

IMPROVEMENT OF POWER FACTOR IN
DISTRIBUTION NETWORK WITH
CORRELATION TO HARMONIC

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B. ENG (HONS.) ELECTRICAL
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IMPROVEMENT OF POWER FACTOR IN DISTRIBUTION NETWORK
WITH CORRELATION TO HARMONIC

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Thesis submitted in fulfillment of the requirements
for the award of the
Bachelor of Electrical Engineering with Honours

College of Engineering
UNIVERSITI MALAYSIA PAHANG

JUNE 2022

ACKNOWLEDGEMENTS

Firstly, all praise to the almighty God with His blesses and chances for me as I can finish this project and thesis writing in order for me to finish my Bachelor in Electrical Engineering, Alhamdulillah. In this opportunity, I would like to give a big gratitude and thank to my beloved parent. A thousand of thanks for both of you that support me without hesitate until I can finish my project. Their moral support gives me hope and push me to exceed my boundary in making this thesis happen.

Next, special thanks to University Malaysia Pahang (UMP) for these chances to continue my studies. I am very grateful to have these chances to meet with many types of professionals who lead me further this year of studies. Without the knowledge that I would not get any chance to finish my final year project.

I also would like to thank and give my gratefulness for my supervisor, and also my Academic Advisor Dr. Ruhaizad Bin Ishak who taught me and lead me until I can successfully finish the project given in the meantime. His guidelines based on his experience in researching skills and knowledge help me a lot in doing this project and writing this thesis. His supportive character always calms me and help me in making good decisions throughout this project development.

Lastly, for my friend I would like to thanks my friend because they ready to help and support through my day to finish this project. With the dateline to finish this project, we are helping each other to complete the task on the time. In this final year, they are willing to share the experience and teaching each other.

ABSTRAK

Salah satu penunjuk yang digunakan untuk mengukur kecekapan elektrik ialah faktor kuasa. Indeks bermula dengan 0 dan mencapai sehingga 1. Semakin hampir nilai kepada 1 akan menunjukkan kualiti kuasa yang lebih baik dan kecekapan yang lebih tinggi untuk sistem rangkaian kuasa elektrik. Disebabkan faktor kuasa fasiliti yang lemah pihak utiliti dikehendaki meningkatkan kapasiti pengeluaran dan penghantarannya. Salah satu penyelesaian untuk meningkatkan faktor kuasa adalah dengan menambah bank kapasitor dalam sistem. Projek ini memberi tumpuan kepada kesan pemasangan atau penambahan bank kapasitor ke dalam rangkaian sistem kuasa elektrik dari segi faktor kuasa, herotan harmonik dan kehilangan kuasa. Harmonik dalam sistem kuasa adalah salah satu penyumbang paling ketara kepada kualiti dan kuasa yang lemah. Ini telah menjadi kebimbangan besar dalam masalah kualiti kuasa, dan analisis harmonik diperlukan untuk mengkaji dalam pemodelan komponen untuk mengurangkan atau menghapuskan arus dan voltan harmonik. Dalam projek ini, bank kapasitor telah ditambahkan pada sistem kuasa dan analisis harmonik telah dilakukan menggunakan perisian ETAP secara terperinci. Untuk menganalisis kesan arus harmonik, analisis Aliran Beban Harmonik dilakukan untuk mengenalpasti herotan harmonik. Untuk menghapuskan herotan harmonik ini, teknik penalaan penapis reactor tunggal digunakan. Itu adalah reka bentuk penapis harmonik bagi reaktor siri dengan bank kapasitor. Keputusan kajian mendapati pemasangan kapasitor bank akan mengimbangi faktor kuasa yang rendah namun resonans harmonic akan berlaku sekali gus meningkatkan tahap THD. Tahap THD akan berkurangan apabila penapis harmonik dipasang. Ini menunjukkan bahawa tenaga elektrik boleh dihantar dengan cekap ke sistem.

ABSTRACT

One of the indicators used to quantify the efficiency of electricity was the power factor. The index began with 0 and reached up to 1. The closer the value to 1 will indicate better power quality and higher efficiency for the electricity power network system. Due to a facility's weak power factor, utility is required to increase its producing and transmission capacity. One of the solutions to improve power factor is by adding a capacitor banks in the system. This project focused on the effect of install or adding capacitor banks into the electrical power system network in term of power factor, harmonic distortion and power losses. Harmonics in the power system are one of the most significant contributors to poor power quality and reliability. This has become a big concern in the power quality problem, and harmonic analysis is required to study in the modelling of components in order to reduce or eliminate the harmonic currents and voltages. In this project, capacitor banks have been added into the power system and harmonic analysis has been performed using ETAP software in details. To analyze the effect of harmonic current, Harmonic Load Flow analysis was performed and harmonic distortion identified. To eliminate this harmonic distortion, the use of single tunes filter of series reactor with capacitor bank are studied. The study shows the insertion of the capacitor banks will compensating for the low power factor however the harmonic resonance occurs thus increase the THD level. The THD level will decrease when the harmonic filter is install. This shows that the electricity can be transmitted efficiently to the system.

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LIST OF SYMBOLS

C	Capacitor
L	Inductor
kW	kiloWatt
MVA	Mega volt ampere
KVAR	Kilovolt-Ampere Reactive

LIST OF ABBREVIATIONS

PF	Power Factor
PFC	Power Factor Correction
THD	Total Harmonic Distortion
IHD	Current Harmonic Distortion
HA	Harmonic Analysis

CHAPTER 1

INTRODUCTION

1.1 Background of Study

The study on the power factor and the harmonics relationship is beneficial as it is very closely related to the power system. It will help in better understanding of power system problems particularly the power factor problems and the concerns over the harmonics. The project will focus on power factor correction using capacitor banks. The effects of adding the capacitor banks is thoroughly analysed on a power system network in terms of power factor level, total harmonics distortion level and power loss.

The main intention of any electrical utility company is to deliver power with better quality. That's indicating to deliver a pure sinusoidal voltage or current waveform. This purpose is very complex to achieve by the fact that there are loads on the system that produce harmonic currents. These currents result in distorted voltages and currents that can badly impact the system performance in different ways.

The harmonics in the power network may result in resonance conditions in the power network and thus causing the deterioration of the power quality in the grid. The outcome of this harmonic resonance is that, it will generate highly rated circulating currents and voltages at the resonant frequency, which could cause power quality problems such as voltage sags, swells, flickers etc. As a consequence of this harmonic distortion, the industrial plants may face pulsating torques in the rotor of the motor, or it may cause nuisance tripping of the smaller units that are associated in the plant site or the power factor correction capacitors has a higher probability of reducing the life time of their operational period due to this high levels of voltage transmission. These harmonics current that are being generated from harmonic source, is resulting in either current or voltage distortion for the entire power network. This has become a major issue for power

quality problem and harmonic analysis needed to investigate how to minimise or remove these harmonics.

Because it is so closely related to the power system, it is beneficial to conduct research on the relationship between power factor and harmonics. It will aid in a better understanding of power system problems, particularly power factor problems and the concerns about harmonics, which will be beneficial. This project will be concerned with power factor adjustment through the use of capacitor banks. The impacts of adding capacitor banks to a power system network are thoroughly investigated in terms of power factor level, total harmonics distortion level, and power loss on a power system network.

Different kinds of power system software can be used to perform the load flow study which is the Power Factor Correction and Harmonic Analysis on the power network. In this study, ETAP 19.0.1 is being utilised to model various power networks and perform harmonic analysis. ETAP is very user-friendly software where key tools that are needed for efficient load flow study which is power factor and harmonic analysis are easy to operate to get better results. It is also proficient of depicting the consequences of implementing the required power network on real life.

1.2 Problem Statement

Power factor is a power quality issue in that low power factor can reduce the efficiency of the system. The low power factor or efficiency of energy can be caused the electric bill boost high. Installing a capacitor bank or employing a synchronous motor can increase the system's power factor. Capacitor banks are generally preferred over other methods for power factor correction. Harmonic voltage and current issues will arise if capacitor banks are installed, which is undesirable. Additionally, a more serious situation may arise when the network experiences resonance. This project will cover the harmonics effect and system issues that arise from the increase of the power factor and the insertion of a capacitor bank in the power system.

Due to nonlinear loads and the use of power electronics, the power system has suffered from harmonics. When a capacitor is inserted, harmonics resonance and power losses need to be examined. The analysis will help us better understand the influence of the capacitor bank insertion on harmonics and power losses.

1.3 Objectives of Project

The main objective of this project is:

1. To investigate the effect of capacitor banks in the operation of power system.
2. To study the correlation between capacitor banks capacitance with total harmonic distortion.
3. To analyse the performance of the system in term of power factor, total harmonics distortion level and power losses.

1.4 Scope of Project

Different kinds of power system software can be used to perform Harmonic Analysis on the power network. In this study, ETAP 19.0.1 is being utilised to model a single line diagram of various power networks and perform the load flow study and harmonic analysis of the project. ETAP is a very user-friendly software where key tools that are needed for load flow study and efficient harmonic analysis are easy to operate to get better results.

All of issues of the project will be analysed on adopting IEEE519-2014 standard, where the harmonic indices will be set accordingly in the software. This project will be carried on the basis of the two analytical methods.

i. Balance Load Flow Study

The load flow study first conducts with a single line diagram or a power network system. The results of the load flow study will show all the information of the power system network including all the losses for the whole system or in branch, the power factor and also the alert for the system to be fixed or troubleshoot. All of the result parameter will be used to make adjustment so that the load flow is efficiency.

ii. Harmonic Load Flow Study

The Harmonic Load Flow study first conduct a load flow calculation at the fundamental frequency. The result of the fundamental load flow sets the base for the fundamental bus voltage and branch currents which are used later to compute different harmonic indices. Then, for each harmonics frequency at which any harmonic source exists in the system, a direct load flow solution is found by using the current injection method.

1.5 Feasibility of the Project within Scope and Time frame

Increased power factor is commonly adopted and utilized in the industrial sector. An example from a network distribution power system will be used in the project, and it will be simulated and analyzed at the conclusion of the project. The duration for this particular project has been set for two semesters, with FYP 1 lasting fourteen weeks and FYP 2 lasting another fourteen weeks for each semester. The project has a reasonable chance of being completed within the specified time frame. Everything related to the FYP 1 project, including its operations and planning, is detailed in the Gantt chart.

1.6 Thesis Organization

This thesis is organized into 5 chapter and appendices section, which are as included as follows:

Chapter 1 describe about the background of the project in general, statement of the problem, the project objective, and thesis organization.

Chapter 2 are presenting the literature review, where it explains about the power quality and the relationship between the power quality and harmonic effect. There is also literature review on few harmonic analyses for optimization field of study.

Chapter 3 provides the research methodology that being used while carrying out this project, which is the software that is being used which is ETAP software to analysis the load flow study to observe the power factor and harmonic analysis to observe the harmonic condition.

Chapter 4 shall present the results for the case study load flow and the effect of adding the capacitor banks to the system. The results will show the effect of the capacitor banks to the power factor, harmonic distortion analysis and power losses.

Chapter 5 summarizes the research work performed. It will draw a clear view for this study in the form of conclusion and recommendations as to understands the optimization for the case study.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Literature review or also known as narrative analysis, is a sort of research article. A literature review can also be interpreted as research article that discusses existing information, including empirical observations as well as theoretical and analytical approaches on a specific topic. This chapter shall present details about the power factor, effect of harmonic and the improvement of the power factor by adding capacitor bank and the effect of it to the power system in theoretically.

2.2 Concept of Power

The apparent power which is represented by symbol S and the units of this power is VA or in commonly this is represented by KVA or MVA. This power is the combination of reactive power and the true power and it is a product of circuits voltage and current without reference to the phase angle. Normally all the sources for example generators, utilities and transformer. They are all rated in apparent power because they can both supply active and reactive power.

Next power is the true power or active power or real power which is represented by letter P and the unit of this power is Watt. This power is actually consumed or utilized in a circuit to do useful work so it can say that this is a useful power which is being utilized to do different types of work. Another type of power is reactive power which is represented by symbol Q and the unit of this power is Var or kVar. This power flows back and forth between source and load which means that it is not utilized or consumed in any circuit therefore it can also say that this part is the waste of apparent power.[1]

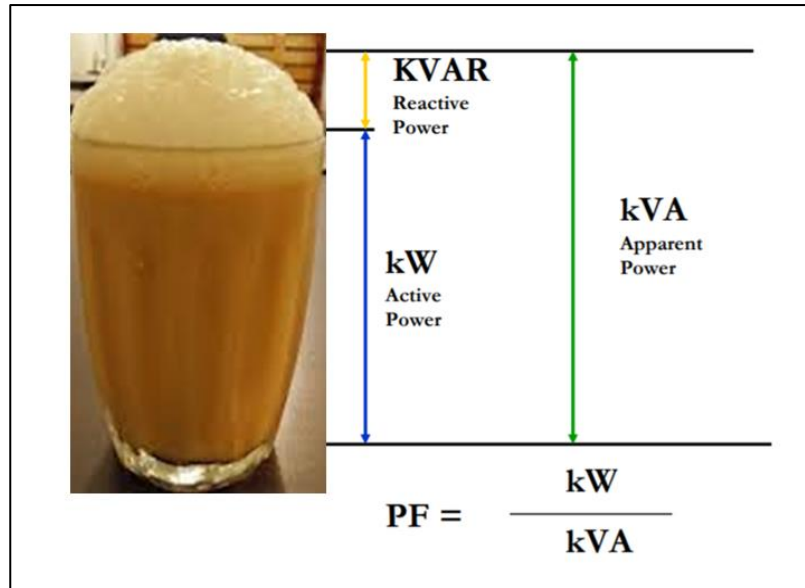


Figure 2.1 Concept of power

An idea of this power in terms of a very common example that is used to represent these three types of power is a carbonated drink example. For example, when a carbonated drink is poured in a glass there is a foam that appears on the top of the glass. So, if the whole glass is taken as a source whose power is represented in KVA, then the actual drink is represented by kilowatt which is the useful power and the foam is the waste of the power. What can this picture infer is that more the foam appears in the glass it means that whenever it has more apparent power and whenever it has more reactive power, less active power can be used. [2]

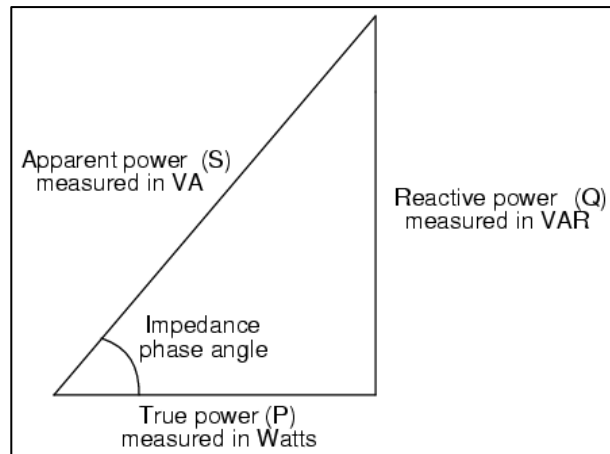


Figure 2.2 Figure of basic power triangle

$$S = IV \text{ (VA)}$$

$$P = S \cos \theta \text{ (W)}$$

$$Q = S \sin \theta \text{ (VAR)}$$

The power component can be related to the equation:

$$S^2 = P^2 + Q^2$$

2.3 Power Factor

Power factor is the ratio in which the denominator is apparent power and the numerator is the real power, so it's mean that the more the real power is closer to the apparent power the higher the power factor is since it is a ratio, therefore the power factor can vary between 0 to 1. It shows how efficient a distribution system is as well as how the energy is cast.

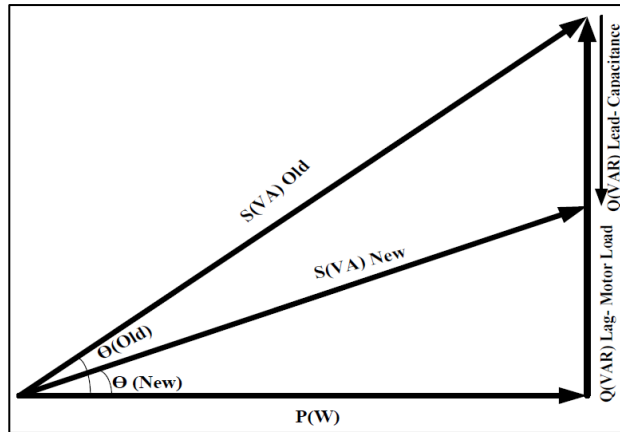


Figure 2.3 Figure of compensated power triangle

$$\text{Power Factor} = \frac{\text{True Power (kW)}}{\text{Apparent Power (kVA)}}$$

$$PF = \cos \theta = \frac{P}{V_{rms} \times I_{rms}}, \quad FP = \frac{P}{S}$$

The power factor becomes more resistive as it approaches 1.0 and it becomes more reactive as it approaches 0.0.[3]

2.3.1 Power Factor at Unity, PF=1 ($\theta = 0$)

Resistive Load

At unity power factor ($\cos \theta = \cos 0 = 1$), there is no difference between the phases of voltage and current which mean its equal to zero therefore the overall power factor is equal to the unity. In this case all the apparent power is the active power and current got its most economical value for driving the load.

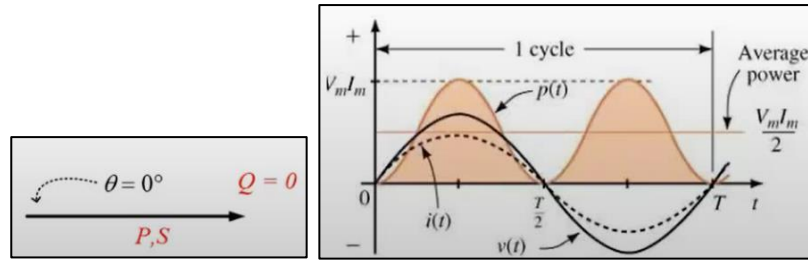


Figure 2.4 Figure of resistive waveform cycle

Unity power factor means that the circuit is purely resistive. For example, the black line represents the voltage and the dotted line represents the current and if we take the product of these two waveforms, we can see that our useful power from the source to the load has positive curve in both the cycles. It means that this power will always flow from the source to the load in only one direction. Since the angle between voltage and current is zero, similarly the angle between the real power and the apparent power is also zero and, in that case, our reactive power is absolutely zero. [3]

2.3.2 Lagging Power Factor ($\theta > 0$)

Pure inductive load

In pure inductive load, in case the current is take as reference, then the angle between the voltage and the current is 90 degree in pure inductive load because in inductors, the load current lags the load voltage by 90 degree and if ($\cos \theta = \cos 90 = 0$) in the power factor relation, it comes out to be equal to zero. It means that the power factor is now zero. The more it is closer to the zero, the more reactive power it has and less is the active power [4]

Process of power flows between source and load

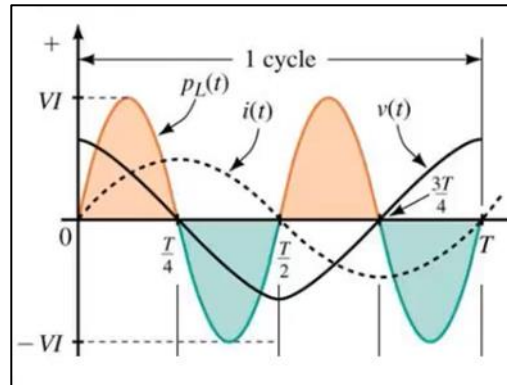


Figure 2.5 Figure of inductive waveform cycle

In the positive cycle, we can see that the voltage is at 90 degree and the current starts from the zero degree which mean that current lags the voltage by 90 degree. whenever we multiply both the voltage and the current, we get the power in a fashion that it is positive for one cycle and in the next cycle the power becomes negative. In one cycle the power flows from the source to the load and in the next cycle or the negative cycle the power flows from load to the source. It means that this power is not consumed in the load and therefore cannot be used to do useful work. That's why that this power is a waste of power. [5]

2.3.3 Leading Power Factor ($\theta < 0$)

Pure Capacitive Load

In case of pure capacitive loads, the angle between the voltage and the current is 90 degree but since the current is taken as reference, therefore the angle is -90° because the current leads the load voltage by 90° . When ($PF = \cos \theta = \cos(-90^\circ) = 0$), it comes out to be zero or power factor in case of pure capacitive load is zero.

Process of power flows between source and load

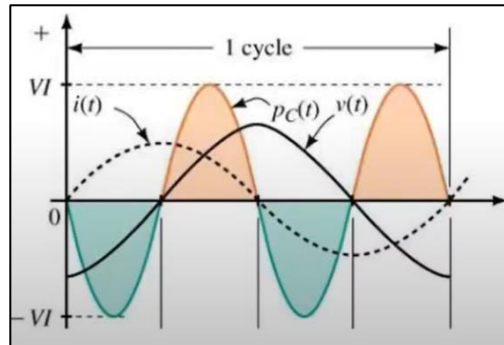


Figure 2.6 Figure of capacitive waveform cycle

From the waveform, in one cycle the power flows from source to the load and another cycle from load to the source. It means that in the capacitive load, the reactive power is maximum and the real power is zero because the power factor is zero and since the current leads the voltage, therefore the power factor is leading in case of capacitor and the power factor is lagging in case of inductor because the current lags in case of inductor. [6]

2.3.4 Economic Effects of Power Factor

The low power factor increases our system (Generation, Transmission) costs. If the power factor of the system is low, the apparent power would be doubled of real power used by load. Due to low power factor, electrical consumers will usually charge a high cost. Power supply Departments make a tariff system in which there is minimum allowable limit below which the consumers should have to pay the penalties charges on drawing of energy.

2.3.5 Disadvantage of Low Power Factor

The low power factor increases the reactive power, so in order to drive a load of same power with a low power factor, more power will be needed, therefore, the load handling capacity of the generating station and the line conductors would be reduced. Due to high value of current, larger equipment such as cables, transformers and generators will be used which will increase the cost. Also, the line losses increase as well as transformers has to transfer more power, so they get overload on the same load with a low power factor. [7]

2.3.6 Penalty for Low PF

The power factor must be more than 90% for the whole electrical system. If the PF is less than 90%, the customer must pay a penalty of 2% increase in the fixed costs for every 1% drop in the PF below 90%. TNB's have to supply more reactive power (KVAR) and apparent power (KVA) for a low Power Factor. TNB is forced to enhance its generating and transmission capacity because of a facility's poor power factor. KVAR consumption is reduced as a result of a higher power factor. There is a Power Factor surcharge if your power factor is less than 0.9 (>132KV) or less than 0.85 (<132KV), which is determined by Tenaga Nasional Berhad (TNB). [8]

2.3.7 Methods for Improving Power Factor / Power Factor Correction Using Capacitor

Some common methods of power factor improvements are static capacitor, synchronous condenser and phase advancer but the capacitor banks are very popular and mainly use in the power system network. Major loads in the industries are inductive, so they need lagging current which decrease the system power factor. In order to compensate the reactive power of the machines, the capacitors should be added, which provides leading current that neutralizes the effect of lagging current of the load. Moreover, they are easier to install due to less weight and no moving components, therefore, less maintenance is required.

2.3.8 Techniques for Using Capacitor

There are different types of loads that is domestic, industrial, commercial and constant variable loads are common. As well as, different methods exist to compensate the power factor according to the load type. Commonly used methods for improving PF are:

A. Separately Power Factor Correction

When we discuss the improvement of power factor of any transmission or distribution system, the good way is by connecting the capacitor banks to the terminals of compensated equipment's means install the capacitor with each inductive load whether

is industrial or any other type of load. And in this way, we get the fixed power factor regulation. But remember in your mind this correction is not economical because this implementation required lot of effort and funds. Because it is difficult to design the capacitor bank for each inductive load.

B. Group Power Factor Correction

In this type, the power factor of several loads is connected by common capacitor. This method automatically corrects the power factor by means of installing automatically power factor connections capacitor banks for each user's main supply. It is very suitable method of improving the Power factor of highly variable loads. In this way capacitor bank is divided into number of units and controlled by reactive power controller (also called PFI regulator).

C. Reactive Power Controller

Main intend of the controller is to check the load variations and switches, capacitor units is on or off, and supply the reactive power to maintain the power factor to its default value which is set in PFI relay. If we find the exact value of reactive power for each bank, we obtained the precise value of $\cos \theta$.

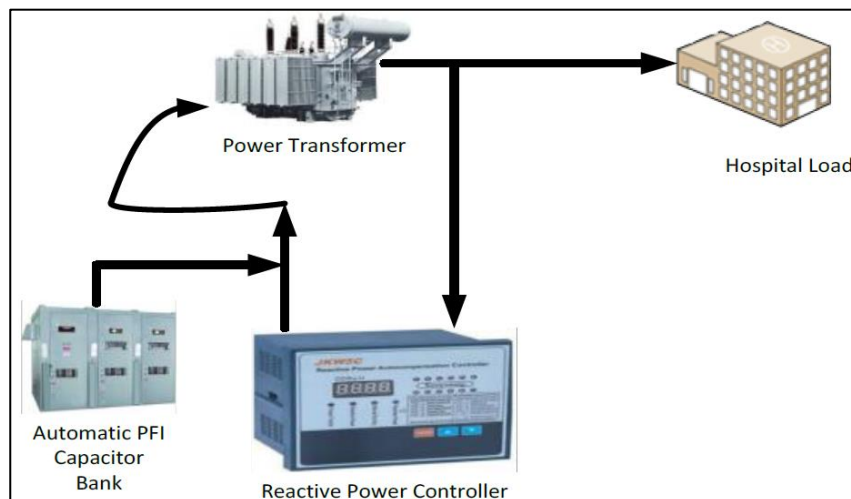


Figure 2.7 PFI system block diagram

D. Central Power Factor Correction

Sometimes additional capacitor bank is installed to the main supply of users to achieve the sufficient degree of correction greater than 0.97, this can be used in individual and grouped power factor correction. Some small fixed value capacitors are used while the remaining reactive power will be controlled with the reactive power controller. Due to fixed capacitors, the problem of over compensation will arise in order to take this problem into account we make the values only the 14-15% of the transformer's rating this system is more economical because capacitors supply the reactive power directly to the load the power does not have to flow all the way from the transformers and the cables so the losses related to the flow of power like resistive power losses can be minimized. [9]

2.3.9 Purpose and Benefit of Improving Power Factor

Below is the reason to improve PF:

- i. Better utilization of electrical machineries
- ii. Better utilization of conductor
- iii. To improve voltage to equipment
- iv. reduction of power losses
- v. Reduction in the cost of electricity and electric bills
- vi. Technical/economic optimization.
- vii. To avoid penalties

2.3.10 Impact of Capacitor to Harmonic

In particular, capacitors are sensitive to harmonic currents, since their impedance decreases in direct proportion to the order of the harmonics present in the current. A substantial quantity of harmonic current is drawn into capacitors due to the fact that the impedance of the capacitor reduces as the frequency of the signal rises.

This may result in a capacitor overload, which will result in a gradual reduction in the capacitor's operational life. In extremely severe conditions, a phenomenon called as resonance may develop, resulting in an amplification of harmonic currents and a significant increase in voltage distortion, both of which are harmful. A significant amount of harmonic current is amplified if the natural resonance frequency of the capacitor and the network combined happens to be close to any of the harmonic frequencies that are

present. As a consequence of this scenario, capacitors have the potential to experience significant overvoltage and overload, which will lead them to fail or break prematurely before their expected lifespan.

When selecting power factor correction equipment, it is important to consider the harmonic level in order to guarantee that the electrical system operates safely and properly. [7]

2.3.11 Capacitor Banks Without Reactor

It is observed that the connection of PFC capacitors (without reactors) causes an amplification of harmonic currents at the level of the busbar, as well as an increase in voltage distortion. Capacitors are linear reactive devices, and as a result, they do not produce any harmonics when operated. It is possible that the installation of capacitors in a power system (in which the impedances are mostly inductive) would result in a complete or partial resonance happening at one of the harmonic frequencies. Because of the presence of harmonics, the current passing through the PFC capacitors is larger than it would be in the case of simply the fundamental current.

It is possible that partial resonance will develop when the natural frequency of the capacitor bank/power system reactance combination is near to a specific harmonic frequency. In this case, magnified values of voltage and current at the harmonic frequency in issue will be seen. It is possible that the increased current may induce overheating of the capacitor, resulting in deterioration of the dielectric and, ultimately, failure of the capacitor in this specific situation. [10]

2.4 Harmonic

A greater focus has been given in dealing with the effects of harmonics on an installation, as the number of harmonics producing by the loads has grown over the years. Two critical aspects of power system harmonics must be considered in order to completely understand the phenomenon's impact. The first is the nature of non-linear loads that produce harmonic currents, and the second one is the way in which harmonic currents flow and the development resulting harmonic voltages. [11]

2.4.1 Linear and Non-linear Loads

If the current flowing through a linear load is proportionate to the voltage in a power system, it is known as a linear load. Specifically, the current waveform will have the same waveform as the voltage waveform. Linear loads include equipment such as motors, heaters, and incandescent lamps, to name a few. Harmonics in linear loads are fractionally smaller than in nonlinear loads, and they may be readily ignored.

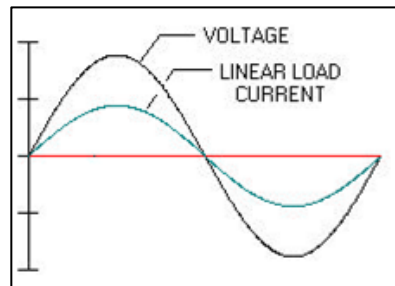


Figure 2.8 Waveform of linear load voltage and current

The current waveform on a non-linear load is not the same as the voltage waveform in this situation. Non-linear loads include rectifiers (power supplies, Uninterruptible Power Supplies, discharge lighting), adjustable speed motor drives, ferromagnetic devices, direct current motor drives, and arcing equipment.

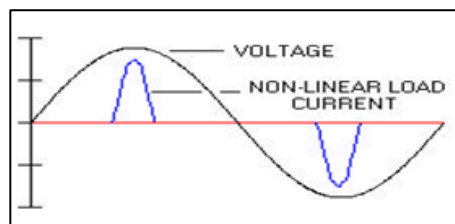


Figure 2.9 Waveform of non-linear load voltage and current

The current waveform from non-linear loads is not sinusoidal but it is periodic, Periodic waveforms can be found mathematically as a series of sinusoidal wave shapes that have been added together. The sinusoidal components are the integer multiples of the primary where the primary in the Malaysia is 50 Hz and the additional elements turned to harmonics.

When non-linear loads are applied, the current waveform is not sinusoidal, rather it is periodic. Periodic waveforms may be calculated theoretically as a series of sinusoidal wave patterns that have been combined.

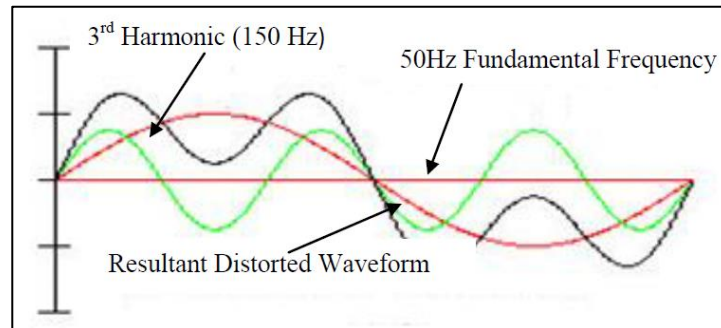


Figure 2.10 Figure of symmetrical harmonic component waveform

Here the third harmonic will have a frequency of three times that is 150 Hz. A symmetrical wave contains only odd harmonics and un-symmetrical waves contain even and odd both harmonics.

In a symmetrical wave the positive portion is identical to the negative portion of the wave. On the other hand, an un-symmetrical wave contains a DC component or the load is such that the positive portion of the wave is different than the negative portion. The example of an un-symmetrical wave is a half wave rectifier.

In power system most of the elements are symmetrical. They produce only odd harmonics and have no DC offset. Arc furnaces are a common source of even harmonics but they are notorious for producing both even and odd harmonics at different stages of the process. [12]

2.4.2 Harmonic current flow

From the given figure below, it can be seen that, when a non-linear load draws current, that current passes through all of the impedance that is between the load and the system source. As an effect of the current flow, the harmonic voltages are produced by impedance in the system for each harmonic.

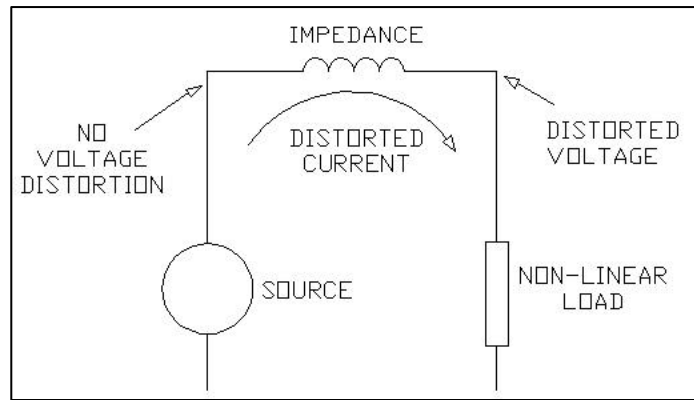


Figure 2.11 Distorted current and voltage induced

The magnitude of the voltage distortion depends on the source impedance and the harmonic voltages produced from the power network. If the source impedance is low then the voltage distortion will be low. If a significant portion of the load becomes non-linear (harmonic currents increase) and/or when a resonant condition prevails (system impedance increases), the voltage can increase dramatically.

In conclusion it can be said that, the harmonic currents can have a significant impact on electrical distribution systems and the facilities that they feed. The increment of renewable power generation will create a major impact on the power network. Power system harmonic analysis needed to improve the power quality by installing appropriate devices. In addition, identifying the size and location of non-linear loads should be an important part of any maintenance, troubleshooting and repair program. [11]

2.4.3 Elimination of Harmonics and Need for Filters

Firstly, it preventing harmonic generation for newer systems such as high input power factor regulators, switching regulators and high pulse number AC/DC converters. Next, for existing sources of harmonics by installing filters on DC side to rectifier and installing filters on AC side. The need of filter is to eliminate/ reduce harmonics in voltage & current waveforms. It also improves the power factor in the system. Lastly, to reduce harmonic power losses. [13]

2.4.3.1 Capacitor Banks with Reactor

Capacitor is generally used for power factor improvement, however at the time of switching on capacitor, the capacitor act as short circuit, hence it draws huge current.

Capacitor oppose sudden change of voltage so whenever you switch on the capacitor is basically as it has no internal voltage and it as like short circuit thus draw huge current to get charge, then gradually the voltage builds up inside it and the current reduce, but this huge amount of starting current the initial current may damage the capacitor.

For that reason, the inductor is introduced in series with the capacitor to limit the current because we know that the inductor opposed the sudden change of current. This kind of arrangement a capacitor in series with a reactor also it acts as an L-C filter harmonic because in industry various semiconductor drives use like battery charger, UPS, VFD, Inverter, this device generate harmonics.

Generally, the inductor is specified as 4% to 7% series reactor or detuned filter that means whenever you have to specify a capacitor bank with an inductor, you have to write that we need such amount of kVar with 7% or 4% inductor. Which means that impedance of the reactor is 7% of impedance of the capacitor.

For a capacitor,

$$v = \frac{1}{c} \int i dt \quad (1)$$

$$\text{Or, } \left(\frac{dv}{dt}\right) c = i$$

Capacitive current is directly proportional

Current flowing in the capacitor is directly proportional rate of change of capacitor voltage. This would mean if we switch on capacitor bank in our power system network, the sudden voltage application, it will tend to make the capacitor current very high. If the voltage is applied suddenly which mean we switch on the capacitor bank

suddenly the dv/dt it will be higher. Within seconds its voltage will be high, so dv/dt will be high and because of this the capacitor current will be high. This is known as high inrush of current due to capacitor switching and this is undesirable for any power system. Sudden switching of capacitor will imply high dv/dt , which implies high current.

For a series inductor,

$$v = L \frac{di}{dt} \quad (2)$$

Inductor stores energy in its magnetic field. This inductor will have its own magnetic field and this magnetic field will store its energy. There is a basic nature's law which actually means that changes in energy cannot happen all of a sudden in a moment. So, when the switch of an inductor is on, its magnetic field and its current will increase slowly and sudden change in current will be opposed by an inductor. [10]

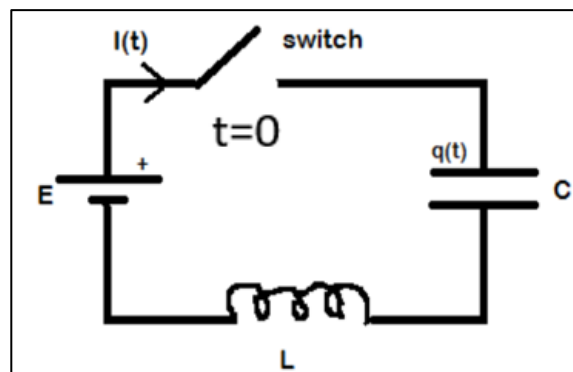


Figure 2.12 Figure of inductor and capacitor circuit

Complete voltage V_{in} occurs across inductor at $t=0$

At $t=0$, current flowing through will be zero because the switch was open. The current through this circuit will remain zero because of the inductor will tend to make the current zero. Hence, it can say that this inductor behaves as an open circuit. Since this inductor open circuit is at times just after $t=0$, it can say that after switching on the switch, whole input voltage appears across this inductor and no voltage is across this capacitor.

Voltage across capacitor gradually increases after $t=0$

The inductor voltage will now decrease gradually after some time and the capacitor voltage increases gradually. Since the capacitor voltage is increasing gradually, the high dv/dt phenomena which was occurring earlier is now prevented and high inrush current due to capacitor switching is also avoided. Also note that the capacitor and the inductor values are so chosen that the combined circuit is overall capacitive and the purpose of power factor improvement is also served.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter discussing on how to undergo the method of experiment. The explanation of the method and techniques will be discussed in this chapter including the computer-aided software that will be used for this project which is the ETAP software. The complete single line diagram of the system will be shown with components and parameters that have been calculated manually and automatically by the software. The load flow study and harmonic analysis of whole system will be clearly explained.

3.2 General Flowchart

Flowchart below is the bench mark to follow the step with properly. It also will drive to do complete project since early until the end of project which starts with understanding about power factor concept, capacitor banks for power factor correction, harmonic distortion effect and how to eliminate it by doing literature review related journals, thesis, IEEE papers and scholar. It is important in order to understand more about the project as well to get more idea and concept of how the project works.

First, it will start with design the single line diagram to get the output load flow which contain the power factor and power losses for the system. If the power factor for the system is poor and below the limit that have been set, then we have to correct the power factor by adding a capacitor banks into the system. Next, after the power factor is in good index, the harmonic analysis will be run to study the total harmonic distortion and troubleshoot the problem that exist in the power system. If the THD is over the limit that has been set by IEEE 519-2014, the harmonic filter will be added into the system

which is the capacitor banks series with inductance which will function as reactor for the system and eliminate the critical harmonic order.

When all the problem and fault was troubleshooting, we can analysis the output and results whether it is expected value and result.

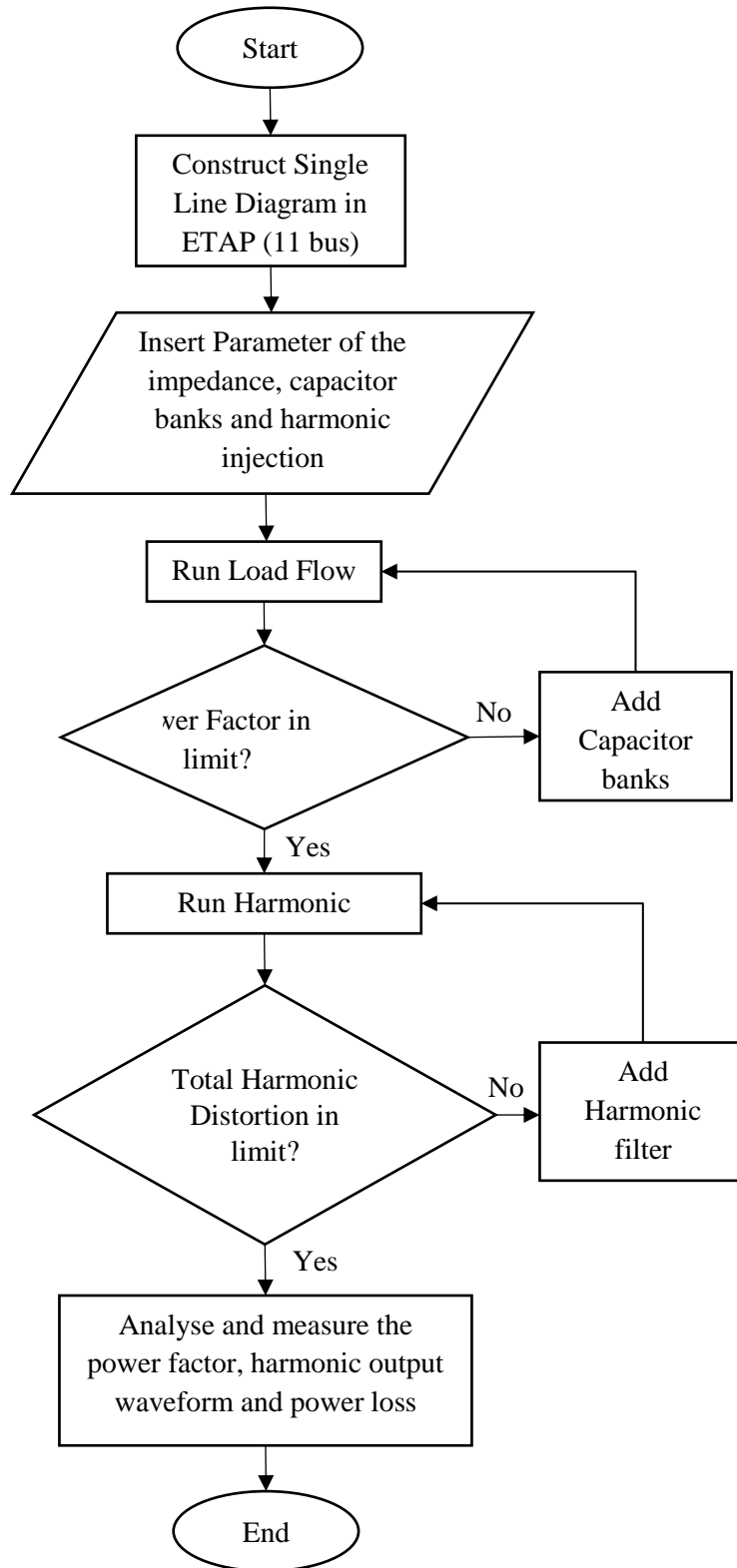


Figure 3.1 Flow chart of project

3.3 ETAP Software

Almost all of the electrical apparatus that are being used in real power systems can be modelled in ETAP easily. However, for this project, the Load Flow Study and Harmonics Analysis module is looked in depth and on this chapter all the toolbars related with the Harmonics Analysis will be described in brief. The ETAP Harmonic Analysis module provides the best tool to accurately model different power system components and devices to include their frequency dependency, nonlinearity, and other characteristics under the presence of harmonic sources.

For load flow analysis, it can study and show the bus voltage in term of magnitude and angle, the power flow results for the branch, source and load of the bus and system in term of voltage and current including the rms value, power factor of the whole system and also separately by the bus and branch and also the power losses of the branch and system.

For harmonic analysis, it employs two analytical methods, Harmonic Load Flow method and Harmonic Frequency Scan method. Both methods are the most popular and powerful approaches for power system harmonic analysis. In combination of those two methods, different harmonic indices are computed and compared with the industrial standard limitations; existing and potential power quality problems, along with security problems associated with harmonics can be easily revealed. Causes to those problems can be identified and different improvement and corrective schemes such as power factor correction, harmonic filter can be tested and finally verified. [14]

3.4 11 Bus System Network

Table below show the various components of modelling the network system for this project

Table 3.1 Components for modelling network system

Components	Label	Rating
Utility Grid	U1	10000MVA _{sc}
Step-Down Transformer	T1	33kv/6.6kv 10MVA
Step-Down Transformer	T2	33kv/415v 4MVA
Bus 1	Bus 1	33kv
Bus 2-6	Bus 2-6	6.6kv
Bus 7-11	Bus 7-11	415v
Lump Load	Lump 1	1MVA
Lump Load	Lump 2	2MVA
Lump Load	Lump 3	2MVA
Lump Load	Lump 4	100kVA
Lump Load	Lump 5	200kVA
Lump Load	Lump 6	200kVA
Static Load	Load 1	4MVA
Static Load	Load 2	80kVA
Static Load	Load 3	400kVA
Cable	Cable 1-4	CU 6.6kV 3/C XLPE
Cable	Cable 5-8	CU 1kV 3/C XLPE
Capacitor	CAP1	1 Mvar
Capacitor	CAP2	250 kvar
Capacitor	CAP3	500 kvar
Capacitor	CAP4	75 kvar
Capacitor	CAP5	70 kvar
Capacitor	CAP6	35 kvar

A 11-bus system network is modelled as one-line diagram to perform load flow study and harmonic analysis. Static load is connected to bus 4, bus 8 and bus 9 is modelled as a harmonic source to create a harmonic distortion in this power network. The power factor for this system will be observed and be corrected and the action of this harmonic source on the power network will be investigated using Harmonic Analysis and the mitigation techniques will be taken to eliminate any harmonic distortion.

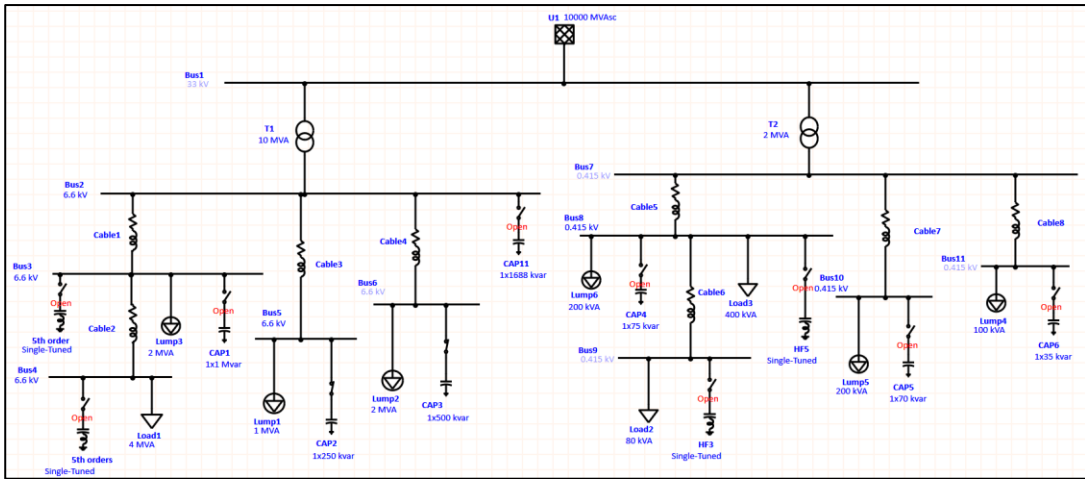


Figure 3.2 11-Bus single line diagram

3.4.1 Network Modelling

The components for this 11-bus network are taken from the ETAP library. The external grid which is rated 10000 MVA is connected to 33 kV bus bar (The Swing bus or Bus 1) and then the voltage level has stepped down from 33 kV to 6.6 kV using 10 MVA rated 2 winding transformer which is connected from Bus 1 and Bus 2. The typical Z% and X/R parameters were fed into the transformer editor page shown below.

Reliability		Remarks			Comment		
Info	Rating	Impedance	Tap	Grounding	Sizing	Protection	Harmonic
10 MVA ANSI Liquid-Fill Other 65 C					33 6.6 kV		
Voltage Rating				Nominal Bus kV		Z Base	
Prim.	kV: 33	FLA: 175			33	MVA	
Sec.	kV: 6.6	FLA: 874.8			6.6	10	
						Other 65	
Power Rating						Alert - Max	
MVA						MVA	
Rated	10					10	
						Other 65	
Derated	10					<input checked="" type="radio"/> Derated MVA <input type="radio"/> User-Defined	

Figure 3.3 Figure of transformer rating parameter

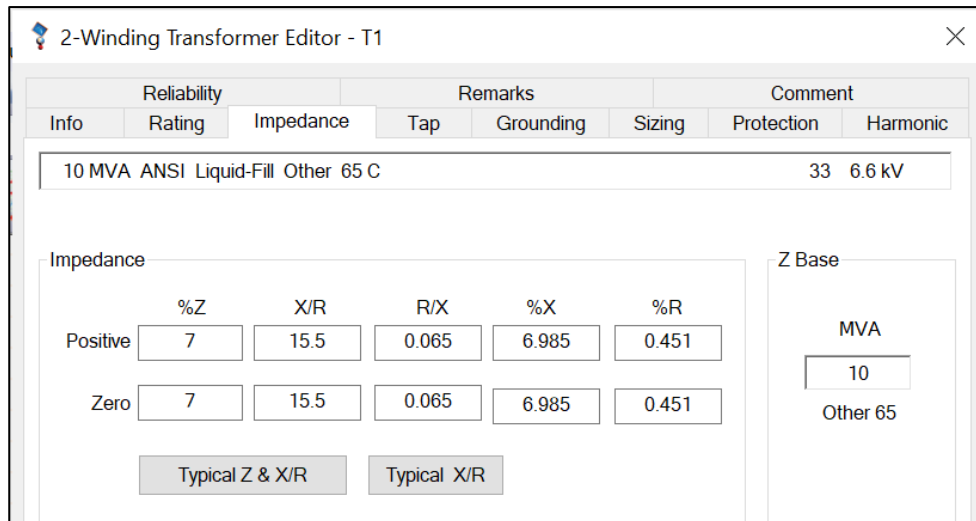


Figure 3.4 Figure of transformer impedance parameter

Bus bar 2 and Bus bar 3 is connected through a cable which is cable 1 rated 1km in length. 6.6 kV 3/C XLPE type of conductor in library column is chosen suitable based on this network project. 3/C mean it has three phases in one cable and if 1/C is chosen it means that only one phase per one cable so it must contain 3 cable. The size phase PE for this cable is $400mm^2$. If the cable is overloaded, the number of Conductor/Phase will be increased and also the size of phase PE. We must choose from smaller value until an acceptable value because if we choose the larger value it will make higher cost. Below is the parameter library that is chosen.

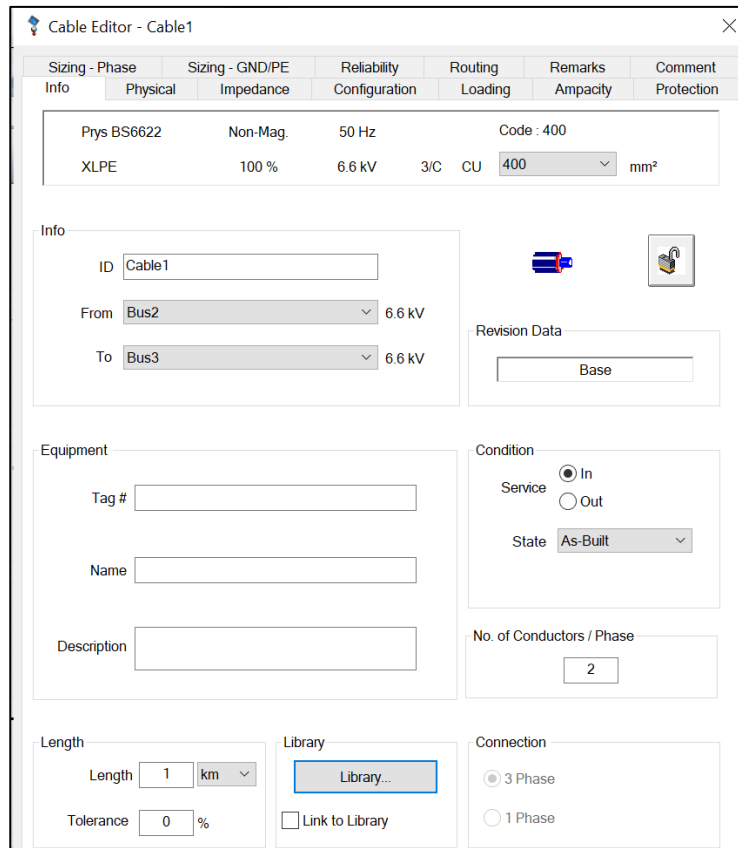


Figure 3.5 Cable length and library parameter

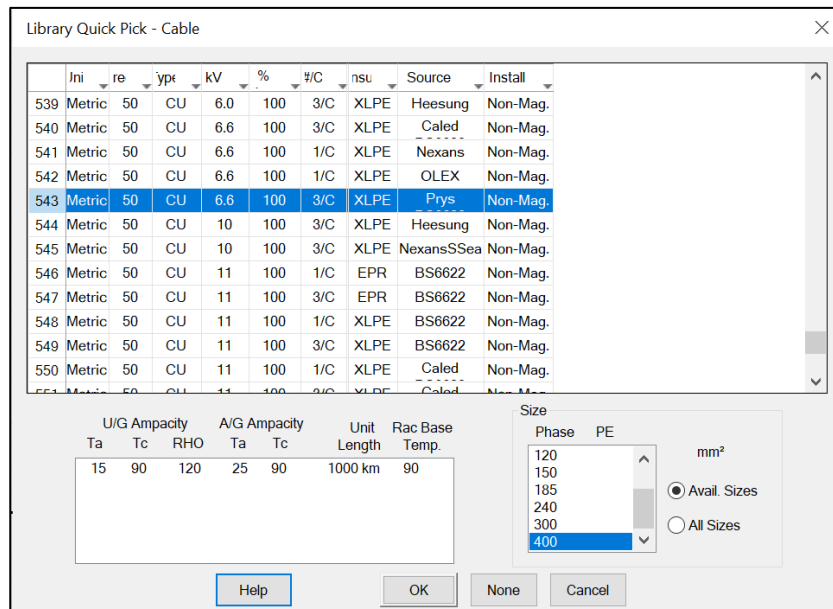


Figure 3.6 Type of cable in library

The Bus bar 3 and Bus bar 4 is connected through another cable which is cable 2 with the same parameter as cable 1. Lump load which is labelled Lump 3 is connected with Bus bar 3 at 6.6 kV nominal voltage and rated 2MVA.

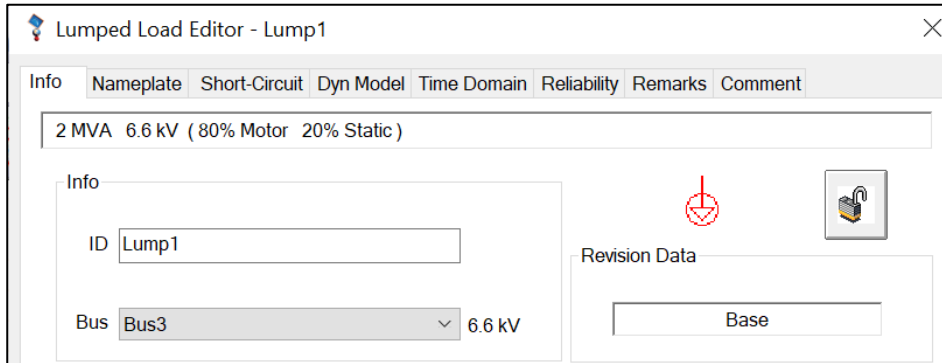


Figure 3.7 Lump load parameter

A static load rated 4 MVA at 6.6 k nominal voltage modelled as a harmonic source named 'Load 1' is connected with bus bar 4. This harmonic source was modelled by clicking the Harmonic page of the load editor. The 6-pulse 1 harmonic was selected from harmonic library which is the worse harmonic source. The harmonic page of the motor is shown in the figure.

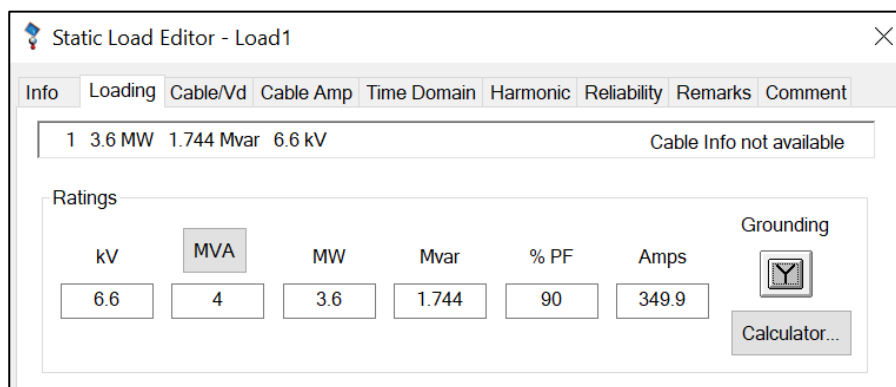


Figure 3.8 Static load parameter



Figure 3.9 Harmonic type, waveform and spectrum

The Bus bar 2 and Bus bar 5 is connected through another cable which is cable 3 with the same parameter as cable 1. Lump load which is labelled Lump 1 is connected with Bus bar 5 at 6.6 kV nominal voltage and rated 1MVA. The Bus bar 2 and Bus bar 6 is connected with cable 4 with the same parameter as cable 1. Lump load which is labelled Lump 2 is connected with Bus bar 6 at 6.6 kV nominal voltage and rated 2MVA.

Next, the external grid rated 10000 MVA is connected to 33 kV bus bar (The Swing bus or Bus 1) and then the voltage level has stepped down from 33 kV to 415 V using 2 MVA rated 2 winding transformer which is connected from Bus 1 and Bus 7. The typical Z% and X/R parameters were fed into the transformer editor page shown below.

Figure 3.10 Transformer rating

	%Z	X/R	R/X	%X	%R
Positive	7.25	14.23	0.07	7.232	0.508
Zero	7.25	14.23	0.07	7.232	0.508

Figure 3.11 Transformer impedance parameter

Bus bar 7 and Bus bar 8 is connected through a cable which is cable 5 rated 1km in length. 1 kV 3/C XLPE type of conductor in library column is chosen suitable based on this network. Below is the parameter library that is chosen.

Cable Editor - Cable5

Sizing - Phase	Sizing - GND/PE	Reliability	Routing	Remarks	Comment	
Info	Physical	Impedance	Configuration	Loading	Ampacity	Protection
Heesung	Non-Mag.	50 Hz	Code : 400			
XLPE	100 %	1.0 kV	3/C CU	400	mm ²	

Info

ID: Cable5

From: Bus7 0.415 kV

To: Bus8 0.415 kV

Revision Data

Base

Equipment

Tag #

Name

Description

Condition

Service: In Out

State: As-Built

No. of Conductors / Phase: 2

Length

Length: 1 km

Tolerance: 0 %

Library

Library...

Link to Library

Connection

3 Phase 1 Phase

Figure 3.12 Cable 5 parameter

Library Quick Pick - Cable

	Ini	re	yp	kV	%	#/C	nsu	Source	Install
528	Metric	50	CU	1.0	100	1/C	XLPE	Heesung	Non-Mag.
529	Metric	50	CU	1.0	100	3/C	XLPE	Heesung	Non-Mag.
530	Metric	50	CU	1.0	100	3/C	Rubber	ICEA	Non-Mag.
531	Metric	50	CU	1.0	100	1/C	Rubber	ICEA	Non-Mag.
532	Metric	50	CU	1.0	100	1/C	XLPE	Prys	Non-Mag.
533	Metric	50	CU	3.3	100	1/C	XLPE	BS5467	Non-Mag.
534	Metric	50	CU	3.3	100	1/C	XLPE	BS5467	Non-Mag.
535	Metric	50	CU	3.3	100	3/C	XLPE	BS5467	Non-Mag.
536	Metric	50	CU	3.3	100	3/C	XLPE	BS5467	Non-Mag.
537	Metric	50	CU	5.0	133	3/C	Rubber	ICEA	Non-Mag.
538	Metric	50	CU	5.0	133	1/C	Rubber	ICEA	Non-Mag.
539	Metric	50	CU	6.0	100	3/C	XLPE	Heesung	Non-Mag.

U/G Ampacity

Ta	Tc	RHO	A/G Ampacity	Ta	Tc	Unit Length	Rac Base Temp.
25	90	120	40	90	1 km	90	

Size

Phase PE

120

150

185

240

300

400

Avail. Sizes All Sizes

mm²

Help OK None Cancel

Figure 3.13 Type of cable

The Bus bar 8 and Bus bar 9 is connected through another cable which is cable 6 with the same parameter as cable 5. Lump load which is labelled Lump 6 is connected with Bus bar 8 at 415 V nominal voltage and rated 200kVA. A static load rated 400 kVA and 80 kVA at 415v nominal voltage modelled as a harmonic source named ‘Load 3’ and ‘Load 2’ is connected with bus bar 8 and bus bar 9. This harmonic source was modelled by clicking the Harmonic page of the load editor. The 6-pulse 1 harmonic was selected from harmonic library. The harmonic page of the motor is shown in the Figure 3.15

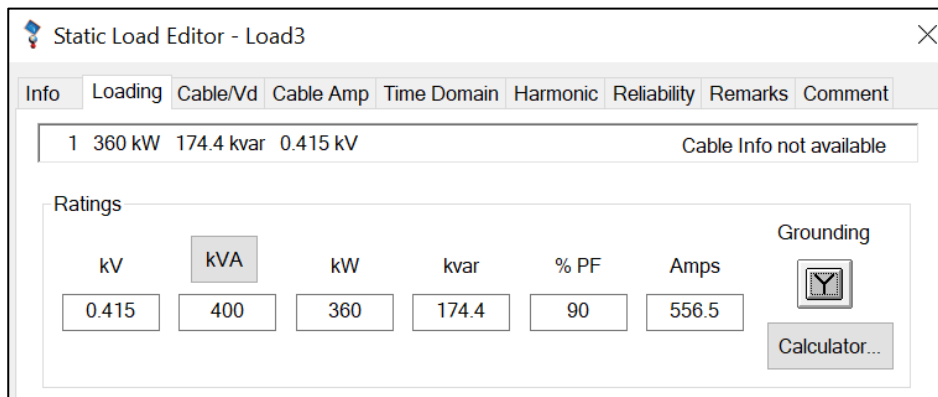


Figure 3.14 Static Load 3 parameter

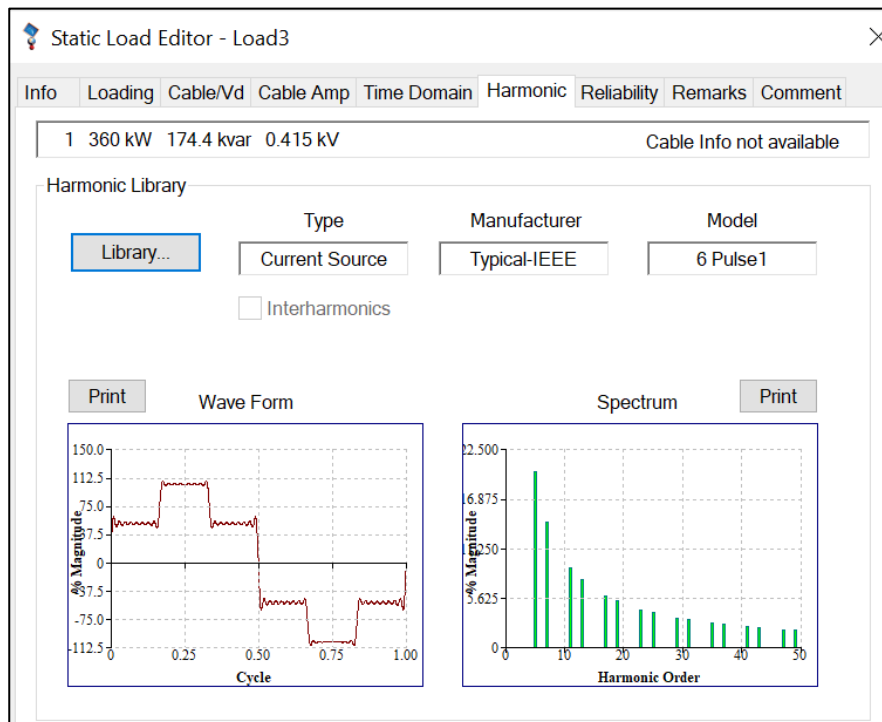


Figure 3.15 Type of harmonic injection for Static Load 3

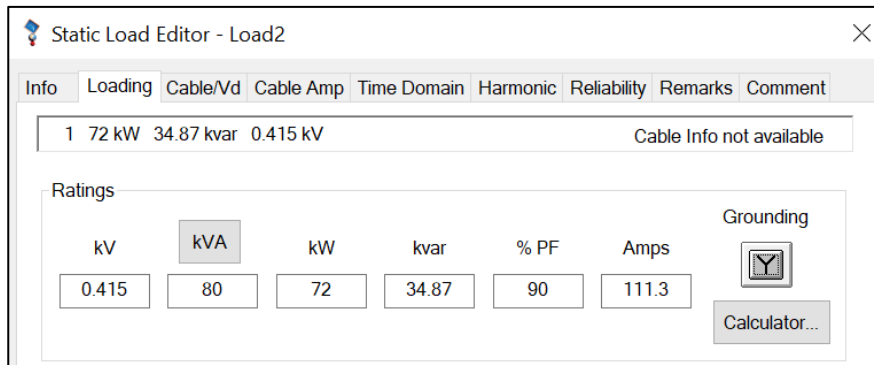


Figure 3.16 Static Load 2 parameter

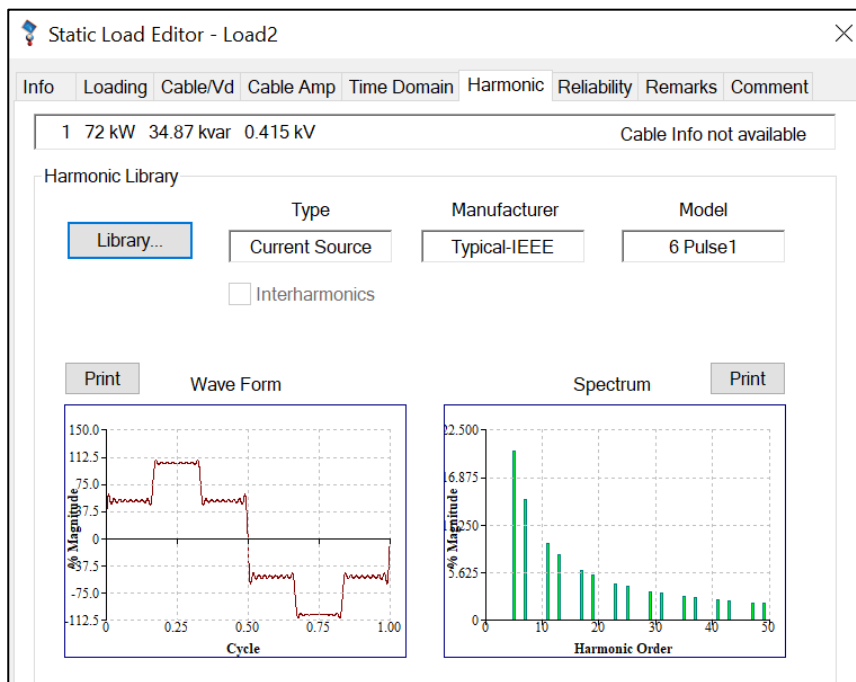


Figure 3.17 Type of harmonic injection for Static Load 2

The Bus bar 7 and Bus bar 10 is connected through another cable which is cable 7 with the same parameter as cable 5. Lump load which is labelled Lump 5 is connected with Bus bar 10 at 415 V nominal voltage and rated 200kVA. The Bus bar 7 and Bus bar 11 is connected with cable 8 with the same parameter as cable 5. Lump load which is labelled Lump 4 is connected with Bus bar 11 at 415 V nominal voltage and rated 100kVA.

All the buses are designed in accordance to the IEEE519 standards to check for the harmonic distortion. By default, ETAP sets all the buses to allow 5% THD (Total Harmonic Distortion) for 6.6kV and 8% for 415V and 3% IHD (Individual Harmonic

Distortion) for 6.6kV and 5% for 415V based on our case study or we can set according to our requirement.

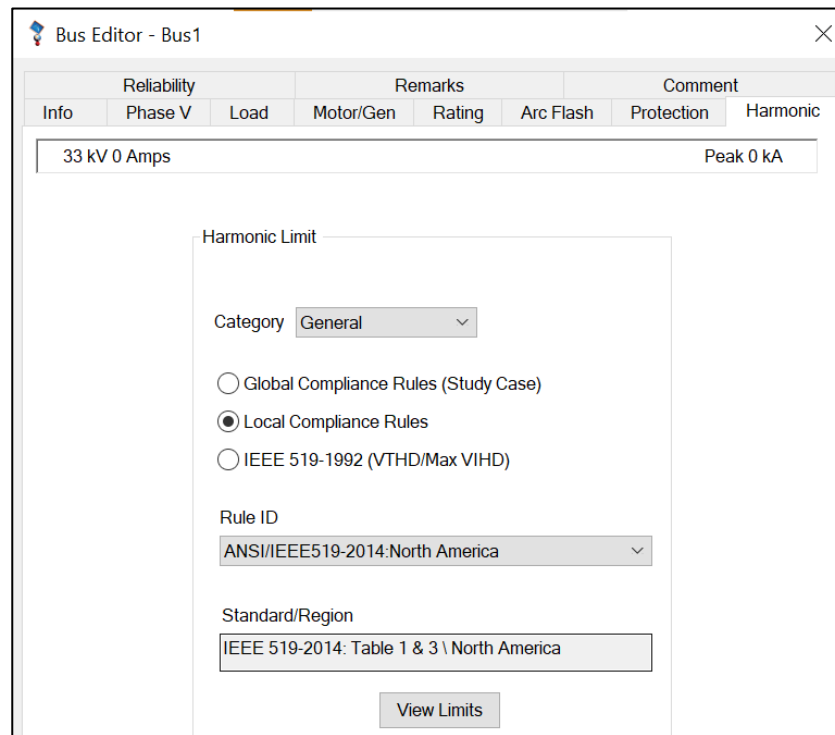


Figure 3.18 Harmonic limit for THD and IHD

These selected values will be compared with the calculated THD and IHD values after performing harmonic load flow study. If any bus goes beyond or above this predefined limit, the alert message will flash to aware this condition by clearly stating the rated limit and operating limit. The over voltage and under voltage conditions also be showed in alert window. This violation could either be critical (where the conditions needs to be checked as soon as possible) or marginal (where load alternation would usually fix the problem). The load flow analysis will be run when the components have been modelled.

3.5 Load Flow Analysis

Load flow study is performed to get the value of power factor of the network system that have been constructed. The power factor must be in the limit that have been set by TNB based on the rating of the system. By perform the load flow analysis, we can calculate the power factor of the network system and the desired power factor to increased it. With this load flow analysis also, we can get the MVA value which can be used at the

time of filter sizing. Here Gauss Seidel Method was conducted to perform the load flow analysis. The results of the load flow analysis are provided on a one-line diagram, which may be displayed by the report manager if desired.

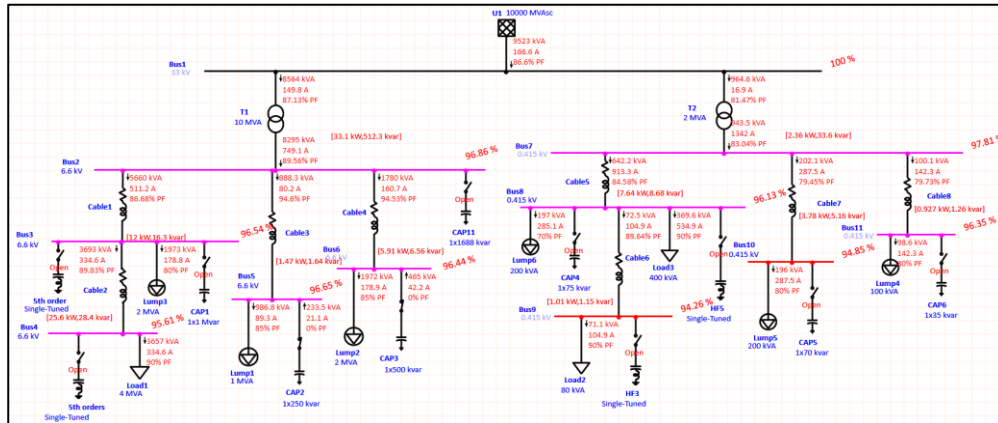


Figure 3.19 Load flow analysis

Based on the load flow analysis, the power flow power factor for the network system is 86.6% and the desired power factor for this project is 95%. The manual calculation for the power factor and power factor improvement is shown below.

3.5.1 Power Factor Calculation for 6.6 kV side

i. Power Factor Calculation for Bus 3

$$\begin{aligned} kvar &= 2803 - 16.2 \\ &= 2786.8kVar \end{aligned}$$

$$kva = 6 \times 10^3 kVa$$

$$\theta = \sin^{-1}\left(\frac{2786.8}{6 \times 10^3}\right)$$

$$\theta = 27.67^\circ$$

$$\cos \theta = \cos 27.67^\circ$$

$$\begin{aligned} \cos \theta &= 0.8856 \\ &= 88.56\% \end{aligned}$$

Calculation to Improve Power Factor at Bus 3

$$\cos \theta_1 = 0.8856^\circ \text{ (current power factor)} \quad \theta_1 = 27.67^\circ$$

$$\cos \theta_2 = 0.95^\circ \text{ (required power factor)} \quad \theta_2 = 18.19^\circ$$

$$\begin{aligned}
 P(\text{active power}) &= 1575kW + 3257kW \\
 &= 4832kW
 \end{aligned}$$

$$\begin{aligned}
 kVar &= P(\tan \theta_1 - \tan \theta_2) \\
 &= 4832(\tan 27.67^\circ - \tan 18.19^\circ) \\
 &= 945.8839kVar
 \end{aligned}$$

ii. Power Factor Calculation for Bus 5

$$\begin{aligned}
 kvar &= 520.8 - 2.04 \\
 &= 518.76kVar
 \end{aligned}$$

$$kva = 1 \times 10^3 kva$$

$$\theta = \sin^{-1}\left(\frac{518.76}{1 \times 10^3}\right)$$

$$\theta = 31.25^\circ$$

$$\cos \theta = \cos 31.25^\circ$$

$$\begin{aligned}
 \cos \theta &= 0.8549 \\
 &= 85.49\%
 \end{aligned}$$

Calculation to Improve Power Factor at Bus 5

$$\cos \theta_1 = 0.8549^\circ \text{ (current power factor)} \quad \theta_1 = 31.25^\circ$$

$$\cos \theta_2 = 0.95^\circ \text{ (required power factor)} \quad \theta_2 = 18.19^\circ$$

$$P(\text{active power}) = 837kW$$

$$\begin{aligned}
 kVar &= P(\tan \theta_1 - \tan \theta_2) \\
 &= 837(\tan 31.25^\circ - \tan 18.19^\circ) \\
 &= 232.8743kVar
 \end{aligned}$$

iii. Power Factor Calculation for Bus 6

$$\begin{aligned}
 kvar &= 1045 - 8.19 \\
 &= 1036.81kVar
 \end{aligned}$$

$$kva = 2 \times 10^3 kva$$

$$\theta = \sin^{-1}\left(\frac{1036.81}{2 \times 10^3}\right)$$

$$\theta = 31.23^\circ$$

$$\cos \theta = \cos 31.23$$

$$\begin{aligned}\cos \theta &= 0.8550 \\ &= 85.50\%\end{aligned}$$

Calculation to Improve Power Factor at Bus 6

$$\cos \theta_1 = 0.8550^\circ \text{ (current power factor)} \quad \theta_1 = 31.23^\circ$$

$$\cos \theta_2 = 0.95^\circ \text{ (required power factor)} \quad \theta_2 = 18.19^\circ$$

$$P(\text{active power}) = 1672kW$$

$$\begin{aligned}kVar &= P(\tan \theta_1 - \tan \theta_2) \\ &= 1672(\tan 31.23^\circ - \tan 18.19^\circ) \\ &= 464.3938kVar[15]\end{aligned}$$

3.5.2 Power Factor Calculation for 415V side

i. Power Factor Calculation for Bus 8

$$\begin{aligned}kvar &= 350.3 - 8.84 \\ &= 341.46kVar\end{aligned}$$

$$kva = 200kVa + 400kVa + 80kVa$$

$$= 680kVa$$

$$\theta = \sin^{-1}\left(\frac{341.46}{680}\right)$$

$$\theta = 30.14^\circ$$

$$\cos \theta = \cos 33.07^\circ$$

$$\begin{aligned}\cos \theta &= 0.8380 \\ &= 83.80\%\end{aligned}$$

Calculation to Improve Power Factor at Bus 8

$$\cos \theta_1 = 0.8380^\circ \text{ (current power factor)} \quad \theta_1 = 33.07^\circ$$

$$\cos \theta_2 = 0.95^\circ \text{ (required power factor)} \quad \theta_2 = 18.19^\circ$$

$$P(\text{active power}) = 218.3kW$$

$$\begin{aligned}kVar &= P(\tan \theta_1 - \tan \theta_2) \\ &= 218.3(\tan 33.07^\circ - \tan 18.19^\circ) \\ &= 70.4140kVar\end{aligned}$$

ii. Power Factor Calculation for Bus 10

$$\begin{aligned}kvar &= 123.4 - 5.04 \\ &= 118.36kVar\end{aligned}$$

$$kva = 200kva$$

$$\theta = \sin^{-1}\left(\frac{118.36}{200}\right)$$

$$\theta = 36.28^\circ$$

$$\cos \theta = \cos 36.28^\circ$$

$$\begin{aligned}\cos \theta &= 0.8061 \\ &= 80.61\%\end{aligned}$$

Calculation to Improve Power Factor at Bus 10

$$\cos \theta_1 = 0.8061^\circ \text{ (current power factor)} \quad \theta_1 = 36.28^\circ$$

$$\cos \theta_2 = 0.95^\circ \text{ (required power factor)} \quad \theta_2 = 18.19^\circ$$

$$P(\text{active power}) = 157.8kW$$

$$\begin{aligned}kVar &= P(\tan \theta_1 - \tan \theta_2) \\ &= 157.8(\tan 36.28^\circ - \tan 18.19^\circ) \\ &= 63.9794kVar\end{aligned}$$

iii. Power Factor Calculation for Bus 11

$$\begin{aligned}kvar &= 60.8 - 1.24 \\ &= 59.56kVar\end{aligned}$$

$$kva = 100kva$$

$$\theta = \sin^{-1}\left(\frac{59.56}{100}\right)$$

$$\theta = 36.55^\circ$$

$$\cos \theta = \cos 36.55^\circ$$

$$\cos \theta = 0.8033$$

$$= 80.33\%$$

Calculation to Improve Power Factor at Bus 11

$$\cos \theta_1 = 0.8033^\circ \text{ (current power factor)} \quad \theta_1 = 36.55^\circ$$

$$\cos \theta_2 = 0.95^\circ \text{ (required power factor)} \quad \theta_2 = 18.19^\circ$$

$$P(\text{active power}) = 79.4 \text{ kW}$$

$$kVar = P(\tan \theta_1 - \tan \theta_2)$$

$$= 79.4(\tan 36.55^\circ - \tan 18.19^\circ)$$

$$= 32.7702 \text{ kVar}$$

The capacitor rated by the calculation will be added to improve the power factor for the whole system. All parameter value for capacitor will be shown below. The capacitor value will be a little bit higher than the calculation value as the capacitor injected into the system by ETAP software will not be exact value.

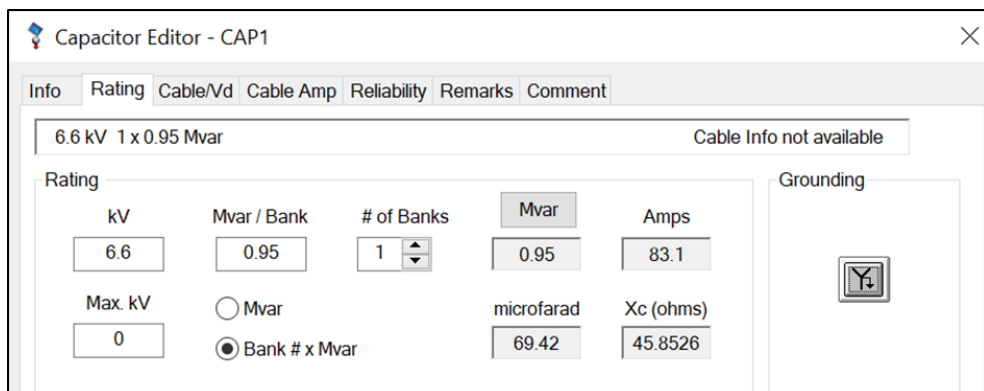


Figure 3.20 Capacitor 1 rating parameter value

Capacitor Editor - CAP2

Info Rating Cable/Vd Cable Amp Reliability Remarks Comment

6.6 kV 1 x 250 kvar Cable Info not available

Rating					Grounding
kV	kvar / Bank	# of Banks	kvar	Amps	
6.6	250	1	250	21.87	<input type="checkbox"/> <input checked="" type="checkbox"/>
Max. kV	<input type="radio"/> kvar		microfarad	Xc (ohms)	
0	<input checked="" type="radio"/> Bank # x kvar		18.27	174.24	

Figure 3.21 Capacitor 2 rating parameter value

Capacitor Editor - CAP3

Info Rating Cable/Vd Cable Amp Reliability Remarks Comment

6.6 kV 1 x 500 kvar Cable Info not available

Rating					Grounding
kV	kvar / Bank	# of Banks	kvar	Amps	
6.6	500	1	500	43.74	<input type="checkbox"/> <input checked="" type="checkbox"/>
Max. kV	<input type="radio"/> kvar		microfarad	Xc (ohms)	
0	<input checked="" type="radio"/> Bank # x kvar		36.54	87.12	

Figure 3.22 Capacitor 3 rating parameter value

Capacitor Editor - CAP4

Info Rating Cable/Vd Cable Amp Reliability Remarks Comment

0.415 kV 1 x 180 kvar Cable Info not available

Rating					Grounding
kV	kvar / Bank	# of Banks	kvar	Amps	
0.415	180	1	180	250.4	<input type="checkbox"/> <input checked="" type="checkbox"/>
Max. kV	<input type="radio"/> kvar		microfarad	Xc (ohms)	
0	<input checked="" type="radio"/> Bank # x kvar		3327	0.95681	

Figure 3.23 Capacitor 4 rating parameter value

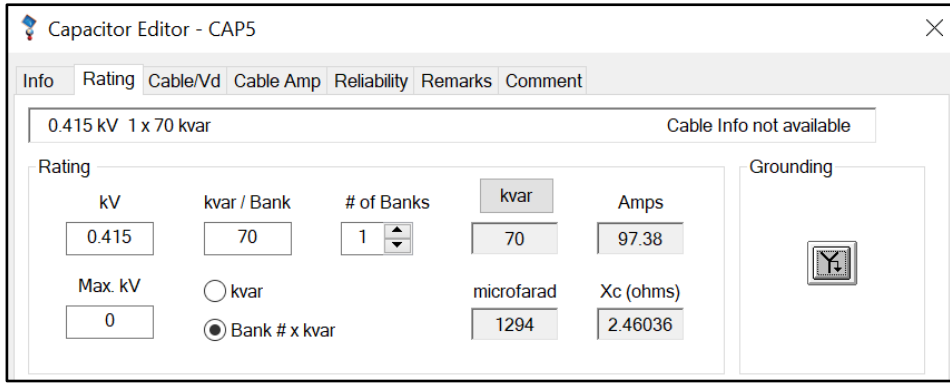


Figure 3.24 Capacitor 5 rating parameter value

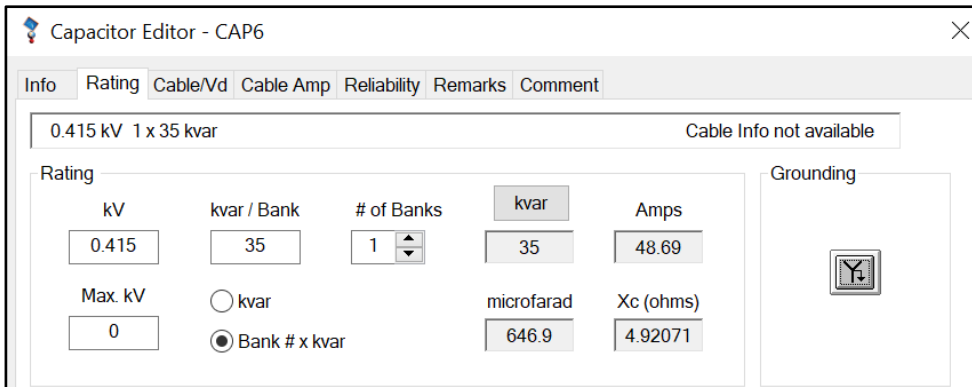


Figure 3.25 Capacitor 6 rating parameter value

3.6 Harmonic Indices

The result of harmonics is usually measured in terms of several indices that are defined below.

Total Harmonic Distortion (THD): Total Harmonic Distortion (THD), also known as Harmonic Distortion Factor (HDF), is to calculate the level of harmonic distortion of voltage and current. It is a measurement that shows the ratio of the mean-square-root of all harmonics to the fundamental component. For an ideal power system, THD is equal to zero.

$$THD = \frac{\sqrt{\sum_2^{\infty} F_i^2}}{F_1} \quad (3)$$

Here F_i is the amplitude of the i^{th} harmonic, and F_1 is the fundamental component.

Individual Harmonic Distortion (IHD): Individual Harmonic Distortion (IHD) measures the ratio of a certain harmonic component with the fundamental component. They are highly efficient to design single tuned filters.

$$IHD = \frac{F_i}{F_1} \quad (4)$$

Root Mean Square (RMS): This is the square root of the sum of the squares of the magnitudes of the fundamental and all the harmonics in the power system. For a power system with no harmonics, the total RMS should be equal to the fundamental component RMS.

$$RMS = \sqrt{\sum_1^{\infty} F_i^2} \quad (5)$$

3.7 Harmonic Load Flow Analysis

To check the harmonic distortion or effect of harmonic source on the power network, Harmonic load flow needs to be performed. The harmonic load flow is performed for general loading condition. In ETAP's Harmonic Analysis module, user can simulate harmonic current and voltage sources, categorize harmonic problems, reduce nuisance trips, design and test filters, and report harmonic voltage and current distortion limit violations. The Harmonic Load Flow Study first carries out a load flow calculation at the fundamental frequency.

To perform harmonic analysis, first we have to go into the harmonic analysis mode and run the harmonic load flow calculation as shown in figure below

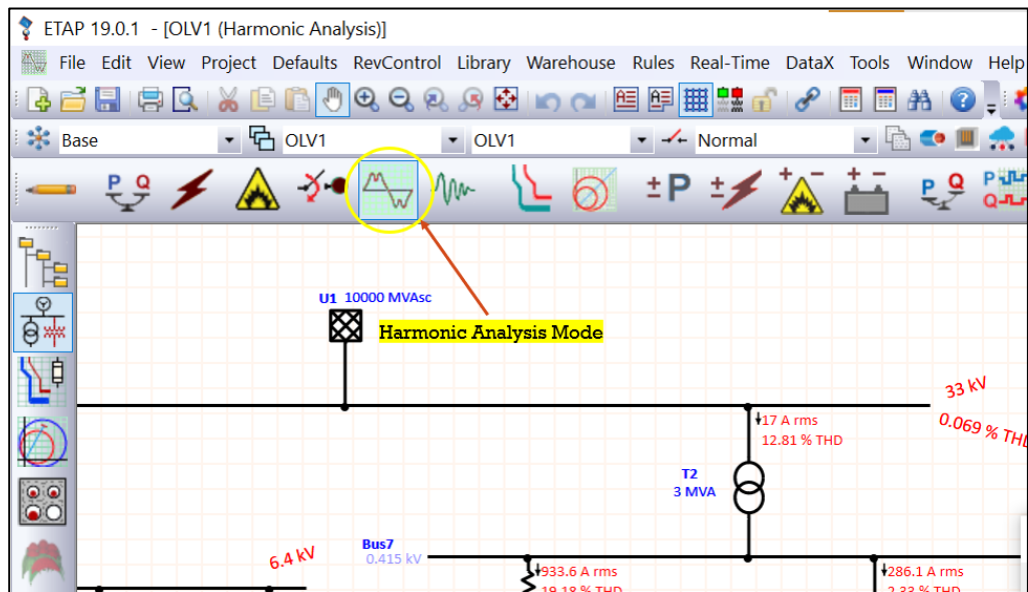


Figure 3.26 Harmonic analysis mode button

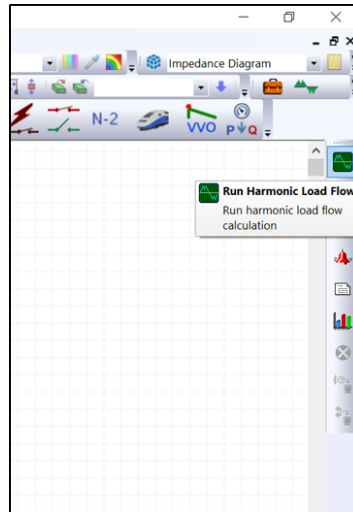


Figure 3.27 Harmonic load flow run button

This load flow calculation is based on either the Newton Raphson Method or the Accelerated Gauss Seidel Method

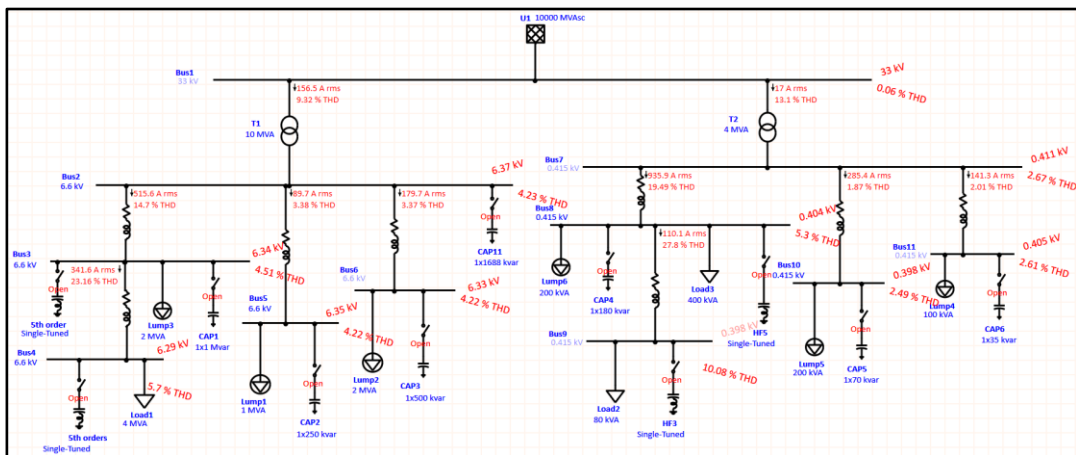


Figure 3.28 Harmonic load flow

On running the harmonic load flow study, it can be seen that there is some harmonic frequency with greater magnitude exceeding the THD and IHD limit.

From the alert window (Figure) it can be seen that, the order of harmonic is contributing in each bus. The harmonic orders given in the alert window are exceeding the predefined limit of THD and IHD.

Harmonic Load Flow Analysis Alert View - Output Report: PSM2						
Study Case: HA	Data Revision: Base	Filter				
Configuration: Normal	Date: 12-06-2022	<input type="checkbox"/> Zone	<input type="checkbox"/> Area	<input type="checkbox"/> Region		
Critical						
Device ID	Type	Condition	Rating / Limit	Operating	% Operating	Harmonic
Bus2	Bus THD	Exceeds Limit	5	5.24	104.74	Total
Bus3	Bus THD	Exceeds Limit	5	5.42	108.39	Total
Bus4	Bus IHD	Exceeds Limit	3	3.59	119.62	5.00
Bus4	Bus IHD	Exceeds Limit	3	3.52	117.43	7.00
Bus4	Bus THD	Exceeds Limit	5	6.27	125.39	Total
Bus5	Bus THD	Exceeds Limit	5	5.47	109.43	Total
Bus6	Bus THD	Exceeds Limit	5	5.73	114.66	Total
Bus9	Bus THD	Exceeds Limit	8	10.55	131.83	Total

Figure 3.29 Alert window figure

3.8 Elimination of Harmonic

Elimination of harmonic is a must to eliminate the harmonic distortion that has been over limit the standard. By adding the capacitor banks to improve the power factor and the desired power factor, the capacitor will cause a higher resonance to the harmonic thus increase the existing THD and IHD of the power system network. The elimination of harmonic can be used by using harmonic filter.

3.8.1 Elimination of Harmonics using Detune Reactor

To remove harmonic distortion in this power network, a single-tuned filter has been selected for its capability. This filter is used in the ETAP to ensure that the plant network receives adequate reactive power while also minimising losses at the fundamental frequency of the system. Using the 'Harmonic Filter Sizing' option, this filter may compute its parameter value based on its modelling. This filter is chosen because it can put the capacitor and inductor in series added to the bus bar which is the inductor will function as a reactor to make the THD and IHD within the limit.

We can design the filter by double clicking the filter component and editing parameter page. Single-Tuned filter can be selected from the filter type drop down option. In initial condition all the parameter for this filter will show zero. In order to calculate the parameter values of filter the 'Size Filter' button need to be pressed to open another page where the required harmonic order in which harmonic distortion needs to be eliminated and the harmonic current for that particular harmonic order can be entered to size the filter properly. The harmonic current can be found on the one-line diagram especially after running a harmonic load flow study at the point of common coupling where the harmonic source is attached to main power grid. By using harmonic load flow

slider, the magnitude of harmonic current of a required harmonic order can be displayed on the one-line diagram.

As described in Harmonic Load Flow analysis, for this power network 5th and 7th harmonic order is contributing harmonic distortion in bus 4. So, if the harmonics from these two harmonic orders can be eliminated, most of the harmonics distortion of this power network can be reduced. In this study one single tuned filters will be designed for those harmonics order to eliminate harmonics distortion. The process of designing harmonic filter for 5th harmonic order will be shown in details. The harmonic distortion spectrum for all the buses given below where Bus bar 4 (6.6kV) is the most distorted one for the harmonic source. In order to design a single tuned filter for 5th order, we need to click parameter page of harmonic filter editor and then 'Size Filter' tab. Depending on the requirements, we have to feed in the data to size an optimal filter. If we willing to design a filter on the basis of the existing correcting the power factor of the system, then on carrying out a balanced load flow analysis, the existing power factor can be found.

From the load flow analysis study that has been discussed before, it can be found that the existing power factor 80%. These values need to feed at the PF correction option and the desired power factor 95% need to put at 'Desired PF' option. After putting all the required value, the Harmonic Filter Editor and Harmonic Filter Sizing window look like as figure

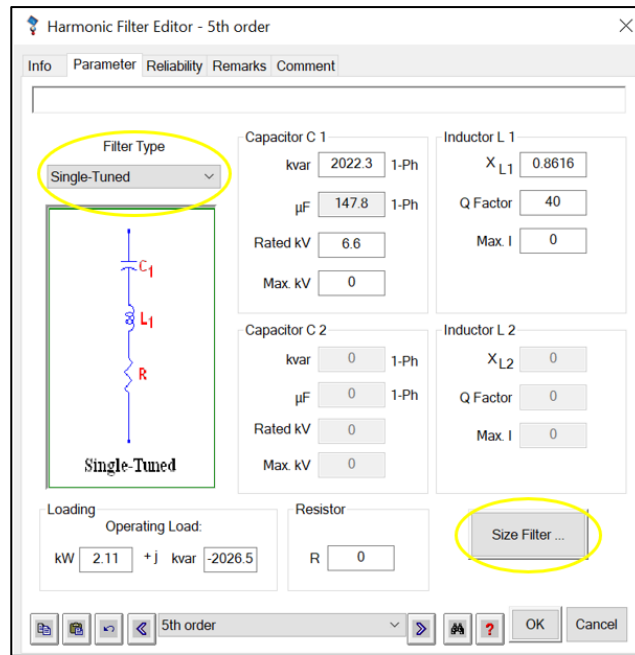


Figure 3.30 Harmonic filter type

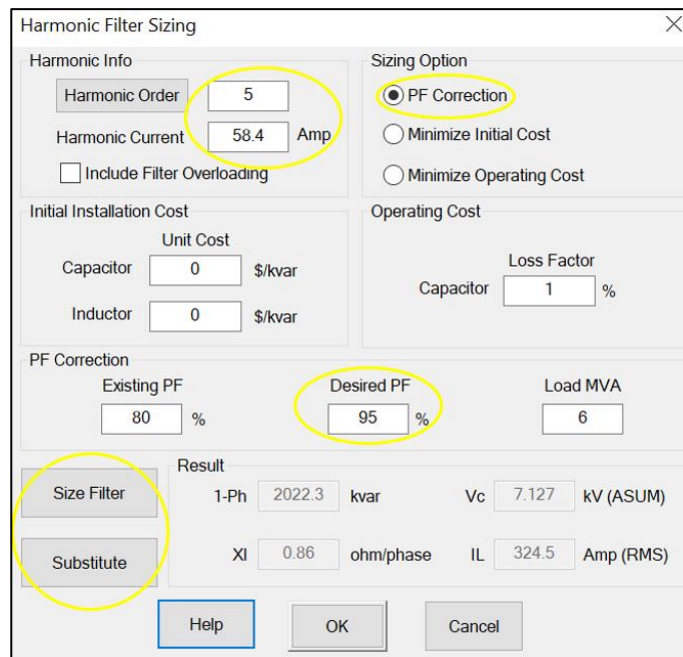


Figure 3.31 Harmonic filter sizing

For 5th harmonic order, harmonic current 58.4 Amp, that can be found at one-line display after performing Harmonic Load Flow study. The result of Harmonic Load Flow Study is given at Figure 3.32

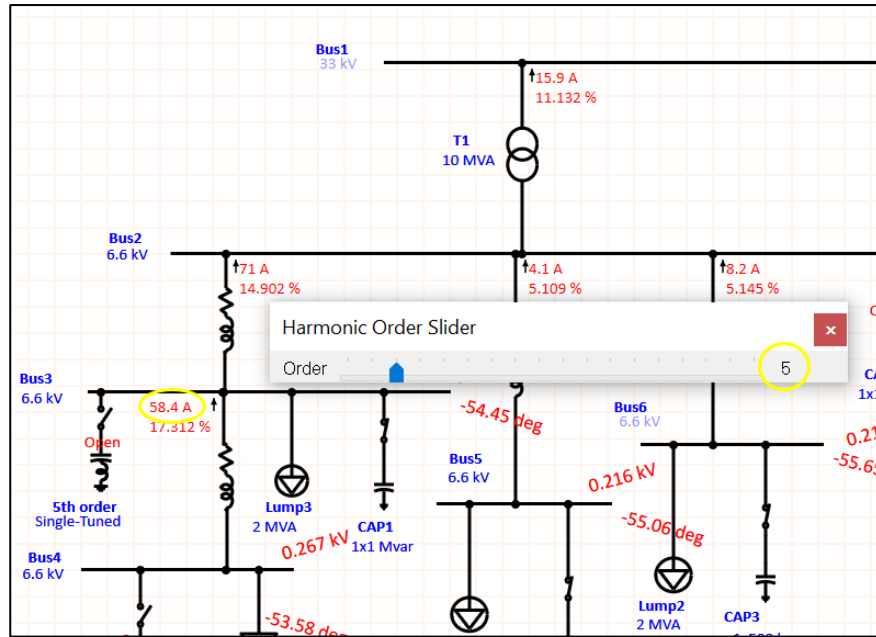


Figure 3.32 Harmonic order current using slider

After putting all the value, user needs to press ‘Size Filter’ and then ‘Substitute’. ETAP has the inbuilt function to compute the appropriate values for the capacitor and inductor. The filter’s quality factor is based at the reactance of the tuned frequency point, that is

$Q = (nXL) / R$ (Here, R = Resistance, XL = Reactance value of the filter that is taken from Filter editor page and n = Order of the Harmonic Frequency.)

For 5th order harmonic,

$$Q = (5 * 0.233) / 1 = 1.165$$

On running Harmonic Load flow study, there were some alert shown on the Alert View for Max kV and Max I value. By following the operating value of the alert window, the Max value can be entered within marginal limitation. The alert page for this harmonic load flow study is given in figure

Harmonic Load Flow Analysis Alert View - Output Report: PSM2						
Study Case: HA		Data Revision: Base		Filter		
Configuration: Normal		Date: 12-06-2022		<input type="checkbox"/> Zone <input type="checkbox"/> Area		
Critical						
Device ID	Type	Condition	Rating /Limit	Operating	% Operating	Harmonic
5th order	kV	Over Voltage	0	4.27	999	Capacitor1 Vmax
5th order	Amp	Overcurrent	0	193.3	999	Inductor1 Amp
Bus9	Bus THD	Exceeds Limit	8	10.54	131.71	Total
Marginal						
Device ID	Type	Condition	Rating /Limit	Operating	% Operating	Harmonic

Figure 3.33 Alert window after install filter

After install the single tune filter at bus bar 4 we can see that there is no critical alert for the power network system which mean the THD is within the standard limit.

3.9 Standards

ETAP Harmonic Analysis module fully complies with the latest version of the following standards given below:

- IEEE Standards 519-2014, IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems
- ANSI/IEEE Standard 399-1997, IEEE Recommended Practice for Industrial and Commercial Power System Analysis
- IEEE Standard 141-1993, IEEE Recommended Practice for Electric Power Distribution for Industrial Plants [16]

3.10 Summary

In this chapter, the method of load flow analysis and harmonic analysis using ETAP software has been investigated. The power load flow, harmonic load flow, harmonic frequency scan, components modelling and harmonic elimination process are included in this chapter.

The next chapter will show the corresponding results using the method from this chapter.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

In this chapter, the results for the simulation and methodology by using the ETAP simulation will be shown and discussed.

4.2 Effect of Adding Capacitor Banks

The effect of adding capacitor banks into the 11-bus system network will be shown below by the simulation results and discussed. The effect of adding equipment capacitor banks in term of power factor, total harmonics distortion level and power losses will be analyses.

4.2.1 Analysis of Power Factor

Figure below shows the effect of adding capacitor bank to increase the power factor from the origin load flow to desired power factor which is 95% for the power network system single line diagram. The manual calculation has been calculated at the methodology part. The manual calculation is accurate with the simulation that has been run as shown below.

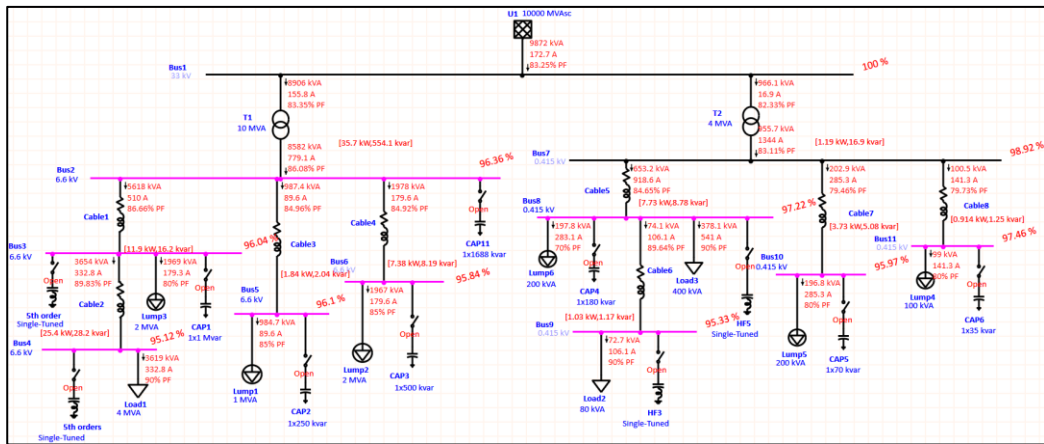


Figure 4.1 Power factor before add capacitor banks

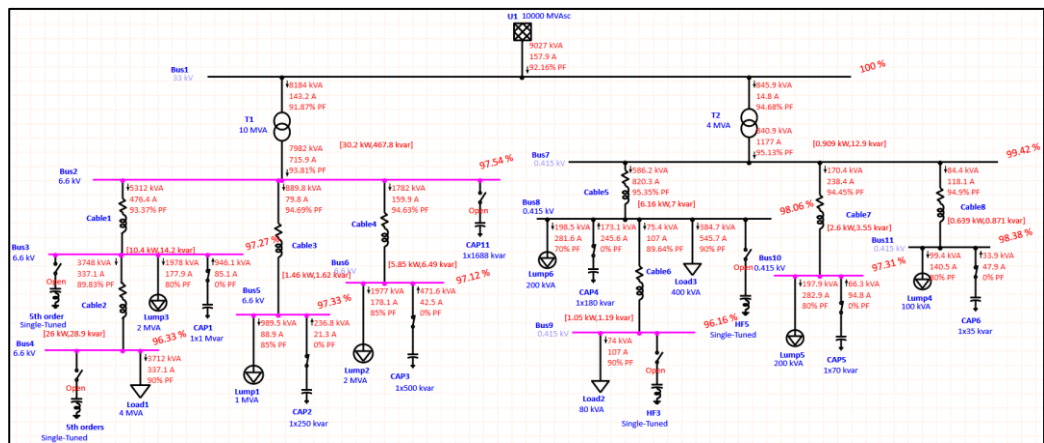


Figure 4.2 Power factor after add capacitor banks

From the Figure 4.1 and Figure 4.2, we can see that the capacitor injects reactive power and current to the bus bar that have low power factor thus improved the power factor for the whole system. The power factor for the network increased from 83.25% to 92.16% and follow the regulation and limit that have been set by utility. Capacitor 1 injects 946.1 kVA and 85.1A to the Bus bar 3 thus improved the power factor for the network from 86.66% to 93.37%. Capacitor 2 injects 236.8 kVA and 21.3A to the Bus bar 5 thus improved the power factor for the network from 84.96% to 94.69%. Capacitor 3 injects 471.6 kVA and 42.5A to the Bus bar 6 thus improved the power factor for the network from 84.92% to 94.63%. Capacitor 4 injects 173.1 kVA and 245.6A to the Bus bar 8 thus improved the power factor for the network from 84.65% to 95.35%. Capacitor 5 injects 66.3 kVA and 94.8A to the Bus bar 10 thus improved the power factor for the network from 79.46% to 94.45%. Capacitor 6 injects 33.9 kVA and 47.9A to the Bus bar 11 thus improved the power factor for the network from 79.73% to 94.49%. The value

has a small different between the manual calculation and simulation due to some error factor.

Table 4.1 Table of summary capacitor effect to power factor

Power Factor	Before Add Capacitor Banks	After Add Capacitor Banks
Bus 1	83.25%	92.16%
Bus 2	86.08%	93.81%
Bus 3	86.66%	93.37%
Bus 4	89.83%	90.00%
Bus 5	84.96%	94.69%
Bus 6	84.92%	94.63%
Bus 7	83.11%	95.13%
Bus 8	84.65%	95.35%
Bus 9	89.4%	90.00%
Bus 10	79.46%	94.45%
Bus 11	79.73%	94.90%

4.2.2 Analysis of Harmonic

For the harmonic analysis study, the network system is divided into two system for the THD limit which is 6.6 kV and 415 V as it is contain of different Voltage Distortion Limits for IEEE519-2014. 6.6 kV system include from Bus 2 until Bus 6 and for 415 V system include from Bus 7 until Bus 11. Harmonic load low analysis is studied for three cases which is before add capacitor, after add capacitor and after add harmonic filter which is passive filter contain of capacitor series with inductor or called as detuned reactor. Figure below shows the effect of adding or varying the amount of capacitance with resonance of harmonic frequency and Total Harmonic Distortion level.

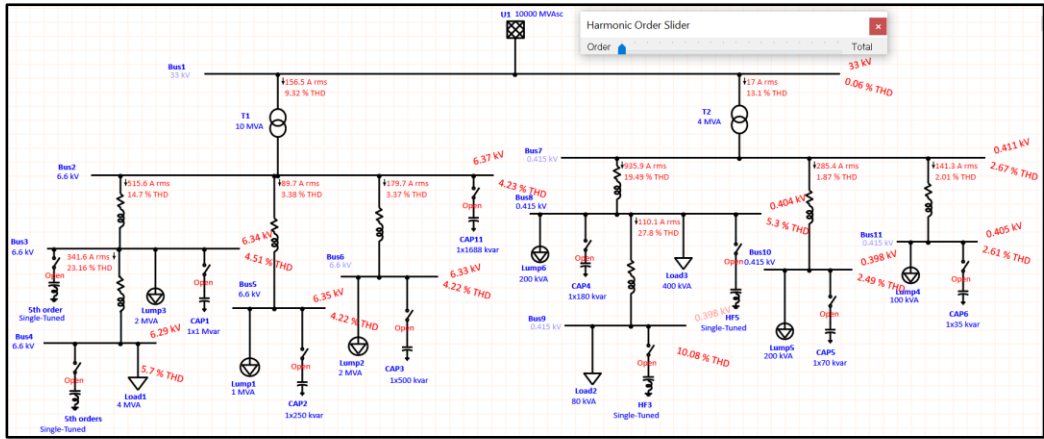


Figure 4.3 Harmonic load flow before add capacitor banks

For this power network system, 3 non-linear load which is the static load is the source of harmonic Typical IEEE-6 Pulse 1 at Bus 4, Bus 8 and Bus 9. Before the capacitor bank is added into the network system, only Bus 4 and Bus 9 that contribute highest harmonic and THD level is exceed the Voltage Distortion Limits for IEEE519-2014 as it is the source of harmonic that contain from static load at that buses. The alert view is shown in the Figure 4.4.

Harmonic Load Flow Analysis Alert View - Output Report: PSM2

Study Case: HA Data Revision: Base Filter
 Configuration: Normal Date: 16-06-2022 Zone

Critical						
Device ID	Type	Condition	Rating /Limit	Operating	% Operating	Harmonic
Bus9	Bus THD	Exceeds Limit	8	10.08	125.95	Total
Bus4	Bus IHD	Exceeds Limit	3	3.28	109.39	5.00
Bus4	Bus THD	Exceeds Limit	5	5.7	114.09	Total

Figure 4.4 Harmonic alert window before add capacitor banks

From the load flow analysis alert view shown in Figure 4.4, it shows that the Bus 9 operating at 10.08% which exceed the limit 8% for system below 1 kV. Bus 4 also exceed the 5% THD limit by operating at 5.7%. The highest harmonic contribute is at 5th order for Bus 4 and total harmonic for Bus 9.

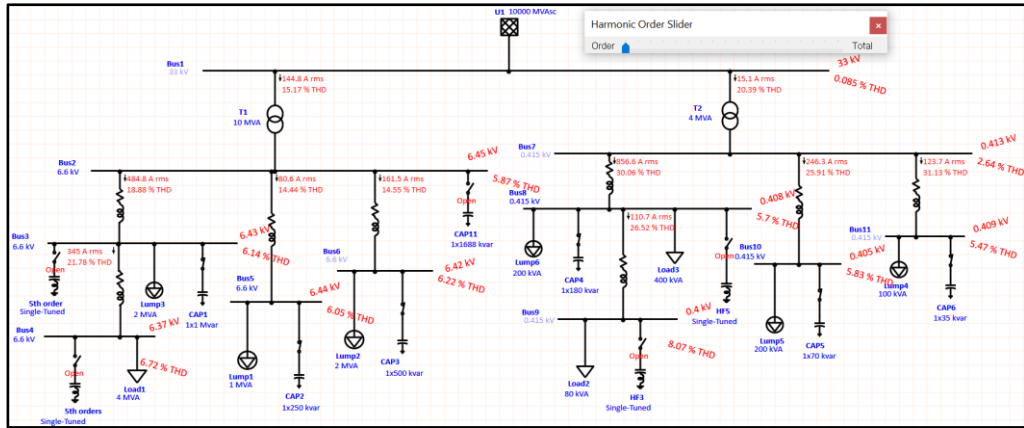


Figure 4.5 Harmonic load flow after add capacitor banks

As shown in the Figure 4.5, the THD level or the whole system is rapidly increase after the capacitor is added into the network system. This is due to the high current of capacitor when switching on process. Capacitors are particularly sensitive to harmonic currents since their impedance decreases proportionally to the order of the harmonics present. Since the impedance of the capacitor decrease with increase in frequency, large harmonic current flows into capacitors.

Table 4.2 will show the increasement of the THD level for all buses after the installation of capacitor.

Table 4.2 Table of THD level comparison for capacitor in power network system

THD level	Before Add Capacitor Banks	After Add Capacitor Banks
Bus 1	0.06%	0.085%
Bus 2	4.23%	5.87%
Bus 3	4.51%	6.14%
Bus 4	5.7%	6.72%
Bus 5	4.22%	6.05%
Bus 6	4.22%	6.22%
Bus 7	2.67%	2.64%
Bus 8	5.3%	5.7%
Bus 9	10.08%	8.07%
Bus 10	2.49%	5.83%
Bus 11	2.61%	5.47%

From the Table 4.2, it can be observed that the THD level at buses which is the source of harmonic is contribute the highest harmonic and worst for the cases after the capacitor is added into the system.

Harmonic Load Flow Analysis Alert View - Output Report: PSM2						
Study Case: HA		Data Revision: Base		Filter		
Configuration: Normal		Date: 16-06-2022		<input type="checkbox"/> Zone	<input type="checkbox"/> Area	
Critical						
Device ID	Type	Condition	Rating /Limit	Operating	% Operating	Harmonic
Bus2	Bus IHD	Exceeds Limit	3	3.32	110.79	5.00
Bus2	Bus IHD	Exceeds Limit	3	3.99	132.87	7.00
Bus2	Bus THD	Exceeds Limit	5	5.87	117.39	Total
Bus3	Bus IHD	Exceeds Limit	3	3.52	117.41	5.00
Bus3	Bus IHD	Exceeds Limit	3	4.19	139.59	7.00
Bus3	Bus THD	Exceeds Limit	5	6.14	122.79	Total
Bus4	Bus IHD	Exceeds Limit	3	4.2	139.93	5.00
Bus4	Bus IHD	Exceeds Limit	3	4.68	155.9	7.00
Bus4	Bus THD	Exceeds Limit	5	6.72	134.41	Total
Bus5	Bus IHD	Exceeds Limit	3	3.36	112	5.00
Bus5	Bus IHD	Exceeds Limit	3	4.07	135.76	7.00
Bus5	Bus THD	Exceeds Limit	5	6.05	120.94	Total
Bus6	Bus IHD	Exceeds Limit	3	3.4	113.22	5.00
Bus6	Bus IHD	Exceeds Limit	3	4.16	138.73	7.00
Bus6	Bus THD	Exceeds Limit	5	6.22	124.49	Total
Bus9	Bus THD	Exceeds Limit	8	8.07	100.91	Total

Figure 4.6 Harmonic alert window after add capacitor banks

As shown in the Figure 4.6, there are some harmonic frequency with greater magnitude exceed the THD and IHD limit that has been set. From the alert report it can be seen that 5th and 7th order of harmonic contributed in six buses each which is Bus 2, Bus 3 and Bus 4, Bus 5, Bus 6 and Bus 9.

Table 4.3 Comparison of waveform before and after add capacitor banks for 6.6kV

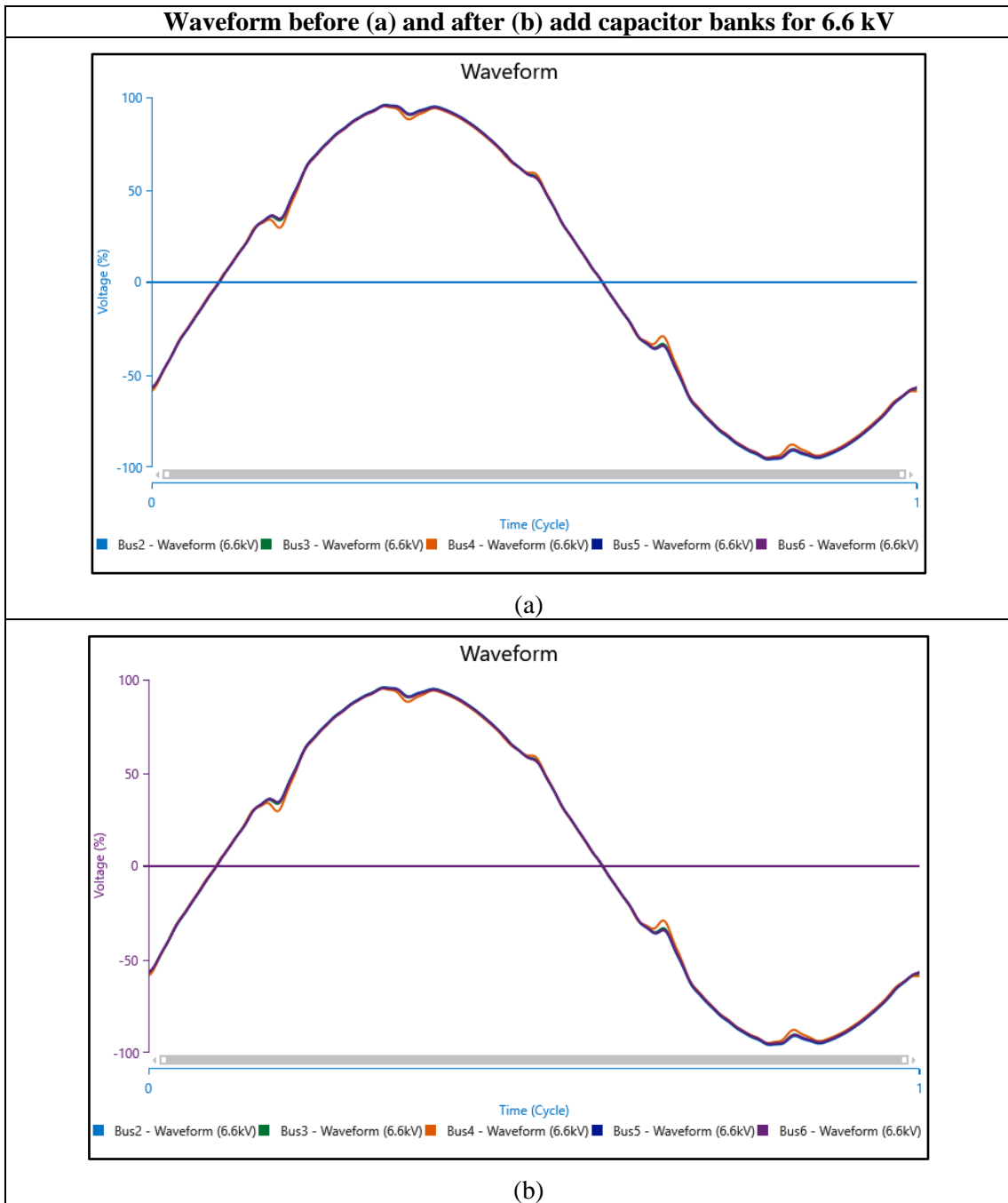
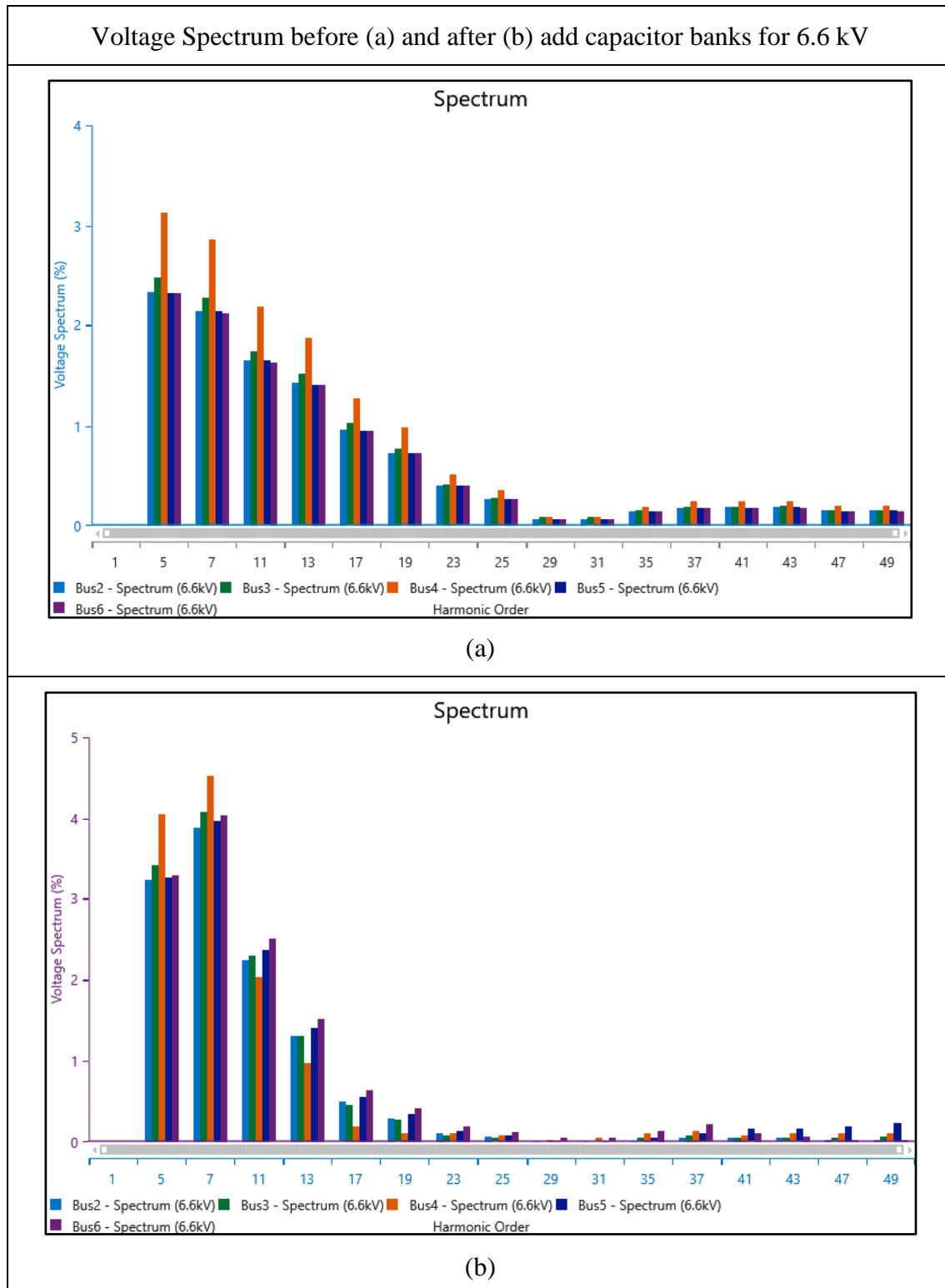


Table 4.4 Comparison of voltage spectrum before and after add capacitor banks for 6.6 kV



From the Table 4.3 and Table 4.4, it shows that from running the harmonic load flow analysis, the THD level is increasing rapidly for the 6.6 kV system. The voltage spectrum for 5th and 7th harmonic order which is the critical harmonic order that exist at

Bus bar 4 for this power network system is increase after we add the capacitor banks as shown in figure above. The voltage spectrum for 5th and 7th harmonic order also exists at Bus bar 2, Bus bar 3, Bus bar 5 and Bus bar 6 and it is increasing rapidly. The waveform of the system also become more distorted from the origin load flow as the capacitor bank is installed into the system.

Table 4.5 Comparison of waveform before and after add capacitor banks for 415 V

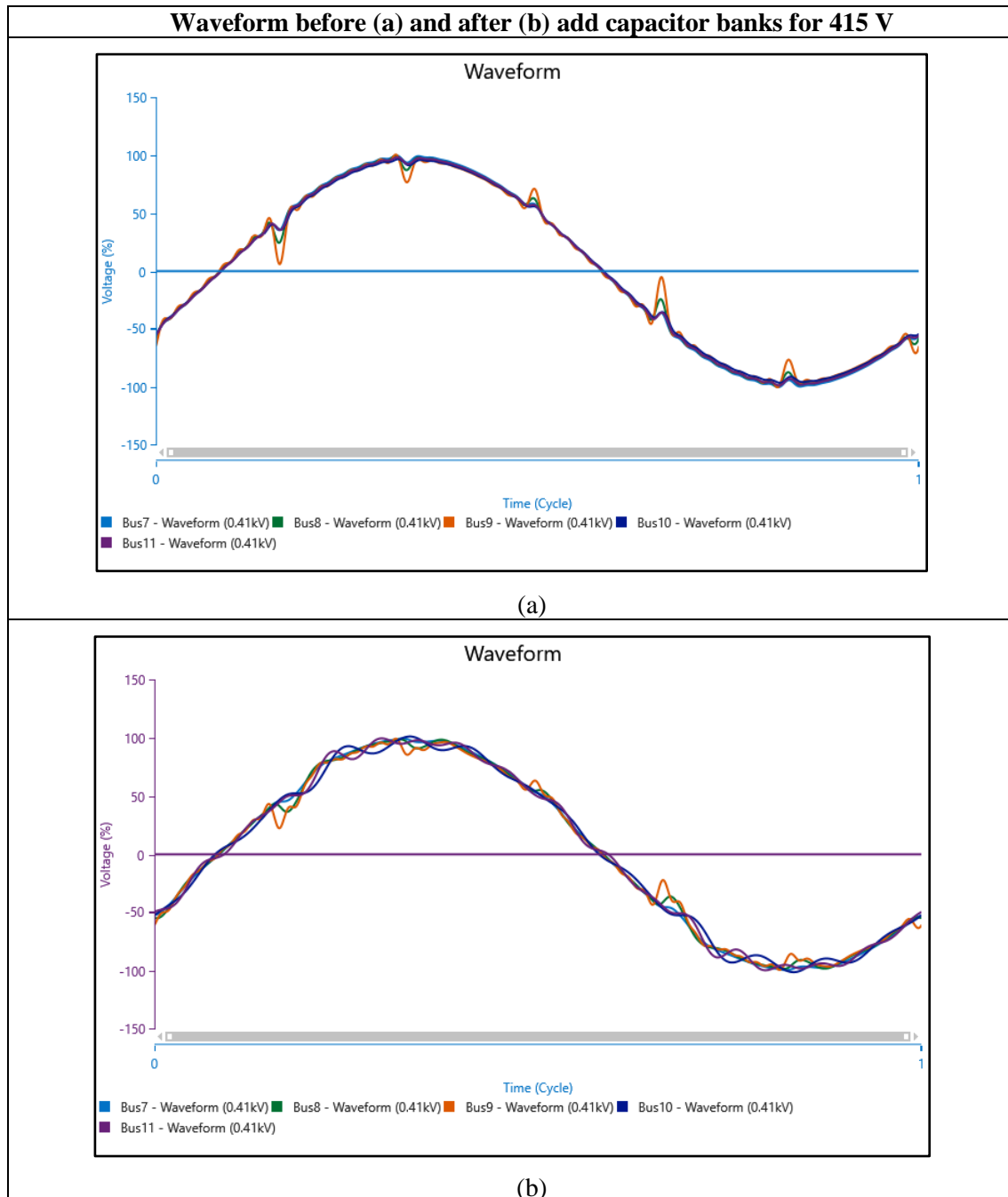
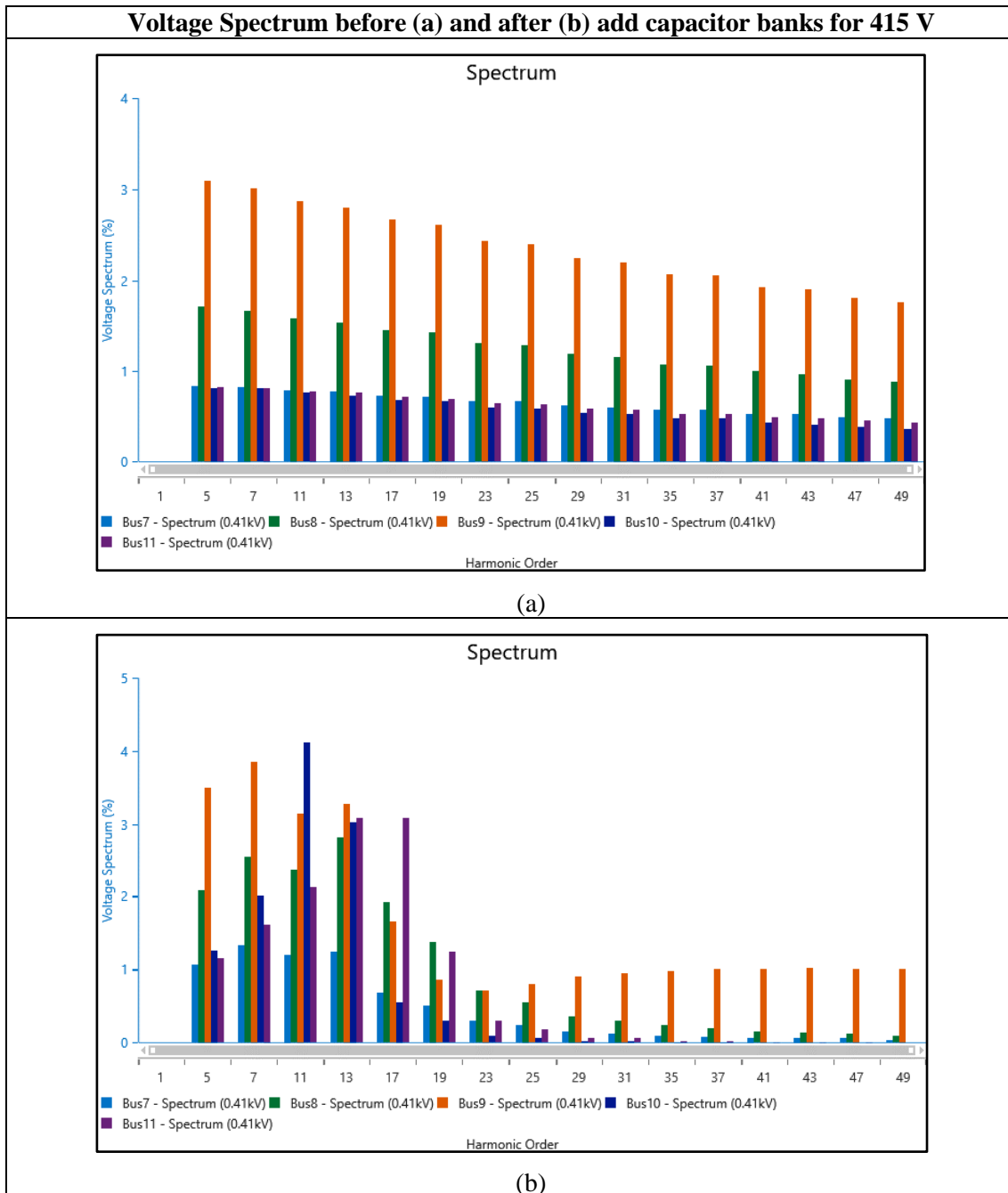


Table 4.6 Comparison of voltage spectrum before and after add capacitor banks for 415 V



From the Table 4.5 and Table 4.6 above, it also shows that from running the harmonic load flow analysis, the THD level is increasing rapidly for the 415 V system. The voltage spectrum for 5th and 7th harmonic order which is the critical harmonic order that exist at Bus bar 9 for this power network system is increase after we add the capacitor banks as shown in figure above. The waveform of the system also become more distorted from the origin load flow as the capacitor bank is installed into the system.

4.2.2.1 Harmonic Elimination by using Detuned Reactor

By using a single-tuned filter in ETAP, the connection of an inductor series with capacitor banks is installed at most critical harmonic distortion which is Bus bar 4 for the 6.6 kV system and Bus bar 8 and Bus bar 9 for the 415 V system to limit the current because the inductor opposed the sudden change of current. This harmonic filter also called as passive filter or LC filter. The configuration and parameter for this filter is explained in the methodology part.

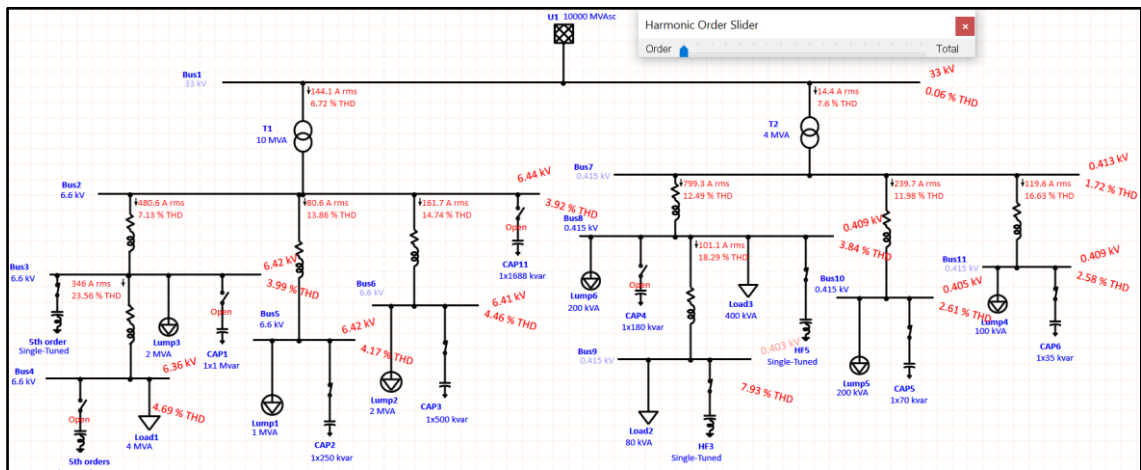


Figure 4.7 Harmonic load flow analysis after adding a single-tuned filter

From the Figure 4.7, it can be seen that the THD level for whole network system is within limit and becoming more better and the alert view window show that no critical value of harmonic order after a single-tuned filter is installed and no trouble for the whole network system.

Harmonic Load Flow Analysis Alert View - Output Report: PSM2						
Study Case: HA		Data Revision: Base		Filter		
Configuration: Normal		Date: 16-06-2022		<input type="checkbox"/> Zone	<input type="checkbox"/> Area	
Critical						
Device ID	Type	Condition	Rating /Limit	Operating	% Operating	Harmonic
HF5	kV	Over Voltage	0	0.27	999	Capacitor1 Vmax
HF5	Amp	Overcurrent	0	380	999	Inductor1 Amp
HF3	kV	Over Voltage	0	0.29	999	Capacitor1 Vmax
HF3	Amp	Overcurrent	0	33.63	999	Inductor1 Amp
5th order	kV	Over Voltage	0	4.62	999	Capacitor1 Vmax
5th order	Amp	Overcurrent	0	100.02	999	Inductor1 Amp

Figure 4.8 Harmonic load flow alert window after adding a single-tuned filter

Table 4.7 shows the THD level for whole system after the single-tuned filter is added.

Table 4.7 Table for THD level summary of the power network system

THD level	After Add Capacitor Banks	After Add Single-tuned Filter
Bus 1	0.085%	0.06%
Bus 2	5.87%	3.92%
Bus 3	6.14%	3.99%
Bus 4	6.72%	4.69%
Bus 5	6.05%	4.17%
Bus 6	6.22%	4.46%
Bus 7	2.64%	1.72%
Bus 8	5.7%	3.84%
Bus 9	8.07%	7.93%
Bus 10	5.83%	2.61%
Bus 11	5.47%	2.58%

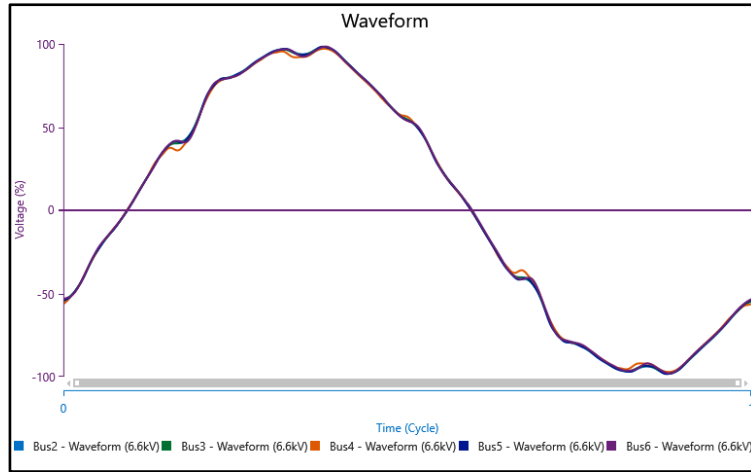


Figure 4.9 Figure of waveform after single-tuned filter installed for 6.6 kV

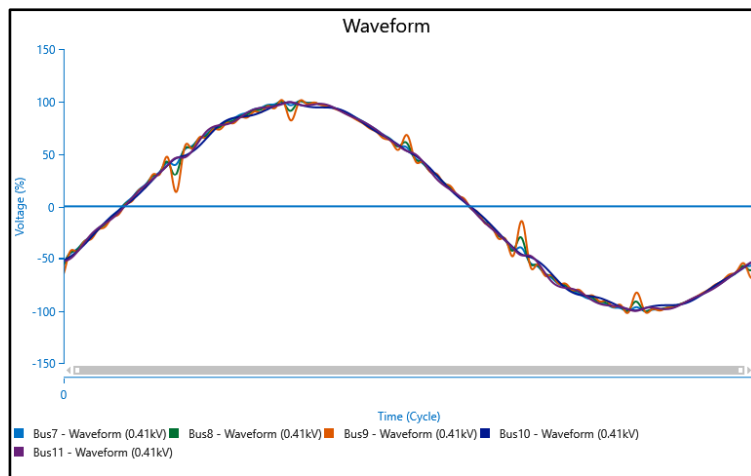


Figure 4.10 Figure of waveform after single-tuned filter installed for 415 V

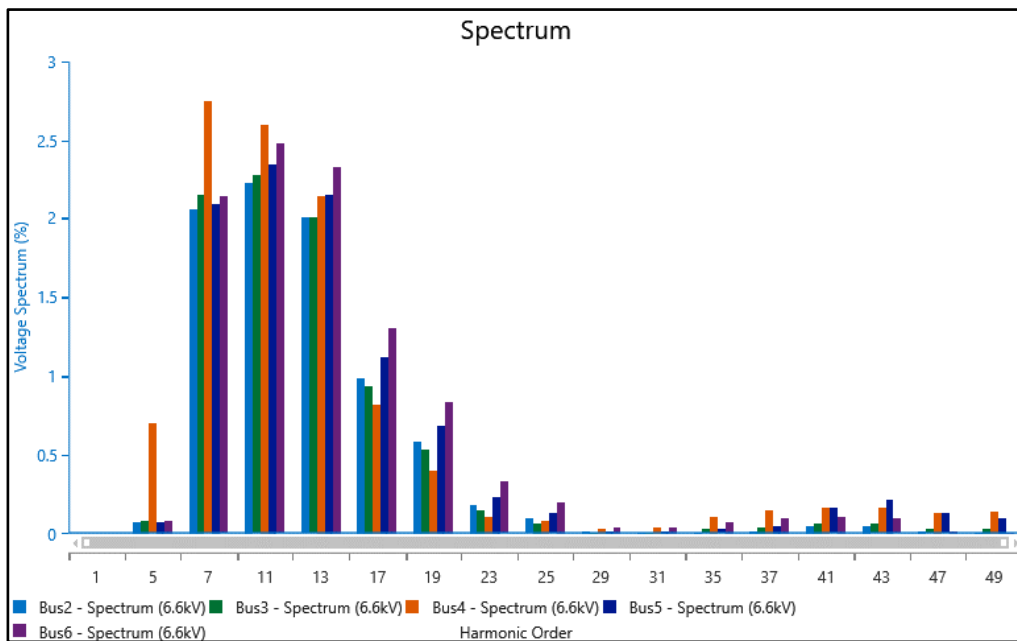


Figure 4.11 Figure of voltage spectrum after single-tuned filter installed for 6.6 kV

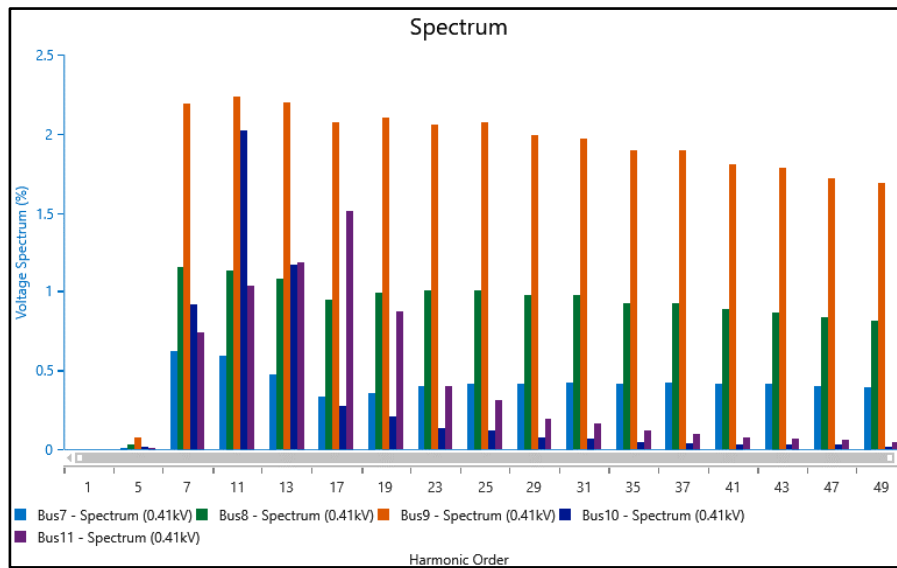


Figure 4.12 Figure of voltage spectrum after single-tuned filter installed for 415 V

After a single-tuned filter is installed at Bus bar 4, Bus bar 8 and Bus bar 9 with a proper value, it can be seen in single line diagram as shown in the figure above, the waveform and the voltage spectrum are reduced significantly. The distorted waveform not exceed 100 for voltage compared to before which is exceed and the waveform is cleaner and closer to sine waveform after a single-tuned is installed. The 5th order of harmonic for Bus bar 2, Bus bar 3, Bus bar 4, Bus bar 5, Bus bar 6 and Bus bar 9 is eliminated and the 5th order harmonic for all buses is reduced in term of voltage spectrum. The eliminated of harmonic order at each critical bus for the network system thus make the THD level reduced significantly and within the limit.

4.2.3 Power Losses

Figure below shows the effect of adding capacitor banks in term of power losses in branch and whole network system.

Branch Losses Summary Report									
Branch ID	From-To Bus Flow		To-From Bus Flow		Losses		% Bus Voltage		Vd % Drop in Vmag
	MW	Mvar	MW	Mvar	kW	kvar	From	To	
Cable1	4.869	2.803	-4.857	-2.787	11.9	16.2	96.4	96.0	0.32
Cable2	3.283	1.606	-3.257	-1.577	25.4	28.2	96.0	95.1	0.92
Cable3	0.839	0.521	-0.837	-0.519	1.8	2.0	96.4	96.1	0.26
Cable4	1.680	1.045	-1.672	-1.036	7.4	8.2	96.4	95.8	0.52
Cable5	0.553	0.348	-0.545	-0.339	7.7	8.8	98.9	97.2	1.70
Cable6	0.066	0.033	-0.065	-0.032	1.0	1.2	97.2	95.3	1.89
Cable7	0.161	0.123	-0.157	-0.118	3.7	5.1	98.9	96.0	2.94
Cable8	0.080	0.061	-0.079	-0.059	0.9	1.2	98.9	97.5	1.46
T1	7.423	4.921	-7.387	-4.367	35.7	554.1	100.0	96.4	3.64
T2	0.795	0.548	-0.794	-0.532	1.2	16.9	100.0	98.9	1.08
					96.8	641.9			

Figure 4.13 Figure of power losses before capacitor banks added

Branch Losses Summary Report									
Branch ID	From-To Bus Flow		To-From Bus Flow		Losses		% Bus Voltage		Vd % Drop in Vmag
	MW	Mvar	MW	Mvar	kW	kvar	From	To	
Cable1	4.959	1.902	-4.949	-1.888	10.4	14.2	97.5	97.3	0.27
Cable2	3.367	1.647	-3.341	-1.618	26.0	28.9	97.3	96.3	0.93
Cable3	0.843	0.286	-0.841	-0.284	1.5	1.6	97.5	97.3	0.21
Cable4	1.687	0.576	-1.681	-0.570	5.8	6.5	97.5	97.1	0.42
Cable5	0.559	0.177	-0.553	-0.170	6.2	7.0	99.4	98.1	1.35
Cable6	0.068	0.033	-0.067	-0.032	1.0	1.2	98.1	96.2	1.91
Cable7	0.161	0.056	-0.158	-0.052	2.6	3.5	99.4	97.3	2.10
Cable8	0.080	0.027	-0.079	-0.026	0.6	0.9	99.4	98.4	1.03
T1	7.519	3.232	-7.488	-2.764	30.2	467.8	100.0	97.5	2.46
T2	0.801	0.272	-0.800	-0.259	0.9	12.9	100.0	99.4	0.58
					85.2	544.5			

Figure 4.14 Figure of power losses after capacitor banks added

Branch Losses Summary Report									
Branch ID	From-To Bus Flow		To-From Bus Flow		Losses		% Bus Voltage		Vd % Drop in Vmag
	MW	Mvar	MW	Mvar	kW	kvar	From	To	
Cable1	4.955	1.995	-4.944	-1.980	10.5	14.3	97.5	97.2	0.28
Cable2	3.362	1.644	-3.336	-1.616	26.0	28.8	97.2	96.3	0.93
Cable3	0.842	0.286	-0.841	-0.285	1.5	1.6	97.5	97.3	0.21
Cable4	1.686	0.577	-1.680	-0.570	5.9	6.5	97.5	97.1	0.42
Cable5	0.563	0.077	-0.557	-0.071	5.8	6.5	99.6	98.4	1.15
Cable6	0.069	0.016	-0.068	-0.015	0.9	1.0	98.4	96.9	1.55
Cable7	0.161	0.056	-0.158	-0.052	2.6	3.5	99.6	97.5	2.10
Cable8	0.080	0.027	-0.080	-0.026	0.6	0.9	99.6	98.6	1.03
T1	7.514	3.329	-7.483	-2.857	30.4	471.8	100.0	97.5	2.53
T2	0.805	0.172	-0.804	-0.159	0.9	12.2	100.0	99.6	0.40
					85.0	547.3			

Figure 4.15 Figure of power losses after single-tuned filter added

From the Figure 4.13, Figure 4.14 and Figure 4.15 above, we can see that the power losses after the capacitor banks is added into the network system is decreasing becoming into a better condition due to supply of reactive power and current. When the power factor improves, there will be a corresponding reduction in the amount of loss that occurs in the conductor on the supply side at the point where power factor correction equipment is applied. The power losses for the whole system will be better after the harmonic filter is added into the system as it eliminated the harmonic current and reduce the voltage drop in the power network system.

Table 4.8 Table for power losses of the power network system

Power Losses		
Before Add Capacitor Banks	After Add Capacitor Banks	After Add Single-tuned Filter
96.8 kW	85.2 kW	85.0 kW

CHAPTER 5

CONCLUSION

5.1 Conclusion

In conclusion, this project focused on the insertion of the capacitor banks to improve the power factor. The effect of adding the capacitor banks is thoroughly analysed in term of power factor, harmonic analysis and power losses. It has been found that the addition of capacitor banks would further enhance reactive power, therefore compensating for the low power factor and also reducing the power system losses as well. This shows that the electricity can be transmitted to the system effectively and efficiently.

However, the harmonic resonance occurs when capacitor is added into the system and thus the Total Harmonic Distortion level increases rapidly. During resonance, current and voltage will be the dominating variables at the resonant frequency. This will result in a significant increase in current and voltage in the electrical network. It has also been observed that by raising the value of the capacitor (kVar), the resonance frequency is moved to a lower frequency but the capacitor banks that were used to mitigate harmonic distortion are very costly in real time and which cannot be used in most of the cases. So, the analysis should be cost effective to get the optimum solution in real time.

In order to eliminate the harmonic with economical and efficient power network system, we have to use detuned reactor along with the capacitor banks which combine an inductor series with capacitor using a single-tuned filter. The distortion of harmonic reduced significantly and the Total Harmonic Distortion level for the system within the limit.

5.2 Recommendation

For future study and recommendation, the capacitor may be used for reducing the total harmonic distortion in the system by varying the value of the capacitor into a proper value by trial and error by using ETAP simulation or by research and calculation. The other sources of harmonic such as transformer and VFD also can be injected into the system to study the effect of these system towards the capacitor and equipment.

Before installing the capacitor, there are a few things that need to be taken into consideration, such as the placement of the capacitor itself, as well as the location of the harmonics load within the network. Because of this, we will be better able to protect the system from the unwelcome effects of harmonics.

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APPENDIX A GANT CHART

PSM Gant Chart.

Task	WEEK													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Meeting with a subject coordinator –PSM 2 briefing session	█													
Meeting with supervisor		█						█						
Specification on the aim of the project's objective		█	█											
Discussion on design of the network system			█											
Identify the Objective and Problems Statement			█	█										
Literature Review				█	█	█	█	█						
Design Single Line Diagram		█		█	█	█	█	█	█	█				
Troubleshoot problem for design					█	█	█	█	█	█				
Analysis the simulation results								█	█	█	█	█	█	
Compare result with previous study														
Report Preparation														
Final year project presentation														
Submission to Supervisor														
Upload to Coordinator														
Report and logbook submission														

APPENDIX B LOAD FLOW REPORT

Load Flow Report

<u>LOAD FLOW REPORT</u>														
Bus		Voltage		Generation		Load		Load Flow					XFMR	
ID	kV	% Mag	Ang.	MW	Mvar	MW	Mvar	ID	MW	Mvar	Amp	%PF	%Tap	
* Bus1	33.000	100.000	0.0	8.318	3.500	0.000	0.000	Bus2	7.514	3.329	143.8	91.4		
								Bus7	0.805	0.172	14.4	97.8		
Bus2	6.600	97.470	-3.0	0.000	0.000	0.000	-0.001	Bus3	4.955	1.995	479.4	92.8		
								Bus5	0.842	0.286	79.8	94.7		
								Bus6	1.686	0.577	159.9	94.6		
								Bus1	-7.483	-2.857	718.9	93.4		
Bus3	6.600	97.194	-3.1	0.000	0.000	1.583	0.336	Bus2	-4.944	-1.980	479.4	92.8		
								Bus4	3.362	1.644	336.8	89.8		
Bus4	6.600	96.260	-3.3	0.000	0.000	3.336	1.616	Bus3	-3.336	-1.616	336.8	90.0		
Bus5	6.600	97.261	-3.1	0.000	0.000	0.841	0.285	Bus2	-0.841	-0.285	79.8	94.7		
Bus6	6.600	97.052	-3.1	0.000	0.000	1.680	0.570	Bus2	-1.680	-0.570	159.9	94.7		
Bus7	0.415	99.598	-0.8	0.000	0.000	0.000	0.000	Bus8	0.563	0.077	793.2	99.1		
								Bus10	0.161	0.056	238.0	94.5		
								Bus11	0.080	0.027	118.0	94.9		
								Bus1	-0.804	-0.159	1144.6	98.1		
Bus8	0.415	98.446	-1.4	0.000	0.000	0.488	0.055	Bus7	-0.557	-0.071	793.2	99.2		
								Bus9	0.069	0.016	99.4	97.4		
Bus9	0.415	96.892	-2.1	0.000	0.000	0.068	0.015	Bus8	-0.068	-0.015	99.4	97.6		
Bus10	0.415	97.499	-1.7	0.000	0.000	0.158	0.052	Bus7	-0.158	-0.052	238.0	95.0		
Bus11	0.415	98.566	-1.3	0.000	0.000	0.080	0.026	Bus7	-0.080	-0.026	118.0	95.2		

* Indicates a voltage regulated bus (voltage controlled or swing type machine connected to it)
Indicates a bus with a load mismatch of more than 0.1 MVA

APPENDIX C FUNDAMENTAL LOAD FLOW REPORT

Fundamental Load Flow Report.

<u>FUNDAMENTAL LOAD FLOW REPORT</u>														
Bus		Voltage			Generation		Load		Load Flow					XFMR
ID	kV	%Mag	Ang	MW	Mvar	MW	Mvar	ID	MW	Mvar	Amp	% PF	% Tap	
* Bus1	33.000	100.000	0.0	8.319	3.501	0	0	Bus2	7.514	3.329	143.8	91.4		
								Bus7	0.805	0.172	14.4	97.8		
Bus2	6.600	97.469	-33.0	0	0	0	0	Bus3	4.955	1.995	479.4	92.8		
								Bus5	0.842	0.286	79.8	94.7		
								Bus6	1.686	0.577	159.9	94.6		
								Bus1	-7.484	-2.858	719.0	93.4		
Bus3	6.600	97.193	-33.1	0	0	1.583	0.336	Bus2	-4.945	-1.980	479.4	92.8		
								Bus4	3.362	1.644	336.8	89.8		
Bus4	6.600	96.259	-33.3	0	0	3.336	1.616	Bus3	-3.336	-1.616	336.8	90.0		
Bus5	6.600	97.261	-33.1	0	0	0.841	0.285	Bus2	-0.841	-0.285	79.8	94.7		
Bus6	6.600	97.051	-33.1	0	0	1.680	0.570	Bus2	-1.680	-0.570	159.9	94.7		
Bus7	0.415	99.598	-30.8	0	0	0	0	Bus8	0.563	0.077	793.2	99.1		
								Bus10	0.161	0.056	238.0	94.5		
								Bus11	0.080	0.027	118.0	94.9		
								Bus1	-0.804	-0.159	1144.6	98.1		
Bus8	0.415	98.446	-31.4	0	0	0.488	0.055	Bus7	-0.557	-0.071	793.2	99.2		
								Bus9	0.069	0.016	99.4	97.4		
Bus9	0.415	96.892	-32.1	0	0	0.068	0.015	Bus8	-0.068	-0.015	99.4	97.6		
Bus10	0.415	97.499	-31.7	0	0	0.158	0.052	Bus7	-0.158	-0.052	238.0	95.0		
Bus11	0.415	98.566	-31.3	0	0	0.080	0.026	Bus7	-0.080	-0.026	118.0	95.2		

* Indicates a voltage regulated bus (voltage controlled or swing type machine connected to it).
Indicates a bus with a load mismatch of more than 0.1 MVA.

APPENDIX D HARMONIC REPORT

<u>System Harmonics Branch Information</u>													
Bus		Current Distortion											
From Bus ID	To Bus ID	Fund. Amp	RMS Amp	ASUM Amp	THD %	TIF	IT Amp	ITB Amp	ITR Amp	TIHD %	TSHD %	THDG %	THDS %
Bus1	Bus2	143.79	144.12	162.62	6.72	89.27	12864.81	12864.81	0.00	0.00	0.00	6.72	6.72
	Bus7	14.39	14.44	17.49	7.60	202.60	2924.59	2924.59	0.00	0.00	0.00	7.60	7.60
Bus2	Bus3	479.41	480.63	561.18	7.13	138.85	66733.13	66733.13	0.00	0.00	0.00	7.13	7.13
	Bus5	79.84	80.60	111.19	13.86	494.02	39818.99	39818.99	0.00	0.00	0.00	13.86	13.86
	Bus6	159.94	161.67	223.60	14.74	441.70	71407.32	71407.32	0.00	0.00	0.00	14.74	14.74
Bus3	Bus1	718.96	720.58	813.10	6.72	89.27	64324.04	64324.04	0.00	0.00	0.00	6.72	6.72
	Bus2	479.41	480.63	561.18	7.13	138.85	66733.13	66733.13	0.00	0.00	0.00	7.13	7.13
	Bus4	336.82	346.04	502.46	23.56	212.83	73648.27	73648.27	0.00	0.00	0.00	23.56	23.56
Bus4	Bus3	336.82	346.04	502.46	23.56	212.83	73648.27	73648.27	0.00	0.00	0.00	23.56	23.56
Bus5	Bus2	79.84	80.60	111.19	13.86	494.02	39818.99	39818.99	0.00	0.00	0.00	13.86	13.86
Bus6	Bus2	159.94	161.67	223.60	14.74	441.70	71407.32	71407.32	0.00	0.00	0.00	14.74	14.74
Bus7	Bus8	793.16	799.32	1113.27	12.49	440.63	352205.20	352205.20	0.00	0.00	0.00	12.49	12.49
	Bus10	238.03	239.74	308.68	11.98	283.39	67940.11	67940.11	0.00	0.00	0.00	11.98	11.98
	Bus11	117.97	119.59	177.84	16.63	709.51	84849.63	84849.63	0.00	0.00	0.00	16.63	16.63
Bus8	Bus1	1144.59	1147.89	1390.63	7.60	202.60	232557.50	232557.50	0.00	0.00	0.00	7.60	7.60
	Bus7	793.16	799.32	1113.27	12.49	440.63	352205.20	352205.20	0.00	0.00	0.00	12.49	12.49
	Bus9	99.42	101.07	159.11	18.29	657.05	66408.16	66408.16	0.00	0.00	0.00	18.29	18.29
Bus9	Bus8	99.42	101.07	159.11	18.29	657.05	66408.16	66408.16	0.00	0.00	0.00	18.29	18.29
Bus10	Bus7	238.03	239.74	308.68	11.98	283.39	67940.11	67940.11	0.00	0.00	0.00	11.98	11.98
Bus11	Bus7	117.97	119.59	177.84	16.63	709.51	84849.63	84849.63	0.00	0.00	0.00	16.63	16.63