247	-21.073
13	2.789	-58.645	12.832	-45.089
14	2.001	-69.254	9.241	-55.249
15	1.558	-74.795	7.224	-60.372
16	1.281	-78.144	5.966	-63.331
17	1.093	-80.375	5.113	-65.2
18	0.956	-81.966	4.498	-66.454
19	0.852	-83.156	4.034	-67.332
20	0.771	-84.08	3.673	-67.969

Appendix 5 (11 kV bus bar)

2.5 MVAR

HARMONIC NO.	INJECTION BUSBAR BUS5 MAGNITUDE	ANG-DEG	TRANSFER BUSBARS BUS3 MAGNITUDE	ANG-DEG
1	0.083	82.747	0.377	84.217
2	0.165	83.033	0.765	87.386
3	0.251	82.785	1.196	88.606
4	0.344	82.503	1.7	89.257
5	0.448	82.332	2.328	89.643
6	0.57	82.352	3.164	89.859
7	0.723	82.641	4.378	89.923
8	0.942	83.29	6.372	89.783
9	1.331	84.361	10.389	89.211
10	2.461	85.152	23.158	86.895
11	14.45	-47.535	174.606	-51.79
12	1.227	-67.148	20.734	-84.189
13	0.47	-38.902	11.299	-85.901
14	0.36	6.168	7.917	-86.436
15	0.441	32.418	6.169	-86.662
16	0.547	43.737	5.095	-86.763
17	0.648	49.304	4.365	-86.804
18	0.742	52.404	3.835	-86.812
19	0.83	54.268	3.431	-86.802
20	0.914	55.44	3.111	-86.78

3 MVAR

1	0.083	82.745	0.377	84.212
2	0.165	83.036	0.769	87.366
3	0.253	82.809	1.213	88.57
4	0.349	82.574	1.75	89.199
5	0.458	82.484	2.449	89.549
6	0.593	82.639	3.445	89.704
7	0.779	83.141	5.047	89.643
8	1.094	84.081	8.184	89.184
9	1.933	85.025	17.515	87.286
10	21.228	-4.279	250.125	-7.791
11	1.114	-67.508	18.913	-84.115
12	0.396	-35.789	9.926	-86
13	0.326	13.303	6.874	-86.553
14	0.42	37.566	5.328	-86.776
15	0.525	47.344	4.388	-86.871
16	0.623	52.053	3.753	-86.906
17	0.713	54.635	3.293	-86.908
18	0.798	56.158	2.943	-86.892
19	0.879	57.087	2.667	-86.865
20	0.957	57.654	2.444	-86.831

3.5 MVAR

HARMONIC NO.	INJECTION BUSBAR BUS5 MAGNITUDE	ANG-DEG	TRANSFER BUSBARS BUS3 MAGNITUDE	ANG-DEG
1	0.083	82.743	0.377	84.207
2	0.166	83.038	0.773	87.347
3	0.254	82.834	1.23	88.533
4	0.353	82.646	1.802	89.137
5	0.47	82.641	2.584	89.445
6	0.621	82.938	3.781	89.518
7	0.855	83.657	5.957	89.263
8	1.368	84.724	11.433	88.11
9	5.084	78.405	54.722	77.095
10	1.451	-70.631	22.445	-82.801
11	0.406	-43.67	9.906	-85.854
12	0.289	10.625	6.523	-86.57
13	0.381	38.496	4.939	-86.838
14	0.486	48.794	4.014	-86.948
15	0.583	53.493	3.405	-86.987
16	0.672	55.976	2.97	-86.99
17	0.755	57.394	2.643	-86.971
18	0.834	58.23	2.388	-86.942
19	0.911	58.715	2.182	-86.905
20	0.986	58.978	2.012	-86.864

4MVAR

HARMONIC NO.	INJECTION BUSBAR BUS5 MAGNITUDE	ANG-DEG	TRANSFER BUSBARS BUS3 MAGNITUDE	ANG-DEG
1	0.083	82.741	0.377	84.202
2	0.166	83.041	0.777	87.327
3	0.256	82.858	1.249	88.495
4	0.358	82.718	1.858	89.071
5	0.482	82.801	2.734	89.329
6	0.656	83.246	4.189	89.293
7	0.966	84.15	7.267	88.715
8	2.003	84.408	18.934	85.623
9	3.44	-69.193	45.272	-75.692
10	0.535	-57.425	11.343	-85.312
11	0.258	-2.909	6.709	-86.47
12	0.33	35.759	4.858	-86.848
13	0.437	48.696	3.855	-86.997
14	0.534	54.074	3.221	-87.052
15	0.623	56.761	2.781	-87.061
16	0.705	58.236	2.457	-87.044
17	0.784	59.073	2.208	-87.014
18	0.86	59.539	2.009	-86.975
19	0.934	59.775	1.846	-86.932
20	1.007	59.858	1.71	-86.887

4.5 MVAR	INJECTION BUSBAR		TRANSFER BUSBARS	
	BUS5		BUS3	
HARMONIC NO.	MAGNITUDE	ANG-DEG	MAGNITUDE	ANG-DEG
1	0.083	82.74	0.377	84.197
2	0.166	83.043	0.781	87.307
3	0.258	82.883	1.267	88.456
4	0.363	82.791	1.917	89.001
5	0.496	82.964	2.902	89.199
6	0.698	83.554	4.695	89.013
7	1.139	84.517	9.314	87.858
8	4.943	75.479	53.664	73.874
9	0.984	-69.021	16.392	-83.566
10	0.277	-29.651	7.586	-86.16
11	0.272	27.184	5.071	-86.786
12	0.378	46.804	3.87	-87.014
13	0.479	53.85	3.16	-87.1
14	0.569	57.088	2.689	-87.122
15	0.651	58.776	2.351	-87.111
16	0.73	59.7	2.096	-87.083
17	0.805	60.199	1.896	-87.044
18	0.879	60.441	1.734	-87
19	0.951	60.518	1.6	-86.953
20	1.022	60.486	1.487	-86.904

2 MVAR

	INJECTION BUSBAR		TRANSFER BUSBARS	
	BUS5		BUS3	
HARMONIC NO.	MAGNITUDE	ANG-DEG	MAGNITUDE	ANG-DEG
1	0.083	82.749	0.377	84.222
2	0.165	83.03	0.761	87.405
3	0.25	82.76	1.179	88.641
4	0.341	82.434	1.654	89.312
5	0.439	82.185	2.219	89.728
6	0.55	82.079	2.925	89.99
7	0.68	82.171	3.866	90.137
8	0.845	82.524	5.217	90.164
9	1.078	83.217	7.382	90.022
10	1.478	84.31	11.523	89.527
11	2.492	85.41	22.923	87.814
12	16.563	61.521	188.763	58.876
13	2.103	-70.552	31.662	-82.897
14	0.738	-52.677	15.404	-85.455
15	0.433	-15.602	10.384	-86.165
16	0.446	18.327	7.933	-86.46
17	0.543	35.362	6.474	-86.599
18	0.648	43.702	5.502	-86.664
19	0.748	48.274	4.805	-86.689
20	0.842	51.016	4.28	-86.691

1MVAR

	INJECTION BUSBAR		TRANSFER BUSBARS	
	BUS5		BUS3	
HARMONIC NO.	MAGNITUDE	ANG-DEG	MAGNITUDE	ANG-DEG
1	0.083	82.752	0.376	84.232
2	0.164	83.024	0.753	87.443
3	0.247	82.711	1.147	88.707
4	0.333	82.298	1.568	89.414
5	0.423	81.904	2.027	89.875
6	0.518	81.575	2.542	90.202
7	0.619	81.334	3.132	90.443
8	0.729	81.202	3.828	90.623
9	0.852	81.199	4.675	90.752
10	0.994	81.349	5.743	90.832
11	1.165	81.686	7.153	90.857
12	1.382	82.251	9.126	90.811
13	1.685	83.097	12.117	90.65
14	2.168	84.264	17.251	90.264
15	3.147	85.629	28.243	89.284
16	6.645	85.233	68.916	85.324
17	14.745	-63.777	181.879	-69.248
18	2.781	-68.894	42.043	-83.401
19	1.292	-55.473	24.2	-85.093
20	0.8	-32.506	17.219	-85.705

Appendix 6: Harmonic Distortion Result

Appendix 6

ERACS Injection module By ERA Technology Ltd. ERACS Version: 3.2.2. Injection Version: 3.2.0
Run on 20-Sep-2004 by Supervisor from data set up on 20-Sep-2004 by Supervisor
Network Name: case study1
Data State Name: Loadflow (Harmonic Distortion at 11 kV busbar)
Study Name: 1

RESULTS FOR HARMONIC NUMBER 1.000

INJECTION CURRENTS

Inj ID	Bus ID	I (pu)	I (A)	I (deg)
Motor1	BUS5	0.0012	21	28.7166

BUSBAR VOLTAGES

Bus ID	V (kV)	V (V)	V (pu)	V (%)	V (deg)
BUS1	0.0043	4.2613	0.0004	0.0387	83.927
BUS2	0.0043	4.2613	0.0004	0.0387	83.927
BUS3	0.0044	4.4454	0.0004	0.0404	82.5239
BUS4	0.0027	2.6651	0.0008	0.0808	124.8363
BUS5	0.0033	3.2516	0.001	0.0985	111.0535
BUS6	0.0003	0.3371	0.0008	0.0812	154.8363

LINE CURRENTS

Line ID	Bus ID	I (pu)	I (A)	I (deg)	Bus ID	I (pu)
1	BUS1	0.0011	5.6317	176.8413	BUS3	0.0011

CABLE CURRENTS

Cable ID	Bus ID	I (pu)	I (A)	I (deg)	Bus ID	I (pu)
cable1	BUS4	0.0001	1.5566	30	BUS5	0.0001

TRANSFORMER CURRENTS

Tx ID	Bus ID	Wnd No	I (pu)	I (A)	I (deg)
Trf1	BUS2	1	0.0001	0.4257	0
Trf1	BUS4	2	0.0001	1.3913	30
Trf2	BUS3	1	0.0011	5.6102	177.0754
Trf2	BUS5	2	0.001	17.8877	27.0754
Trf3	BUS4	1	0	0	30
Trf3	BUS6	2	0	0	60

INDUCTION MACHINE CURRENTS

IM ID	Bus ID	I (pu)	I (A)	I (deg)
Motor2	BUS6	Disconnected.		
Motor2	BUS5	0.0001	1.725	30

SYNCHRONOUS MACHINE CURRENTS

SM ID	Bus ID	I (pu)	I (A)	I (deg)
	BUS1	0.0006	2.9958	178.3056
	BUS2	0.0006	2.9958	178.3056

SHUNT CURRENTS

Shunt ID	Bus ID	I (pu)	I (A)	I (deg)
Shunt1	BUS2	0	0.0367	27.6171
Shunt2	BUS4	0	0.1914	112.8491
	BUS3	0	0.0383	26.2139
	BUS5	Disconnected.		
	BUS3	0	0.053	172.5239

RESULTS FOR HARMONIC NUMBER 5.000

INJECTION CURRENTS

Inj ID	Bus ID	I (pu)	I (A)	I (deg)
Motor1	BUS5	0.0007	13	23.5832

BUSBAR VOLTAGES

Bus ID	V (kV)	V (V)	V (pu)	V (%)	V (deg)
BUS1	0.0164	16.4413	0.0015	0.1495	142.8815
BUS2	0.0164	16.4413	0.0015	0.1495	142.8815
BUS3	0.0171	17.1263	0.0016	0.1557	142.5818
BUS4	0.0101	10.0812	0.0031	0.3055	108.4453
BUS5	0.011	10.9897	0.0033	0.333	105.2715
BUS6	0.0013	1.275	0.0031	0.3072	78.4453

LINE CURRENTS

Line ID	Bus ID	I (pu)	I (A)	I (deg)	Bus ID	I (pu)
1	BUS1	0.0008	4.3687	0	BUS3	0.0008

CABLE CURRENTS

Cable ID	Bus ID	I (pu)	I (A)	I (deg)	Bus ID	I (pu)
cable1	BUS4	0.0001	1.1966	30	BUS5	0.0001

TRANSFORMER CURRENTS

Tx ID	Bus ID	Wnd No	I (pu)	I (A)	I (deg)
Trf1	BUS2	1	0.0001	0.3016	0

Trf1	BUS4	2	0.0001	0.9857	30
Trf2	BUS3	1	0.0006	3.3424	0
Trf2	BUS5	2	0.0006	10.6569	30
Trf3	BUS4	1	0	0	30
Trf3	BUS6	2	0	0	60

INDUCTION MACHINE CURRENTS

IM ID	Bus ID	I (pu)	I (A)	I (deg)
Motor2	BUS6	Disconnected.		
Motor2	BUS5	0.0001	1.1669	30

SYNCHRONOUS MACHINE CURRENTS

SM ID	Bus ID	I (pu)	I (A)	I (deg)
	BUS1	0.0004	2.3182	-126.241
	BUS2	0.0004	2.3182	-126.241

SHUNT CURRENTS

Shunt ID	Bus ID	I (pu)	I (A)	I (deg)
Shunt1	BUS2	0	0.0337	60.4762
Shunt2	BUS4	0	0.2113	-119.026
	BUS3	0	0.0352	60.1764
	BUS5	Disconnected.		
	BUS3	0.0002	1.0215	-127.418

RESULTS FOR HARMONIC NUMBER 7.000

INJECTION CURRENTS

Inj ID	Bus ID	I (pu)	I (A)	I (deg)
Motor1	BUS5	0.0005	8	133.0165

BUSBAR VOLTAGES

Bus ID	V (kV)	V (V)	V (pu)	V (%)	V (deg)
BUS1	0.0193	19.2776	0.0018	0.1753	-167.565
BUS2	0.0193	19.2776	0.0018	0.1753	-167.565
BUS3	0.0201	20.0912	0.0018	0.1826	-167.794
BUS4	0.0103	10.2859	0.0031	0.3117	-143.001
BUS5	0.0111	11.0581	0.0034	0.3351	-145.076
BUS6	0.0013	1.3009	0.0031	0.3135	-113.001

LINE CURRENTS

Line ID	Bus ID	I (pu)	I (A)	I (deg)	Bus ID	I (pu)

1	BUS1	0.0007	3.7247	0	BUS3	0.0007

CABLE CURRENTS

Cable ID	Bus ID	I (pu)	I (A)	I (deg)	Bus ID	I (pu)
cable1	BUS4	0	0.7666	30	BUS5	0

TRANSFORMER CURRENTS

Tx ID	Bus ID	Wnd No	I (pu)	I (A)	I (deg)
Trf1	BUS2	1	0	0.1869	0
Trf1	BUS4	2	0	0.6108	30
Trf2	BUS3	1	0.0004	2.0112	0
Trf2	BUS5	2	0.0004	6.4125	30
Trf3	BUS4	1	0	0	30
Trf3	BUS6	2	0	0	60

INDUCTION MACHINE CURRENTS

IM ID	Bus ID	I (pu)	I (A)	I (deg)
Motor2	BUS6	Disconnected.		
Motor2	BUS5	0	0.8387	30

SYNCHRONOUS MACHINE CURRENTS

SM ID	Bus ID	I (pu)	I (A)	I (deg)
	BUS1	0.0004	1.9417	-76.9381
	BUS2	0.0004	1.9417	-76.9381

SHUNT CURRENTS

Shunt ID	Bus ID	I (pu)	I (A)	I (deg)
Shunt1	BUS2	0	0.0283	107.8755
Shunt2	BUS4	0	0.1558	-13.9817
	BUS3	0	0.0296	107.6466
	BUS5	Disconnected.		
	BUS3	0.0003	1.6776	-77.7938

RESULTS FOR HARMONIC NUMBER 11.000

INJECTION CURRENTS

Inj ID	Bus ID	I (pu)	I (A)	I (deg)
Motor1	BUS5	0.0002	3	175.8831

BUSBAR VOLTAGES

Bus ID	V (kV)	V (V)	V (pu)	V (%)	V (deg)
BUS1	0.1267	126.6958	0.0115	1.1518	130.8096
BUS2	0.1267	126.6958	0.0115	1.1518	130.8096
BUS3	0.1323	132.27	0.012	1.2025	130.6309
BUS4	0.0363	36.2674	0.011	1.099	104.5566
BUS5	0.1323	36.4884	0.0111	1.1057	104.8861
BUS6	0.0046	4.5867	0.0111	1.1052	74.5566

LINE CURRENTS

Line ID	Bus ID	I (pu)	I (A)	I (deg)	Bus ID	I (pu)
1	BUS1	0.0031	16.444	-138.903	BUS3	0.003

CABLE CURRENTS

Cable ID	Bus ID	I (pu)	I (A)	I (deg)	Bus ID	I (pu)
cable1	BUS4	0	0.1959	30	BUS5	0

TRANSFORMER CURRENTS

Tx ID	Bus ID	Wnd No	I (pu)	I (A)	I (deg)
Trf1	BUS2	1	0	0.0919	0
Trf1	BUS4	2	0	0.3003	30
Trf2	BUS3	1	0.0003	1.4747	0
Trf2	BUS5	2	0.0003	4.7019	30
Trf3	BUS4	1	0	0	30
Trf3	BUS6	2	0	0	60

INDUCTION MACHINE CURRENTS

IM ID	Bus ID	I (pu)	I (A)	I (deg)
Motor2	BUS6	Disconnected.		
Motor2	BUS5	0.0001	1.7611	30

SYNCHRONOUS MACHINE CURRENTS

SM ID	Bus ID	I (pu)	I (A)	I (deg)
	BUS1	0.0015	8.1209	-138.792
	BUS2	0.0015	8.1209	-138.792

SHUNT CURRENTS

Shunt ID	Bus ID	I (pu)	I (A)	I (deg)
Shunt1	BUS2	0	0.1189	44.2779

Shunt2	BUS4	0	0.3522	50.3245
	BUS3	0	0.1243	44.0991
	BUS5	Disconnected.		
	BUS3	0.0033	17.3559	-139.369

RESULTS FOR HARMONIC NUMBER 13.000

INJECTION CURRENTS

Inj ID	Bus ID	I (pu)	I (A)	I (deg)
Motor1	BUS5	0.0002	3	-26.6836

BUSBAR VOLTAGES

Bus ID	V (kV)	V (V)	V (pu)	V (%)	V (deg)
BUS1	0.0165	16.5028	0.0015	0.15	-143.869
BUS2	0.0165	16.5028	0.0015	0.15	-143.869
BUS3	0.0172	17.2493	0.0016	0.1568	-144.042
BUS4	0.0025	2.4956	0.0008	0.0756	-77.069
BUS5	0.0024	2.3931	0.0007	0.0725	-67.0424
BUS6	0.0003	0.3156	0.0008	0.0761	-47.069

LINE CURRENTS

Line ID	Bus ID	I (pu)	I (A)	I (deg)	Bus ID	I (pu)
1	BUS1	0.0004	1.8775	0	BUS3	0.0003

CABLE CURRENTS

Cable ID	Bus ID	I (pu)	I (A)	I (deg)	Bus ID	I (pu)
cable1	BUS4	0	0.2312	30	BUS5	0

TRANSFORMER CURRENTS

Tx ID	Bus ID	Wnd No	I (pu)	I (A)	I (deg)
Trf1	BUS2	1	0	0.0748	0
Trf1	BUS4	2	0	0.2444	30
Trf2	BUS3	1	0.0002	0.8884	0
Trf2	BUS5	2	0.0002	2.8327	30
Trf3	BUS4	1	0	0	30
Trf3	BUS6	2	0	0	60

INDUCTION MACHINE CURRENTS

IM ID	Bus ID	I (pu)	I (A)	I (deg)
Motor2	BUS6	Disconnected.		
Motor2	BUS5	0	0.0977	30

SYNCHRONOUS MACHINE CURRENTS

SM ID	Bus ID	I (pu)	I (A)	I (deg)
	BUS1	0.0002	0.8951	-53.5315
	BUS2	0.0002	0.8951	-53.5315

SHUNT CURRENTS

Shunt ID	Bus ID	I (pu)	I (A)	I (deg)
Shunt1	BUS2	0	0.0131	129.0667
Shunt2	BUS4	0	0.0205	-132.184
	BUS3	0	0.0137	128.8941
	BUS5	Disconnected.		
	BUS3	0.0005	2.6749	-54.0416

DISTORTION RESULTS

BUSBAR VOLTAGES

Bus ID	Distortion (%)	TFF
BUS1	1.18476	15.74167
BUS2	1.18476	15.74167
BUS3	1.23809	16.44915
BUS4	1.19187	14.8745
BUS5	1.18356	14.60244
BUS6	1.19187	14.8745

LINE CURRENTS

Line ID	Bus ID	Distortion (%)	TFF	Bus ID	Distortion (%)	TFF
1	BUS1	5.27231	64.02401	BUS3	5.05694	60.9674

CABLE CURRENTS

Cable ID	Bus ID	Distortion (%)	TFF	Bus ID	Distortion (%)	TFF
cable1	BUS4	1.42548	4.4052	BUS5	1.42222	4.3746

TRANSFORMER CURRENTS

Tx ID	Bus ID	Wnd No	Distortion (%)	TFF
Trf1	BUS2	1	2.07128	7.97053
Trf1	BUS4	2	2.07129	7.97056

Trf2	BUS3	1	2.11266	8.65526
Trf2	BUS5	2	2.11266	8.65528
Trf3	BUS4	1	0	0
Trf3	BUS6	2	0	0

INDUCTION MACHINE CURRENTS

IM ID	Bus ID	Distortion (%)
Motor2	BUS6	Disconnected.
Motor2	BUS5	0.66847

SYNCHRONOUS MACHINE CURRENTS

SM ID	Bus ID	Distortion (%)
	BUS1	4.02451
	BUS2	4.02451

SHUNT CURRENTS

Shunt ID	Bus ID	Distortion (%)
Shunt1	BUS2	0.14013
Shunt2	BUS4	0.20307
	BUS3	0.14641
	BUS5	Disconnected.
	BUS3	13.48051

Appendix 6

ERACS Injection module By ERA Technology Ltd. ERACS Version: 3.2.2. Injection Version: 3.2.0
Run on 18-Sep-2004 by Supervisor from data set up on 18-Sep-2004 by Supervisor
Network Name: case study
Data State Name: Loadflow (Harmonic Distortion at 3.3 kV busbar)
Study Name: 1

RESULTS FOR HARMONIC NUMBER 1.000

INJECTION CURRENTS

Inj ID	Bus ID	I (pu)	I (A)	I (deg)
Motor1	BUS5	0.0012	21	28.5969

BUSBAR VOLTAGES

Bus ID	V (kV)	V (V)	V (pu)	V (%)	V (deg)
BUS1	0.0043	4.3071	0.0004	0.0392	83.6937
BUS2	0.0043	4.3071	0.0004	0.0392	83.6937
BUS3	0.0045	4.4931	0.0004	0.0408	82.2891
BUS4	0.0027	2.6981	0.0008	0.0818	124.8221
BUS5	0.0033	3.304	0.001	0.1001	110.7665
BUS6	0.0003	0.3372	0.0008	0.0812	154.8221

LINE CURRENTS

Line ID	Bus ID	I (pu)	I (A)	I (deg)	Bus ID	I (pu)	I (A)
1	BUS1	0.0011	5.6916	176.568	BUS3	0.0011	5.6895

CABLE CURRENTS

Cable ID	Bus ID	I (pu)	I (A)	I (deg)	Bus ID	I (pu)	I (A)
cable1	BUS4	0.0001	1.6091	30	BUS5	0.0001	1.6088

TRANSFORMER CURRENTS

Tx ID	Bus ID	Wnd No	I (pu)	I (A)	I (deg)
Trf1	BUS2	1	0.0001	0.4365	0
Trf1	BUS4	2	0.0001	1.4438	30
Trf2	BUS3	1	0.0011	5.7233	176.7597
Trf2	BUS5	2	0.001	18.2482	26.7597
Trf3	BUS4	1	0	0	30
Trf3	BUS6	2	0	0	60

INDUCTION MACHINE CURRENTS

IM ID	Bus ID	I (pu)	I (A)	I (deg)
Motor2	BUS6	Disconnected.		
Motor2	BUS5	0.0001	1.7527	30

SYNCHRONOUS MACHINE CURRENTS

SM ID	Bus ID	I (pu)	I (A)	I (deg)
	BUS1	0.0006	3.0303	178.0668
	BUS2	0.0006	3.0303	178.0668

SHUNT CURRENTS

Shunt ID	Bus ID	I (pu)	I (A)	I (deg)
Shunt1	BUS2	0	0.037	27.3838
Shunt2	BUS4	0	0.1916	112.8349
	BUS3	0	0.0387	25.9791
	BUS5	0	0.4379	-129.234
	BUS3	Disconnected.		

RESULTS FOR HARMONIC NUMBER 5.000

INJECTION CURRENTS

Inj ID	Bus ID	I (pu)	I (A)	I (deg)
Motor1	BUS5	0.0007	13	22.9843

BUSBAR VOLTAGES

Bus ID	V (kV)	V (V)	V (pu)	V (%)	V (deg)
BUS1	0.0256	25.5978	0.0023	0.2327	133.6264
BUS2	0.0256	25.5978	0.0023	0.2327	133.6264
BUS3	0.0266	26.6447	0.0024	0.2422	133.331
BUS4	0.0178	17.7866	0.0054	0.539	98.4119
BUS5	0.0196	19.5808	0.0059	0.5934	94.9323
BUS6	0.0022	2.2227	0.0054	0.5356	68.4119

LINE CURRENTS

Line ID	Bus ID	I (pu)	I (A)	I (deg)	Bus ID	I (pu)	I (A)
1	BUS1	0.0013	6.6771	-135.671	BUS3	0.0013	6.6148

CABLE CURRENTS

Cable ID	Bus ID	I (pu)	I (A)	I (deg)	Bus ID	I (pu)	I (A)

cable1	BUS4	0.0001	2.3517	30	BUS5	0.0001	2.3404

TRANSFORMER CURRENTS

Tx ID	Bus ID	Wnd No	I (pu)	I (A)	I (deg)
Trf1	BUS2	1	0.0001	0.5997	0
Trf1	BUS4	2	0.0001	1.9838	30
Trf2	BUS3	1	0.0013	6.6692	-135.609
Trf2	BUS5	2	0.0012	21.264	14.3908
Trf3	BUS4	1	0	0	30
Trf3	BUS6	2	0	0	60

INDUCTION MACHINE CURRENTS

IM ID	Bus ID	I (pu)	I (A)	I (deg)
Motor2	BUS6	Disconnected.		
Motor2	BUS5	0.0001	2.079	30

SYNCHRONOUS MACHINE CURRENTS

SM ID	Bus ID	I (pu)	I (A)	I (deg)
	BUS1	0.0007	3.612	-135.497
	BUS2	0.0007	3.612	-135.497

SHUNT CURRENTS

Shunt ID	Bus ID	I (pu)	I (A)	I (deg)
Shunt1	BUS2	0	0.0525	51.2211
Shunt2	BUS4	0	0.3686	-129.059
	BUS3	0	0.0547	50.9256
	BUS5	0.0007	12.9764	34.9323
	BUS3	Disconnected.		

RESULTS FOR HARMONIC NUMBER 7.000

INJECTION CURRENTS

Inj ID	Bus ID	I (pu)	I (A)	I (deg)
Motor1	BUS5	0.0005	8	132.1781

BUSBAR VOLTAGES

Bus ID	V (kV)	V (V)	V (pu)	V (%)	V (deg)
BUS1	0.0637	63.6846	0.0058	0.579	107.8608
BUS2	0.0637	63.6846	0.0058	0.579	107.8608
BUS3	0.0663	66.2751	0.006	0.6025	107.6411
BUS4	0.0444	44.4034	0.0135	1.3456	130.0651
BUS5	0.0487	48.6874	0.0148	1.4754	127.5697

BUS6	0.0055	5.5488	0.0134	1.3371	160.0651

LINE CURRENTS

Line ID	Bus ID	I (pu)	I (A)	I (deg)	Bus ID	I (pu)	I (A)
1	BUS1	0.0023	11.8625	-161.521	BUS3	0.0022	11.6455

CABLE CURRENTS

Cable ID	Bus ID	I (pu)	I (A)	I (deg)	Bus ID	I (pu)	I (A)
cable1	BUS4	0.0002	4.2022	30	BUS5	0.0002	4.1627

TRANSFORMER CURRENTS

Tx ID	Bus ID	Wnd No	I (pu)	I (A)	I (deg)
Trf1	BUS2	1	0.0002	1.0693	0
Trf1	BUS4	2	0.0002	3.5372	30
Trf2	BUS3	1	0.0022	11.7428	-161.47
Trf2	BUS5	2	0.0021	37.4409	48.5303
Trf3	BUS4	1	0	0	30
Trf3	BUS6	2	0	0	60

INDUCTION MACHINE CURRENTS

IM ID	Bus ID	I (pu)	I (A)	I (deg)
Motor2	BUS6	Disconnected.		
Motor2	BUS5	0.0002	3.6925	30

SYNCHRONOUS MACHINE CURRENTS

SM ID	Bus ID	I (pu)	I (A)	I (deg)
	BUS1	0.0012	6.4192	-161.513
	BUS2	0.0012	6.4192	-161.513

SHUNT CURRENTS

Shunt ID	Bus ID	I (pu)	I (A)	I (deg)
Shunt1	BUS2	0	0.0936	23.3012
Shunt2	BUS4	0	0.6651	-100.916
	BUS3	0	0.0976	23.0815
	BUS5	0.0026	45.1717	67.5697
	BUS3	Disconnected.		

RESULTS FOR HARMONIC NUMBER 11.000

INJECTION CURRENTS

Inj ID	Bus ID	I (pu)	I (A)	I (deg)
Motor1	BUS5	0.0002	3	174.5656

BUSBAR VOLTAGES

Bus ID	V (kV)	V (V)	V (pu)	V (%)	V (deg)
BUS1	0.0044	4.392	0.0004	0.0399	135.0734
BUS2	0.0044	4.392	0.0004	0.0399	135.0734
BUS3	0.0046	4.5683	0.0004	0.0415	134.9206
BUS4	0.0031	3.0554	0.0009	0.0926	93.8929
BUS5	0.0033	3.3375	0.001	0.1011	92.3257
BUS6	0.0004	0.3818	0.0009	0.092	63.8929

LINE CURRENTS

Line ID	Bus ID	I (pu)	I (A)	I (deg)	Bus ID	I (pu)	I (A)
1	BUS1	0.0001	0.5211	0	BUS3	0.0001	0.4976

CABLE CURRENTS

Cable ID	Bus ID	I (pu)	I (A)	I (deg)	Bus ID	I (pu)	I (A)
cable1	BUS4	0	0.183	30	BUS5	0	0.1788

TRANSFORMER CURRENTS

Tx ID	Bus ID	Wnd No	I (pu)	I (A)	I (deg)
Trf1	BUS2	1	0	0.0465	0
Trf1	BUS4	2	0	0.1538	30
Trf2	BUS3	1	0.0001	0.5019	0
Trf2	BUS5	2	0.0001	1.6002	30
Trf3	BUS4	1	0	0	30
Trf3	BUS6	2	0	0	60

INDUCTION MACHINE CURRENTS

IM ID	Bus ID	I (pu)	I (A)	I (deg)
Motor2	BUS6	Disconnected.		
Motor2	BUS5	0	0.1611	30

SYNCHRONOUS MACHINE CURRENTS

SM ID	Bus ID	I (pu)	I (A)	I (deg)
	BUS1	0.0001	0.2817	-134.528

	BUS2	0.0001	0.2817	-134.528

SHUNT CURRENTS

Shunt ID	Bus ID	I (pu)	I (A)	I (deg)
Shunt1	BUS2	0	0.0041	0
Shunt2	BUS4	0	0.0293	39.6608
	BUS3	0	0.0043	0
	BUS5	0.0003	4.8659	-147.674
	BUS3	Disconnected.		

RESULTS FOR HARMONIC NUMBER 13.000

INJECTION CURRENTS

Inj ID	Bus ID	I (pu)	I (A)	I (deg)
Motor1	BUS5	0.0002	3	-28.2407

BUSBAR VOLTAGES

Bus ID	V (kV)	V (V)	V (pu)	V (%)	V (deg)
BUS1	0.0032	3.1649	0.0003	0.0288	-129.563
BUS2	0.0032	3.1649	0.0003	0.0288	-129.563
BUS3	0.0033	3.2909	0.0003	0.0299	-129.698
BUS4	0.0022	2.1923	0.0007	0.0664	-111.995
BUS5	0.0024	2.3911	0.0007	0.0725	-113.293
BUS6	0.0003	0.274	0.0007	0.066	-81.9953

LINE CURRENTS

Line ID	Bus ID	I (pu)	I (A)	I (deg)	Bus ID	I (pu)	I (A)
1	BUS1	0.0001	0.3181	0	BUS3	0.0001	0.298

CABLE CURRENTS

Cable ID	Bus ID	I (pu)	I (A)	I (deg)	Bus ID	I (pu)	I (A)
cable1	BUS4	0	0.1105	30	BUS5	0	0.1069

TRANSFORMER CURRENTS

Tx ID	Bus ID	Wnd No	I (pu)	I (A)	I (deg)
Trf1	BUS2	1	0	0.028	0
Trf1	BUS4	2	0	0.0928	30
Trf2	BUS3	1	0.0001	0.3006	0
Trf2	BUS5	2	0.0001	0.9586	30
Trf3	BUS4	1	0	0	30
Trf3	BUS6	2	0	0	60

INDUCTION MACHINE CURRENTS

IM ID	Bus ID	I (pu)	I (A)	I (deg)
Motor2	BUS6	Disconnected.		
Motor2	BUS5	0	0.0977	30

SYNCHRONOUS MACHINE CURRENTS

SM ID	Bus ID	I (pu)	I (A)	I (deg)
	BUS1	0	0.1718	-39.2263
	BUS2	0	0.1718	-39.2263

SHUNT CURRENTS

Shunt ID	Bus ID	I (pu)	I (A)	I (deg)
Shunt1	BUS2	0	0.0025	0
Shunt2	BUS4	0	0.0178	-167.11
	BUS3	0	0.0026	0
	BUS5	0.0002	4.12	6.7075
	BUS3	Disconnected.		

DISTORTION RESULTS

BUSBAR VOLTAGES

Bus ID	Distortion (%)	TFF
BUS1	0.62713	2.3853
BUS2	0.62713	2.3853
BUS3	0.65335	2.46754
BUS4	1.45308	5.11703
BUS5	1.54628	5.42519
BUS6	1.45308	5.11703

LINE CURRENTS

Line ID	Bus ID	Distortion (%)	TFF	Bus ID	Distortion (%)	TFF
1	BUS1	4.11356	11.91632	BUS3	4.03156	11.61041

CABLE CURRENTS

Cable ID	Bus ID	Distortion (%)	TFF	Bus ID	Distortion (%)	TFF
cable1	BUS4	2.48956	7.45819	BUS5	2.47428	7.39383

TRANSFORMER CURRENTS

Tx ID	Bus ID	Wnd No	Distortion (%)	TFF
Trf1	BUS2	1	13.59784	40.08793
Trf1	BUS4	2	13.59816	40.0889
Trf2	BUS3	1	5.16959	14.87212
Trf2	BUS5	2	5.16959	14.87213
Trf3	BUS4	1	0	0
Trf3	BUS6	2	0	0

INDUCTION MACHINE CURRENTS

IM ID	Bus ID	Distortion (%)
Motor2	BUS6	Disconnected.
Motor2	BUS5	1.08521

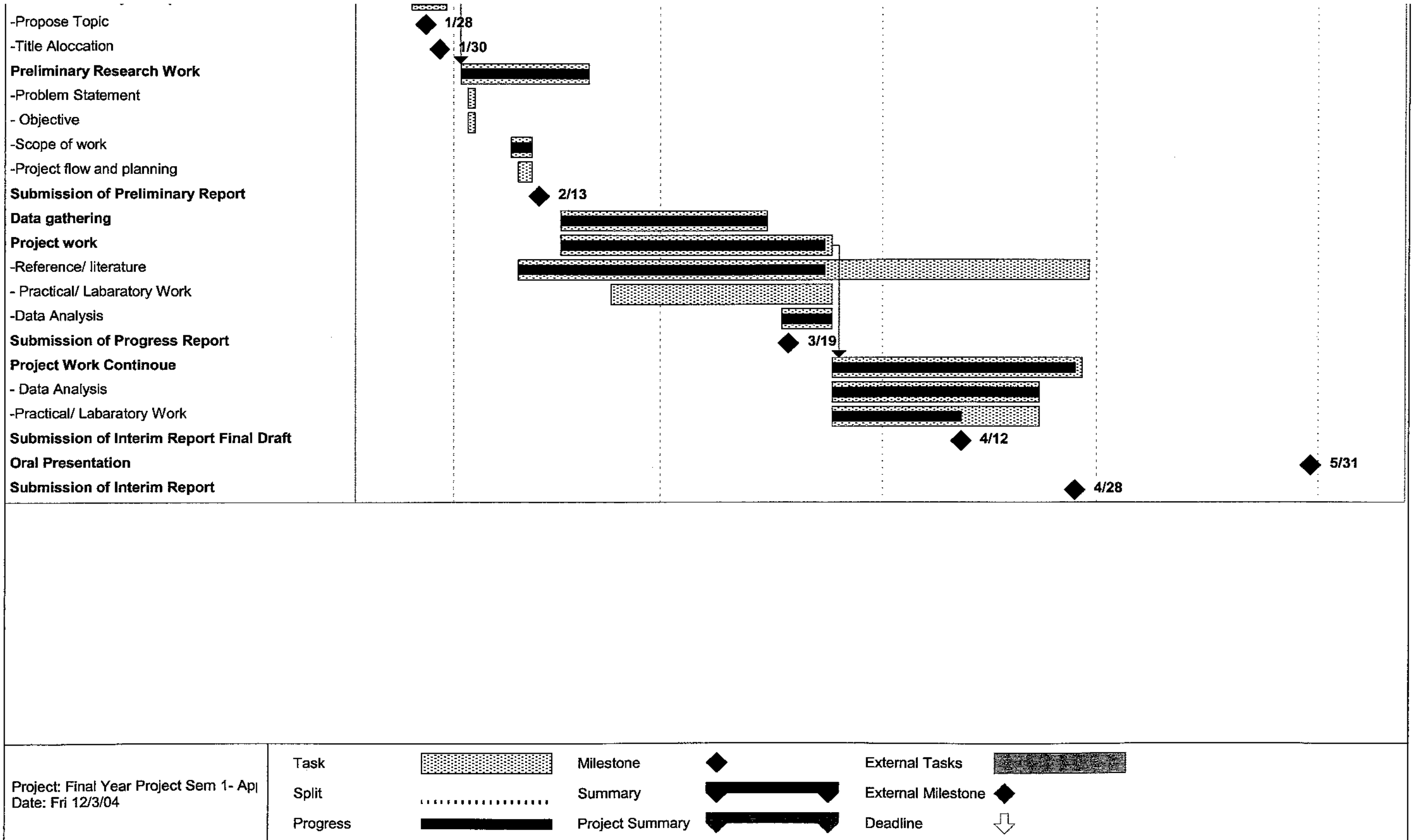
SYNCHRONOUS MACHINE CURRENTS

SM ID	Bus ID	Distortion (%)
	BUS1	3.52685
	BUS2	3.52685

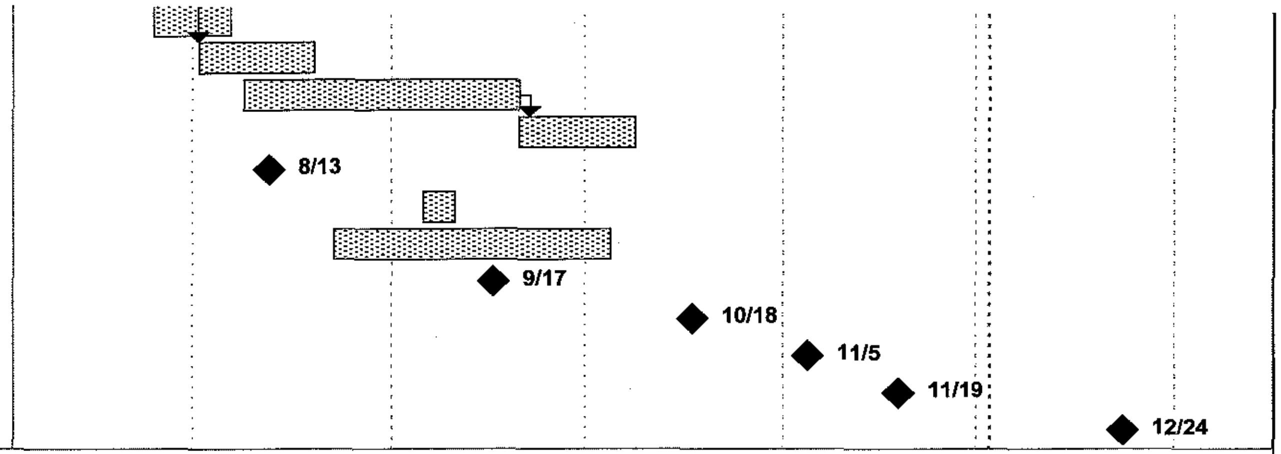
SHUNT CURRENTS

Shunt ID	Bus ID	Distortion (%)
Shunt1	BUS2	0.1201
Shunt2	BUS4	0.3342
	BUS3	0.12516
	BUS5	10.49175
	BUS3	Disconnected.

Appendix 7: Project's Gantt chart


-Propose Topic
1/28
-Title Aloccation
1/30
Preliminary Research Work
-Problem Statement
- Objective
-Scope of work
-Project flow and planning
Submission of Preliminary Report
2/13
Data gathering
Project work
-Reference/ literature
- Practical/ Labaratory Work
-Data Analysis
Submission of Progress Report
3/19
Project Work Continoue
- Data Analysis
-Practical/ Labaratory Work
Submission of Interim Report Final Draft
4/12
Oral Presentation
5/31
Submission of Interim Report
4/28
Project: Final Year Project Sem 1- Ap
Date: Fri 12/3/04
Task
Split
Progress
Milestone
Summary
Project Summary
External Tasks
External Milestone
Deadline

Reference/ literature review
Data gathering for harmonic analysis modelling
Practical/ Labaratory Work
Data Analysis
Submission of Progress Report 1
Harmonic field measurement
Result Analysis
Submission of Progress Report 2
Submission of Draft Report
Submission of Final Report
Submission of Technical Report
Submission of Final Report



Project: Final Year Project Sem2-Appı
Date: Fri 12/3/04

Task		Milestone		External Tasks	
Split		Summary		External Milestone	
Progress		Project Summary		Deadline	