SIMULATION ON HARMONIC RESONANCE IMPACT OF POWER FACTOR CORRECTION CAPACITOR IN DISTRIBUTION SYSTEM

Nur Athykah binti Basiran

Bachelor of Electrical Engineering (Power Industry)

June 2014

" I hereby declare that I have read through this report entitle "Simulation on Harmonic Resonance Impact of Power Factor Correction Capacitor in Distribution System" and found that it has comply the partial fulfillment for awarding the degree of Bachelor of Electrical Engineering (Industrial Power)"

Signature : ______________________________

Supervisor's Name : DR. AIDA FAZLIANA BINTI ABDUL KADIR

Date : 18 JUNE 2014

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NUR ATHYKAH BINTI BASIRAN

A report submitted in partial fulfillment of the requirements for the degree of Bachelor of Electrical Engineering (Industrial Power)

Faculty of Electrical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2014

I declare that this report entitle "Simulation on Harmonic Resonance Impact of Power Factor Correction Capacitor in Distribution System" is the result of my own research except as cited in the references. The report has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : ______________________________

Name : NUR ATHYKAH BINTI BASIRAN

Date : 18 JUNE 2014

Specially dedicated to

my beloved father and mother,

to my family and friends.

Thanks for all the encouragement and support.

ACKNOWLEDGEMENT

I would like to take this opportunity to express my deepest gratitude to my project supervisor, Puan Aida Fazliana binti Abdul Kadir for her advice and guidance throughout the whole process of my final year project. My utmost thanks also go to my family, especially my beloved father Basiran bin Ali and mother Rosiah binti Othman whom I owe my love and gratitude.

I would also like to thank to all my friends and course mates for their advice and support throughout this project. I wish you all the best in life and hope that our friendship will last forever.

ABSTRACT

Today, electricity has become an important need in the world. As the number of modern technologies have increased over the years, it has become increasingly necessary to maintain the system stability and efficiency. These modern technologies may sometimes contribute to high levels of harmonic distortion and resonance in the system. This project aims to analyze the impact of power factor correction capacitor on harmonic distortion and resonance in power system. The analysis was performed for power factor correction capacitor connected to the test system. The test system used in this project to analyze the harmonic interference and resonance are the 2-bus test system and IEEE 5-bus test system. The test systems were simulated by using MATLAB/SimPowerSystem. To investigate the harmonic distortion and resonance phenomenon, frequency scan was conducted while the Fast Fourier Transform analysis was carried out to measure the voltage and current distortion in the system. The results shows that power factor correction capacitor can be used to reduce harmonic distortion and resonance phenomenon in the system.

ABSTRAK

Pada masa kini, bekalan elektrik merupakan keperluan yang amat penting kepada dunia. Bilangan teknologi moden yang kian bertambah sepanjang tahun menyebabkan perlunya untuk mengekalkan kestabilan dan kecekapan sesebuah sistem. Teknologi-teknologi moden ini boleh menyumbang kepada tahap tinggi herotan harmonik dan gema di dalam sistem kuasa. Projek ini menyasarkan untuk menganalisis kesan kapasitor pembetulan faktor kuasa terhadap herotan harmonik dan gema. Analisis dijalankan dengan penyambungan kapasitor pembetulan faktor kuasa dengan sistem ujian. Sistem ujian yang digunakan untuk menganalisis gangguan harmonik dan gema adalah sistem ujian 2-bas dan sistem ujian IEEE 5-bas. Sistem ini diuji dengan menggunakan perisian MATLAB/SimPowerSystem. Untuk menyiasat fenomena herotan harmonik dan gema, imbas frekuensi dijalankan manakala analisis *Fourier Transform dilakukan* untuk mengukur herotan yang berlaku di voltan dan arus. Hasil keputusan menunjukkan bahawa kapasitor pembetulan faktor kuasa boleh digunakan untuk mengurangkan herotan harmonik dan gema di dalam sistem.

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LIST OF ABBREVIATIONS

C	-	Capacitance (Farads)
L	-	Inductance (Henries)
f	-	Frequency (Hertz)
kVAR	-	Reactive Power (Q)
kW	-	Real Power (P)
kVA	-	Apparent Power (S)
V	-	Voltage (Volt)
I	-	Current (Ampere)
PFCC	-	Power Factor Correction Capacitor
pf	-	Power Factor
THD	-	Total Harmonic Distortion
FFT	-	Fast Fourier Transform
APLC	-	Active Power Line Conditioners
DC	-	Direct Current
AC	-	Alternating Current
PWM	-	Pulse Width Modulation
MOSFET	-	Metal Oxide Semiconductor Field Effect Transistor

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CHAPTER 1

INTRODUCTION

1.1 Research Background

Power transmission and distribution system are designed for operation with sinusoidal voltage and current waveform in constant frequency. On the other hand, certain type of loads like thyristor drives, converters and arc furnace producing currents and voltages that have integer multiple frequencies of the fundamental frequency. These higher frequencies are known as power system harmonics. Power system harmonics are not a new issue as concern over this problem has been retreated and flowed during the history of electric power systems [1]. Harmonic resonance is caused by the energy exchange between capacitive elements and inductive elements in a system. Since a power system contains numerous inductive and capacitive elements, the phenomenon of harmonic resonance can become quite complicated [2].

The consequences of the harmonic resonance that result in their premature failure are the cause of overheating and it increases the dielectric stress of power capacitors. Capacitors can interact with harmonics which lead to harmonic amplifications at the resonant frequency. This causes the capacitors or the components of the system to be damaged. Furthermore, high power factor cannot be achieved because of the harmonic distortion. These have encouraged the requirement for a different method in power factor correction [3].

This project presents a simulation of power factor correction capacitor (PFCC) in the distribution system following to harmonic resonance analysis. It focuses on the impact of PFCC through the system by generating the harmonic resonance analysis. It is one of the methods used in reducing the harmonic distortion in the system.

1.2 Problem Statement

Harmonic distortion can cause severe disturbance to certain electrical equipment. It is the role of the electric utility to provide a clean supply to customers. Many countries now set limits to the harmonic distortion and resonance allowed on the distribution networks [4]. Evaluation of harmonic resonance filter is crucial to make sure the filter is in optimum design, not under or over design. The design must be able to reduce the harmonic distortion and resonance in the system. Therefore, the estimation of the power factor correction capacitor is crucial to make sure that it is suitable in reducing harmonic distortion and resonance phenomenon. It is important because this aspect related to the distribution system requirement.

1.3 Objectives

The aim of this project is:

1. To evaluate the performance of power factor correction capacitor (PFCC) in the distribution system.
2. To investigate the significance of PFCC in power system.
3. To analyze the impact of the PFCC devices on harmonic distortion.

1.4 Scope of Project

Based on the objectives, the scopes of study are highlighted as follows:

1. The PFCC was tested using MATLAB/SimPowerSystem.
2. The test systems used in this project are the 2-bus test system and IEEE 5-bus test system.

1.5 Thesis Outline

This thesis is divided into five chapters. Chapter 1 is a brief review of this project. This chapter generally discussed about the background of research, problem statement and scope of the project. Chapter 2 is the literature review which is done based on journals, books, internet resources and IEEE paper related to this project. This chapter describes about the main topic of this project that is harmonic resonance and PFCC.

In Chapter 3 presents on the methodology of the project, which is consisted of use case, flow chart, design and details description on how this project was implemented. Chapter 4 describes about the result and discussion gained through this project. It also covered the harmonic resonance analysis. Finally, Chapter 5 consists of a conclusion in project implementation and thus any recommendation for future development.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter will explain the basic concept about the power factor correction capacitor, harmonic distortion and resonance. The review of the previous studies is important in order to develop the system.

2.2 Theory and Basic Principles

Devices causing harmonics are present in all industrial, commercial and residential installations. Harmonics are caused by nonlinear loads. The loads become nonlinear when the current it draws does not have the same waveform as the supply voltage. The circuit is said to be resonant when the voltage applied to an electrical network contains resistance, inductance and capacitance are in phase with the resulting current. At resonance, the equivalent network impedance is purely resistive since the supply voltage and current are in phase.

2.2.1 Harmonic Distortion

Harmonic distortion is the change in the waveform of the supply voltage from the ideal sinusoidal waveform. It is caused by the interaction of distorting customer loads with the impedance of the supply network. Its major adverse effects are the heating of induction motors, transformers and capacitors and the overloading of neutrals [5].

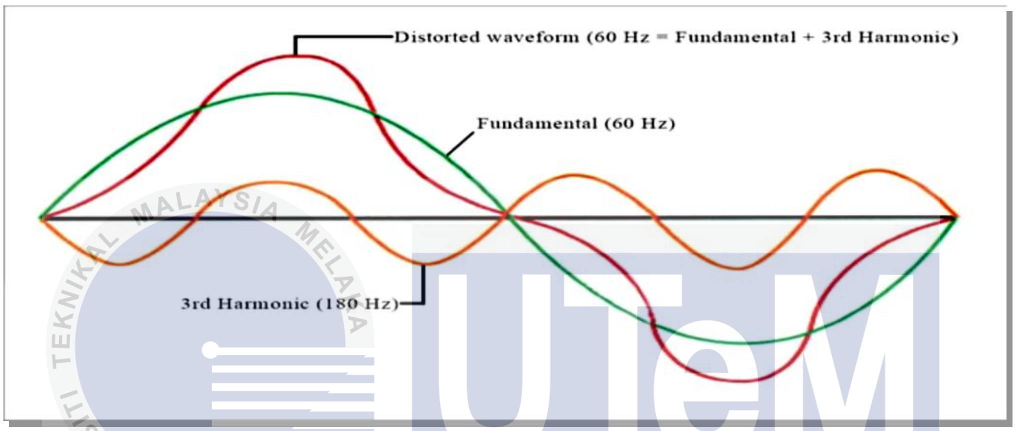

Figure 2.1: Harmonic distortion of the electrical current waveform [6].

Figure 2.1 shows the waveform of harmonic distortion on current in the electrical system. Equipment responds to harmonics differ depending on their method of operation. On the other hand, induction motor windings are overheated by harmonics, causing accelerated degradation of insulation and loss of life. Harmonic voltages can give correspondingly higher currents than do 50 Hz voltages and one can easily underestimate the degree of additional heating in the motor.

Harmonics have frequencies that are integer multiple of the waveform's fundamental frequency. For example, given a 60 Hz fundamental waveform, the 2nd, 3rd, 4th and 5th harmonic components will be at 120 Hz, 180 Hz, 240 Hz and 300 Hz respectively. Thus, harmonic distortion is the degree to which a waveform deviates from its pure sinusoidal values as a result of the summation of all these harmonic elements.

Total harmonic distortion, THD is the summation of all harmonic components of the voltage or current waveform compared against the fundamental component of the voltage or current wave;

$$\mathrm{THD} = \frac{\sqrt{{V_2}^2 + {V_3}^2 + {V_4}^2 + \cdots + {V_n}^2}}{V_1} \times 100\% \qquad (2.1)$$

Where,

V_1 = Fundamental voltage value

$V_n (n = 2, 3, 4, \text{etc} \dots)$ = Harmonic voltage values

Equation (2.1) shows the calculation for THD on a voltage signal. The end result is a percentage comparing the harmonic components to the fundamental component of a signal. The higher the percentage, the more distortion that is present on the mains signals [7].

2.2.2 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 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 the capacitive reactance are equal. This crossover point, called the parallel resonant point, is where the power system has a coincidental similarity of system impedances [8].

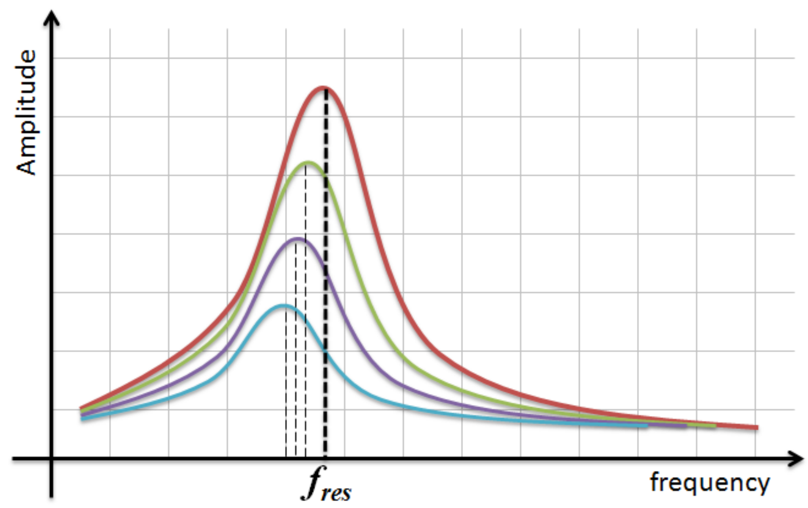

Figure 2.2: Resonance frequency graph [9]

Figure 2.2 shows the graph of a system undergoing resonance at its resonance frequency. Parallel resonance causes problems only if a source of harmonic exists on the frequency where the impedances match. This is typically called harmonic resonance results in very high harmonic currents and voltages at the resonant frequency.

2.2.3 Power Factor Correction Capacitor (PFCC)

Several IEEE transaction papers have been written and published which introduce the theory and implementation of advanced techniques for controlling harmonic current flow such as magnetic flux compensation, harmonic current injection, DC ripple injection, series/shunt active filter systems, and pulse width modulated static Var harmonic compensators. However, these practical systems have not been extensively installed and are not available on the market yet. It may take more time before these advanced techniques are fully developed and readily available [7].

The very important aspect of improving the quality of supply is the control of power factor. When low power factor produced, it means that the electrical system has poor efficiency. The lower the power factor, the higher the apparent power drawn from the distribution network [9]. Figure 2.3 shows the relationship between real power, reactive power and apparent power.

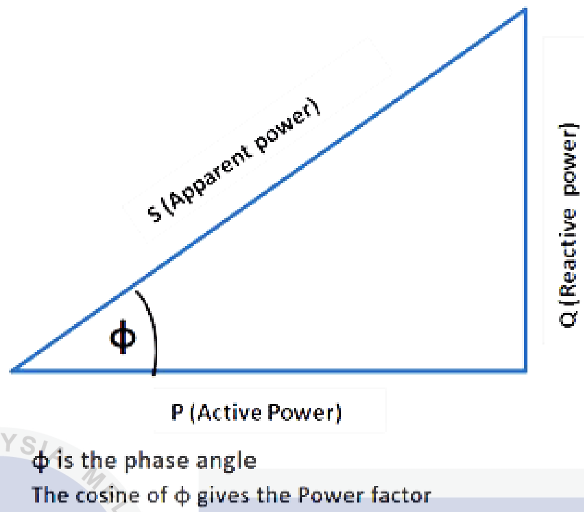

Figure 2.3: The power triangle [10].

In general, power is the capacity to do the work. In electrical domain, electrical power is the amount of electrical energy that can be transferred to some other form (heat, light etc.) per unit time. Mathematically, it is the product of voltage drop across the element and electric current flowing through it. Both inductor and capacitor offer certain amount of impedance given by,

$$X_L = 2\pi f L \tag{2.2}$$

$$X_C = \frac{1}{2\pi f C} \tag{2.3}$$

The power that involves,

$$\text{Active power, } P = VI\cos\theta \tag{2.4}$$

$$\text{Reactive Power, } Q = VI\sin\theta \tag{2.5}$$

These powers are represented in the form of triangle in Figure 2.3.

2.3 Review of Previous Related Works

There are several ways to solve the harmonic resonance. As in [14], it submits a combined system of a passive filter and a small-rated active filter, which are connected in series with each other. The passive filter will eliminate the harmonic currents produced by the load, whereas the active filter improves the filtering characteristics of the passive filter and acts as a "harmonic isolator" between the source and the load. The primary circuit of the active filter with a rating of 0.5 kVA is a three-phase voltage-source PWM inverter using six MOSFET's. The role of a small-rated LC filter is to restrain switching ripples generated by the active filter. Whereas in [15] points out that the shunt active filter is superior in stability based on detection of voltage at the stage of installation to others. The shunt filter which will be installed by an electric utility, putting much emphasis on the control strategy and the best point of installation of the shunt active filter on a feeder in a power distribution system. The aim of the shunt active filter is to damp harmonic propagation, which results from harmonic resonance line inductors in the feeder, rather than to minimize voltage distortion throughout the feeder.

By referring to [1], in this paper, the commonly employed solutions when harmonics become a problem is by limiting the harmonic current injection from nonlinear loads. The harmonics in a three-phase system can be reduced by using parallel delta-delta and Wye-delta transformers to yield net 12-pulse operation, or by using delta connected transformers to block the triplen harmonics. The second method is by modifying the system frequency response through feeder sectionalizing, adding or removing capacitor banks, change the size of the capacitor banks, adding shunt filters, or add reactors to detune the system away from harmful resonances [1,9]. Moreover, by placing the shunt filters at the load or on the system, it will try to block the harmonic currents produced by loads. There a number of devices to solve this problem where it can be as simple as an in-line reactor (i.e., choke) as in a PWM-based adjustable speed drive applications, or as complex as an active filter. Their choice is largely dependent upon the nature of the problems that happened. Harmonic controls can be exercised at the utility and end-user sides. The objective of IEEE Std 519 is to propose steady-state harmonic limits for electrical systems that are considered reasonable by both electric utilities and their customers. The basic idea is that customers should limit harmonic currents since they have control over their loads, electric utilities should limit harmonic voltages since they have control over the system impedances and both parties should share the responsibility for holding harmonic levels in check.

The article [16] further states that due to the high harmonics and complex system operation, a more in-depth computer modeling and filter design was needed and installed at the large rectifier-type graphitizing furnaces, and also with the three power factor correction bank. There are two categories of solutions that available as in [17] which are by reducing the harmonics at their source or by using filters to reduce the unwanted harmonics. The harmonics at the origin can be reduced through various transformer connections to cancel certain harmonics are practical. In most cases, however, reducing or eliminating harmonics at their root is effective only in the design or expansion stage of a new facility and for existing facilities. This is to determine which harmonic filters will regularly provide the least-cost solution.

Harmonic filters can be divided into two types which is active and passive. For a load that injects certain harmonic currents in the supply system, a DC to AC inverter can be controlled such that the harmonic current to the load is supplied by inverter, while it allow the power system to supply the power frequency current for the load. For high power applications or for applications where power factor correction capacitors already exist, the used of passive filtering generally is more expensive. Passive filtering is based on the series resonance principle that low impedance at a specific frequency is a series-resonant characteristic and can be easily implemented. It should be noted that passive filtering cannot always make use of existing capacitor banks. In filter applications, the capacitors will usually be exposed nonstop to voltages that greater than their ratings (which were determined based on their original application). However, passive filtering is still present as the most cost effective in solving the harmonic problem.

In article [18], the author classifies that the two basic types of harmonic filter configurations are the series and shunt filters. The series filter refers to the filter formed of a capacitor and inductor connected in parallel with each other but in series with the load. This type of filter provides a high-impedance path for harmonic currents and blocks them from reaching the power supply but allows the fundamental 60Hz current to pass through. This type of configuration has the drawback of having to bear the entire load current. The other type of harmonic filter configuration is a shunt filter that consists of a capacitor and an inductor connected in series with each other but in parallel or shunt with the load. This type of filter configuration provides a low-impedance path for harmonic currents and diverts them to earth. The shunt filter is more common and less expensive, because it doesn't have to bear the entire load current. Even so, the shunt filters must be selected carefully as they can resonate with existing electrical components and cause additional harmonic currents.

Passive harmonic filters use static inductors and capacitors because they do not change their values of inductance (Henries) and capacitance (Farads). The passive harmonic filter is designed to handle specific harmonics. They are called passive because they do not respond to changes in frequency. They include small plug-in devices and large hard-wired devices. They are often connected to electrical devices that cause harmonics, such as variable-speed drives and fluorescent lights. Harmonic filters sometimes are referred to as *traps* or *chokes*. They may become ineffective if the harmonics change because the load changes. Active filter may be the answer to changing harmonic currents. Active harmonic filters are sometimes referred to as *active power line conditioners* (APLCs). They differ from passive filters in that they condition the harmonic currents rather than block or divert them. Active harmonic filters use electronic means (bridge inverters and rectifiers) to monitor and sense the harmonic currents and create counterharmonic currents. They then inject the counterharmonic current to cancel out the harmonic current generated by the load. They also regulate sags and swells by eliminating the source voltage harmonics. While expensive in the past, they are becoming more cost effective. They are most effective in compensating for unknown or changing harmonics.

Referred to [19], it concludes that there are two types of harmonic filters can be employed: a high-impedance series filter or a low-impedance shunt filter. Since the filter can be accommodated the full-load current and must be insulated for line-to-line voltage, it is usually a very expensive option. The shunt filter is not only less expensive, but also provides reactive power at the fundamental frequency. Because of their dual functionality of removing harmonics and correcting the power factor, shunt filters are the most common type of harmonic filter. Before a harmonic filter can be designed, a harmonic analysis must be conducted to determine the magnitudes and frequencies of the harmonic currents to be filtered. This analysis can be done with a power quality meter. The harmonic filter consists of a capacitor in series with reactor, connected line to neutral. The capacitor should be sized first, since it also will be a source of reactive power. By sizing a capacitor correctly, it can optimize the use for both filtering and power factor correction.

Sometimes an existing capacitor bank can be utilized as part of the harmonic filter. If a new capacitor is involved, it is advisable to fix one with a slightly higher voltage rating than the nominal line-to-neutral voltage of the system to account for fundamental-frequency overvoltage. Likewise, the current rating of the capacitor must be chosen wisely. In addition to the harmonic currents identified by the harmonic analysis, the filter undoubtedly will need to handle slightly higher current magnitudes, because it will tend to act as a sink for harmonic currents produced elsewhere in the system. If the filter must handle large magnitudes of high-order harmonics, particular attention must be paid to the current rating of the capacitor, as high-frequency currents tend to substantially increase loading on the capacitor due to the capacitor's low impedance at high frequencies. Finally, capacitor fusing must be considered. It is common to fuse capacitors as low as 125% of rated current. When a capacitor is used as a harmonic filter, the fuse rating may be more of a limiting factor than the capacitor itself. Increasing the size of the fuse may be necessary.

After a capacitor is selected, a reactor must be sized to achieve the desired tuning. The current rating of the reactor must be based on the total effective current that will flow through the reactor. The inductance value is chosen so that the filter is resonant at the desired frequency. If several harmonic orders are problematic, filtering the lowest frequency first will attenuate the higher order harmonics somewhat. If this attenuation is not sufficient, multiple filters can be connected in parallel. A common practice is to tune the harmonic filter slightly below (3% to 10%) the harmonic of concern. Doing so reduces the duty on the filter, since the path to neutral will not be a short circuit at the harmonic frequency. This allows other system components to absorb a portion of the harmonic currents while still providing a low impedance path to neutral for the harmonic of concern. Tuning slightly below the harmonic frequency also allows for the tolerance in the kVar rating of the capacitor, which is 0 to +10%. After the reactor is sized, the interaction of the filter with the rest of the system should be simulated. The THD should be checked throughout the range of the capacitor and reactor tolerances. An analysis of unwanted resonant conditions also should be made. These analyses are complex and require computer modeling.

2.4 Summary and Discussion of Review

There are several power system problems that which can cause such effects as increased of losses in the windings of transformer, capacitor, heating of motor or generator, dysfunction of electronic equipment (which relies on voltage zero crossing detection or is sensitive to wave shape), incorrect reading of meters, dysfunction of protective relays, and interference with telephone circuits and so on.

From the research, it finds that there are several methods to eliminate the harmonics in power systems. The harmonics can be eliminated by using a combined system of a passive filter and a small-rated active filter or by using a shunt active filter. The harmonics can be reduced by limiting the harmonic current injection from nonlinear loads through the parallel delta - delta and Wye-delta transformers to yield net 12-pulse operation, or delta connected transformers to block triplen harmonics. The other method is by modifying the system frequency response. This can be done by feeder sectionalizing, adding or removing capacitor banks, changing the size of the capacitor banks, adding shunt filters, or adding reactors to detune the system away from harmful resonances. Moreover, instead of changing the capacitor sizes, it also can be done by changing the capacitor locations or changing the source characteristics. It is suggested that to reduce the harmonic is at their point of origin (before they enter the origin) or by applying filters to reduce the harmonics which are a high-impedance series filter or a low-impedance shunt filter.

For this research, the system that will be used to eliminate the harmonic resonance is by using the power factor correction capacitor (PFCC).

Table 2.1: Comparison of filters

Method	Advantage	Disadvantage
Shunt Active Filter	• Reduction in capacity of shunt active filter. • Conventional shunt active filter applicable.	• Harmonic current may flow from source to shunt active filter.
Series Active Filter	• Great reduction in capacity of series active filter.	• Isolation and protection of series active filter.
Shunt Passive Filter	• Can handle large currents and high voltages. • Noise arises from resistances only.	• Inductors large for lower frequencies. • Limited standard sizes, often requiring variable inductors and therefore tuning.
Power Factor Correction Capacitor (PFCC)	• Improving power factor, reduction of losses and voltage drops. • Better utilization of electrical machines (generators and transformers) and of electrical lines (transmission and distribution lines).	

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter will explain about the procedure and methods that will be used to complete project. Basically, the project will be divided into a few parts and the project will be executed stage by stage.

3.2 Project Research and Literature Review

Some research and literature review that are related to the topic must be done before the start of the project. Information about past year's projects and related theory about PFCC and harmonic resonance need to be studied. Analyze and chosen process will be complemented each other to ensure that the information obtained will fulfill the expectation of the project.

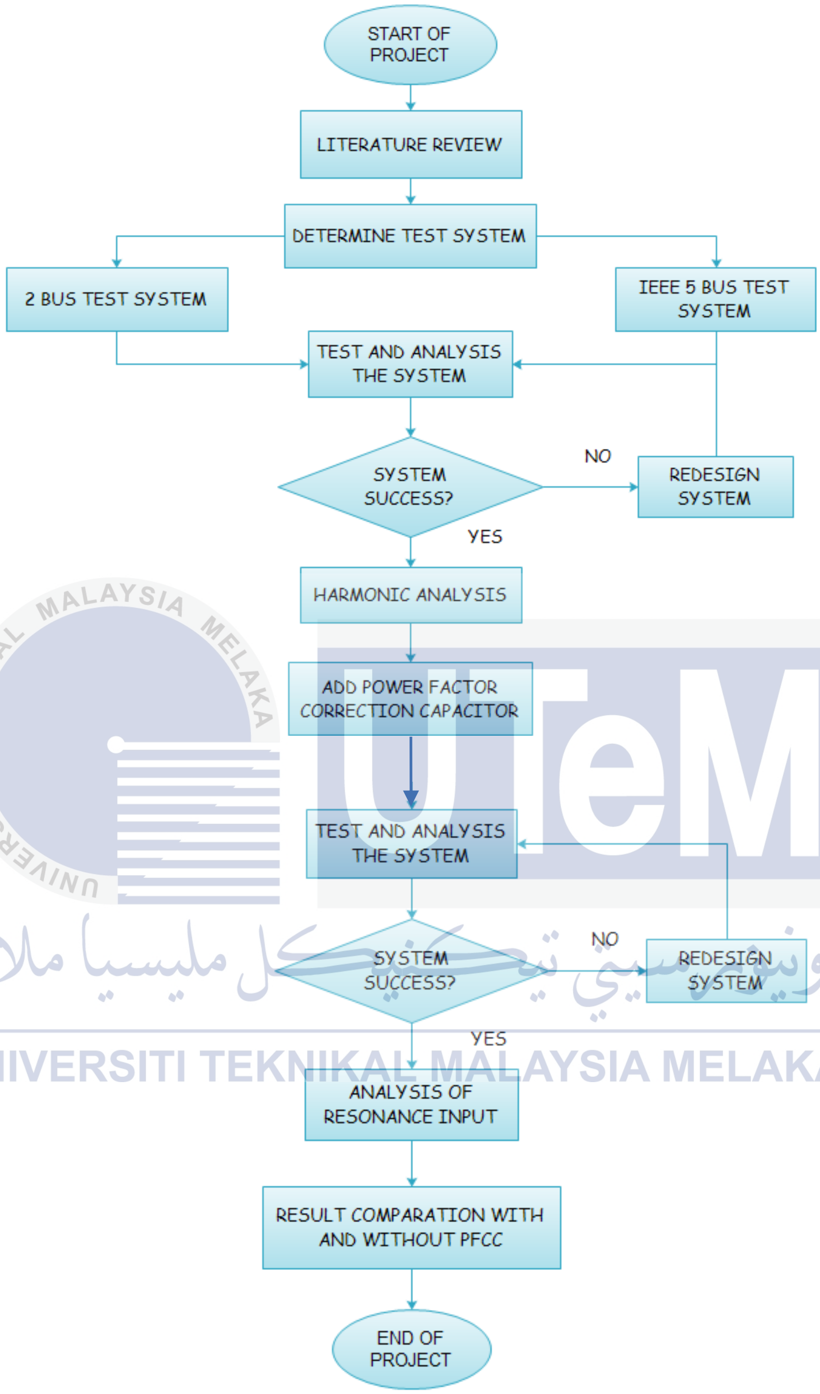

Figure 3.1: Project Flowchart

The flowchart in Figure 3.1 will represent the process and steps taken to complete the project. First, this project will start with literature review where it will give ideas and better understanding about the system. The process of literature review is done by searching for journals, articles, internet and book and analyzed the relation to the system of this project.

Then, the project proceeds with determining the test system of the project. There are two different test systems to be tested. The test system must be to determine the harmonic resonance and the impact of PFCC to the system. The test system is simulated by using MATLAB/SimPowerSystem to acquire the harmonic and resonance produced. The block diagram is the initial step to produce the desired result.

The elimination of the harmonic resonance is start by designing the system that included PFCC. The block diagram is the initial step to produce the desired result. The circuit is then simulated for analysis of resonance input by using MATLAB/SimPowerSystem. The following task is done to ensure that the design will fulfill all the specifications and achieve the objective. In addition, the data or result obtained must be relevant to the system.

3.3 Test System

The performance of PFCC was tested on two different test systems which are the 2-bus test system and the IEEE 5-bus test system. The test systems are modeled and simulated in MATLAB/SimPowerSystem.

3.3.1 2-Bus Test System

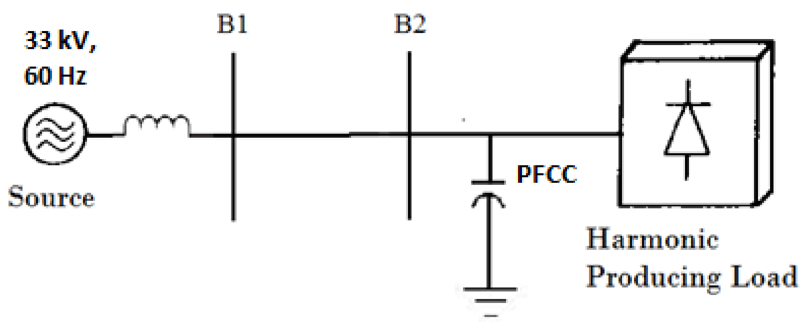

Figure 3.2: Basic principle of PFCC in 2-bus test system.

A single line diagram of the 2-bus test system is shown in Figure 3.2. The problem defined as a three-phase six pulse thyristor converter, a typical harmonic producing load operates from a three-phase source 33 kV, 60 Hz with a PFCC. The PFCC is connected in parallel to the load in the system. The load in the system is 50 MW and 10 MVar. The harmonic source used in the system is as in Table 3.1.

Table 3.1: Harmonic Data [25].

Harmonic	**RMS Voltage**		**RMS Current**	
	Magnitude	**Phase**	**Magnitude**	**Phase**
5	5.38	91.9	0.117	-11.4
7	0.19	0.00	0.064	15.7
11	0.07	0.00	0.049	58.2

3.3.2 IEEE 5-Bus Test System

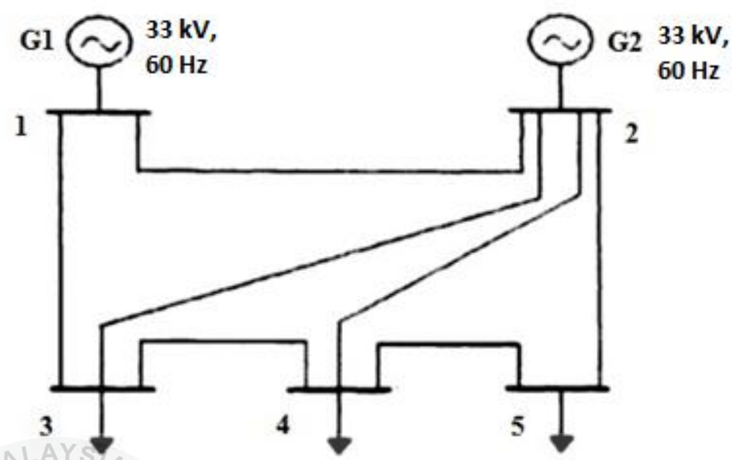

Figure 3.3: Single line diagram of IEEE standard 5-bus test system [24].

A single line diagram of the IEEE 5-bus standard test system extracted from [24] is shown in Figure 3.3. The IEEE 5-bus test system has three generators of 33 kV, 60 Hz and seven transmission lines. There are 3 loads of 50 MW and 10 MVar connected to the system. The harmonic source used in the system is same as in Table 3.1.

3.4 Power Factor Calculation

The power factor can be an important aspect to consider because any power factor less than 1 (unity) means that the system has to carry more current than what would be necessary with zero reactance in the system to have delivered the same amount of Active Power, P to the resistive load.

Poor power factor can be corrected by adding another load to the system drawing an equal and opposite amount of Reactive Power, Q to cancel out the effects of the load's inductive reactance. Inductive reactance can only be cancelled by capacitive reactance.

In order to determine the Reactive Power, Q and the new value of the capacitor, the following formulae is applied;

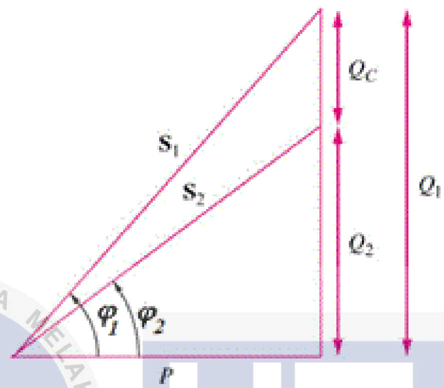

Figure 3.4: Power triangle

$$\text{Reactive Power, } Q = S\sin\theta = VI\sin\theta \tag{3.1}$$

From Figure 3.4, to calculate Q at correct capacitor size, Q_C

$$Q_C = Q_1 - Q_2 \tag{3.2}$$

$$Q_C = \frac{V^2}{X_C} \tag{3.3}$$

$$X_C = \frac{1}{2\pi fC} \tag{3.4}$$

Where,

Q_1 = the new Reactive Power

Q_2 = the old Reactive Power

Q_C = the corrected Reactive Power

X_C = corrected capacitor reactance

The following steps are taken to measure the power factor of the system,

$$\text{Apparent Power, } S = V_{rms} \times I_{rms} \tag{3.5}$$

The power factor can be obtained by,

$$\text{Power Factor, } \theta = \frac{P}{S} \tag{3.6}$$

Where,

P = Active Power, W

S = Apparent Power, VA

3.5 Modeling of Harmonic Source in SimPowerSystem

Electrical power system harmonic problems are mainly due to the substantial increase of nonlinear loads due to the technological advances, such as the use of power electronic circuits and devices, in AC/DC transmission links or loads in the control of power systems using power electronics or microprocessor controllers. Such equipment creates load-generated harmonics throughout the system. Figure 3.2 illustrates the basic principles of the 2-bus test system. This system consists of an AC source, impedance, PFCC and the harmonic source.

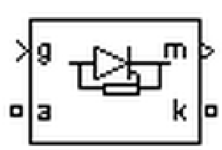

Figure 3.5: Thyristor in MATLAB/SimPowerSystem

The harmonic source used in this system is thyristor as in Figure 3.5. Thyristor is a special type of diode that only allows current to flow when a control voltage is applied to its gate terminal. In an AC circuit the forward current drops to zero during every cycle so there will always be a turn off function [26]. The PFCC is required to eliminate the current and voltage harmonics and resonance created by the thyristor.

3.6 Modeling of Test System in MATLAB/SimPowerSystem

3.6.1 2-Bus Test System

The effectiveness of the method using PFCC is carried out on 2-bus test system. The system is simulated in MATLAB/SimPowerSystem which gives the platform to study the harmonic distortions in voltage and current waveform due to the existence of a nonlinear load in the system.

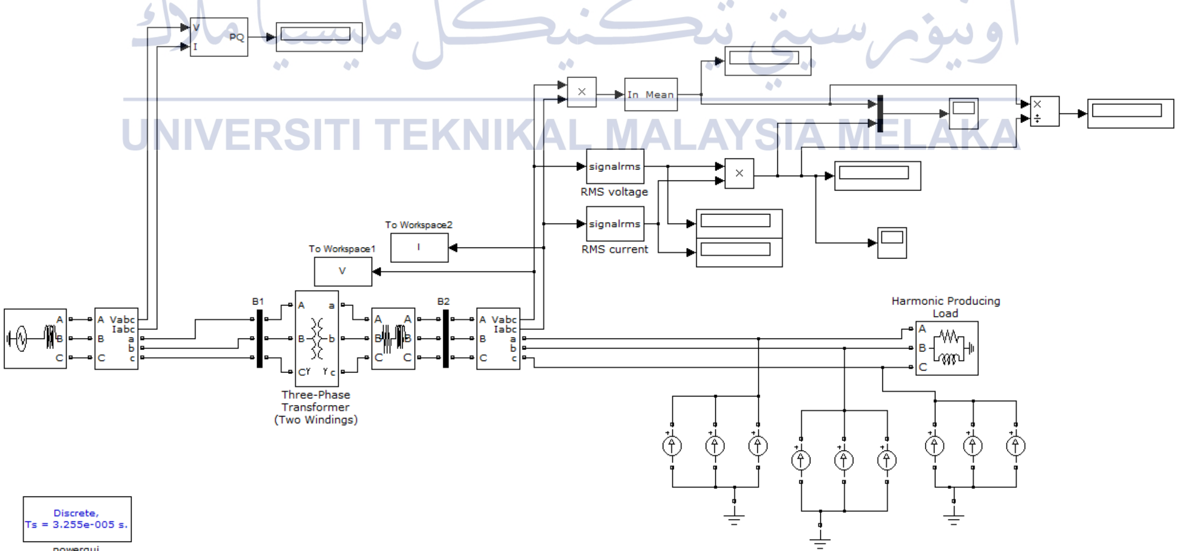

Figure 3.6: Simulation model of the 2-bus test system without PFCC

Figure 3.6 shows the 2-bus test system modeled in MATLAB/SimPowerSystem. The system consists of a six-pulse thyristor model as a nonlinear load on the system and the three-phase source. It is based on the single line diagram depicted in Figure 3.2.

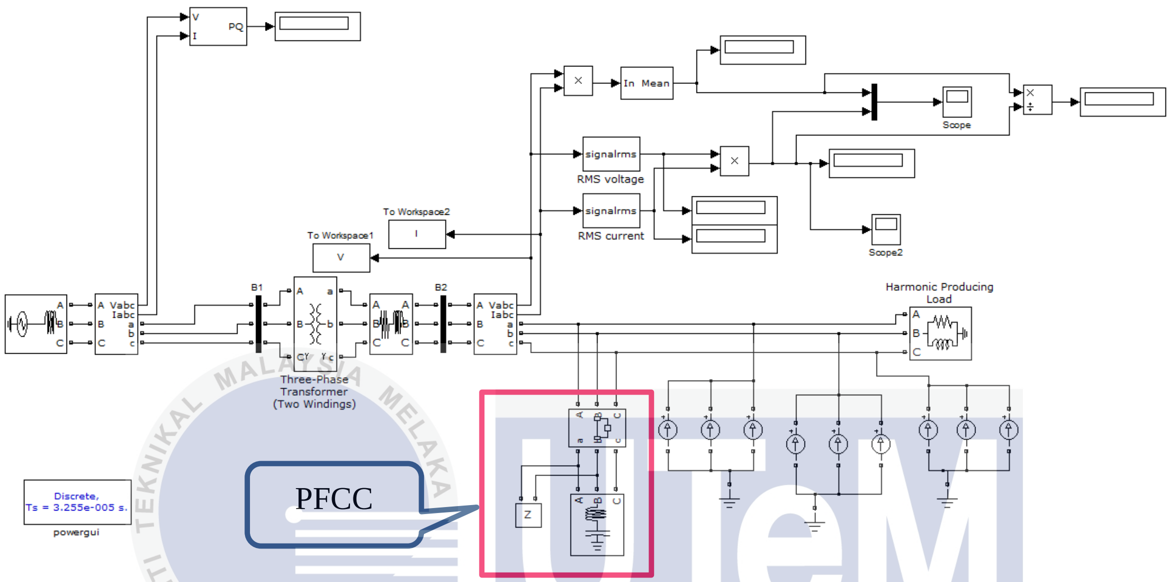

Figure 3.7: Simulation model of the 2-bus test system with PFCC

The Simulink model of the 2-bus test system with PFCC is shown in Figure 3.7. The PFCC is connected to study the effectiveness of the PFCC to get better and improved power factor.

3.6.2 IEEE 5-Bus Test System

IEEE 5-bus test system [24], as depicted in Figure 3.3, is used for this project. In this project, the original IEEE 5-bus test system is modified by adding a nonlinear load (thyristor). A power factor correction capacitor (PFCC) is placed at bus 5.

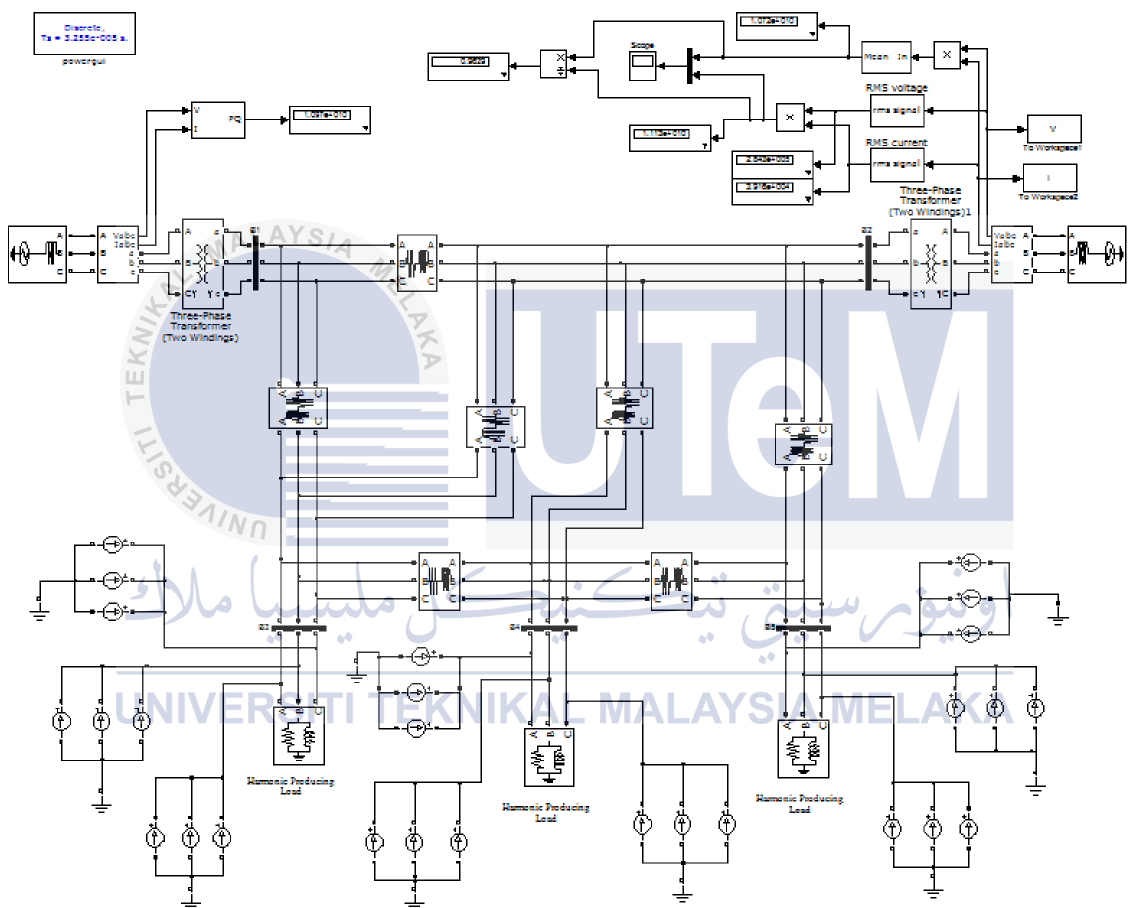

Figure 3.8: Simulation model of the IEEE 5-bus test system without PFCC

Figure 3.8 shows the simulation model of the IEEE 5-bus test system in MATLAB/SimPowerSystem without PFCC.

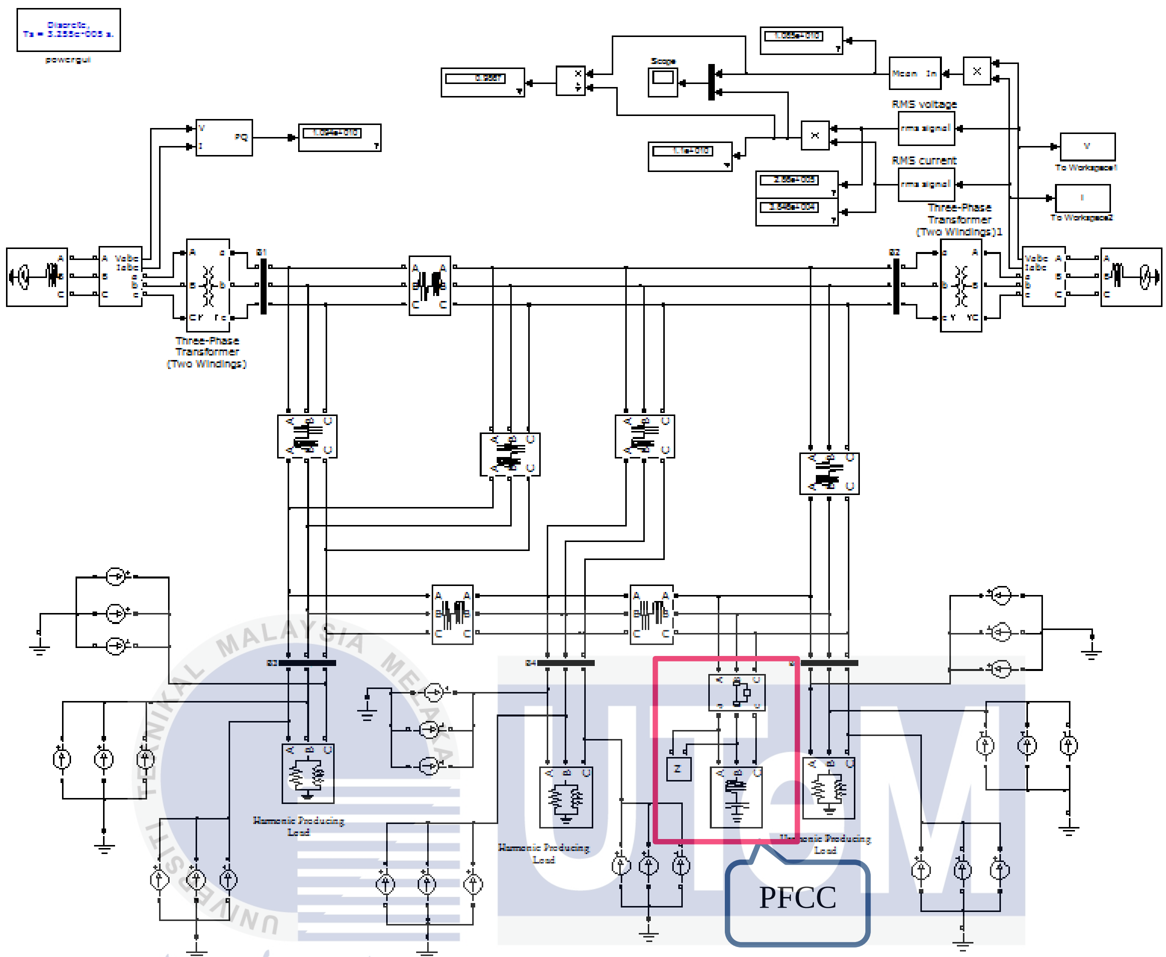

Figure 3.9: Simulation model of the IEEE 5-bus test system with PFCC

Figure 3.9 shows the simulation model of the IEEE 5-bus test system with PFCC. The PFCC is located on bus 5.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

There are two types of test system to be tested, 2-bus test system and IEEE 5-bus test system. The system will be tested and analyzed by using MATLAB/SimPowerSystem. The objective of the project is to analyze the impact of PFCC on the network resonance and harmonic distortion.

4.2 2-Bus Test System

4.2.1 Harmonic Resonance Analysis

This project is conducted to verify the performance of the PFCC. The simulation results of the 2-bus test system with and without PFCC are presented. This project uses Fast Fourier Transform (FFT) to detect and analyze the harmonic veracity and obtain the data of harmonic number and contents.

Figure 4.1 shows the harmonic current spectrum for 2-bus test system without and with PFCC assembly. Based on the harmonic spectrum obtained from the simulation, it is seen that the harmonic distortions are slightly reduced when PFCC is connected in the system.

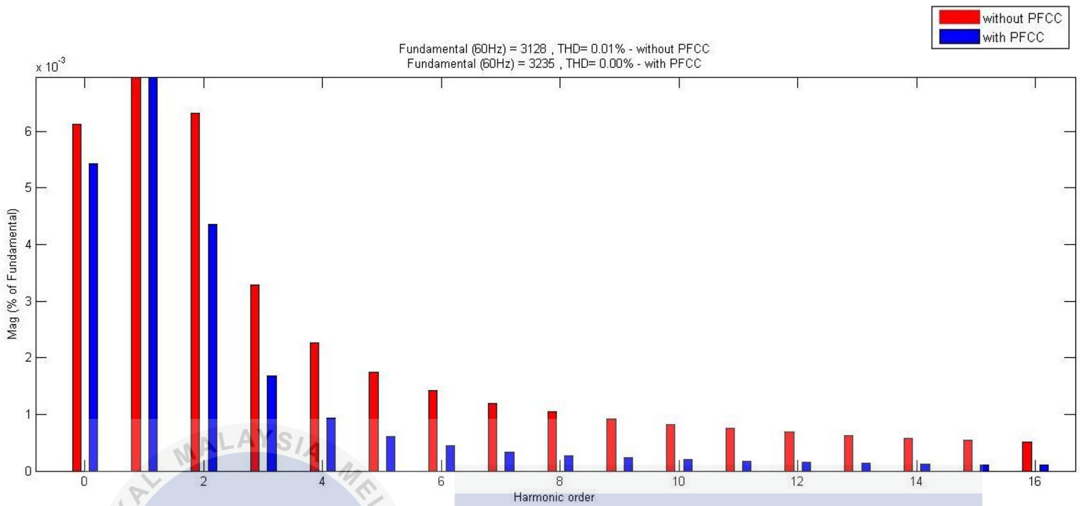

Figure 4.1: Harmonic current spectrum for 2-bus test system without and with PFCC

Figure 4.2 shows the current waveform for 2-bus test system without and with PFCC assembly in the system. The current waveforms for both conditions are same.

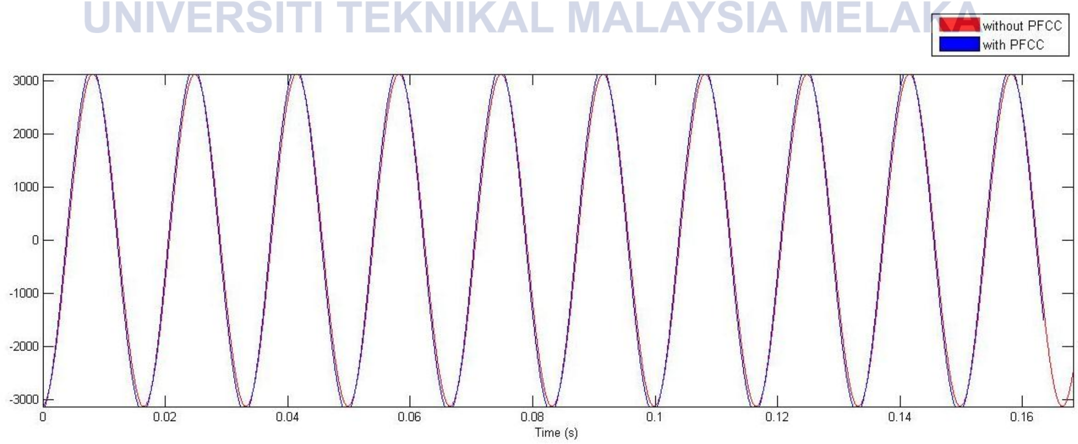

Figure 4.2: Current waveform for 2-bus test system without and with PFCC

Figure 4.3 shows the harmonic voltage spectrum for 2-bus test system without and with PFCC assembly. There are reductions in harmonic distortion after PFCC assembly.

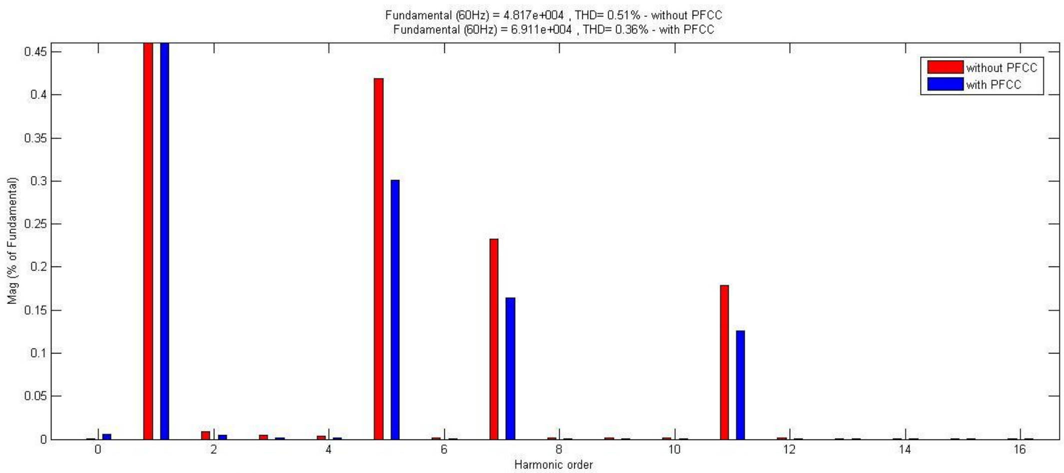

Figure 4.3: Harmonic voltage spectrum for 2-bus test system without and with PFCC

Figure 4.4 shows the voltage waveform for the 2-bus test system. By referring to the waveform, there are differences between without and with PFCC assembly.

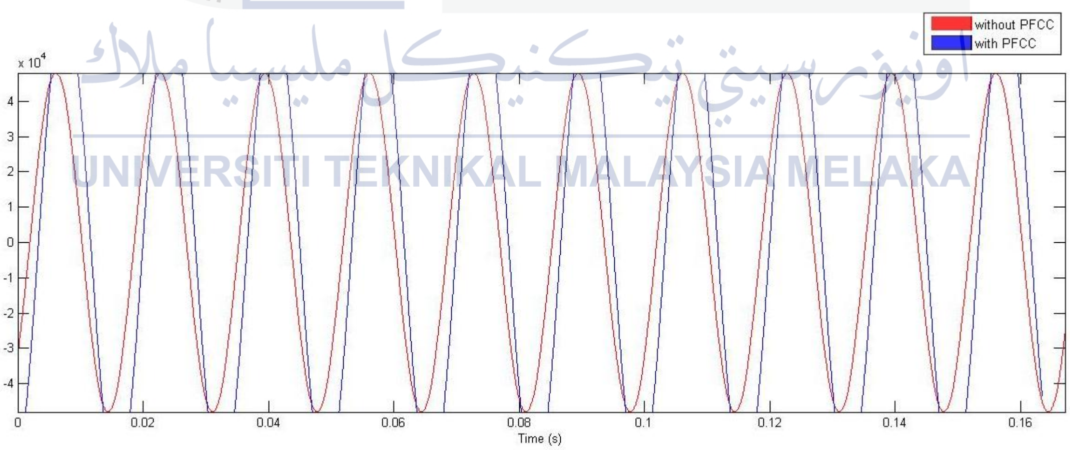

Figure 4.4: Voltage waveform for 2-bus test system without and with PFCC

Figure 4.5 shows the frequency scan of the 2-bus test system.

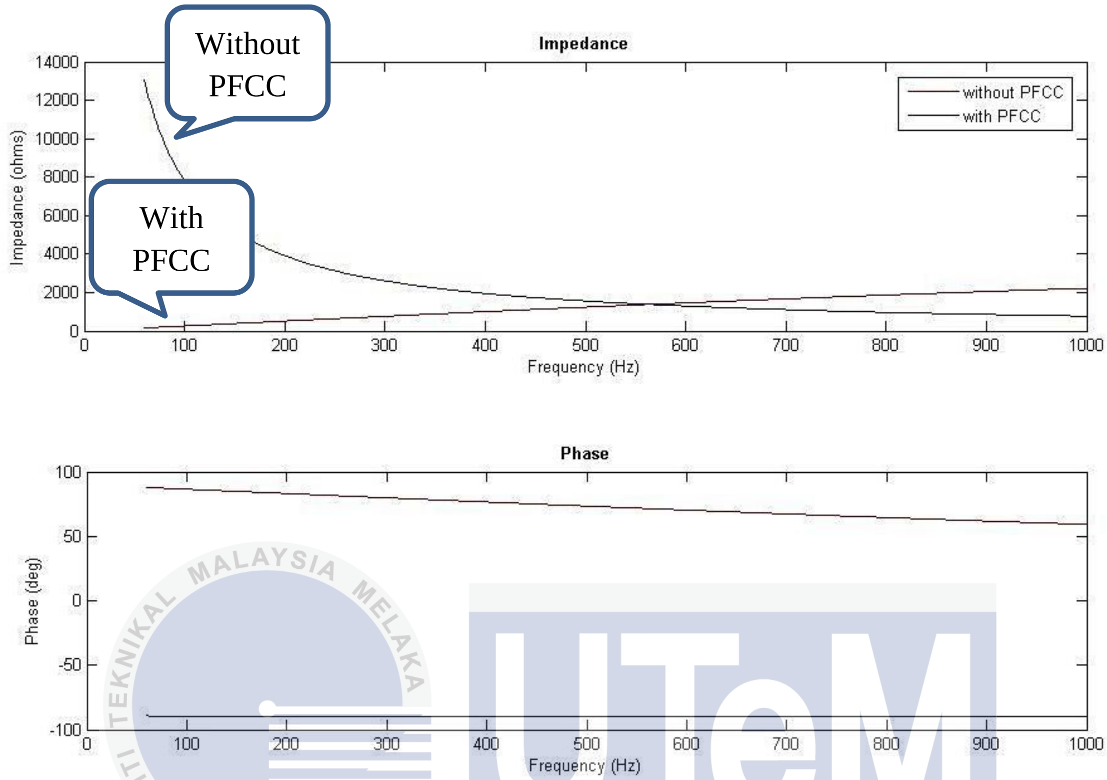

Figure 4.5: Frequency scan for 2-bus test system

Table 4.1: Comparison of system with and without PFCC assembly in 2-bus test system

	Without PFCC	**With PFCC**
Power Factor (pf)	0.71	0.98
THD_I	0.01%	0.00%
THD_V	0.51%	0.36%

Through the simulation of the 2-bus test system, the power factor is improved from 0.71 (without PFCC) to 0.98 (with PFCC). The frequency scan shows a different graph between without PFCC and with PFCC. Two simulation scenarios are created which is the 2-bus test system without connection of PFCC and with the connection of PFCC. This is to analyze the impact of PFCC in eliminating the presence of harmonic distortion and also to improve the power factor.

The total harmonic distortion of current and voltage (THD_I and THD_V) for both scenarios are shown in Table 4.1. The THD_I and THD_V are obtained through a Fast Fourier Transform (FFT) analysis. From the result, it can be seen that with the absence of PFCC, the THD_V is 0.51% where with the presence of PFCC, the THD_V is 0.36%. From the result, it is evidence that with the PFCC assembly at the 2-bus test system, the harmonic distortion and the power factor has improved. The PFCC gives an impact where the presence of harmonic distortion in the 2-bus test system is reduced.

4.3 IEEE 5-Bus Test System

4.3.1 Harmonic Resonance Analysis

The same process is used to verify the performance of the PFCC at IEEE 5-bus test system. The simulation result of the IEEE 5-bus test system with and without PFCC is presented.

Figure 4.6 shows the harmonic current spectrum for IEEE 5-bus test system without and with PFCC assembly.

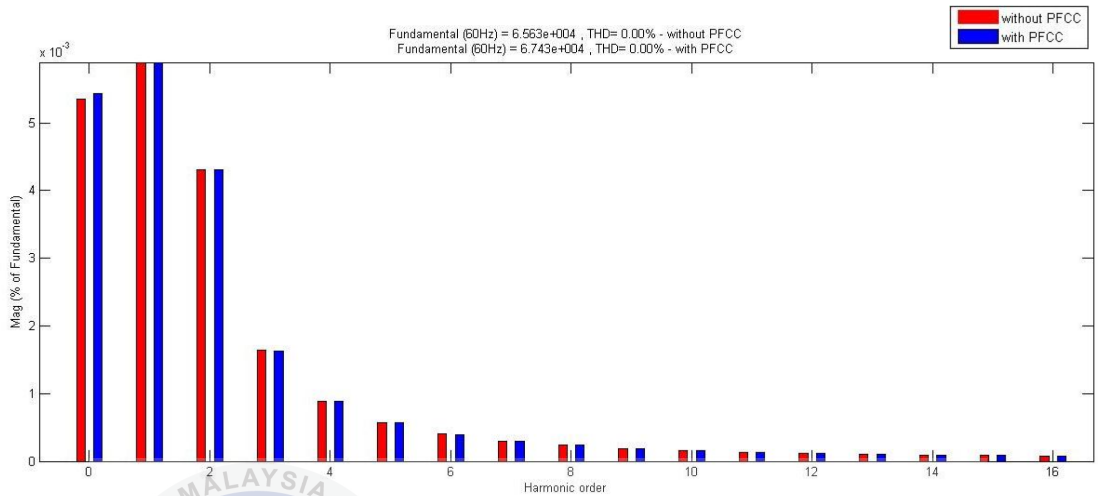

Figure 4.6: Harmonic current spectrum for IEEE 5-bus test system without and with PFCC

Figure 4.7 shows the current waveform for IEEE 5-bus test system without and with PFCC assembly. The waveform shows that there is no difference between before and after PFCC assembly.

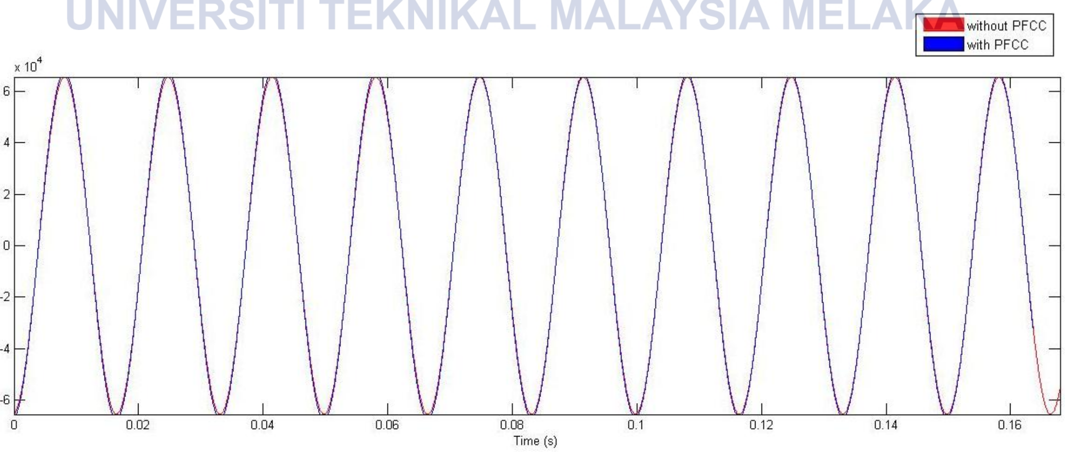

Figure 4.7: Current waveform for IEEE 5-bus test system without and with PFCC

Figure 4.8 shows the harmonic voltage for IEEE 5-bus test system without and with PFCC. The harmonic distortions are reduced after PFCC assembly in the system.

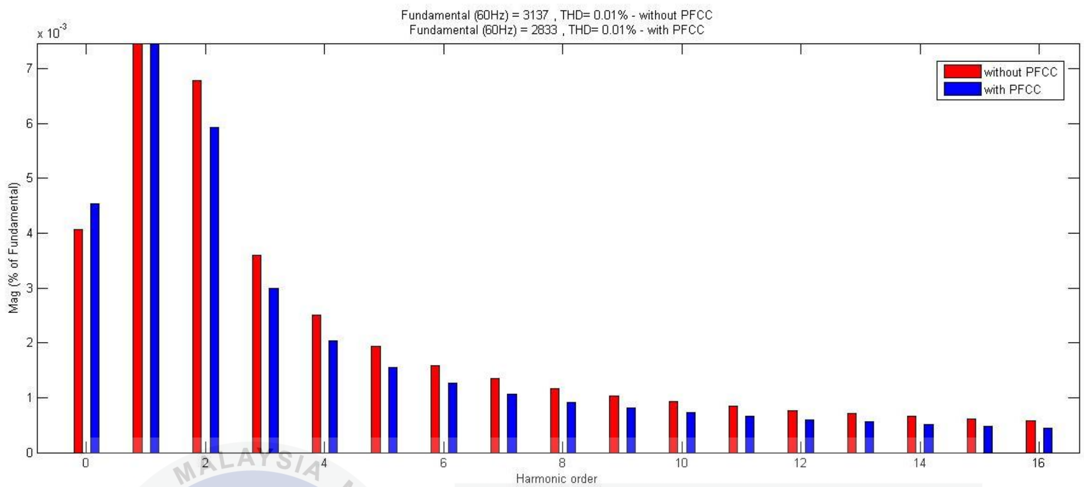

Figure 4.8: Harmonic voltage for IEEE 5-bus test system without and with PFCC

Figure 4.9 shows the voltage waveform for IEEE 5-bus test system without and with PFCC. Based on the waveform, it can be seen that there are slightly difference between the two waveforms.

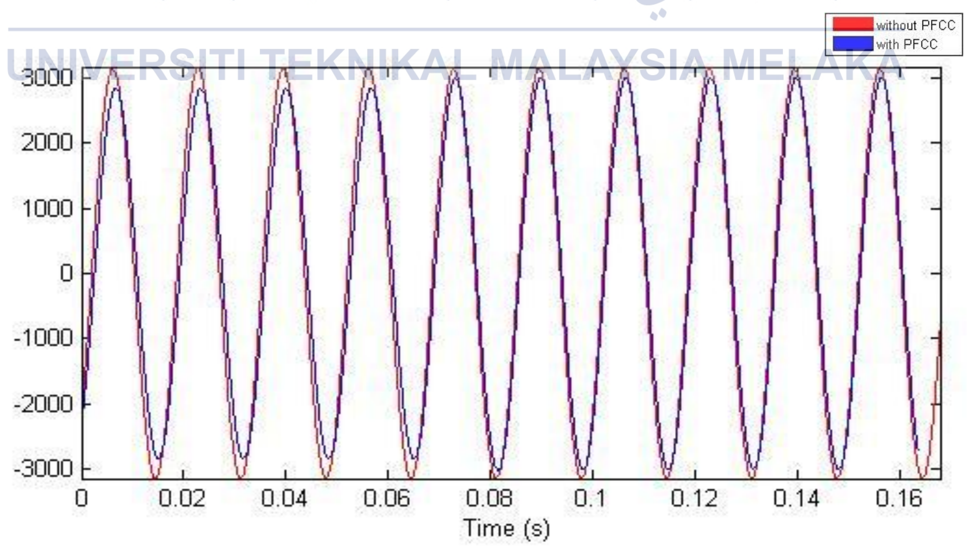

Figure 4.9: Voltage waveform for IEEE 5-bus test system without and with PFCC

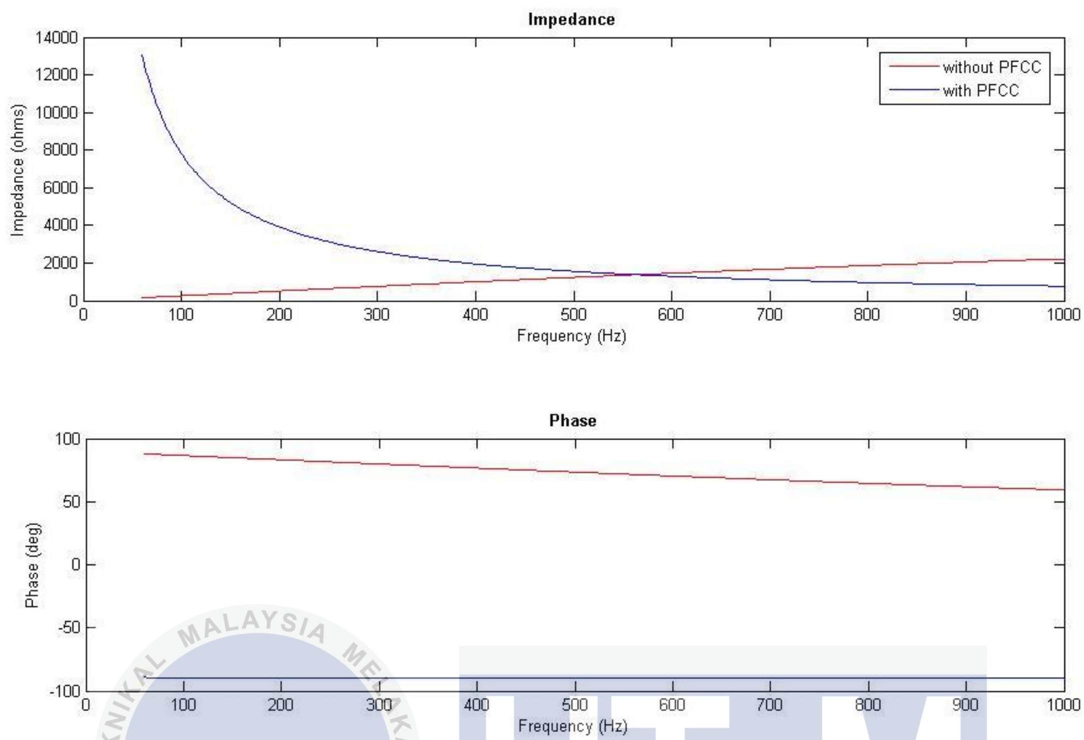

Figure 4.10: Frequency scan for IEEE 5-bus test system

Table 4.2: Comparison of system with and without PFCC assembly in IEEE 5-bus test system

	Without PFCC	**With PFCC**
Power Factor (pf)	0.74	0.82
THD_I	0.00%	0.00%
THD_V	0.01%	0.01%

From the simulation of IEEE 5-bus test system, the result shows that the power factor is improved from 0.74 (without PFCC) to 0.82 (with PFCC). There are differences of the frequency scan between with PFCC and without PFCC. The two conditions of the systems that being tested in MATLAB/SimPowerSystem, are IEEE 5-bus test system without connection of PFCC and with the connection of PFCC. This is to analyze the impact of PFCC in the IEEE 5-

bus test system in eliminating the presence of harmonic distortion and also to improve the power factor.

The total harmonic distortion of current and voltage (THD_I and THD_V) for both scenarios are shown in Table 4.2. The THD_I and THD_V are obtained through a Fast Fourier Transform (FFT) analysis. From the result, it can be seen that with the absence of PFCC, the THD_V is 0.01% where with the presence of PFCC, the THD_V is 0.01%. From the simulation, there are no distortions on current, THD_I . Even though the THD_I and THD_V results give no difference, but there is an improvement in terms of power factor.

CHAPTER 5

CONCLUSION

5.1 Conclusion

In this project, the MATLAB/SimPowerSystem environment is used to simulate the model of 2-bus test system and the IEEE 5-bus test system. This project presents the PFCC which is used for improvement of power factor and to eliminate the harmonic distortions. The efficiency of PFCC has been proven in the 2-bus test system and the IEEE 5-bus test system. Simulation results show the effectiveness of PFCC where it confirms that the method used in this project, which is the PFCC is one of the alternatives to eliminate or minimize the harmonic distortions in the electrical system.

5.2 Suggestion For Future Improvement

As for the future outlook of this project, there are many possible enhancements and improvements that can be made. It is hoped that the suggestions given will be able to be used as a guideline to some other ken developers or researchers in the future.

This project is not limited to the 2-bus test system and IEEE 5-bus test system only. This project can be tested on other system configuration, such as the IEEE 9-bus test system or the IEEE 13-bus test system. This will prove the effectiveness of PFCC in improving power factor and eliminating harmonic distortions and resonance.

The harmonic producing load used on the system is not limited to thyristor only. It can be substituted with other harmonic producing load. For example, another nonlinear load is inverter, motors and heaters. As for eliminating the harmonic resonance, this project uses PFCC as a filter. For future study and research, the filter can be substituted with other filter such as shunt passive filter or active filter.

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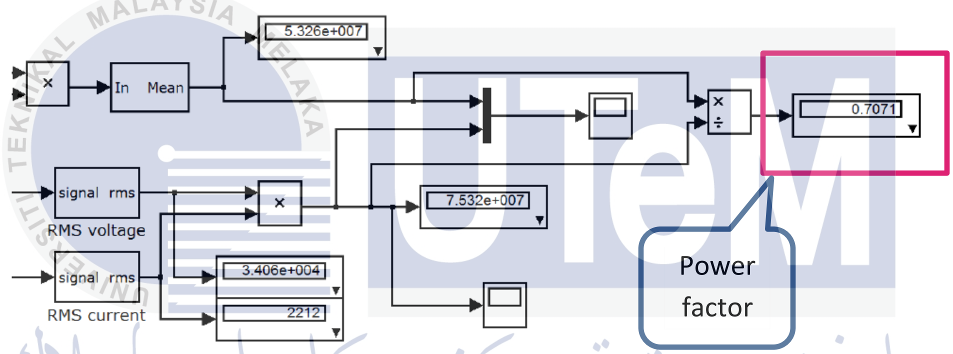
Appendix A

Appendix B

- **2-Bus Test System**

i) System without PFCC

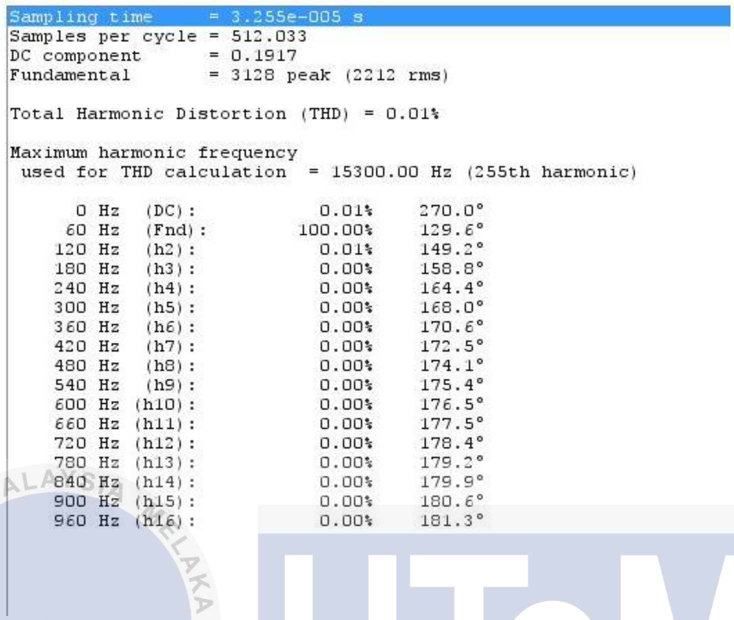
▪ Power factor



▪ Total Harmonic Distortion on voltage (THD_V)

```
Sampling time       = 3.255e-005 s
Samples per cycle = 512.033
DC component      = 0.3112
Fundamental       = 4.817e+004 peak (3.406e+004 rms)

Total Harmonic Distortion (THD) = 0.51%

Maximum harmonic frequency
 used for THD calculation  = 15300.00 Hz (255th harmonic)

     0 Hz  (DC):          0.00%     270.0°
    60 Hz  (Fnd):       100.00%     174.5°
   120 Hz  (h2):          0.01%     177.8°
   180 Hz  (h3):          0.00%     179.2°
   240 Hz  (h4):          0.00%     180.2°
   300 Hz  (h5):          0.42%      -0.9°
   360 Hz  (h6):          0.00%     183.5°
   420 Hz  (h7):          0.23%      95.1°
   480 Hz  (h8):          0.00%     176.8°
   540 Hz  (h9):          0.00%     177.8°
   600 Hz (h10):          0.00%     175.7°
   660 Hz (h11):          0.18%     -82.8°
   720 Hz (h12):          0.00%     189.5°
   780 Hz (h13):          0.00%     186.9°
   840 Hz (h14):          0.00%     186.3°
   900 Hz (h15):          0.00%     186.2°
   960 Hz (h16):          0.00%     186.3°
```

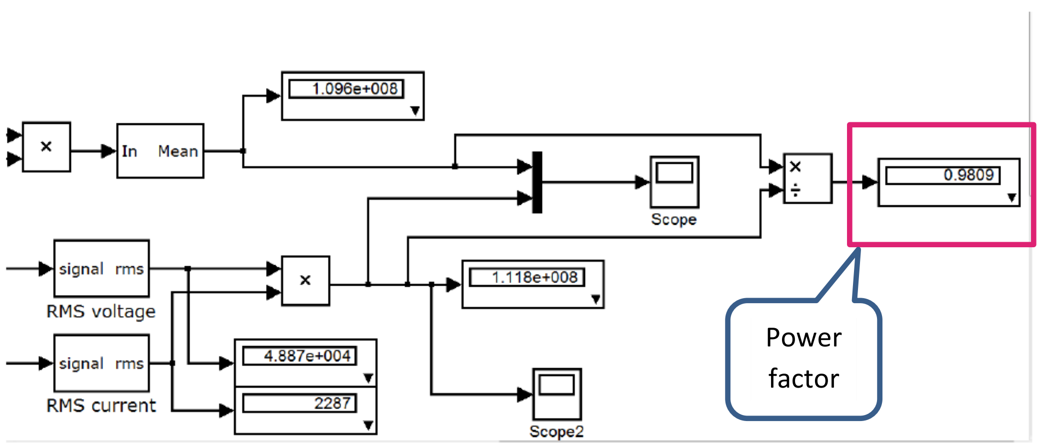
- Total Harmonic Distortion on current (THD_I)



```
Sampling time        = 3.255e-005 s
Samples per cycle = 512.033
DC component       = 0.1917
Fundamental        = 3128 peak (2212 rms)

Total Harmonic Distortion (THD) = 0.01%

Maximum harmonic frequency
 used for THD calculation  = 15300.00 Hz (255th harmonic)

     0 Hz   (DC):          0.01%     270.0°
    60 Hz  (Fnd):        100.00%     129.6°
   120 Hz   (h2):          0.01%     149.2°
   180 Hz   (h3):          0.00%     158.8°
   240 Hz   (h4):          0.00%     164.4°
   300 Hz   (h5):          0.00%     168.0°
   360 Hz   (h6):          0.00%     170.6°
   420 Hz   (h7):          0.00%     172.5°
   480 Hz   (h8):          0.00%     174.1°
   540 Hz   (h9):          0.00%     175.4°
   600 Hz  (h10):          0.00%     176.5°
   660 Hz  (h11):          0.00%     177.5°
   720 Hz  (h12):          0.00%     178.4°
   780 Hz  (h13):          0.00%     179.2°
   840 Hz  (h14):          0.00%     179.9°
   900 Hz  (h15):          0.00%     180.6°
   960 Hz  (h16):          0.00%     181.3°
```

ii) System with PFCC

- Power factor



- Total Harmonic Distortion on voltage (THD_V)

```
Sampling time      = 3.255e-005 s
Samples per cycle = 512.033
DC component      = 3.931
Fundamental       = 6.911e+004 peak (4.886e+004 rms)

Total Harmonic Distortion (THD) = 0.36%

Maximum harmonic frequency
 used for THD calculation  = 15300.00 Hz (255th harmonic)

      0 Hz  (DC):          0.01%     90.0°
     60 Hz  (Fnd):       100.00%    -71.4°
    120 Hz  (h2):          0.00%    -57.7°
    180 Hz  (h3):          0.00%    -47.4°
    240 Hz  (h4):          0.00%    -41.0°
    300 Hz  (h5):          0.30%     -9.7°
    360 Hz  (h6):          0.00%    -29.0°
    420 Hz  (h7):          0.16%     16.4°
    480 Hz  (h8):          0.00%    -17.3°
    540 Hz  (h9):          0.00%    -18.7°
    600 Hz (h10):          0.00%    -23.7°
    660 Hz (h11):          0.13%     57.9°
    720 Hz (h12):          0.00%      1.9°
    780 Hz (h13):          0.00%     -1.8°
    840 Hz (h14):          0.00%     -2.5°
    900 Hz (h15):          0.00%     -2.3°
    960 Hz (h16):          0.00%     -1.9°
```

- Total Harmonic Distortion on current (THD_I)

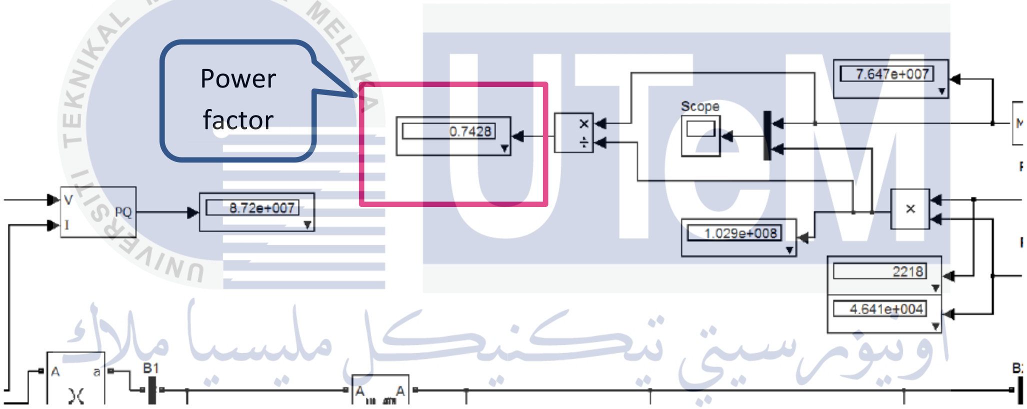
```
Sampling time      = 3.255e-005 s
Samples per cycle = 512.033
DC component      = 0.1756
Fundamental       = 3235 peak (2287 rms)

Total Harmonic Distortion (THD) = 0.00%

Maximum harmonic frequency
 used for THD calculation  = 15300.00 Hz (255th harmonic)

      0 Hz  (DC):          0.01%     90.0°
     60 Hz  (Fnd):       100.00%    -82.7°
    120 Hz  (h2):          0.00%    -76.2°
    180 Hz  (h3):          0.00%    -69.9°
    240 Hz  (h4):          0.00%    -64.0°
    300 Hz  (h5):          0.00%    -58.5°
    360 Hz  (h6):          0.00%    -53.5°
    420 Hz  (h7):          0.00%    -48.9°
    480 Hz  (h8):          0.00%    -44.8°
    540 Hz  (h9):          0.00%    -41.1°
    600 Hz (h10):          0.00%    -37.7°
    660 Hz (h11):          0.00%    -34.7°
    720 Hz (h12):          0.00%    -31.9°
    780 Hz (h13):          0.00%    -29.4°
    840 Hz (h14):          0.00%    -27.1°
    900 Hz (h15):          0.00%    -25.0°
    960 Hz (h16):          0.00%    -23.1°
```

Appendix C

- **IEEE 5-Bus Test System**

iii) System without PFCC

- Power factor



- Total Harmonic Distortion on voltage (THD_V)

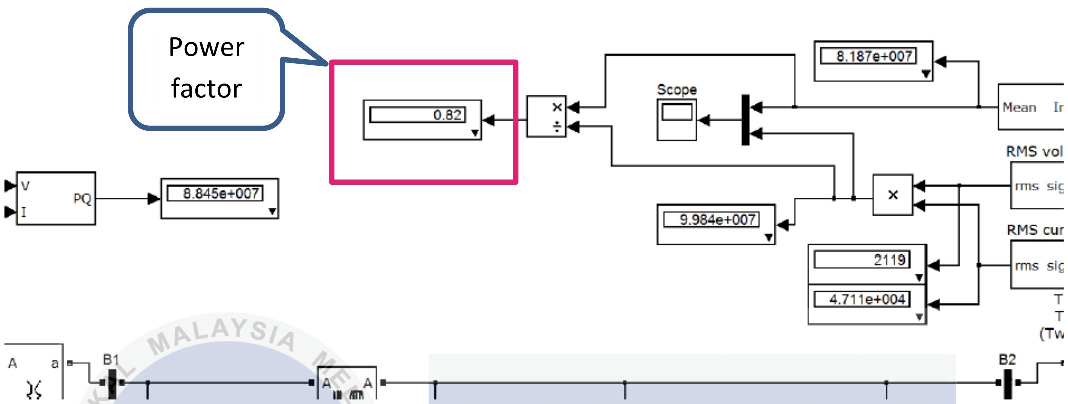
```
Sampling time      = 3.255e-005 s
Samples per cycle = 512.033
DC component      = 0.1273
Fundamental       = 3137 peak (2218 rms)

Total Harmonic Distortion (THD) = 0.01%

Maximum harmonic frequency
 used for THD calculation  = 15300.00 Hz (255th harmonic)

      0 Hz  (DC):          0.00%     90.0°
     60 Hz  (Fnd):       100.00%    -43.0°
    120 Hz  (h2):          0.01%    -25.0°
    180 Hz  (h3):          0.00%    -16.8°
    240 Hz  (h4):          0.00%    -12.2°
    300 Hz  (h5):          0.00%     -9.2°
    360 Hz  (h6):          0.00%     -7.1°
    420 Hz  (h7):          0.00%     -5.4°
    480 Hz  (h8):          0.00%     -4.1°
    540 Hz  (h9):          0.00%     -3.0°
    600 Hz (h10):          0.00%     -2.0°
    660 Hz (h11):          0.00%     -1.2°
    720 Hz (h12):          0.00%     -0.4°
    780 Hz (h13):          0.00%      0.3°
    840 Hz (h14):          0.00%      1.0°
    900 Hz (h15):          0.00%      1.6°
    960 Hz (h16):          0.00%      2.2°
```

- Total Harmonic Distortion on current (THD_I)


```
Sampling time      = 3.255e-005 s
Samples per cycle = 512.033
DC component      = 3.517
Fundamental       = 6.563e+004 peak (4.641e+004 rms)

Total Harmonic Distortion (THD) = 0.00%

Maximum harmonic frequency
 used for THD calculation  = 15300.00 Hz (255th harmonic)

      0 Hz  (DC):          0.01%     90.0°
     60 Hz  (Fnd):       100.00%    -85.1°
    120 Hz  (h2):          0.00%    -80.7°
    180 Hz  (h3):          0.00%    -76.4°
    240 Hz  (h4):          0.00%    -72.1°
    300 Hz  (h5):          0.00%    -68.0°
    360 Hz  (h6):          0.00%    -64.0°
    420 Hz  (h7):          0.00%    -60.2°
    480 Hz  (h8):          0.00%    -56.6°
    540 Hz  (h9):          0.00%    -53.3°
    600 Hz (h10):          0.00%    -50.1°
    660 Hz (h11):          0.00%    -47.1°
    720 Hz (h12):          0.00%    -44.3°
    780 Hz (h13):          0.00%    -41.6°
    840 Hz (h14):          0.00%    -39.1°
    900 Hz (h15):          0.00%    -36.8°
    960 Hz (h16):          0.00%    -34.6°
```

iv) System with PFCC

- Power factor



- Total Harmonic Distortion on voltage (THD_V)

```
Sampling time      = 3.255e-005 s
Samples per cycle = 512.033
DC component       = 0.1284
Fundamental        = 2833 peak (2003 rms)

Total Harmonic Distortion (THD) = 0.01%

Maximum harmonic frequency
 used for THD calculation  = 15300.00 Hz (255th harmonic)

    0 Hz   (DC):          0.00%     90.0°
   60 Hz   (Fnd):       100.00%    -54.9°
  120 Hz   (h2):          0.01%    -35.6°
  180 Hz   (h3):          0.00%    -25.1°
  240 Hz   (h4):          0.00%    -18.8°
  300 Hz   (h5):          0.00%    -14.8°
  360 Hz   (h6):          0.00%    -11.8°
  420 Hz   (h7):          0.00%     -9.5°
  480 Hz   (h8):          0.00%     -7.7°
  540 Hz   (h9):          0.00%     -6.2°
  600 Hz  (h10):          0.00%     -4.9°
  660 Hz  (h11):          0.00%     -3.8°
  720 Hz  (h12):          0.00%     -2.8°
  780 Hz  (h13):          0.00%     -1.9°
  840 Hz  (h14):          0.00%     -1.1°
  900 Hz  (h15):          0.00%     -0.4°
  960 Hz  (h16):          0.00%      0.3°
```

- Total Harmonic Distortion on current (THD_I)

```
Sampling time     = 3.255e-005 s
Samples per cycle = 512.033
DC component      = 3.667
Fundamental       = 6.743e+004 peak (4.768e+004 rms)

Total Harmonic Distortion (THD) = 0.00%

Maximum harmonic frequency
 used for THD calculation  = 15300.00 Hz (255th harmonic)

    0 Hz  (DC):          0.01%     90.0°
   60 Hz  (Fnd):       100.00%    -84.8°
  120 Hz  (h2):          0.00%    -80.7°
  180 Hz  (h3):          0.00%    -76.5°
  240 Hz  (h4):          0.00%    -72.3°
  300 Hz  (h5):          0.00%    -68.2°
  360 Hz  (h6):          0.00%    -64.3°
  420 Hz  (h7):          0.00%    -60.6°
  480 Hz  (h8):          0.00%    -57.0°
  540 Hz  (h9):          0.00%    -53.7°
  600 Hz (h10):          0.00%    -50.5°
  660 Hz (h11):          0.00%    -47.5°
  720 Hz (h12):          0.00%    -44.7°
  780 Hz (h13):          0.00%    -42.1°
  840 Hz (h14):          0.00%    -39.6°
  900 Hz (h15):          0.00%    -37.3°
  960 Hz (h16):          0.00%    -35.1°
```

Appendix D

Interpreting IEEE Std 519 and Meeting its Harmonic Limits in VFD Applications

Paper No. PCIC-2003-15

Tony Hoevenaars, P. Eng.
Member IEEE
Mirus International Inc.
#12, 6805 Invader Cres.
Mississauga, ON L5T 2K6
Canada

Kurt LeDoux, P.E.
Member, IEEE
Toshiba International Corp.
13131 West Little York Rd.
Houston, TX 77041
USA

Matt Colosino

Crescent Power Systems, Inc.
129 Polk St.
New Orleans, LA 70124
USA

Abstract –

IEEE Std 519 was first introduced in 1981 to provide direction on dealing with harmonics introduced by static power converters and other nonlinear loads so that power quality problems could be averted. It is being applied by consulting engineers and enforced by Utilities more frequently in recent years as the use of Variable Frequency Drives and other non-linear loads has grown.

Two of the more difficult aspects of applying IEEE Std 519 are (i) determining an appropriate point of common coupling (PCC) and (ii) establishing a demand current at the design stage. This is because the standard does not provide a concise definition of the PCC and the recommended definition of demand current is a value that can only be determined by measurements taken after installation.

This paper represents the authors' best interpretation of IEEE Std 519. It attempts to provide clarity in the determination of the PCC and offers a means by which IEEE Std 519 can be applied at the design stage when the precise demand current is unknown.

Index Terms —

Point of Common Coupling (PCC): *(As found on p75 of IEEE Std 519-1992)* A point of metering, or any point as long as both the utility and the consumer can either access the point for direct measurement of the harmonic indices meaningful to both or can estimate the harmonic indices at point of interference (POI). Within an industrial plant, the PCC is the point between the nonlinear load and the other loads.[1]
(As presently defined by IEEE 519 Working Group) The Point of Common Coupling (PCC) with the consumer/utility interface is the closest point on the utility side of the customer's service where another utility customer is or could be supplied. The ownership of any apparatus such as a transformer that the utility might provide in the customer's system is immaterial to the definition of the PCC.[2]

Short Circuit Ratio (I_{SC}/I_L): The ratio of the short circuit current (I_{SC}) available at the point of common coupling (PCC) to the maximum fundamental load current (I_L).[1]

Maximum Load Current (I_L): Is recommended to be the average current of the maximum demand for the preceding 12 months.[1] *(Unfortunately, this value is inherently ambiguous making it difficult to derive at the design stage when measured load is not available)*.

Voltage THD: Total Harmonic Distortion of the voltage waveform. The ratio of the root-sum-square value of the harmonic content of the voltage to the root-mean-square value of the fundamental voltage.[1]

$$V_{THD} = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + V_5^2 + \ldots}}{V_1} \times 100\%$$

Current THD: Total Harmonic Distortion of the current waveform. The ratio of the root-sum-square value of the harmonic content of the current to the root-mean-square value of the fundamental current.[1]

$$I_{THD} = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + I_5^2 + \ldots}}{I_1} \times 100\%$$

Current TDD: Total Demand Distortion of the current waveform. The ratio of the root-sum-square value of the harmonic current to the maximum demand load current.[1]

$$I_{TDD} = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + I_5^2 + \ldots}}{I_L} \times 100\%$$

Variable Frequency Drive (VFD): A solid-state device that converts utility power to a variable voltage and frequency in order to control the speed of a three-phase induction motor. Drives typically use harmonic generating rectifiers on their front-end for AC-DC conversion.

I. INTRODUCTION

With their many benefits, Variable Frequency Drives (VFD's) have grown rapidly in their usage in recent years. This is particularly true in the Petrochemical Industry where their use in pumping and other applications has led to significant energy savings, improved process control, increased production and higher reliability.

An unfortunate side effect of their usage however, is the introduction of harmonic distortion in the power system. As a non-linear load, a VFD draws current in a non-sinusoidal manner, rich in harmonic components. These harmonics flow through the power system where they can distort the supply voltage, overload electrical distribution equipment (such as transformers) and resonate with power factor correction capacitors among other issues.

In order to prevent harmonics from negatively affecting the Utility supply, IEEE Std 519 has been established as the 'Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems'. This standard has been widely adopted, particularly in North America, but has often been misinterpreted and/or misapplied creating installations that have either been expensively overbuilt or critically under designed.

IEEE Std 519 in 1981 gave simple guidelines for limits on voltage distortion. In 1992, it more clearly established limits for both voltage and current distortion. Its 100 pages cover many aspects of harmonics in very technical detail making it difficult for the non-expert to decipher and isolate the important aspects of its implementation. This paper will attempt to simplify interpretation of the most applicable portions of the standard, allowing consulting and facility engineers to become more comfortable with applying the standard where necessary and appropriate.

In addition, a case study is presented which describes an application where a passive harmonic filter was used in an Electrical Submersible Pump application. The filter was applied to a standard AC PWM Variable Frequency Drive with a 6-pulse rectifier front-end to meet the limits proposed in IEEE Std 519 while maintaining optimum VFD performance.

II. IEEE STD 519

IEEE Std 519 was introduced in 1981 and was most recently revised in 1992. It was intended to provide direction on dealing with harmonics introduced by static power converters and other nonlinear loads. The list of static power converters is extensive. It includes power rectifiers, adjustable speed or variable frequency drives (both AC and DC), switch-mode power supplies, uninterruptible power supplies and other devices that convert ac to dc, dc to dc, dc to ac or ac to ac. The standard recognizes the responsibility of an electricity user to not degrade the voltage of the Utility by drawing heavy nonlinear or distorted currents. It also recognizes the responsibility of the Utility to provide users with a near sine wave voltage.

The standard was written to establish goals for the design of electrical systems with both linear and nonlinear loads. Distortion limits for both current and voltage are defined in order to minimize interference between electrical equipment. It is presented as a guideline for power system design when nonlinear loads are present and assumes steady-state operation.

Sections 4 through 9 of the standard provide quite extensive discussion on the generation of harmonics, typical system response to these harmonics, their effects, methods of reduction, methods of analysis and measurement techniques. This information can help in developing a better understanding of the problem and those interested should take some time to read these sections. This paper will make reference to these sections when appropriate but will not cover them in detail.

From an electrical users perspective, Section 10 is the most important section in the standard. It describes the 'Recommended Practices for Individual Consumers'. The primary focus of this paper will be on the items in this section and how they can be applied to VFD applications. Section 11, which describes 'Recommended Practices for Utilities', will not be discussed.

IEEE Std 519 was intended to be used as a system standard. The voltage and current harmonic limits presented in the standard were designed to be applied while taking the entire system into consideration, including all linear and non-linear loading. However, many consulting and facility engineers have found it difficult to apply IEEE Std 519 as a system standard because detailed information on the system and its loading is often not available at the design stage. It is therefore, difficult to accurately determine compliance at this stage. And even when the information is available, the resources required to do a proper analysis does not always exist. Further complicating matters is that the standard applies to the maximum load current which may be a poor estimate at the design stage.

Therefore, in order to ensure that some harmonic limits are applied, these engineers have often resorted to applying the standard on an individual equipment basis. By insisting that the current harmonic limits be met at the terminals of the non-linear equipment, compliance on a system basis can be ensured. Although this approach can be effective, it often requires very costly and sometimes unreliable treatment equipment that many VFD manufacturers have been reluctant to integrate into their product offerings.

III. IEEE STD 519 RECOMMENDED PRACTICES FOR INDIVIDUAL CONSUMERS

Section 10 of IEEE Std 519 defines the limits for various harmonic indices that the authors of the standard believe strongly correlate to harmonic effects. The defined indices are:

1. Depth of notches, total notch area, and distortion of the bus voltage by commutation notches
2. Individual and total voltage distortion
3. Individual and total current distortion

The philosophy adopted to develop the limits for these indices was to restrict harmonic current injection from individual customers so that they would not cause unacceptable voltage distortion levels when applied to normal power systems. Notches and voltage distortion are presented in a single table, Table 10.2, 'Low-Voltage System Classification and Distortion Limits'. Current distortion limits are found in 3 separate tables based on bus voltage levels. Table 10.3 is applied to distribution systems of 120 V to 69,000 V. Table 10.4 is 69,001 V to 161,000 V and Table 10.5 is > 161 kV. Since essentially all VFD applications fall into the 120 V to 69,000 V range, only Table 10.3 will be analyzed in this paper.

IV. IEEE STD 519 VOLTAGE HARMONIC LIMITS

Table 10.2 in IEEE Std 519 establishes harmonic limits on voltage as 5% for total harmonic distortion and 3% of the fundamental voltage for any single harmonic (see Figure 1). The justification for these limits is not fully explained but a reference in Section 6.6 states that:

"Computers and allied equipment, such as programmable controllers, frequently require ac sources that have no more than a 5% harmonic voltage distortion factor, with the largest single harmonic being no more than 3% of the fundamental voltage. Higher levels of harmonics result in erratic, sometimes subtle, malfunctions of the equipment that can, in some cases, have serious consequences. Instruments can be affected similarly, giving erroneous data or otherwise performing unpredictably. Perhaps the most serious of these are malfunctions in medical instruments."[1]

The reference to medical equipment sensitivity provides some indication as to why the limits are even more severe (less than 3% V_{THD}) for special applications such as hospitals and airports (see note 1 in Figure 1). In contrast, the limits are relaxed (V_{THD} < 10%) for dedicated systems. A dedicated system is defined as one that is exclusively dedicated to converter loads assuming the equipment manufacturer will allow for operation at these higher distortion levels.

For applications in the petrochemical industry, the general system limits are most appropriate. This means that we must design our systems for < 5% V_{THD} and with no single harmonic greater than 3%. These generally will be met at the PCC provided the current harmonic limits are met.

It should be noted that even if the voltage distortion limits are met at the PCC, they could very easily be exceeded downstream where connected equipment could be affected. Since voltage distortion is the result of harmonic currents passing through the impedance of the power system, voltage distortion will always be higher downstream where the harmonic currents are generated and where system impedance is highest.[3]

V. IEEE STD 519 CURRENT HARMONIC LIMITS

The level of harmonic voltage distortion on a system that can be attributed to an electricity consumer will be the function of the harmonic current drawn by that consumer and the impedance of the system at the various harmonic frequencies. A system's impedance can be represented by the short circuit capacity of that system since the impedance will limit current that will be fed into a short circuit. Therefore, the short circuit capacity can be used to define the size and influence of a particular consumer on a power system. It can be used to reflect the level of voltage distortion that current harmonics produced by that consumer would contribute to the overall distortion of the power system to which it is connected.

To define current distortion limits, IEEE Std 519 uses a short circuit ratio to establish a customers size and potential influence on the voltage distortion of the system. The short circuit ratio (I_{SC}/I_L) is the ratio of short circuit current (I_{SC}) at the point of common coupling with the utility, to the customer's maximum load or demand current (I_L). Lower ratios or higher impedance systems have lower current distortion limits to keep voltage distortion at reasonable levels.

For power systems with voltage levels between 120 V and 69,000 V, the limits can be found in Table 10.3 of the standard (see Figure 2). The table defines Total Demand Distortion (current) limits as well as individual harmonic current limits. The limits are most severe for short circuit ratios of less than 20 because this lower ratio indicates a high impedance power system or a large customer or both. Voltage distortion is more likely to develop from current harmonics consumed at a PCC where the short circuit ratio is low, thereby justifying the more severe limits.

VI. DETERMINING AN APPROPRIATE POINT OF COMMON COUPLING (PCC)

Table 10.2, p77
Low-Voltage System Classification and Distortion Limits

	Special Applications[1]	General System	Dedicated System[2]
Notch Depth	10%	20%	50%
THD (voltage)	**3%**	**5%**	10%
Notch Area (A_N)[3]	16 400	22 800	36 500

NOTE: The Value A_N for other than 480 V systems should be multiplied by V/480
1 **Special applications include hospitals and airports**
2 A dedicated system is exclusively dedicated to the converter load
3 In volt-microseconds at rated voltage and current

Figure 1: Table of voltage distortion limits in IEEE Std 519

Table 10.3, p78
Current Distortion Limits for General Distribution Systems
(120 V Through 69,000 V)

Maximum Harmonic Current Distortion in Percent of I_L
Individual Harmonic Order (Odd Harmonics)

I_{SC}/I_L	<11	11≤h<17	17≤h<23	23≤h<35	35≤h	TDD
<20*	4.0	2.0	1.5	0.6	0.3	5.0
20<50	7.0	3.5	2.5	1.0	0.5	8.0
50<100	10.0	4.5	4.0	1.5	0.7	12.0
100<1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

Where:
I_{SC} = maximum short-circuit current at PCC.
I_L = maximum demand load current (fundamental frequency component) at PCC.

Figure 2: Table of current distortion limits in IEEE Std 519

One of the most difficult aspects to applying IEEE Std 519 is determining the location of the Point of Common Coupling or PCC. Since the original objective of IEEE Std 519 was to prevent the proliferation of non-linear loads from creating power system problems and in particular voltage distortion, the limits were intended to be applied at the point where a high level of harmonics generated by one customer could distort the power system to a level that might affect other customers on the power grid.

The concept of PCC has been used to define this point but unfortunately, the existing standard has not provided a clear definition. Two definitions are provided in the earlier 'Index Terms' section. The first is as found in Section 10 of IEEE Std 519. It has been found to be too ambiguous to be effectively applied on a consistent basis therefore, the 519 Working Group has provided a second definition which can be found on their website.

The second definition is more precise in that it stipulates that the PCC is 'the closest point on the utility side of the customer's service where another utility customer is or could be supplied'. It also points out that the ownership of any supply transformer is irrelevant. That is, if a supply transformer connected to the public power grid supplies only one customer, the PCC will be located at the primary of that transformer, rather than the secondary, regardless of whether the transformer is owned by that customer or the utility. This is an important distinction because the transformer's impedance will decrease the short circuit ratio and consequently increase the harmonic current limits. Also, voltage distortion will be higher on the secondary side of the transformer making it more difficult to meet the voltage distortion limits.

Although applying IEEE Std 519 limits at the transformer primary is allowed, good engineering practice should include consideration of the secondary side voltage distortion. Voltage distortion will always be higher downstream near the harmonic generating loads and therefore, meeting IEEE Std 519 limits at the PCC will not necessarily ensure that voltage distortion is less than 5% throughout the power distribution system.

VII. HOW TO ESTABLISH A DEMAND CURRENT DURING THE DESIGN STAGE

Maximum load current (or demand current), as used in the short circuit ratio (I_{SC}/I_L) and Total Demand Distortion (TDD) calculations, is given a recommended, rather than firm, definition in IEEE Std 519. It is recommended to be the average current of the maximum demand for the preceding 12 months. Unfortunately since this definition is a measured value, it is totally dependent upon the operating mode of the application, which makes determination at the design stage extremely difficult, if not impossible. Also, since the performance of many treatment methods will vary significantly with loading, designing an installation that will meet the limits under any and all operating conditions is very challenging when this definition is used.

What then should be used? It seems more practical to use the full load rated current of the non-linear load and apply a treatment method whose performance level does not degrade too severely under lighter loading conditions. This strategy is effective because, in general, a loads maximum contribution to harmonic distortion (both current and voltage) occurs when operating at full load. If percent current total harmonic distortion (I_{THD}) was the same at all load levels, a non-linear load running at rated current would draw more harmonic current than it would while running at a lighter load. And although I_{THD} normally increases as loading decreases, a non-linear load will draw less harmonic current at lighter loads even when the I_{THD} is higher provided the increase is proportionately less than the load decrease.

Figure 3 shows measurements taken on a 150HP, 6-pulse VFD that has had no harmonic treatment. As percent loading decreases, I_{THD} increases but the magnitude of the individual harmonic currents decreases. Since both voltage distortion and harmonic overheating are the result of the ampere level of the harmonic currents, they will be worse at full load operation even though the I_{THD} is higher at the lighter loads. Therefore if treatment applied to the VFD resulted in IEEE Std 519 limits being met at full load operation, then both voltage distortion and overheating would be satisfied at all load levels.

	Current (amps)		Current Harmonics (amps)					
Load	**RMS**	**60 Hz**	**5th**	**7th**	**11th**	**13th**	I_{THD}	I_{TDD}
Full	233	182	118	80	12	12	79%	79%
75%	187	142	96	70	15	7	86%	65%
50%	134	96	69	54	17	5	96%	48%
25%	67	43	33	29	14	9	120%	30%

Figure 3: Current measurements on a 150HP, 6-pulse VFD with no harmonic treatment

If we accept the premise that maximum load current should be the full rated current of the non-linear load, then we can determine current total demand distortion (I_{TDD}) and apply the limits found in Table 10.3 of the standard at the design stage. Total demand distortion is defined as 'the ratio of the root-sum-square value of the harmonic current to the maximum demand load current' (see 'Index Terms'). Therefore at rated load, I_{TDD} and I_{THD} are the same value. As load drops, the value of I_{TDD} relative to I_{THD} will drop proportionately with the load. For example, if I_{THD} is 96% at 50% loading, then I_{TDD} at that load would be ½ that value or 48% (see Figure 3).

VIII. CASE STUDY

Location: Amerada Hess Corporation, Tioga, ND
Application: Down Hole Electrical Submersible Pump (ESP)
VFD: 200HP, 480V AC PWM VFD
Harmonic Filter: 200HP, 480V series connected passive LC filter

The VFD was operating as part of an Electrical Submersible Pump (ESP) installation in a remote area of North Dakota. It was equipped with a built-in DC link reactor which reduced the harmonic currents reflected back into the power system by approximately 2 times. However, even at this reduced level, the harmonic currents generated by the VFD exceeded the limits as defined by IEEE Std 519, Table 10.3.

The Utility provided three 100 kVA, 12.5kV-480V 1-ph transformers with an impedance of 2.6% to supply the 200HP VFD. Fault current, Isc, on the primary side was 900A and 8,700A on the secondary side. The Utility was not specific as to the location of the PCC so both primary and secondary locations were considered.

Even without the installation of harmonic treatment, voltage distortion (V_{THD}) was comfortably below IEEE std 519 limits. V_{THD} on the secondary side of the transformer was measured at 3.4% (< 5% limit) with the largest harmonic being the 5^{th} at 2.3% (< 3% limit). Even though measurements could not be taken on the primary side because the measuring instrumentation was not suitably rated for the higher voltage, meeting the limits on the secondary side ensured that they were being met on the primary side. This is because the transformers impedance always results in higher voltage distortion on its secondary side than on its primary side.

To determine whether current distortion limits were met, the short circuit ratio was calculated.

For PCC at primary:
- I_{SC} = 900A
- I_L = 7A (full load 60 Hz current)
- I_{SC}/I_L = 128
- From Table 10.3, I_{TDD} <15%

For PCC at secondary:
- I_{SC} = 8,700A
- I_L = 180A (full load 60 Hz current)
- I_{SC}/I_L = 48
- From Table 10.3, I_{TDD} <8%

Current THD (I_{THD}) at the secondary of the transformer before installation of the Lineator filter was measured to be 35% when operating at 60% load which was the maximum operating load attainable at the time. Since the load current contained no zero sequence harmonic currents, the primary side I_{THD} could be assumed to be essentially the same as the secondary side. Using full load current rating as the peak demand, I_{TDD} was calculated to be 21% (35% x .6) which exceeded the IEEE 519 maximum limits on both the primary (15%) and the secondary (8%).

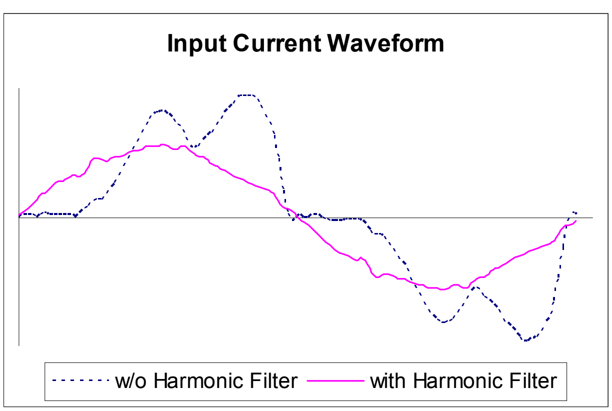


Figure 4: Input Current Waveform with and without harmonic filter

With the harmonic filter installed, I_{THD} dropped to 5.4% which was comfortably below the IEEE Std 519 limit at both the primary and secondary even without calculating I_{TDD} based on full load rating. Figure 4 shows the input current waveforms both with and without the harmonic filter. With the filter, current is virtually sinusoidal with a much lower peak level than without the filter.

One other benefit of the filter installation was a reduction in Radio Frequency Interference (RFI) which eliminated an AM reception problem experienced by a neighboring farmer.

IX. CONCLUSIONS

Applying the harmonic limits as defined in IEEE Std 519 to VFD applications is a useful exercise but often a challenging one. Most VFD suppliers and filter manufacturers can help by running a power system harmonic analysis for a specific application to determine THD levels at the point of common coupling. This analysis can be developed considering various harmonic attenuation methods while comparing hardware requirements, performance and cost.

It is also important to keep in mind that the entire power system comes into play when analyzing performance and reliability. For example, a 'weak' power system using onsite generation may not have the voltage and frequency stability to work in conjunction with an active filter or some passive filters with high capacitive reactance. Experience has also shown that drive performance can sometimes be impacted as the system architecture is modified in an attempt to lower THD levels. For critical systems, on-site performance testing may be helpful.

Overall, it is important to understand how the various system components interact with each other and with the power system. It is essential that a coordinated solution be provided which meets THD levels, system performance demands and power system requirements. Fixing a harmonic distortion problem in the field after installation can be difficult, time consuming and expensive.

V. ACKNOWLEDGEMENTS

Alan Hartwell, Amerada Hess Corporation, Williston, ND

VI. REFERENCES

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[3] A. H. Hoevenaars, "The Answer to Harmonics: Is it Mitigation or a Robust Transformer?", *CEE News – The Power Quality Advisor,* pp PQ14-17, February 2000.

[4] I. C. Evans, "Methods of Mitigation", *Middle East Electricity,* pp 25-26, December 2002.

VIII. VITA

Tony Hoevenaars is Vice President of MIRUS International Inc., a company specializing in the treatment of power system harmonics. Prior to joining MIRUS in 1996, Tony was the Chief Facilities Electrical Engineer at an IBM manufacturing facility in Toronto where he gained extensive experience in solving power quality related problems, particularly in the area of harmonics. He graduated from the University of Western Ontario, London ON Canada with a BESc degree in 1979. He is a Professional Engineer, member of IEEE and has published numerous papers on power quality.

Kurt LeDoux is an electrical engineer that has worked for Toshiba for more than 20 years in all aspects of AC and DC motor speed control. He presently works as a Product Manager in marketing of Medium Voltage Drives. Previous positions in the company were in technical writing, field service, quality control, and low voltage AC drive marketing.

Matt Colosino is Owner of Crescent Power System, a company specializing in providing industrial grade power systems and the application of adjustable speed drives. Crescent Power Systems services the refining, chemical, production, pipeline, material handling, mining, pulp, paper, water and waste water industries. Matt has a BSEE from Tulane University and has been involved in the sales and service of electrical power systems for over 23 years.