

Electric Power Loss Reduction Technique for Power Distribution System

by

Mohammad Hafeiz bin Jumeren

A Project Final Report Submitted

In partial fulfillment of the requirements for the

Bachelor of Engineering (Hons)

(Electrical & Electronic Engineering)

MEI 2004

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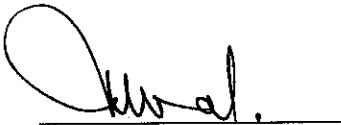
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A Project Final Report Submitted to
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Approved by,



(IR Perumal Nallagownden)

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MEI 2004

CERTIFICATION OF ORIGINALITY

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



(MOHAMMAD HAFEIZ BIN JUMEREN)

ABSTRACT

Distribution system forms an important part of the electrical power system connecting high voltage transmission lines to low voltage consumers through feeders, distributors and service mains. Losses in the distribution system vary up to 70% of the total losses. Investigating techniques for the reduction of these losses will be the aim of this project. The project title is '**Electric Power Loss Reduction Techniques for Power Distribution System**'.

Continuous and on-going research work is being conducted, with an infinite number of literatures done on the power distribution system. Various factors have been identified to be the causes of the losses in the specified system. Various techniques have been proposed to reduce these losses in the distribution entity.

Among the common and most discussed technique for loss reduction in distribution system is the *reactive power compensation* by capacitor placement. Capacitor placement is implemented in two ways; shunt compensation (capacitors are placed in parallel with load) and series compensation (capacitors are placed in series with line).

Series and shunt compensation helps to control and compensate the reactive power in the system, reducing the voltage regulation to make the voltage profile at the rated value, improving the power factor and enhancing the capacity of the power supplied to the load or customers. By having all those as a result of capacitor placement implementation, the end consumer as well as the power utility companies will take the benefits in term of the reduced cost in supplying and consuming electrical power.

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CHAPTER 1

INTRODUCTION

1.1. BACKGROUND OF STUDY

From the previous and ongoing researches that are being carried out in the field of power grid, it has been established that 70% of the total losses exist and occurs in the primary and secondary distribution system, while the transmission and sub transmission lines account for only about 30% of the total losses. Distribution losses affect the generation capacity by 15.5%, and the target level desired by many researches and engineers for loss reduction would be 7.5%. In the current real situation, the cost for the losses are fully reimbursed to the consumers through the tariff rate predetermined by the government and authorized national electricity utility company. The benefit will come to all consumers when the losses are able to be reduced and the total energy capacity delivered to the users increases as a result from the loss reduction. Therefore, the study on electrical power distribution system losses is totally significant to the benefit of mankind in term of the efficient and economical way of utilizing the electrical energy. Reducing the power losses will be directly pulling down the economic losses in the power distribution system, and finally will cheer up the customers as the tariff rate will definitely lower than ever.

In power system, the main losses are contributed by the line losses. There are various factors that contribute to the increase in the line losses in the primary and secondary distribution system, which are:

- a.) Feeder length
- b.) Inadequate size of conductor
- c.) Location of distribution transformers
- d.) Use of over rated distribution transformers
- e.) Low voltage
- f.) Low power factor

g.) Poor workmanship in fittings

Among the aforementioned factors for the causes of the line losses, low voltage become as one of the important matter to be focused on, in order to reduce the losses in the system. In power system, we experience some amount of voltage regulation, which sometimes reduces the voltage magnitude supplied to the consumers, due to the line length and also the existence of capacitive and inductive load in the line or at the receiving-end. Reactive power is produced in the line together with the active power, when power is sent along the line. Both reactive power and active power sums up to produce an apparent power. Therefore, at this point, we can see that the increasing magnitude of reactive power will reduce the magnitude of active power in the system, bringing to the loss of some amount of power generated and delivered to the consumer.

Voltage	Supply Voltages	Steady State Voltage Variation
Low Voltage		
Single Phase	240V	+ 5% to - 10%
Three Phase	415V	+ 5% to - 10%
Medium Voltage	6,600V 11,000V 22,000V 33,000V	± 6%
High Voltage	132,000V 275,000V	+ 10% to - 5% + 10% to - 5%

Table 1TNB's Voltage Standard

Therefore, one of the solutions to reduce the power loss in the system is by performing the **reactive power compensation**. In reactive power compensation, we try to control the amount of reactive power in the line, in order to make the voltage regulation to be at the most possible minimum value, and to make the power factor to approach unity. There are two common methods implemented for the reactive power compensation: **series compensation** and **shunt compensation**.

1.2. PROBLEM STATEMENT

Distribution system forms an important part of the electrical power system connecting high voltage transmission lines to low voltage consumers through feeders, distributors and service mains. Losses in the distribution system vary up to 70% of the total losses. Reactive power compensation controls the magnitude of reactive power in the system, so that the voltage supplied and received in the line can be regulated at a minimum value, or at any desired value. In this report, the author proposes to implement the series capacitor compensation method to compensate the reactive power, with the scope given on the load compensation project.

1.3. OBJECTIVE

- To conduct preliminary research on the type of losses that exist in the power distribution system
- To conduct a study on the factors that contribute to the losses, and the effect of losses on distribution system
- To study and develop the series capacitor compensation method
- To simulate the developed technique to reduce losses in distribution line using the simulation software such as MATLAB and PSCAD

1.4. SCOPE OF STUDY

This project involves the analysis, computer programming, modeling and simulations in pursue to achieve all of the predetermined objectives, within the allocated time. Area of interest or case study is focused on the power distribution system or network. Reactive power compensation that has been proposed is implemented from the aspect of load compensation only, involving the basic concept of capacitor placement in the line.

CHAPTER 2

LITERATURE REVIEW AND/OR THEORY

Voltage regulation and power-handling capacity are two important features of a transmission line, as well as distribution line. Thus, the voltage of a transmission line and distribution line should remain as constant as possible, even under variable load conditions. The ability of the power system to keep the voltage level at a rated value will be among the factors that determine how much the active power or true power can be delivered to the load or consumers. Ordinarily, the voltage regulation from zero to full-load should not exceed $\pm 5\%$ of the nominal voltage. In Malaysia, the standard steady-state voltage variation or voltage regulation percentage are preset at different voltage magnitude scale; low voltage, medium voltage and high voltage (**Table 1**).

There are number of factors that cause the voltage variation to occur in the system. Actually, the voltage regulation is closely related to the reactive power produced along the line and at the consumer end. The key point that brings to the matter of reactive power and voltage regulation is the **system reactance** and **load reactance**. Whenever the system energized, the AC networks and the devices connected to them create associated time-varying electrical fields related to the applied voltage, as well as magnetic field dependent on the current flow.

We are going to discuss about the system reactance and load reactance that exist in the power system. **Load reactance** consists of either inductance or capacitance effect, caused by the nature of the load that consumers have in the line. The nature of the load produces the capacitive and inductive reactance at the load-end in the system.

For **system reactance**, the line also has the capacitive and inductive reactance itself. The existence of the reactance components will be discussed. The current-carrying conductor produces a magnetic field around the conductor. Under this condition, the inductance created from the magnetic field effect, where

$$L = \frac{\lambda}{I}$$

Equation 1

with λ = flux linkages, in Weber turns. The inductance of the conductor can be defined as the sum of contribution from the flux linkages internal and external to the conductor.

Transmission line conductors also exhibit capacitance with respect to each other due to the potential difference between them. The amount of capacitance between conductors is a function of conductor size, spacing, and height above ground. By definition, the capacitance C is the ratio of charge q to the voltage V , is given by

$$C = \frac{q}{V}$$

Equation 2

Capacitive and inductive reactance makes up the reactive power variation in the line. Purely inductive load will create lagging power factor, and will give some amount of the positive voltage regulation magnitude. Purely capacitive load will create leading power factor, and will give some amount of the negative voltage regulation magnitude.

After having above discussion, our main interest is now focusing on the **reactive power control**. At this point, we can see that, the power that can be transported from source to load depends upon the impedance that consists of either capacitive or inductive load or both. The existence of the capacitance will also produce the reactive power, which magnitude depends on the line and load impedance itself. We are mainly interested in transmitting active power because only it can do useful work.

Reactive power compensation and power factor are elementary considerations in achieving efficient energy distribution network. While these terms may be fundamental, the importance of a thorough understanding of basic principles is necessary before we consider the effect of distorted voltage waveforms and the high magnitude of voltage regulation from the line and load impedance.

2.1. SO WHAT IS REACTIVE POWER?

In this section, we will go into details on discussing about the reactive power and its relationship with the power loss in the distribution system or transmission system.

In mathematical terms, reactive power is the product of the instantaneous voltage v and the current i multiplied by the sine function of the displacement angle θ , or $v.i.\sin \theta$. The fact that this formula takes into account a sine function emphasizes that this definition relates to alternating sinusoidal voltages and currents.

To make a comprehensive way of explaining the concept of reactive power, we can compare some common aspects in mechanical engineering and electrical engineering and find some similarities between them. Reactive power is found to exist in mechanical engineering, but under different name. There are some parameters in both engineering field that have relationship to each other; are shown and compared in the table below.

Electrical Engineering	Mechanical Engineering
Voltage	Force
Current	Velocity
Inductance	Mass
Capacitance	Spring Constant
Electrical Energy	Mechanical Energy
Electric Power	Mechanical Power

Table 2 Comparison between Electrical & Mechanical Engineering Quantities

To examine how the comparison is made between those parameters, we can implement them into a real example that relates between the two engineering disciplines. An example of a train of mass m accelerates to a required speed by the electric locomotive driving it, is taken.

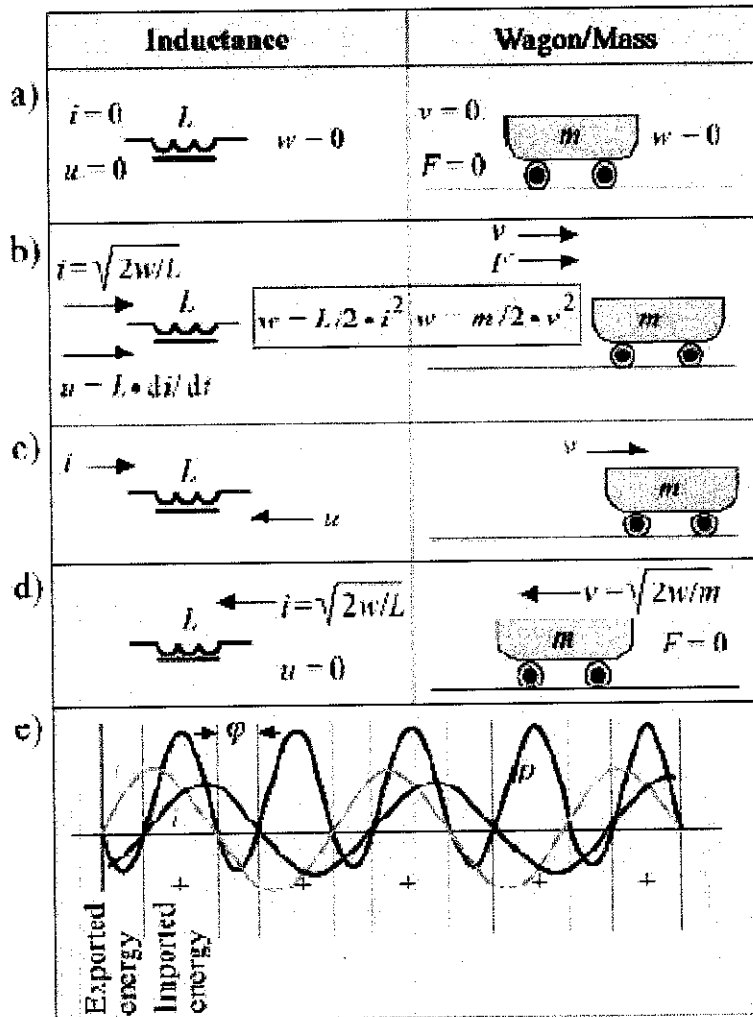


Figure 2 Comparison between Electric Energy & Mechanical Energy
On the Basis of Inductance L and Mass m

The coasting phase is indicated in Figure 1, by a motion direction that is still positive, where it also experiences the mechanical friction and air resistance that also can be assumed as the 'inverse voltage'. This phenomenon we can see similarly as in the electrical reactors with copper and eddy current losses.

By referring to the Figure 1 again, during the braking phase, the kinetic energy from the wagon is converted into the electrical power that fed back into the overhead contact system.

A sudden reversal of voltage polarity applied to a reactor does not cause a sudden reversal in the direction of the current flow. So, negative - better known as reactive - energy will occur (**Figure 2c**). This is the temporary reverse power that is compensated in electrical technology.

A certain period of reactive power and energy will always occur when power (voltage) and direction of movement (current) are in opposition to each other. We can see in the **Figure 2e** the portion of power that lies in the negative value region. This wattless energy - called reactive energy - must be compensated in order to avoid unnecessary loading of cables and distribution network.

2.2. REACTIVE POWER COMPENSATION

In this section, we will look in depth on the importance of the need for reactive-power control. Let take an example of a lossless short-transmission line connecting a source V_s to a load $Z \angle \phi$. Also, to make life easier, let the line is represented only by its inductive reactance X_l .

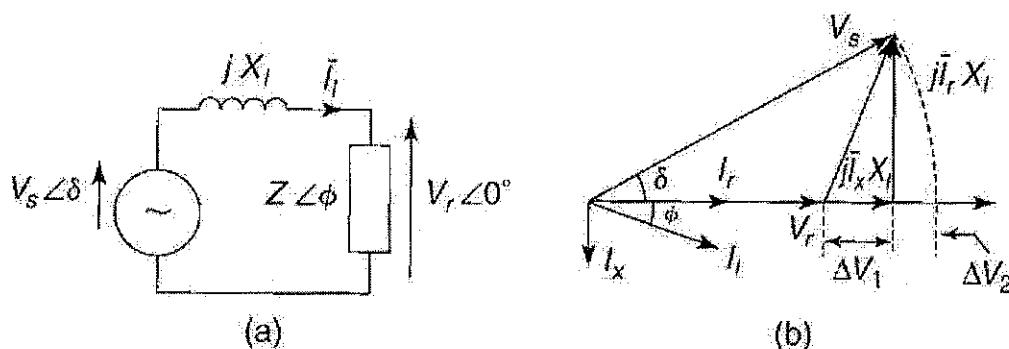


Figure 3 A Short, Lossless Transmission Line Feeding a Load

Figure 3 above shows such a network with its parameters, as well as phasor diagram that relates between the voltages and currents. In Figure 3(b), we can see the voltage magnitude variation between the sending end voltage V_s , and receiving end voltage V_r , also the phase difference that is created. The most significant voltage drop in the line reactance ($\Delta V_1 = jI_x X_l$) is due to the reactive component of the load current, I_x . To

maintain the voltages at nearly rated value between the sending end and receiving end, there are two control actions seem possible:

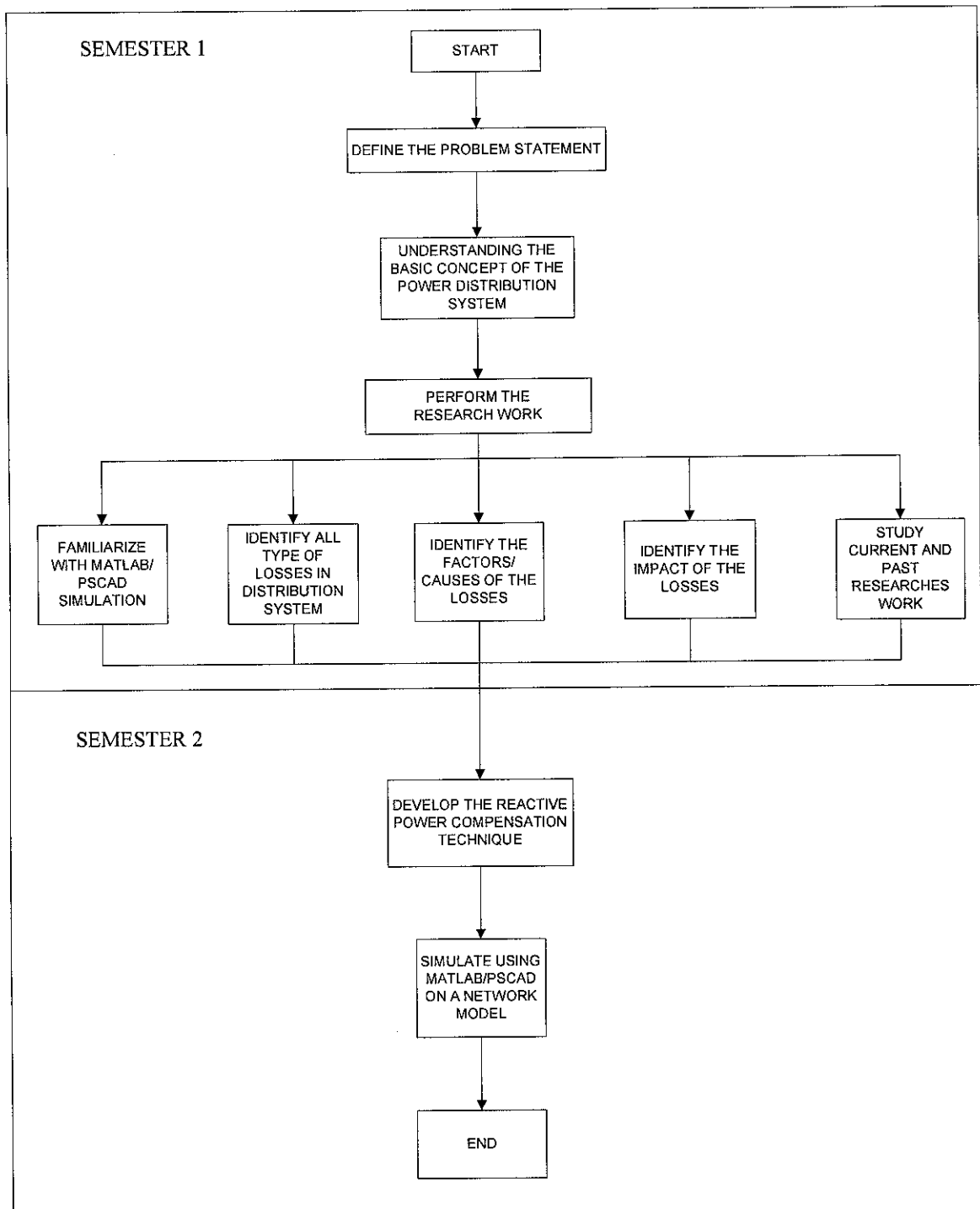
- a.) Load compensation
- b.) System compensation

It has been mentioned before that the scope of this project is given on the load compensation. Further explanation of system will be presented in the RESULTS & DISCUSSION part.

CHAPTER 3

METHODOLOGY/PROJECT WORK

3.1. PROCEDURE IDENTIFICATION



3.2. METHODOLOGY

3.2.1. Desk Study

Desk study includes research work sourced by books, journals, previous research papers, articles and magazine. Desk study is a basic and essential kind of research method used to gain all the required information. More than 60% research work is based on the desk study method.

3.2.2. Online Research

Online research is another important method used to find any information and important reference from the professional and commercial website that works on the field that related to the project topic. Such as IEEE website, it is an indispensable online reference for any person doing projects that related to the electrical & electronic engineering.

3.2.3. Consultation with Other Lecturers

In order to ensure the project is going smoothly and running on the right track, consultation with lecturers other than project supervisor is always held. The consultation involves discussion on possible solution on any problems that may arise from the project besides learning any new lesson regarding with the project taken.

3.2.4. Project Tools and Equipments

The project shall finally being modeled and simulated through the application of related software such as MATLAB or PSCAD.

CHAPTER 4

RESULT AND DISCUSSION

4.1. SYSTEM COMPENSATION

Refer to the figure below. In order to regulate the receiving-end voltage at the rated value, a power producer company may install a reactive-power compensator as shown in the figure. The compensator draws a reactive current, I_C to overcome both components of the voltage drop ΔV_1 and ΔV_2 as a consequence of the load current I_l through the line reactance X_l . To compensate for ΔV_2 , an additional capacitive current, ΔI_C , over and above I_C that compensates for IX , is drawn by the compensator. When $\Delta \bar{I}_C X_l = \Delta V_2$, the receiving-end voltage, V_r , is equals the sending-end voltage, V_s . Such compensators are employed by power utilities to ensure the quality of supply to their customers.

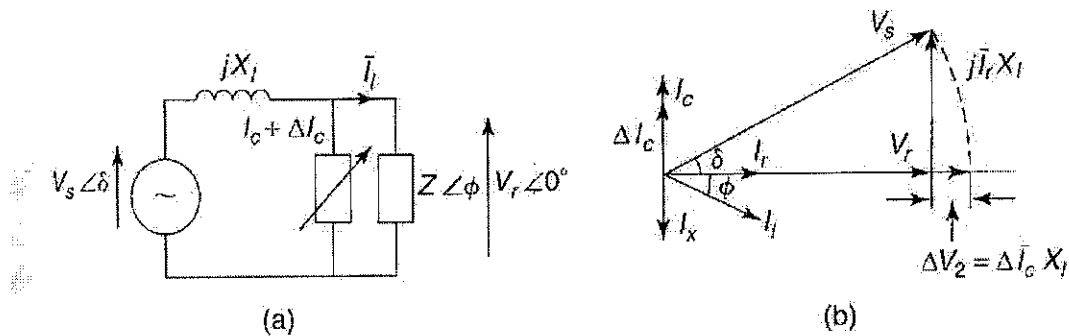


Figure 4 The Reactive-power Control for Voltage Regulation

4.2. SERIES COMPENSATION

A method of reactive power compensation, which is series compensation, is being tested for the implementation on this project. The method is based and taken from the previous literature done on the series compensation method [1].

From the literature, the method to find the location and size of series capacitor are being discussed. Also, the series compensation can be represented in Z_{bus} by adding a new parallel line in the circuit.

4.2.1. Finding the Line to Place the Series Capacitor

Resistive power loss sensitivity index (RPLSI) is the rate of change in reactive power loss due to line reactance. By finding the RPLSI, the suitable location which we can apply the series capacitor application can be found. It is already known that the magnitude of reactive power Q will be reduced with the series compensation, and by this index, the most suitable line from all lines available can be found to be implemented with the series compensation method.

Consider a figure below:

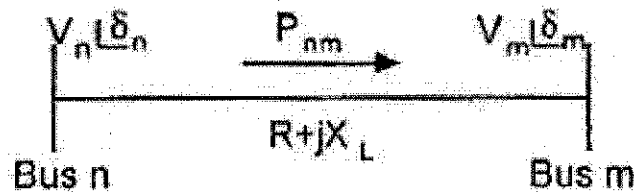


Figure 5 Power Flow in a Transmission Line

Loss equation of the line, from the figure, can be given as:

$$P_{loss} + jQ_{loss} = \sigma \left(\frac{R}{R^2 + X_L^2} + \frac{jX_L}{R^2 + X_L^2} \right) \quad \text{Equation 3}$$

$$\text{where } \sigma = (V_n^2 + V_m^2 - 2V_n V_m \cos(\delta_n - \delta_m)) \quad \text{Equation 4}$$

then RPLSI is

$$\frac{\partial Q_{loss}}{\partial X_L} = \sigma \frac{R^2 - X_L^2}{(R^2 + X_L^2)^2} \quad \text{Equation 5}$$

4.2.2. Power Flow Maximization by Series Compensation

This section will discuss and investigate the use of series compensation to maximize the power transfer capability of the transmission line. We take an example of a transmission line that is represented as only series impedance, as shown in **Figure 5**. The net effect of series compensation is often noted by letting X represent the net reactance,

$$X = (1-k)X_L$$

where X_L = equivalent inductive reactance of the line

k = degree of compensation ($0 < k < 1$)

The terminal voltages at the ends of the line are defined as:

$$V_n = V_n e^{j\delta_n} = V_n (\cos \delta_n + j \sin \delta_n) \quad \text{Equation 6}$$

$$V_m = V_m e^{j\delta_m} = V_m (\cos \delta_m + j \sin \delta_m) \quad \text{Equation 7}$$

Let the voltage at bus m be the reference and define $\delta = \delta_n - \delta_m$, then, the power from bus m to bus n can be given as:

$$P_{nm} + jQ_{nm} = \frac{V_m^2}{Z^2} \left\{ \left[R \left(\frac{V_n}{V_m} \cos \delta - 1 \right) + X \left(\frac{V_n}{V_m} \sin \delta \right) \right] - j \left[R \left(\frac{V_n}{V_m} \sin \delta \right) - X \left(\frac{V_n}{V_m} \right) \right] \right\}$$

Equation 8

The transferred power from bus n to m can also be expressed as:

$$P_{nm} + jQ_{nm} = \frac{V_n V_m}{Z} [\cos(\phi - \delta) + j \sin(\phi - \delta)] - \frac{V_m^2}{Z} (\cos \phi + j \sin \phi) \quad \text{Equation 9}$$

$$\text{where } \phi = \tan^{-1} \frac{X}{R} = \tan^{-1} \frac{X_L (1-k)}{R} \quad \text{Equation 10}$$

We are always looking for the maximum value of the transferred power. When we look back into the **Equation 8**, it is a function of voltage magnitude at the both ends of the line, the angle δ and the line impedance. It can be maximized with respect to any of these variables. But then, the voltage magnitudes are not varying over a wide range, therefore they are limited in their net effect on the power transferred. Here, the effect of maximizing the transferred power with respect to the voltage angular differences and the impedance will be examined.

The maximum power transferred with respect to the angular difference can be obtained by taking the derivative of **Equation 8** with respect to δ .

$$\frac{\partial P_{nm}}{\partial \delta} = \left(\frac{-RV_n}{V_m} \sin \delta - \frac XV_m \cos \delta \right) = 0 \quad \text{Equation 11}$$

The result of **Equation 10** is $\delta = \Phi$. Therefore, for the given line parameters the maximum power can be transferred by adjusting the power angle equal to the line impedance angle. This adjustment can be done by using series compensation, which reduces the line impedance angle. The required degrees of compensation for this condition is

$$k = 1 - \frac{R}{X} \tan \delta \quad \text{Equation 12}$$

4.3. DISCUSSION

4.3.1. Finding Location & Size of Series Capacitor In a Simple Transmission System

The model implemented is taken from [4], Example 5.1. Three models were used from this example, where the two models are modified from

this example of case study. The three models are named as **LINE 1**, **LINE 2** and **LINE 3**.

LINE 1

From **Example 5.1 [4]** ,

A 220-kV, three-phase transmission line is 40km long. The resistance per phase is 0.15Ω per km and the inductance per phase is 1.3263mH per km. The shunt capacitance is negligible. The **short line model** is used to find the voltage and power at the sending end and the voltage regulation and efficiency when the line is supplying a three phase load of 381MVA at 0.8 power factor lagging at 220kV.

From the question, only relevant and important data are taken for the RPLSI calculation.

$$V_n \angle \delta_n = V_s \text{ (sending end voltage per phase)} = 144.3 \angle 4.93^\circ kV$$

$$V_m \angle \delta_m = V_R \text{ (receiving end voltage per phase)} = 127 \angle 0^\circ kV$$

$$\mathbf{X_L \text{ per phase} = 1.3263 \text{ mH/km}}$$

$$R \text{ per phase} = 0.15\Omega/\text{km}$$

$$R + jX_L = 6 + j20\Omega$$

Therefore, finding value of σ ,

$$\begin{aligned} \sigma &= \left(V_n^2 + V_m^2 - 2V_n V_m \cos(\delta_n - \delta_m) \right) \\ &= [144.33^2 + 127^2 - 2(144.33)(127) \cos(4.93^\circ - 0^\circ)] \\ &= \mathbf{435.95} \end{aligned}$$

Therefore, RPLSI,

$$\frac{\partial Q_{loss}}{\partial X_L} = \sigma \frac{R^2 - X_L^2}{(R^2 + X_L^2)^2}$$

$$= 435.95 \frac{6^2 - 20^2}{(6^2 + 20^2)^2}$$

$$= \underline{\underline{-0.835}}$$

LINE 2

From Example 5.1 [4],

Similar model to be used, but with different line reactance per phase value,

X_L per phase = 0.3263mH/km

$$R + jX_L = 6 + j 4.92 \Omega$$

$$V_m \angle \delta_m = 127 \angle 0^\circ \text{ kV}$$

$$V_n \angle \delta_n = V_m \angle \delta_m + ZI_m = 127 \angle 0^\circ + (6 + j4.92)(1,000 \angle -36.87^\circ)(10^{-3})$$

$$= 134.75 + j 0.336$$

$$= 134.75 \angle 0.143^\circ \text{ kV}$$

$$\sigma = (V_n^2 + V_m^2 - 2V_n V_m \cos(\delta_n - \delta_m))$$

$$= [134.75^2 + 127^2 - 2(134.75)(127) \cos(0.143^\circ)]$$

$$= \mathbf{60.169}$$

$$\frac{\partial Q_{loss}}{\partial X_L} = \sigma \frac{R^2 - X_L^2}{(R^2 + X_L^2)^2}$$

$$= 60.169 \times \frac{6^2 - 4.92^2}{(6^2 + 4.92^2)^2}$$

$$= \underline{\underline{0.196}}$$

LINE 3

From Example 5.1 [4],

Similar model to be used, but with different line reactance per phase value,

X_L per phase = 2.0 mH/km

$$R + jX_L = 6 + j 30.159 \Omega$$

$$V_m \angle \delta_m = 127 \angle 0^\circ \text{ kV}$$

$$\begin{aligned} V_n \angle \delta_n &= V_m \angle \delta_m + ZI_m = 127 \angle 0^\circ + (6 + j30.159)(1,000 \angle -36.87^\circ)(10^{-3}) \\ &= 134.75 + j 20.53 \\ &= 151.29 \angle 7.799^\circ \text{ kV} \end{aligned}$$

$$\begin{aligned} \sigma &= (V_n^2 + V_m^2 - 2V_n V_m \cos(\delta_n - \delta_m)) \\ &= [134.75^2 + 127^2 - 2(134.75)(127) \cos(0.143^\circ)] \\ &= \mathbf{-31,312.55} \end{aligned}$$

$$\begin{aligned} \frac{\partial Q_{loss}}{\partial X_L} &= \sigma \frac{R^2 - X_L^2}{(R^2 + X_L^2)^2} \\ &= -31,312.55 \times \frac{6^2 - 30.159^2}{(6^2 + 30.159^2)^2} \\ &= \mathbf{30.59} \end{aligned}$$

The results gained can be summarised as below:

Line	Inductive Reactance, X_L (mH/km)	$\frac{\partial Q_{loss}}{\partial X_L}$
LINE 1	1.3263	- 0.835
LINE 2	0.3263	0.196
LINE 3	2.0	30.59

Table 3 RPLSI Value for All Lines

From the result in the table, it seems that LINE 3 has the highest index of RPLSI. Therefore, LINE 3 has the highest priority for the series compensation in terms of RPLSI.

But then, from the table, we can see that the value of RPLSI for every lines seems that much different between each other, with the existence of the '-' value and the unrealistic high value of RPLSI of line 3. Therefore, after having discussion with project supervisor, the value of line inductive reactance, **L should not exceed than 1 ($X_L \leq 1$)**. The correction for this will be detailed in the next weekly report.

Next, we proceed with finding the degree of compensation for the above lines. The value of the inductive reactance will not be influenced the value of k.

From the literature, we are going to implement **Equation 12**, to find the degree of compensation, k. Therefore, the results gained are as below:

Line	Line Inductance, X_L (mH/km)	Degree of compensation, k
LINE 1	1.3263	0.974
LINE 2	0.3263	0.997
LINE 3	2.0	0.973

Table 4 k Value for Different Lines

Using the method proposed by the literature [1] need the author to go into further analysis, as the results gained give some inaccurate values when compared with the trend of results data presented in the literature.

From the previous result gained for the RPLSI for different lines, we found that the values of RPLSI gained are quite confusing, when compared with the literature result [1]. Although the literature [1] use

different system, the value shown here are absolutely different to each other in term of very high magnitude for LINE 3, and the negative ‘-‘ value for LINE 1.

Lines	$\frac{\partial Q_{loss}}{\partial X}$
1-2	1.76661
1-5	0.4631
2-3	0.4339

Table 5 RPLSI Value for Different Lines in Literature [1], using IEEE 14-bus network

To proceed with further analysis, the value of line inductance, L for all models are modified, so that $0 < L < 1$. Therefore, the results are as below:

Line	Line Inductance, L (mH/km)	$\frac{\partial Q_{loss}}{\partial X_L}$
Line 1	0.9999	- 72.670e ⁶
Line 2	0.3263	0.196e ⁶
Line 3	0.1111	85.520e ⁶

Table 6 RPLSI for Lines with Different Inductive Reactance based on Modified Example 5.1 [4]

From the result in the table, it seems that LINE 3 has the highest index of RPLSI. Therefore, LINE 3 has the highest priority for the series compensation in terms of RPLSI.

But then, from the table, we can see that the value of RPLSI for every lines in **Table 6** seems that much different when compared with results in **Table 5**, with the existence of the ‘-‘ value and the unrealistic high value

of RPLSI of line 3. Anyway, the author planned to proceed with finding the **degree of compensation**, using the given results from those two tables.

Next, we proceed with finding the degree of compensation for the above lines. The value of the inductive reactance will not be influenced the value of k.

$$k = 1 - \frac{R}{X} \tan \delta, \quad \text{where } 0 < k < 1 \quad \text{Equation 13}$$

$$\text{and } X = (1 - k)XL \quad \text{Equation 14}$$

Variable X is the notation that represents the net reactance as a result of net effect of series compensation. X_L is the equivalent inductive reactance of the line, and k is the “degree of compensation”. Equation 1 and 2 are modified to relate between X_L and k, where the resultant equations give two different equation of k, which are noted as k_1 and k_2 .

$$k_1 = (XL - R) \tan \delta \quad \text{Equation 15}$$

$$k_2 = 1 + \frac{R}{XL} \times \tan \delta \quad \text{Equation 16}$$

After calculating the value of k using **Equation 15 & Equation 16**, the value of k_1 and k_2 for those 3 lines are listed as below:

Line	Line Inductance, X_L (mH/km)	RPLSI	k1	k2
1	0.9999	- 72.670e ⁶	2.8943	1.1268
2	0.3263	0.196e ⁶	-0.0027	1.0030
3	0.1111	85.520e⁶	0.528	0.5627

Table 7 Value of k1 and k2 for Different Line Inductance, XL

At this stage, we can see that the values of k1 and k2 for all lines are not within 0 and 1, except that for Line 3. Until now, the author is still trying to figure out about this problem, so that the project can be proceed with this technique proposed by the literature [1]. But then, in case this technique cannot be continued, it is proposed that this project can be resumed in the future by other student, specifically in implementing the *series compensation* method.

4.3.2. PSCAD Simulation – Load Compensation Concept on Distribution System Model

The purpose of the simulation work is to investigate the existence of the reactive power component in the distribution network, due to the different end loads that consist of resistive, capacitive or inductive load. The simulation work also investigates the effect of capacitor in overcoming the reactive power in the system. In other words, the author tries to demonstrate the **load compensation method** through the simulation process. By using PSCAD software, a distribution model is developed by modifying a simple transmission model with applying the voltage range that is appropriate for distribution network. The simulation model consists of 3 parts; *distribution system sending-end, distribution line and distribution system receiving-end (Figure 6)*.

The system specification is as below:

Frequency = 50Hz,

Resistive Load Resistance = 500Ω

Line Length = 50km,

Rated Voltage = 33kV,

3 phase 2 Winding Transformer Rated Power = 100MVA

At the distribution system sending-end, 132 kV voltage supplied from the transmission line that is represented by the simple three phase source, is being stepped down to 33kV through the transformer, to be delivered in the distribution network (**Figure 7**). This simple model implements a distribution line with length of 50km. At the distribution system receiving-end, a single-type of loads, which are resistive loads, with same magnitude is implemented (**Figure 8**).

There are 3 type of loads are being simulated and tested using PSCAD. Other than purely resistive load, RL load is also tested in **Figure 10**, and

RLC load in **Figure 12**. Analysis is made for every different type of loads of the simulated distribution network model.

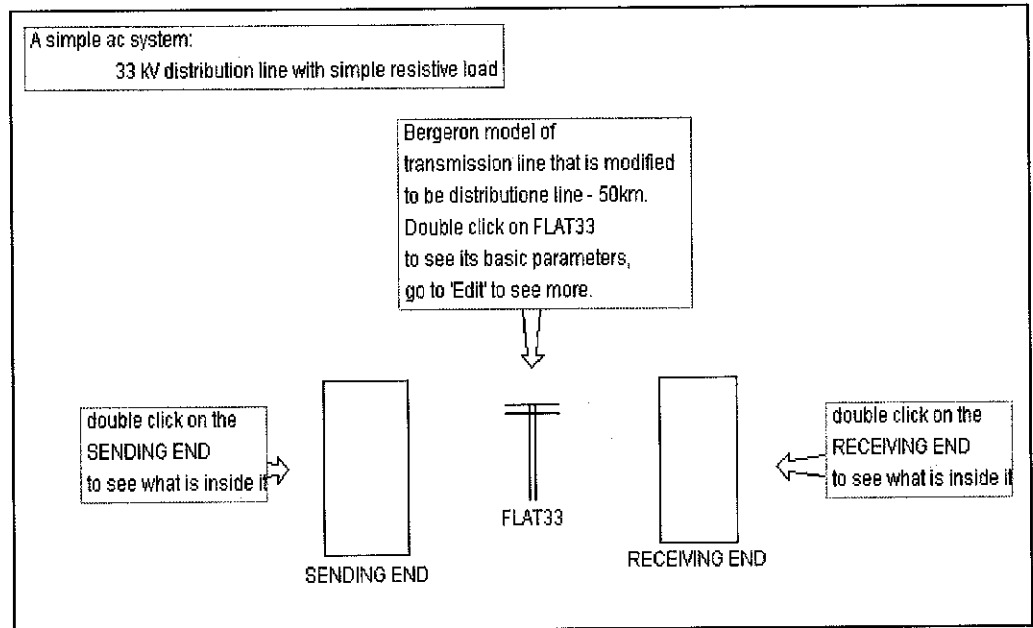


Figure 6 Simple AC Distribution System Model

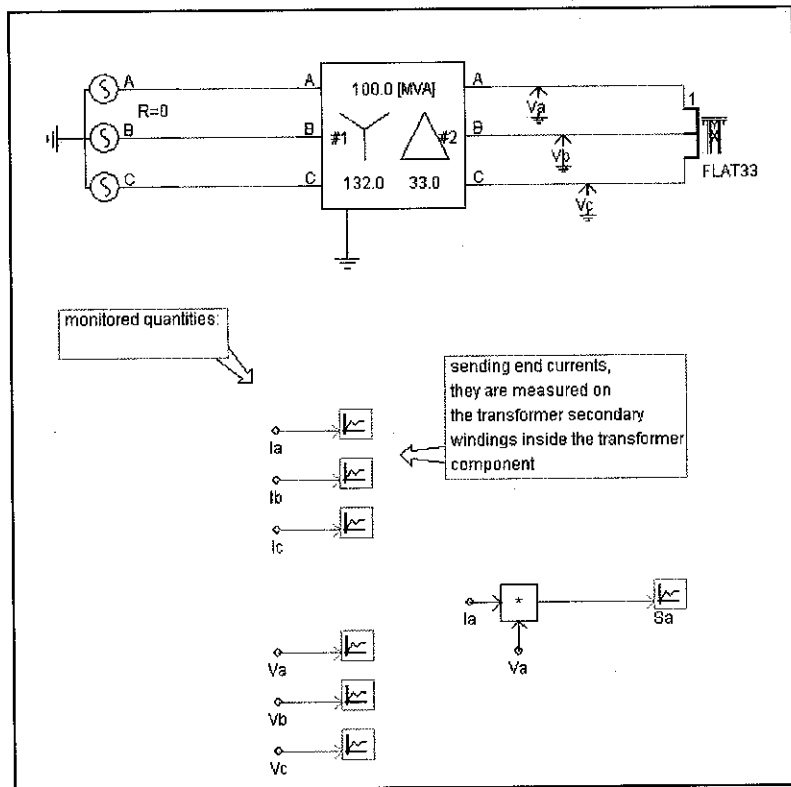


Figure 7 Distribution System Sending-end Circuit Configuration

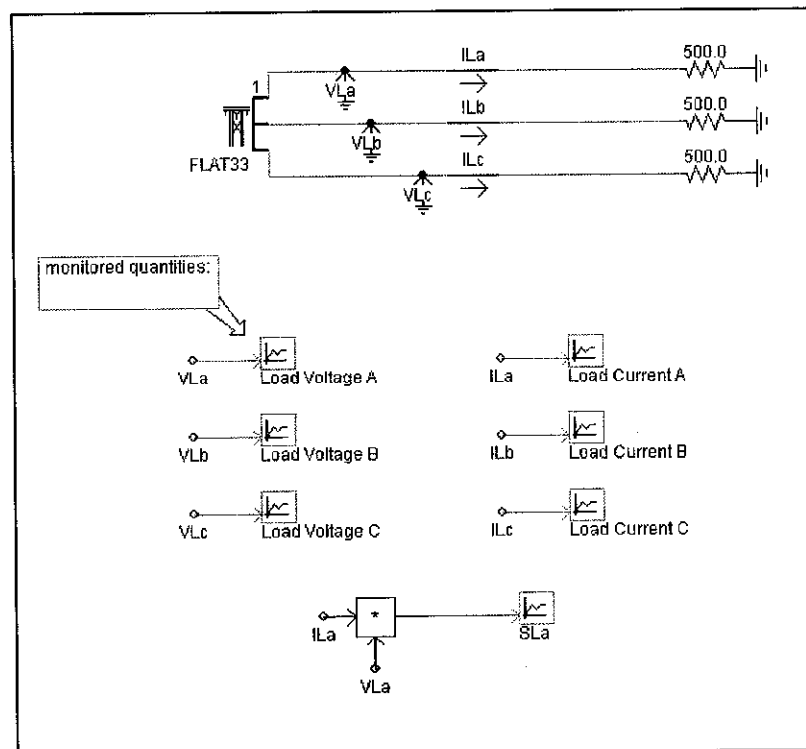


Figure 8 Receiving-end Circuit Configuration with Purely Resistive Loads

Analysis on Purely Resistive Load System

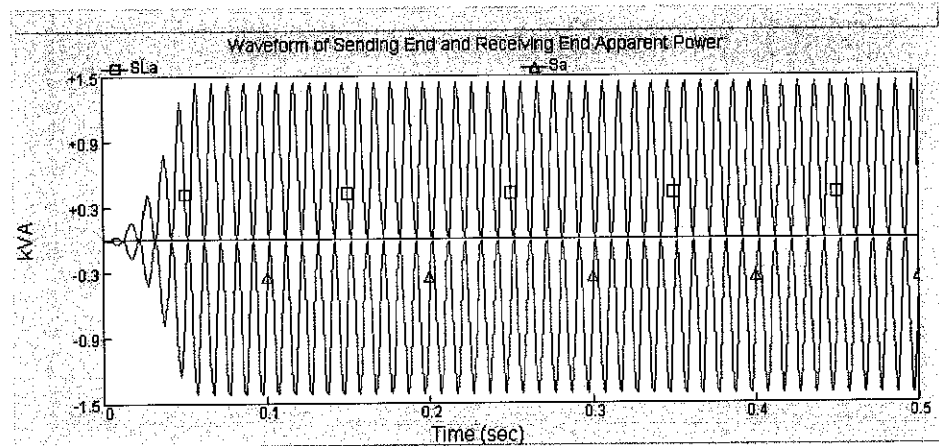


Figure 9 Apparent Power Waveform Comparison for Purely Resistive Load System

In a purely resistive load system, the output waveform for the sending-end and receiving-end apparent power are monitored and being compared. Therefore, we can see that, both waveforms has similar peak value but exist in different direction to each other. The peak value of receiving-end apparent power, SLa (single phase) is **1.43978 kVA** and the peak value of sending-end apparent power, Sa (single phase) is **-1.42309 kVA**.

	Sending-end Single Phase Apparent Power, Sa (kVA)	Receiving-end Single Phase Apparent Power, SLa (kVA)
Positive Peak Value	0	1.43978
Negative Peak Value	-1.42309	0

Table 8 Comparison between Sending-end & Receiving-end Apparent Power

The total apparent power in the sending-end is totally seen to exist in a reactive power form. But at the distribution system receiving-end, the apparent power appears completely in the form of real power.

	Distribution System Sending-end	Distribution System Receiving-end
Active Power, P (kW)	2.1937	2.17201
Reactive Power, Q (kVAR)	0.892376	-1.7345e-9

Table 9 Active & Reactive Power Magnitude for Both End System

The reactive power component does not exist in the distribution system receiving-end, as shown in the **Figure 9** and **Table 3**. Due to the nature of purely resistive load and the lossless line, the apparent power appears only in the form of active power at the receiving-end. As the power is continually fluctuating, the power in this system is taken to be the average value of the apparent power waveform. The average power can be easily obtained from the rms current in the circuit, which is

$$P = I^2 R \quad \text{Equation 17}$$

where I = rms current. This relation can also be expressed as

$$P = VI \quad \text{Equation 18}$$

Analysis on RL (Resistive & Inductive) Load System

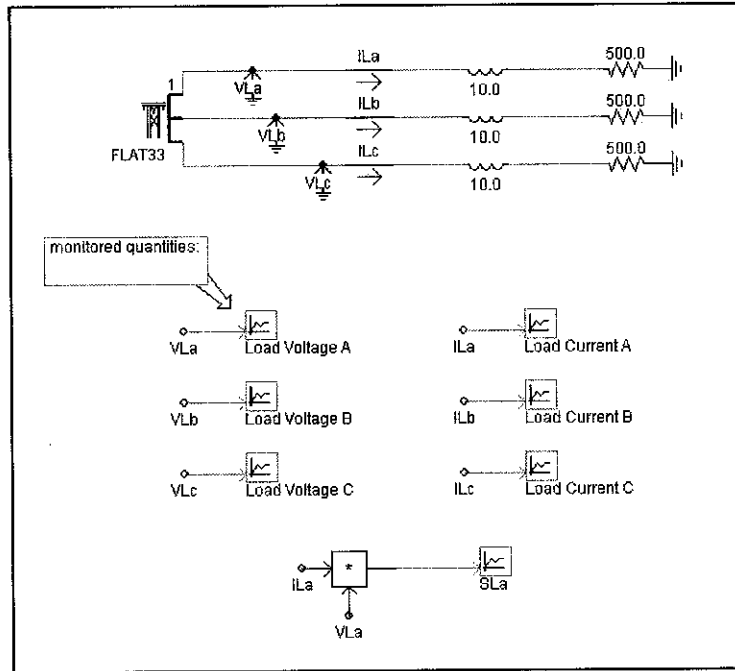


Figure 10 Receiving-end Circuit Configuration with RL Load

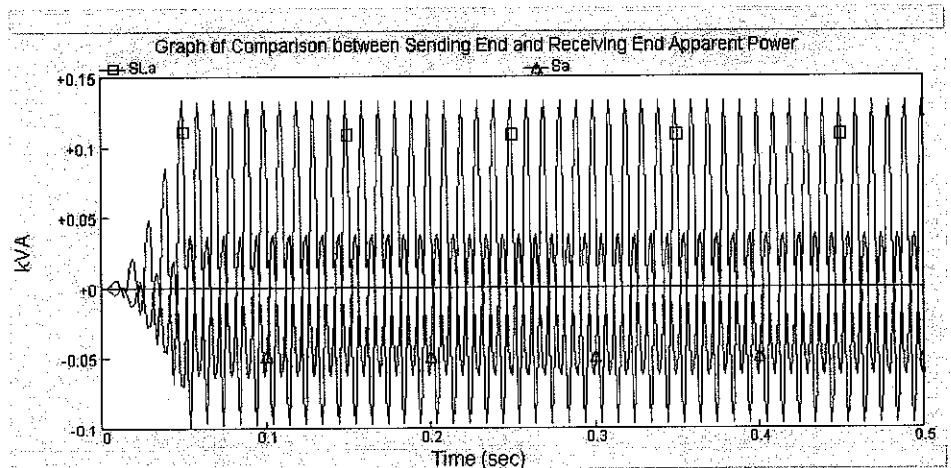


Figure 11 Apparent Power Waveform Comparison for RL Load System

In this type of system, an RL load is implemented, with the resistive value is given as 500Ω and inductive value as $10H$. The waveform comparison between the sending-end and receiving-end apparent power can be seen in **Figure 11**. The apparent power at the receiving-end is seen to have larger value than the sending-end apparent power with sending-

end apparent power peak value, S_a (single phase, positive value) = 0.0367622 kVA and S_a (single phase, negative value) = -0.0624865 kVA. The receiving-end apparent power is found to be S_{La} (single phase, positive value) = 0.133627 kVA and S_{La} (single phase, negative value) = -0.096724 kVA.

	Sending-end Single Phase Apparent Power (kVA)	Receiving-end Single Phase Apparent Power (kVA)
Positive Peak Value	0.0367622	0.133627
Negative Peak Value	-0.0624865	-0.096724

Table 10 Comparison between Sending-end & Receiving-end Apparent Power

Therefore, at this point, we can see the existence of the reactive power component, as the apparent power at the receiving-end gives the positive and negative magnitude of kVA. The negative magnitude of kVA represents the reactive power component. This is due to the effect from the inductive load which is represented by the three inductors of 10H each. From the simulation result, the active and reactive power is given as below:

	Distribution System Sending-end	Distribution System Receiving-end
Active Power, P (kW)	0.0744	0.0533
Reactive Power, Q (kVAR)	1.15576	0.3353

Table 11 Active & Reactive Power Magnitude for Both End System

We already know that in a purely inductive circuit, current I lag voltage, V by 90° . In this RL load circuit, the value of the line impedance will be

more than the resistance value, with some amount of phase difference between the applied voltage and current. Absolutely the current will again lag the voltage, and therefore produces negative cycle in the apparent power waveform. If this circuit is to be the purely inductive circuit, then the average power will be zero, as the positive and negative quarter cycle give similar value to each other with differs only in direction. But in this RL load system, the magnitude of positive quarter cycle is higher than the negative quarter cycle and therefore giving the positive average power. Basically, in any inductive circuit, whether purely inductive or not, during the alternate quarter-cycles, the electrical energy is being sent from the generator to the coil, and during the other quarter-cycles the less or same amount of energy is sent back from the coil to the generator.

Analysis on RL (Resistive & Inductive) Load with Series Capacitor Added System

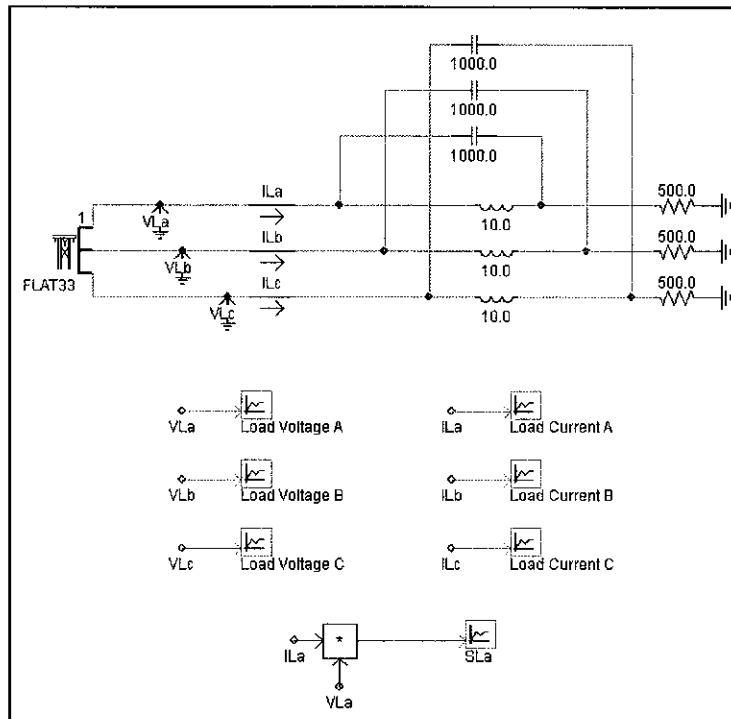


Figure 12 Receiving-end Circuit Configuration with RLC Load

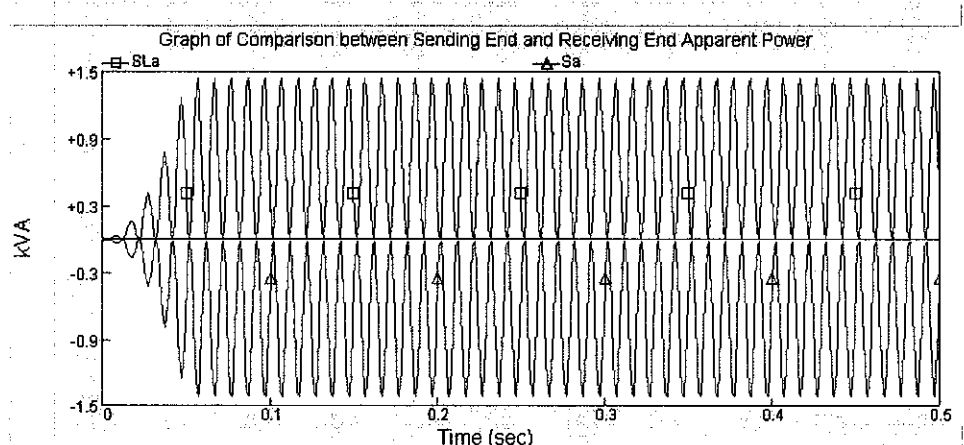


Figure 13 Apparent Power Waveform Comparison for RLC Load System.

In this circuit configuration, the RL load is implemented at the receiving-end but with the parallel capacitor across the inductor in every line. The capacitive loads which are represented by the 3 capacitors are taken, with the value of $1000\mu\text{F}$ each of them.

Whenever the system is simulated, the output waveform is recorded for the apparent power at the sending-end and the receiving-end. Comparing both waveforms, the peak value of sending end single phase apparent power, $S_a = 1.43998$ kVA while the peak value of receiving-end single phase apparent power, $S_{La} = -1.4231$ kVA. The sending-end single phase apparent power is seen to completely exist in the negative direction; contrast to the receiving-end single phase does. From this condition, with an appropriate value of capacitor that is connected in parallel across the inductor (mathematically), the effect of the reactive power production by the inductive load can be compensated well. The voltage profile will be similarly as in the purely resistive load circuit model. The apparent power at both ends appears to be the same with the purely resistive load system. This is one of the techniques among various reactive power compensation method, which is *series capacitor placement*.

	Sending-end Single Phase Apparent Power, S_a (kVA)	Receiving-end Single Phase Apparent Power, S_{La} (kVA)
Positive Peak Value	0	1.43998
Negative Peak Value	-1.4231	0

Table 12 Comparison between Sending-end & Receiving-end Apparent Power

Basically, in any capacitive circuit, whether purely capacitive or not, the current leads the voltage by an angle of 90° . The curve representing the variation of power is derived from the multiplication of the corresponding instantaneous values of the voltage and current. The positive quarter cycle of the power curve represents the transfer of power from the generator to the capacitor, where the electrostatic energy stored in the capacitor at the instant the quarter cycle ends. During the negative quarter cycle of the power curve, the potential difference across the capacitor

decreases from its maximum value to zero and the whole of the energy stored in the capacitor previously is returned to the generator if the circuit is purely capacitive. In this RLC circuit model, the returned power is similar to the amount of power developed by the inductor at any instant, thus canceling each other. Therefore, the power that exists in the power curve is actually produced by the 'purely resistive circuit'.

CHAPTER 5

CONCLUSION

5.1. CONCLUSION

It is proven that the capacitor placement in the circuit can help to control and compensate the amount of reactive power in the system. With the controlled reactive power in the system, the voltage profile can be kept at the rated value, the power factor can be increased to almost unity and the capacity of the power supply delivered can also be increased. Therefore, capacitor placement is one of the best techniques in reducing the power loss in power distribution system.

5.2. RECOMMENDATION

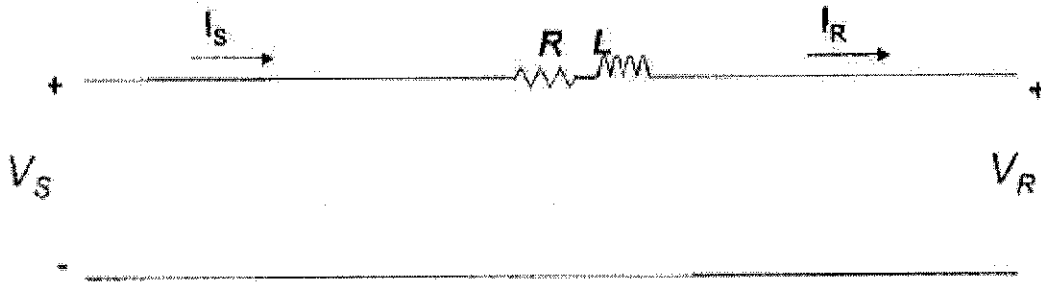
The recommendations to improve the project are:

- To come out with the real model of circuit if possible, in order to demonstrate the project, together with the simulation work.
- To study in details on the load compensation and system compensation how do shunt and series compensation can 'deal' with them.
- To cooperate with the power utilities company, such as Tenaga Nasional Berhad (TNB) to make the project is applicable for national power grid system, for the benefit of all Malaysian citizen
- To implement and integrate the series and shunt capacitor placement with the current technology available, such as Fuzzy Logic, artificial intelligence etc.

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**APPENDIX 1: SAMPLE OF CASE STUDY USING EXAMPLE
FROM [4]**



Given that the above example has following values:

Transmission Length = 40km

Rated receiving end voltage = 220kV

Resistance / phase = 0.15 Ω /km

Inductance / phase = 1.3263 mH/km

Rated apparent power = 381 MVA

Power factor = 0.8 lagging.

Therefore,

$$Z = 6 + j20\Omega$$

Receiving end voltage/phase, $V_R = 127\angle 0^\circ kV$

Apparent power, $S_{R(3\phi)} = 304.8 + j228.6$ MVA

Current/ phase, $I_R = 1000\angle -36.87^\circ A$

From that,

$$\begin{aligned} \text{Sending end voltage, } V_S &= V_R + ZI_R \\ &= 144.3\angle 4.93^\circ kV \end{aligned}$$

$$|V_{S(L-L)}| = 250kV$$

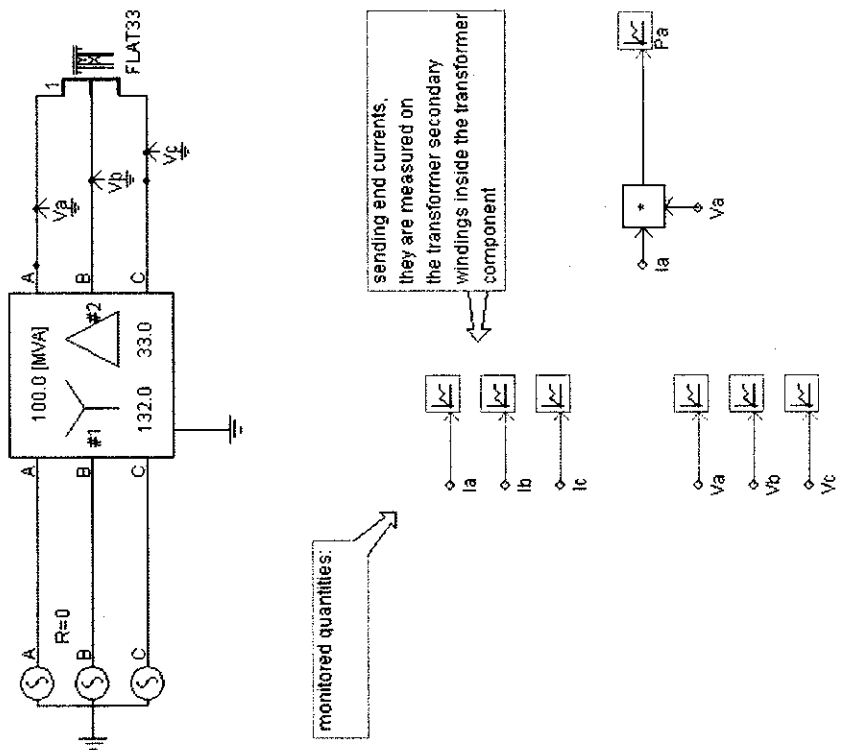
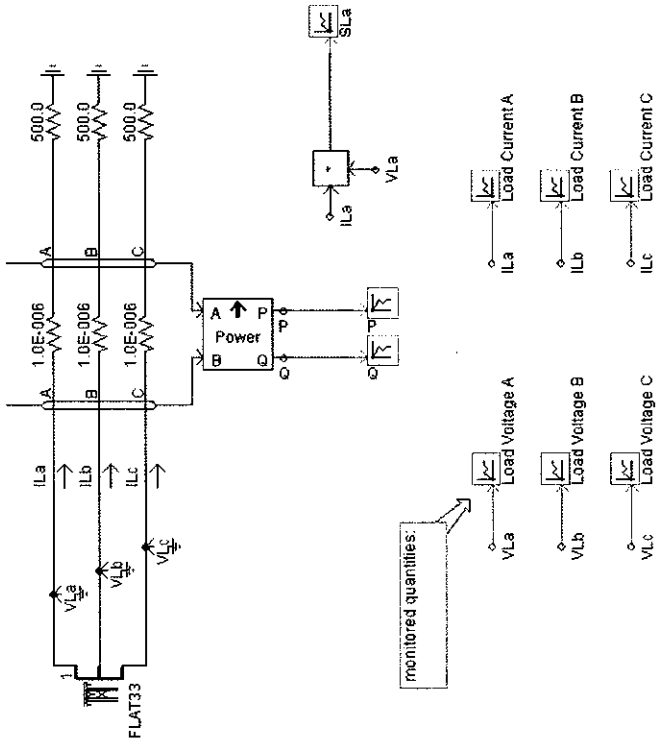
Sending end power is

$$S_{S(3\phi)} = 433\angle 41.8^\circ MVA$$

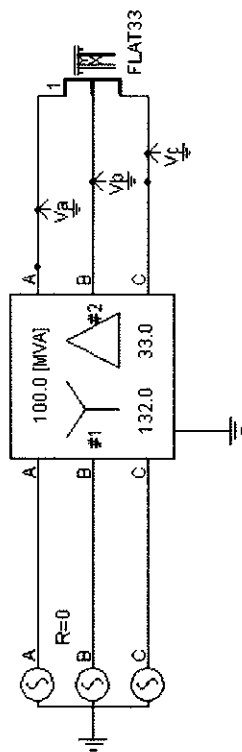
$$\begin{aligned}\text{VOLTAGE REGULATION} &= \frac{250 - 220}{220} \times 100\% \\ &= 13.6\%\end{aligned}$$

$$\begin{aligned}\text{TRANSMISSION LINE EFFICIENCY} &= \frac{P_{R(3\phi)}}{P_{S(3\phi)}} \\ &= \frac{304.8}{322.8} \times 100\% \\ &= 94.4\%\end{aligned}$$

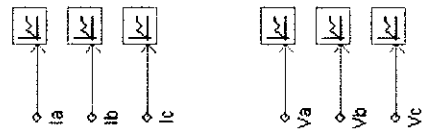
**APPENDIX 2 : PSCAD SIMULATION DIAGRAM FOR PURELY
RESISTIVE LOAD DISTRIBUTION MODEL**



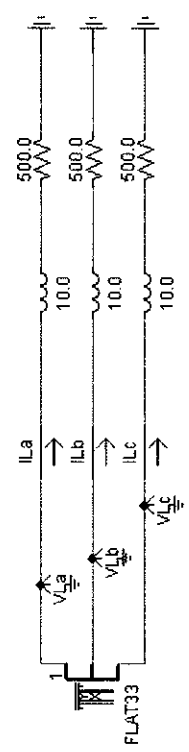
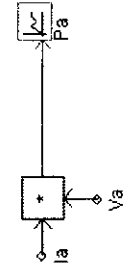
**APPENDIX 3 : PSCAD SIMULATION DIAGRAM FOR RL
(RESISTIVE & INDUCTIVE) LOAD DISTRIBUTION MODEL**



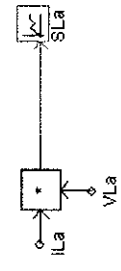
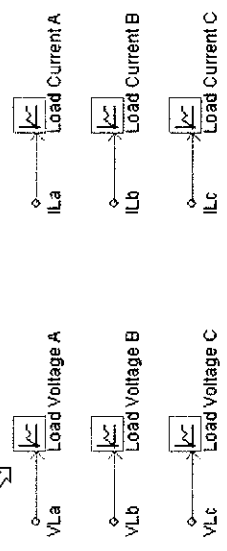
monitored quantities:



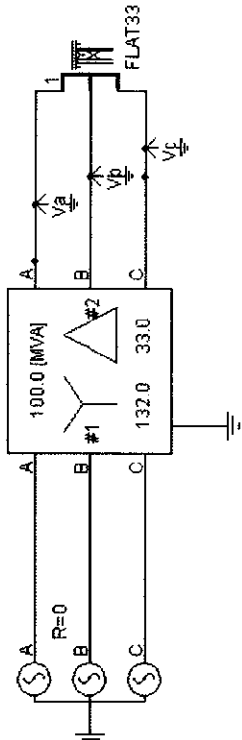
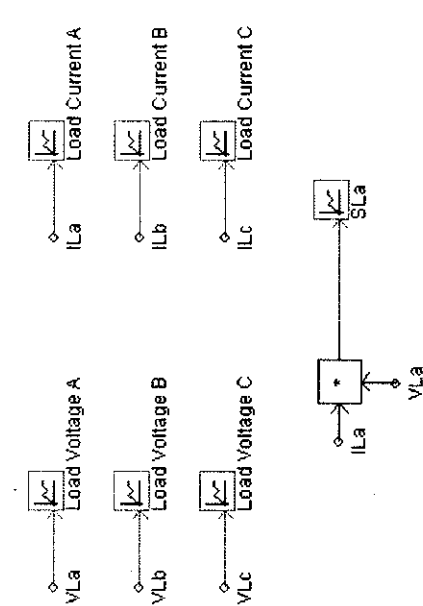
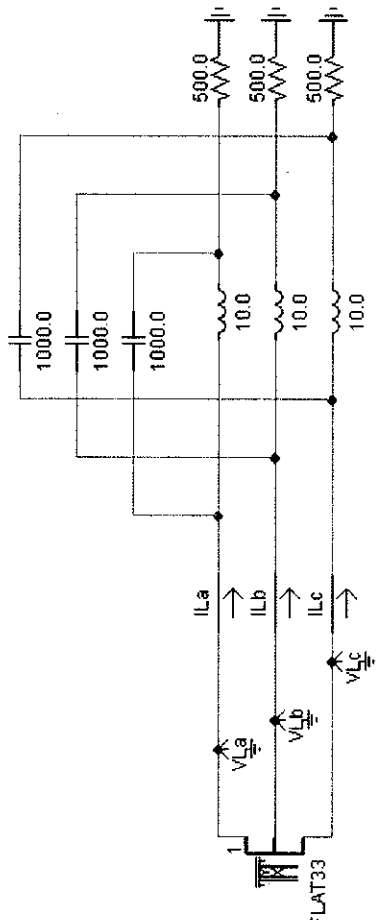
sending end currents, they are measured on the transformer secondary windings inside the transformer component



monitored quantities:



**APPENDIX 4 : PSCAD SIMULATION DIAGRAM FOR RLC
(RESISTIVE, INDUCTIVE & CAPACITIVE)
LOAD DISTRIBUTION MODEL**



monitored quantities.

sending end currents, they are measured on the transformer secondary windings inside the transformer component

