POWER SYSTEM DESIGN, SIMULATION AND ANALYSIS

By

MAS RIZAL BIN ABD RAHIM

FINAL REPORT

Submitted to the Electrical & Electronics Engineering Programme
in Partial Fulfillment of the Requirements
for the Degree
Bachelor of Engineering (Hons)
(Electrical & Electronics Engineering)

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CERTIFICATION OF APPROVAL

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Approved:

16/12-04

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CERTIFICATION OF ORIGINALITY

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

Mas Rizal bin Abd Rahim

ABSTRACT

Power system studies are performed for a variety of reasons. One of them is to ascertain whether the designed power system is fit for operation. For this purpose, many calculations need to be done by the electrical engineer. In most cases, the manual methods of calculation used in these studies are tedious and time consuming. To overcome this problem, a software solution should be used. The software should be able to perform the various calculations and studies besides providing a means to simulate the designed power system using a minimal amount of time.

This project has two main objectives. The first objective is to study a model of an electrical power system in general. The power system is first designed using various guidelines from literature, Tenaga Nasional Berhad (TNB) and examples of existing power systems. To study this network, load flow and fault studies are performed using the ERACS software.

The second objective of the project is to identify the major components of a power system and develop a software simulation program. Here, the MATLAB software is used. The major components identified are the synchronous generator, transformer and transmission line. It is possible to model them using the mathematical equations governing their behavior. The models of each component are combined to form the simulation program in MATLAB.

The ERACS and MATLAB programs are then used to simulate several case studies. The results obtained are compared and discussed. During the course of the project, a full understanding of power systems and the main equipment associated with them shall be obtained.

The methodology to be used in this project is outlined as follows:

i) Conceptual design
ii) Gathering of necessary data and manual calculations
iii) Simulating and testing of the system

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First and foremost, all praise to Allah s.w.t for granting me the opportunity to complete this final year project, which has proven to be a very enriching experience.

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LIST OF ABBREVIATIONS

Ea	Internal generated voltage
I_a	Armature current
R_a	Armature resistance
X_s	Synchronous reactance
θ	Power factor angle
Z%	Transformer impedance in percent impedance
E_2	Secondary induced voltage
V_2	Secondary voltage
V_1	Supply voltage
Z_2	Secondary impedance
I_2	Secondary current
R_{e1}	Equivalent resistance referred to primary side of transformer
X_{e1}	Equivalent reactance referred to primary side of transformer
Z	Total impedance of transmission line
R	Total resistance of transmission line
L	Total reactance of transmission line
l	Transmission line length
V_S	Sending end voltage
V_R	Receiving end voltage
I_S	Sending end current
I_R	Receiving end current
$S_{S(3\Phi)}$	Three phase sending end power
$S_{R(3\Phi)}$	Three phase receiving end power
$P_{S(3\Phi)}$	Three phase sending end real power
$P_{R(3\Phi)}$	Three phase receiving end real power
$S_{L(3\Phi)}$	Three phase line power loss
$V_{R(NL)}$	No load receiving voltage
$V_{R(FL)}$	Full load receiving voltage

CHAPTER 1
INTRODUCTION

1.1 Background of Study

An electrical power system is an energy transportation system. It is a safe, convenient, efficient way to transport large amounts of power for long distances. The high efficiency of electrical machines-generators are over 98% with efficiencies reaching over 99%, transformer efficiencies routinely reach 98% and can reach over 99.5%, and electric motors have efficiencies that are routinely over 80% and many devices over 90%-makes the conversion of energy to electricity for transportation and reconversion to heat, light, and mechanical power cost effective. [1]

The electrical power system can be divided into three major parts:

i) Generation, the production of electricity
ii) Transmission, the system of lines that transport the electricity from the generating plants to the area in which it will be used.
iii) Distribution, the system of lines that connect the individual customer to the electric power system.

A fault is a malfunction in the system. Most faults are, or result in, short circuits. Some faults are the result of lighting and wind of storms, with lightning causing the greatest number. The major categories of faults are: line to ground, line to line, double line to ground, three-phase faults to ground, and open circuits not accompanied by a short. People and equipment must be protected from system faults by disconnecting the faulted system segment with circuit breakers, sectionalizers, and fuses. [5]

The greatest threat to the security of a supply system is the short circuit, which imposes a sudden and sometimes violent change on system operation. The large current which then flows accompanied by the localized release of considerable amount of energy, can cause fire at the fault location, and mechanical damage throughout the system.

1.2 Problem Statement

1.2.1 Problem Identification

To further understand the characteristics of the main components of a power system, a model must be formulated for each of them. These models serve as a tool for conducting tests or experiments to understand their physical behavior. The models shall be based on existing mathematical equations. Using data inputs from a user, the models can then be simulated in computer software. The software being used in this project for that purpose is MATLAB.

The simulations in MATLAB shall be complemented with simulations using more advanced software, namely ERACS. While MATLAB is used only to simulate basic components, ERACS shall be used for the simulation of more complex electrical networks. The simulation results of both software are then compared and the results analyzed.

1.2.2 Project Significance

This project is a significant step towards a more efficient way of conducting power system studies and analysis. Using the results of the simulation, the sizing of equipment such as switchgears and transformers can be done. This will help the engineer produce cost estimates based on the calculated equipment size.

Using this simulation, a substantial amount of time normally used to perform manual calculations can be saved. This will help engineers complete projects faster and meet their planned schedules.

Besides producing results faster, the simulation results can be used to justify the accuracy of manual calculations. By comparing the software and manual calculation results, mistakes in the manual calculations can be quickly traced and corrected. More importantly, the results of the manual calculations become more convincing when supported by simulation results.

The simulation software can also be used for research purposes. By conducting various case studies, the behavior of a particular power system can be fully understood. The data acquired can be used to produce better-designed power systems.

1.3 Objective and Scope of Study

The objectives of this project are:

i) To study a model of an electrical power system in general. This model involves a network containing residential and industrial loads in a distribution area.

ii) To study the basic principles underlying the operation of major power system components such as generators, transformers and transmission lines.

iii) To produce models for each component in MATLAB and to integrate all these components to form a workable simulation program.

iv) To design a power system and to conduct studies whereby the results are to be compared with the results of the MATLAB simulation.

CHAPTER 2
LITERATURE REVIEW AND THEORY

2.1 Components of Electrical Power Systems

An electrical machine is a device that can convert either mechanical energy to electric energy or vice versa. When such a device is used to convert mechanical energy to electrical energy, it is called a generator. When it converts electric energy to mechanical energy, it is a motor. Another closely related device is the transformer. These three types of electric devices are ubiquitous in modern daily life. [2]

2.2 Synchronous Generators

Synchronous generators or alternators are synchronous machines used to convert mechanical power to ac electric power. Large-scale power is generated by three-phase synchronous generators, driven either by steam turbines, hydroturbines, or gas turbines.

The rotor of the synchronous machine may be of cylindrical or salient construction. The cylindrical type of rotor, also called round rotor, has one distributed winding and a uniform air gap. These generators are driven by steam turbines and are designed for high speed 3600 or 1800 rpm (two and four-pole machines, respectively) operation. Roughly 70 percent of large synchronous generators are cylindrical rotor type ranging from about 150 to 1500 MVA. [3]

2.2.1 The Generator Model

The main equation used in the generator model involves mainly the excitation voltage, E, terminal voltage, V_ϕ, armature resistance, R_a, reactance of the armature reaction, X_{ar}, leakage reactance voltage drop, X_l and the armature current I_a. The relationship between these components is represented by the equation below:

$$\mathbf{E = V_\phi + [R_a + j(X_l + X_{ar})]I_a} \qquad (1)$$

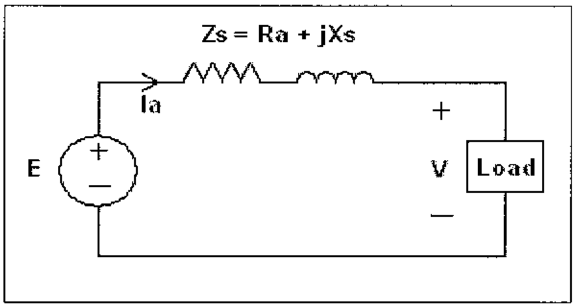

Figure 1 : Synchronous machine equivalent circuit

In Figure1, $X_l + X_{ar}$ has been replaced by X_s, giving:

$$\mathbf{E = V_{\phi} + [R_a + j(X_s)]I_a} \qquad (2)$$

Usually, R_a is much smaller than X_s, so the equation can be further simplified:

$$\mathbf{E = V_{\phi} + jX_sI_a} \qquad (3)$$

2.2.2 Effect of Load Variations on Synchronous Generator Operating Alone

The behaviour of a synchronous generator under load varies greatly depending on the power factor of the load and on whether the generator is operating alone or in parallel with other synchronous generators.

An increase in the load causes an increase in the load current drawn from the generator. Because the field resistor has not been changed, the field current is constant, and therefore the flux ϕ is constant. Since the prime mover also keeps a constant speed ω, the magnitude of the internal generated voltage, $E = K\phi\omega$ is constant.[2]

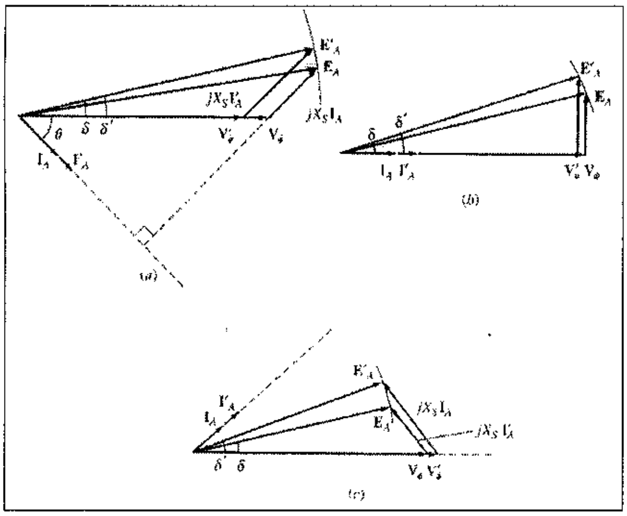

Figure 2 :The effect of an increase in generator loads with constant power factor upon its terminal voltage

From Figure 2, the right triangle gives

$$\mathbf{E_A^2 = (V_\Phi + X_sI_a\sin\theta)^2 + (X_sI_a\cos\theta)^2} \qquad \mathbf{(4)}$$

Solving for V_Φ:

$$\mathbf{V_\Phi = [E_A^2 - (X_sI_a\cos\theta)^2]^{0.5} - X_sI_a\sin\theta} \qquad \mathbf{(5)}$$

This equation is for lagging loads. For leading loads, there is only a small change in the equation:

$$\mathbf{V_\Phi = [E_A^2 - (X_sI_a\cos\theta)^2]^{0.5} + X_sI_a\sin\theta} \qquad \mathbf{(6)}$$

For a given phase voltage and armature current, a larger internal generator voltage Ea, is needed for lagging loads than for leading loads. Therefore, a larger field current is needed with lagging loads to get the same terminal voltage. Alternatively, for a given field current and magnitude of load current, the terminal voltage is lower for lagging loads and higher for leading loads.

In real synchronous machines, the synchronous reactance is normally much larger than the winding resistance Ra, so Ra is often neglected in the qualitative study of voltage variations.

2.3 Transformer

Transformers are essential elements in any power system. They allow the relatively low voltages from generators to be raised to a very high level for efficient power transmission. At the user end of the system, transformers reduce the voltage to the values most suitable for utilization. In modern utility systems, the energy may undergo four or five transformations between generator and the ultimate user.

The equivalent circuit model of a single phase transformer is shown in Figure 3. The equivalent circuit consists of an ideal transformer of ratio N_1:N_2 together with elements which represent the imperfections of the real transformer.

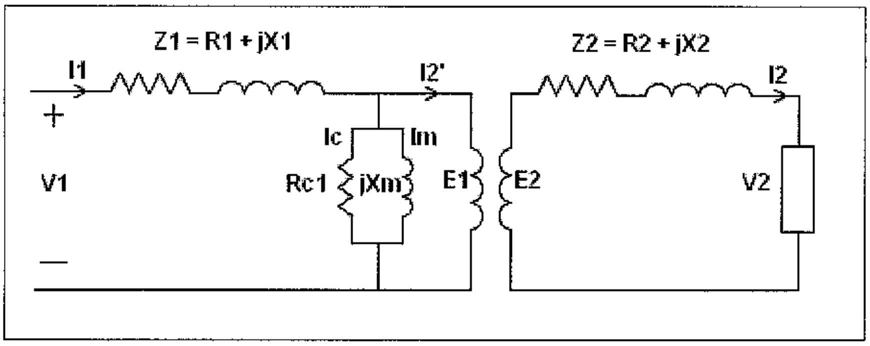

Figure 3 :Transformer equivalent circuit

To obtain the performance characteristics of a transformer, it is convenient to use an equivalent circuit model referred to one side of the transformer. From Kirchhoff's voltage law (KVL), the voltage equation of the secondary side is

$$\mathbf{E_2 = V_2 + Z_2I_2} \qquad \textbf{(7)}$$

From the relationship developed for the ideal transformer, the secondary induced voltage and current are $E_2 = (N_2/N_1)E_1$ and $I_2 = (N_1/N_2)I_2'$, respectively. Upon substitution, Equation (7) becomes

$$\begin{aligned} E_1 &= (N_1/N_2)V_2 + (N_1/N_2)^2Z_2I_2' \\ &= \mathbf{V_2' + Z_2'I_2'} \end{aligned} \qquad \textbf{(8)}$$

where

$$Z_2' = R_2' + jX_2' = (N_1/N_2)^2 R_2 + j(N_1/N_2)^2 X_2$$

The equivalent circuit of Figure 3 can be redrawn as shown in Figure 4, so the same effects are produced in the primary as would be in the secondary.

On no-load, the primary voltage drop is very small, and V_1 can be used in place of E_1. Thus, the shunt branch can be moved to the left of the primary series impedance with very little loss of accuracy. In this manner, the primary quantities R_1 and X_1 can be combined with the referred secondary quantities R'_2 and X'_2 to obtain the equivalent primary quantities R_{e1} and X_{e1}. The equivalent circuit is shown in Figure 4 where we have dispensed with the coils of the ideal transformer. [3]From Figure 4,

$$\mathbf{V_1 = V'_2 + (R_{e1} + jX_{e1})I'_2} \qquad \mathbf{(9)}$$

where

$R_{e1} = R_1(N_1/N_2)^2 R_2$

$X_{e1} = X_1 + (N_1/N_2)^2 X_2$

$I'_2 = S_L{}^*/3V'_2{}^*$

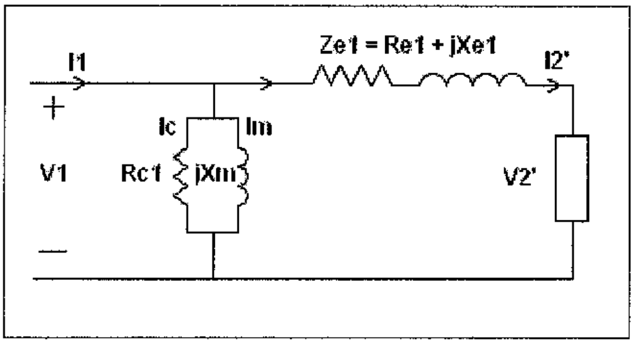

Figure 4 :Approximate equivalent circuit referred to the primary

2.4 Transmission Line

The purpose of a transmission network is to transfer the electric energy from generating units at various locations to the distribution system which ultimately supplies the load. Transmission lines also interconnect neighboring utilities which permits not only economic dispatch of power within regions during normal conditions, but also transfer of power between regions during emergencies.

The model used to calculate voltages, currents, and power flows depends on the length of the line. The model used in the MATLAB simulation is the short line model.

Capacitance may often be ignored without much error if the lines are less than about 80 km long, or if the voltage is not over 69 kV. The short line model is obtained by multiplying the series impedance per unit length by the line length.

$$\mathbf{Z = (r + jwL)l} \quad \text{(10)}$$

Where r and L are the per-phase resistance and inductance per unit length, respectively, and l is the line length. The short line model on a per-phase basis is shown in Figure 5. V_S and I_S are the phase voltage and current at the sending end of the line, and V_R and I_R are the phase voltage and current at the receiving end of the line. [3]

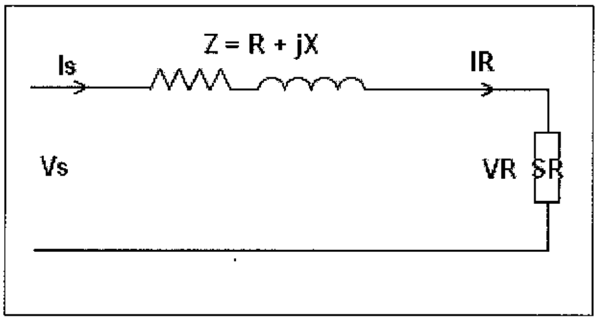

Figure 5 :Short line model

If a three-phase load with apparent power $S_{R(3\Phi)}$, is connected at the end of the transmission line, the receiving end current is obtained by

$$\mathbf{I_R = S_{R(3\Phi)}^*/3V_R^*} \quad \text{(11)}$$

The phase voltage at the sending end is

$$\mathbf{V_S = V_R + ZI_R} \quad \text{(12)}$$

Since the shunt capacitance is neglected, the sending end and the receiving end current are equal:

$$\mathbf{I_S = I_R} \qquad \textbf{(13)}$$

Voltage regulation of the line may be defined as the percentage change in voltage at the receiving end of the line expressed as percent of full-load voltage in going from no-load to full-load.

$$\textbf{Percent VR} = \frac{|\mathbf{V_{R(NL)}}| - |\mathbf{V_{R(FL)}}|}{|\mathbf{V_{R(FL)}}|} \textbf{ X 100} \qquad \textbf{(14)}$$

Once the sending end voltage is calculated the sending-end power is obtained by

$$\mathbf{S_{S(3\Phi)} = 3V_S I_S^*} \qquad \textbf{(15)}$$

The total line loss is then given by subtracting the three phase receiving-end power from the sending end power.

$$\mathbf{S_{L(3\Phi)} = S_{S(3\Phi)} - S_{R(3\Phi)}} \qquad \textbf{(16)}$$

and the transmission line efficiency is given by

$$\text{Efficiency, } \eta = \frac{\mathbf{P_{R(3\Phi)}}}{\mathbf{P_{S(3\Phi)}}} \qquad \textbf{(17)}$$

CHAPTER 3
METHODOLOGY/PROJECT WORK

3.1 Project Methodology

The project involves two major objectives, namely the study of a power system model and the writing of a simulation program. The flow of activities is illustrated in the flowchart.

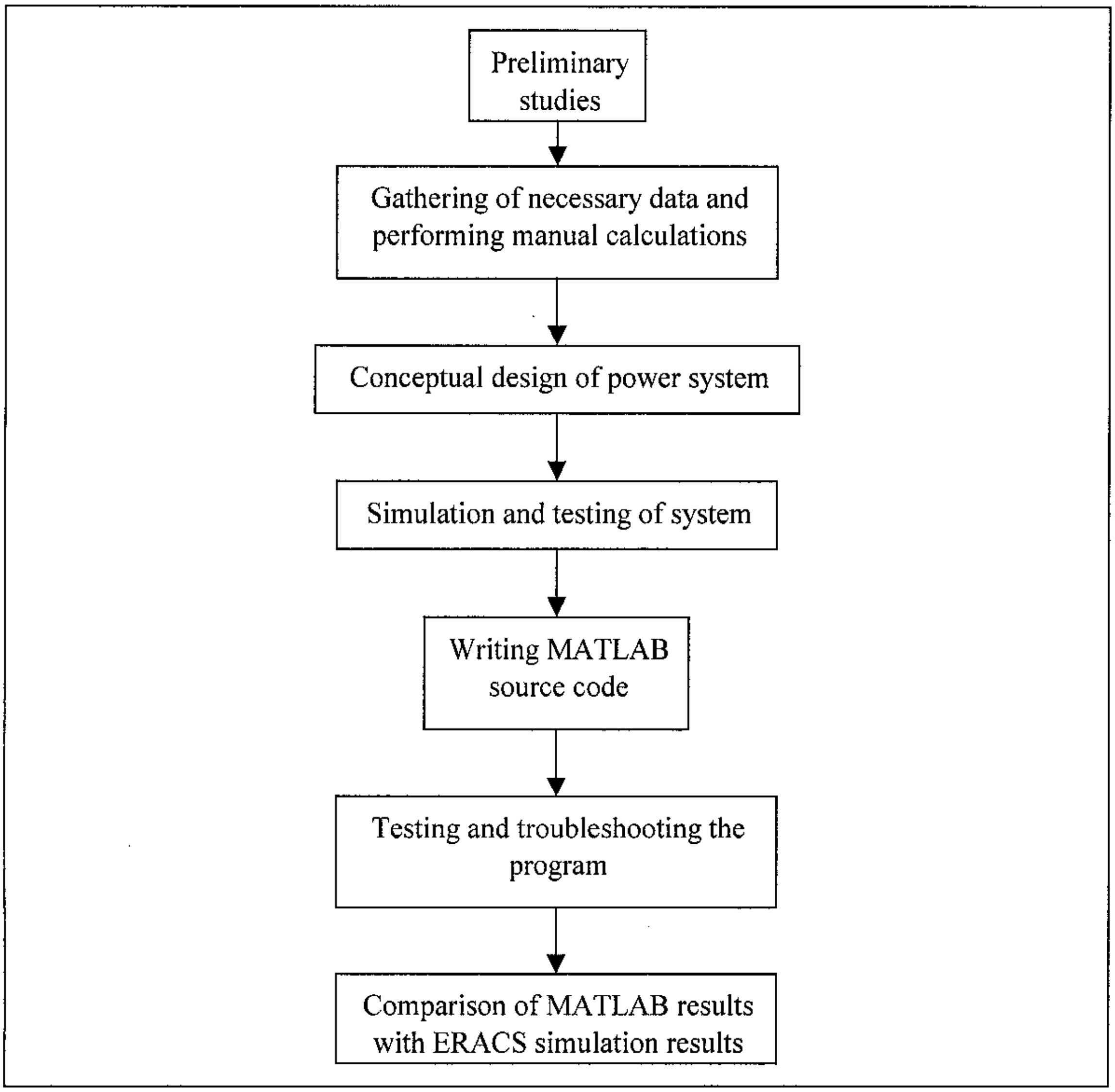

Figure 6 :Project activities flowchart

The project has gone through a few phases of procedures. The main activity conducted during the first 8 weeks of the project was literature review concerning the subject of power systems. This was to gain the necessary knowledge of the theory involved before embarking on the design and simulation phase of the project. The literature review was done by studying various texts from the university resource center and also from the internet. Besides that, the manuals for the ERACS simulation software were also studied.

To proceed with the design phase of the project, data from various sources were required. Guidelines on the TNB electricity system were obtained from the TNB supply handbook and also from consultations with TNB engineers. Data on the electrical components used in the simulation were taken from the ERACS reference library, catalogues and textbooks.

The power system was then designed based on the guidelines obtained. From basic network, it was refined and improved from time to time until the final design was completed. The network was then simulated using ERACS. This involved a series of tests to determine the loadflow parameters and also the short circuit current within the designed network.

The next activity was the writing of the MATLAB program designed to emulate one of the features of ERACS. The program was designed to perform a simple version of the Loadflow study featured in ERACS. Once this was completed, the MATLAB program was tested using the same parameters as those used in ERACS. Some time was also used for troubleshooting the program.

Once the MATLAB program was completed, both the ERACS and MATLAB were used to conduct several studies. The results obtained were then compared and analyzed.

3.2 Tools

3.2.1 ERACS software

ERACS is ERA Technology's suite of power systems analysis software. It allows network design and planning engineers to simulate electrical power systems quickly and easily to judge their correct, safe and timely operation under user defined, and sometimes arduous situations.

The economic design of power systems is critically dependent on being able to predict the system behavior under both normal and abnormal conditions. Hand calculations and estimates are possible but increasingly expensive in engineers' time and run the risk of introducing errors resulting in significant safety and reliability implications. ERACS saves costs, reduces risk, improves quality, and increases reliability and safety. Among the main program modules and options are as follows:

i) Load Flow

The Loadflow module serves a number of purposes, the first of which is to calculate the steady state conditions of the power system network. Under given conditions the program will determine the network voltage profile, current and the real and reactive power flows. Convergence is achieved by modifying the voltage magnitude and angle of the synchronous machines, tap position of on load tap changers, and slip for induction machines.

ii) Fault Analysis

The Fault calculation program enables the user to establish currents and voltages around a network immediately following a fault condition. The program provides facilities to simulate the following types of fault: phase to earth, two phase to earth, phase to phase, three phase to earth faults, single phase open circuit and two phase open circuit. A prerequisite of any Fault study is the interpretation of system data and determination of pre-fault voltage, loading and generating conditions. For this reason a Loadflow calculation must precede all Fault studies. The program uses a single phase representation of the network and the symmetrical component transformation to simulate fault conditions. This means that any one of the fault types may be easily represented by a simple interconnection of the sequence networks. [8]

3.2.2 MATLAB software

MATLAB is a matrix-based software package, which makes it ideal for power system analysis. MATLAB, with its extensive numerical resources, can be used to obtain numerical solutions that involve various types of vector-matrix operations. In addition, SIMULINK provides a highly interactive environment for simulation of both linear and nonlinear dynamic systems. MATLAB is to be used extensively for the modeling of electrical components in the project.

3.3 ERACS Simulation

The developed electrical network shown in Figure 7 is arbitrarily named the Tronoh power system network. It is an interconnected network, where two incoming power supply feeders are connected to two substations. An interconnected system will give continuous service even when one of the power stations is shut down. One of the main advantages of interconnection is increased security of service; another is the reduction in stand-by plant, and a third is the economy obtained by dividing the total load in such a way as to reduce the total capital cost and running costs to a minimum.

The incoming voltage of 132 kV is stepped down to 11kV for distribution. The network is divided into two parts, namely the residential and industrial parts. At 33 kV, industrial consumers' supplied voltage is much higher than residential distribution voltage of 11kV. The loads at each town is represented by PQ, indicating real and reactive power.

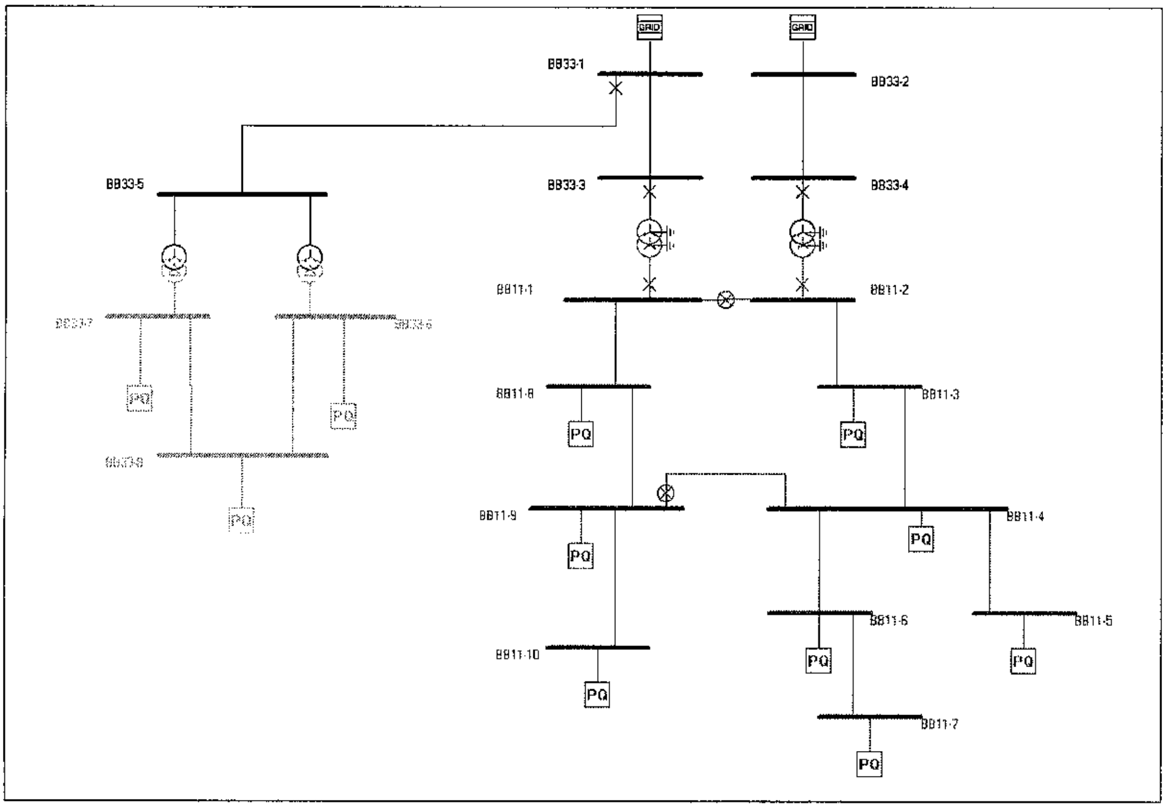

Figure 7 :Electrical network of residential and industrial consumers

3.3.1 Grid Infeed

The model is configured such that the three phase fault level provided by the grid is unaffected by connected load. This point is debatable, as in reality the fault current at a point in the network will be load dependent. Since it is common practice in the UK Electrical Supply Industry for supplier to specify fault MVA or kA at the point of connection, which implies fault levels independent of load, grid infeeds are modeled in the same way.

Short circuit MVA from TNB switchboard is considered as 4158MVA, calculated using figures from the TNB guidelines shown in Appendix B. Since the short circuit rating at 132 kV is given as 31.5kA, the MVA fault infeed is calculated as follows:

MVA fault rating = 31.5kA X 132kV = 4158 MVA

This figure was entered into ERACS using the interface in Figure 8

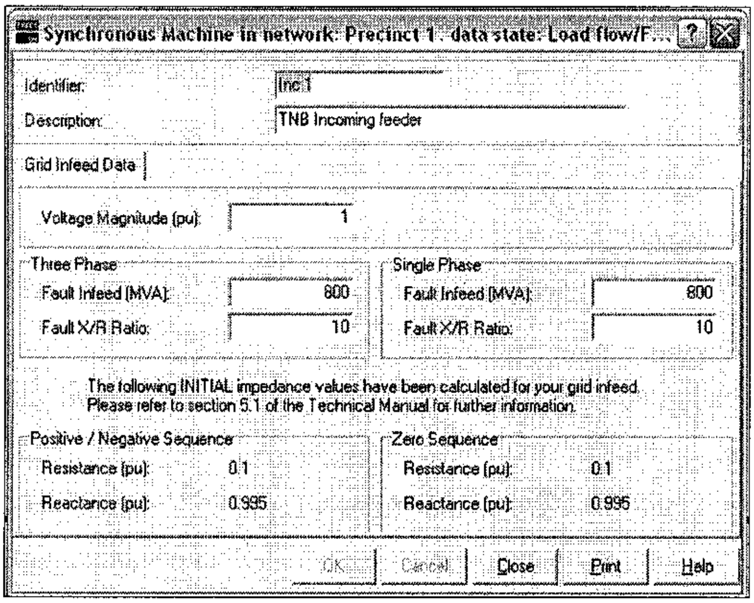

Figure 8 : Input Interface for Grid Infeed

3.3.2 Busbars

The main inputs for the busbars are the voltage rating in kilovolts and the frequency in Hertz. Based on these inputs, ERACS automatically calculates the three phase and single phase fault ratings which are rated in MVA units.

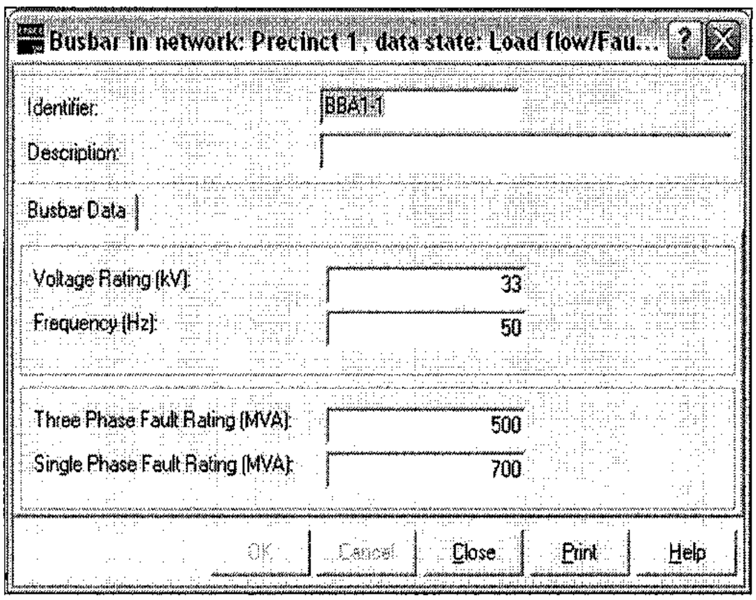

Figure 9 : Input Interface for Busbars

3.3.3 Transformers

Typical transformer sizes for various transformation ratios in Malaysia are shown in Table 1.

Distribution	
11 / 0.433 kV	50,100,500,750,1000,1500,2000 kVA
Transmission	
33/11 kV	5 to 20 MVA
132/33 kV	30 to 90 MVA
275/132 kV	110 to 240 MVA
Generation	
Voltage rating matches that of generators	10 to 500 MVA

Table 1: Typical transformer sizes

In the design, the transformers used are 132/11 kV star-star transformers. The advantages of using star-star transformers are as follows:

i) Star Winding is mechanically more robust

ii) Secondary neutral is used for earthing and 4-wire supply

iii) Easy for parallel operation

The chosen capacity for the transformers was set at 110 MVA. Since the primary winding is delta, the angle can be set to values -180, -30, 0, 30, 180. The typical phase shift for star-star transformers is +30° and -30°. In this simulation 30° is chosen as the angle for secondary winding and 0 degrees for primary. The off load tap changer at the secondary winding was set at 5% to accommodate voltage drops which occur in the distribution line.

The positive and negative sequence resistance values are divided equally between the two windings of the transformer. Cable data is not provided, since the simulation is not detailed.

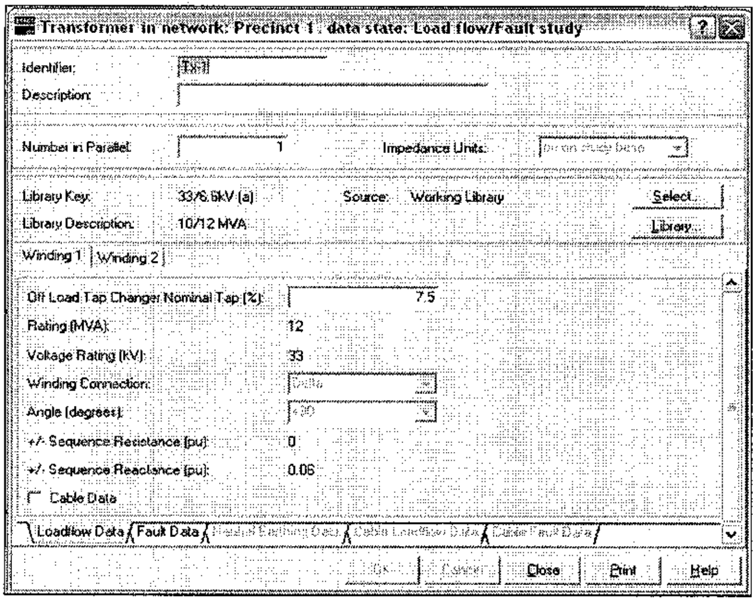

Figure 10 : Input Interface for Transformers

3.3.4 Shunt loads

The power system is divided into a residential and an industrial area. 8 residential consumers are connected to a 11 kV distribution supply while 3 industrial consumers receive 132 kV power supply. The residential consumers are categorized into various towns and villages while industrial consumers are taken as individual plants. The power factor for residential loads is assumed to be at an average of 0.8, while industrial loads are rated at 0.85 power factor. The list of consumers is shown in Table 3. The names associated with each of the busbars have been arbitrarily chosen.

Busbar Identifier	Town/Village/Plant	Demand (MVA)
BB11-3	Bandar Seri Iskandar	20
BB11-4	Bandar Universiti	15
BB11-5	Kampung Bota	15
BB11-6	Taman Maju	7.5
BB11-7	Kampung Perak	7.5
BB11-8	Batu Gajah	20
BB11-9	Pusing	15
BB11-10	Kampung Baru	7.5

BB33-6	Scanwolf factory	12
BB33-7	Nikko factory	18
BB33-8	Hitachi factory	14

Table 3: List of consumers and power demand

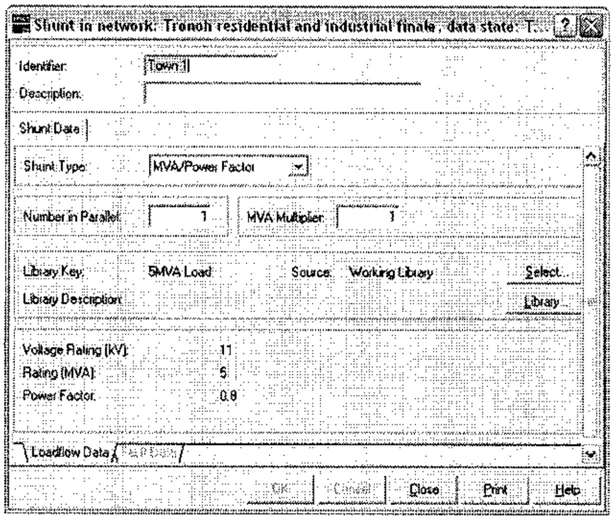

Figure 11 Input Interface for Shunt Loads

3.3.5 Simulation Studies

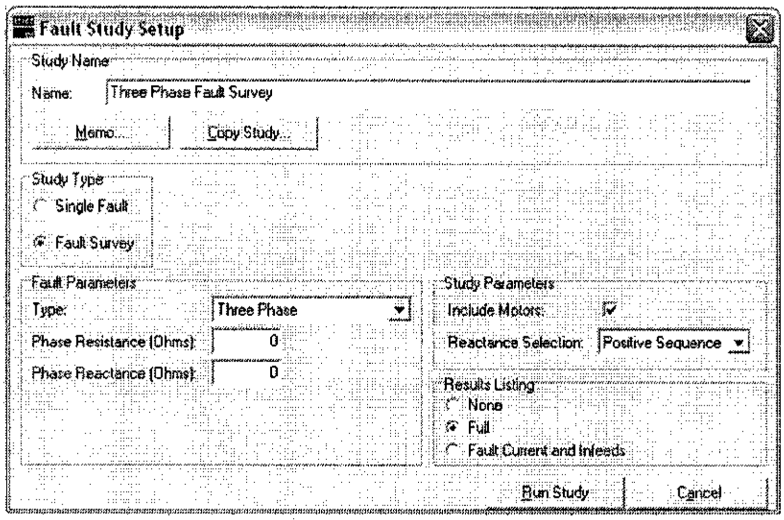

Figure 12 Interface for Fault Study

Several studies were conducted on the network using ERACS. The studies are listed as follows:

i) Loadflow studies

ii) Three phase fault survey

iii) Single phase to earth fault at BB11-1

iv) Single phase to earth fault at BB11-6

3.4 MATLAB Simulation

The purpose of modeling power system components such as the synchronous generator, transformer, and motor is to understand the principles behind the workings of these machines. These machines are all represented by mathematical equations, which make it possible to model using software. Two programs were written using MATLAB for this purpose. The first program, "**powersys.m**" analyzes a basic power system consisting of a generator, two transformers, a transmission line and a load. The second program, "**phasor.m**" draws the phasor diagram of the synchronous generator produces a table demonstrating the effect of an increasing load on the generator internal voltage.

3.4.1 Modelling of Power System Components

The structure of the power system model used in "**powersys.m**" is shown in Figure 13. The generator supplies power at 11kV, which is stepped up by transformer 1 to 33kV and transmitted through the transmission line. The supply is then stepped down to 11kV by transformer 2 and distributed to the load.

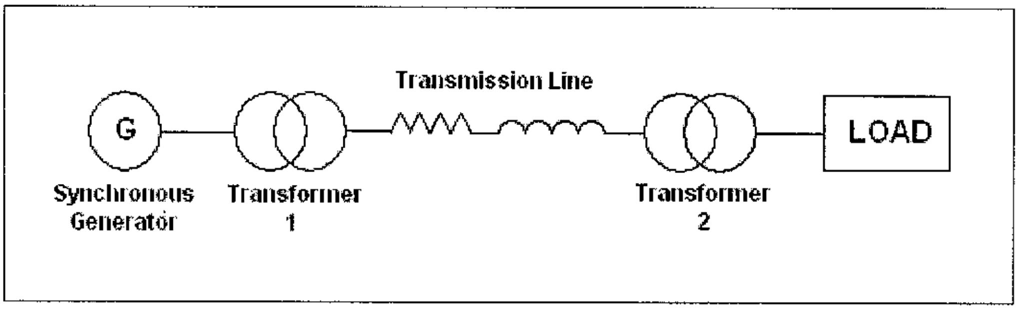

Figure 13 :Power system model

The simulation of the model was run using the parameters in Table 2. All inputs were based on data in the ERACS simulation as shown in Figure 12. Here, busbars BB33-2 to BB11-2 and the components in between them were used to test the MATLAB program. The values of busbar voltage, transmission line, and transformer data were taken from the component data and simulation results in ERACS. The simulation results of the MATLAB program were then compared with the ERACS results.

Generator data	
Armature resistance (Ω)	3.2
Synchronous Reactance (Ω)	1.8
Transformer 1 data	
Primary voltage (kV)	11
Transmission line	
Resistance per unit length (Ω)	0.1234
Inductance per unit length (Ω)	0.2523
Line length (km)	40
Supply frequency (Hz)	50
Transformer 2 data	
Primary voltage (kV)	33
Series branch resistance referred to HV side (Ω)	0.0545
Series branch inductance referred to HV side (Ω)	1.6335
Load data	
Load MVA	11.1482
Power factor	0.8 (lagging)
Terminal voltage (kV)	11

Table 2: Input data for power system model

3.5 Case Studies

The MATLAB program was also tested using various values load power. This was to examine the effect of lagging and leading loads on the voltage regulation. The program was used to simulate the following loads:

i) 40 MVA lagging load
ii) 40 MVA leading load
iii) 60 MVA lagging load
iv) 60 MVA leading load

3.6 Synchronous Generator MATLAB Model

During a synchronous generator's operation, the load demands on the generator may vary with time. The effect is directly observable from the value of Ia, which varies with load change. Normally, it is desirable to keep the voltage supplied to the load constant, even though the load itself varies. The obvious approach to keeping the terminal voltage constant is to vary the magnitude of Ea to compensate for changes in the load.

The effects of increasing the load on the generator are studied using the "**phasor.m**" program. The study is done for lagging and leading loads.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 ERACS Simulation

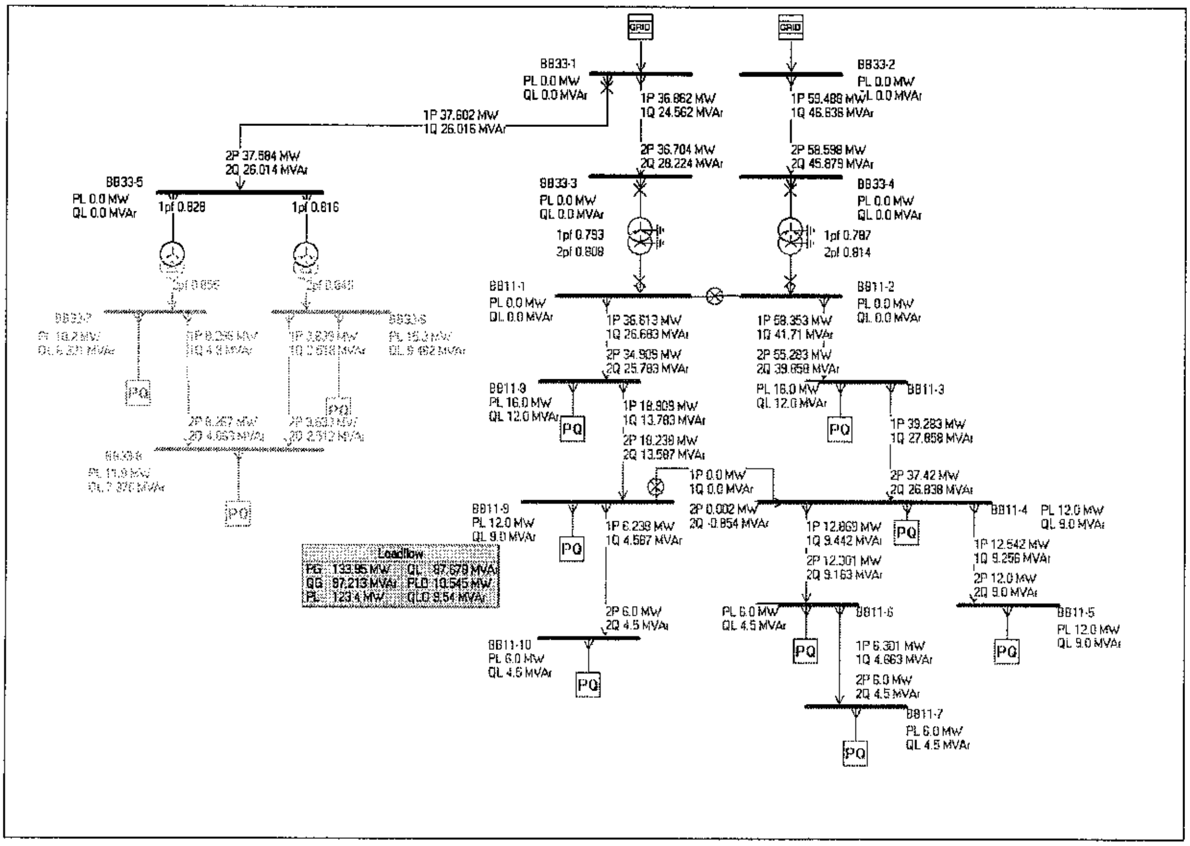

Figure 14 :Real and Reactive power profile using Loadflow simulation

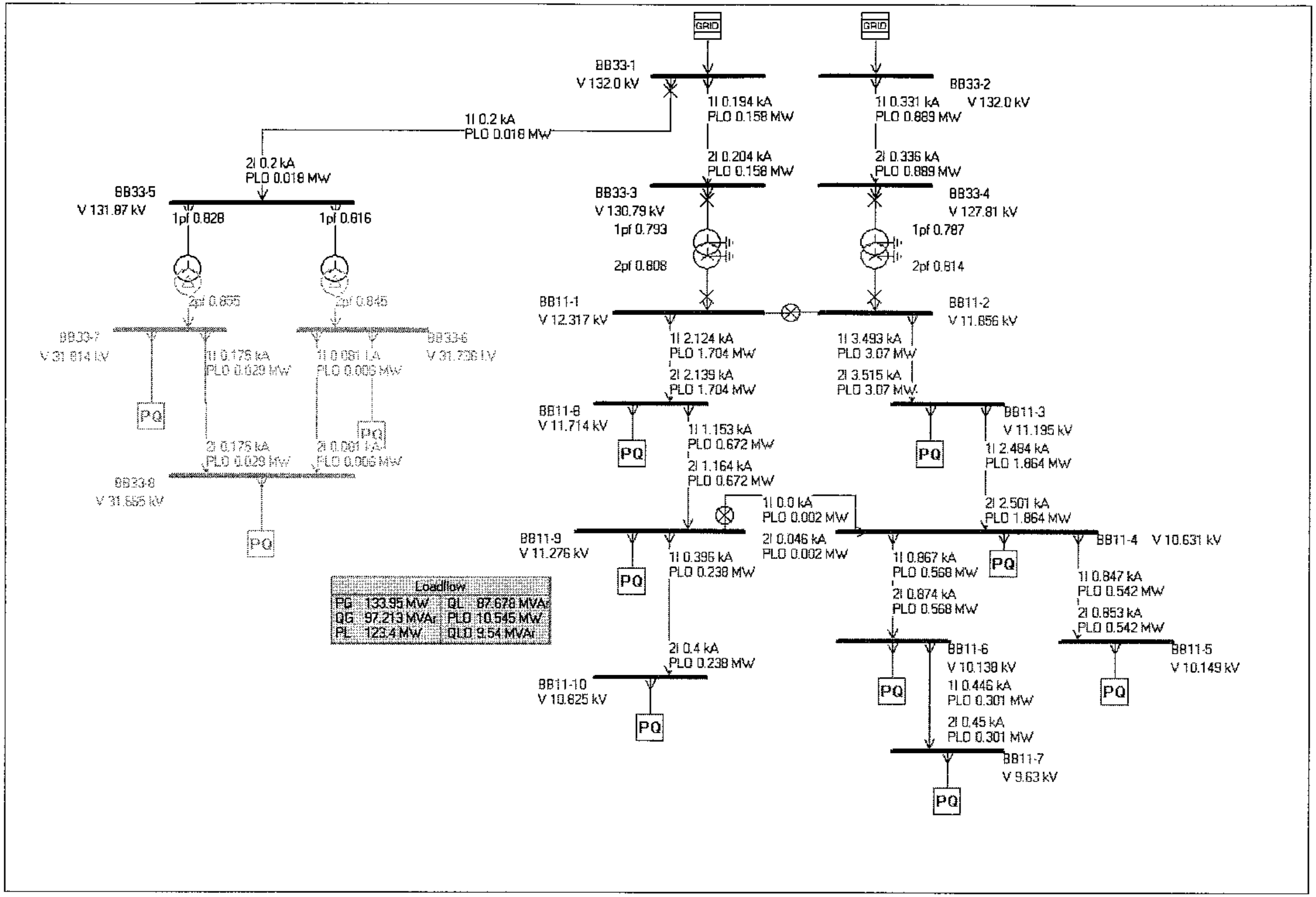

Figure 15 :Transmission line losses using Loadflow simulation

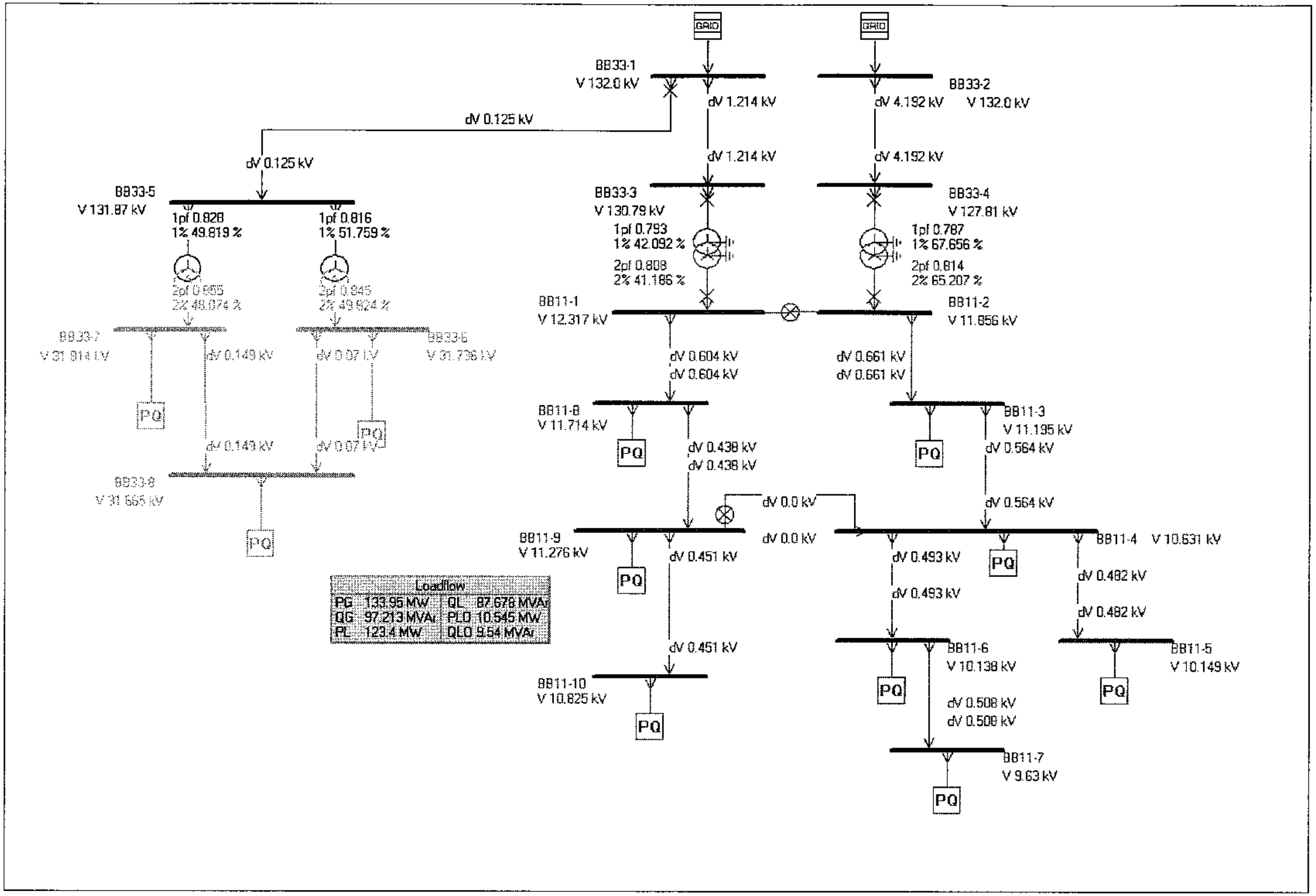

Figure 16 Voltage profile of network using Loadflow simulation

4.1.1 Fault Simulation

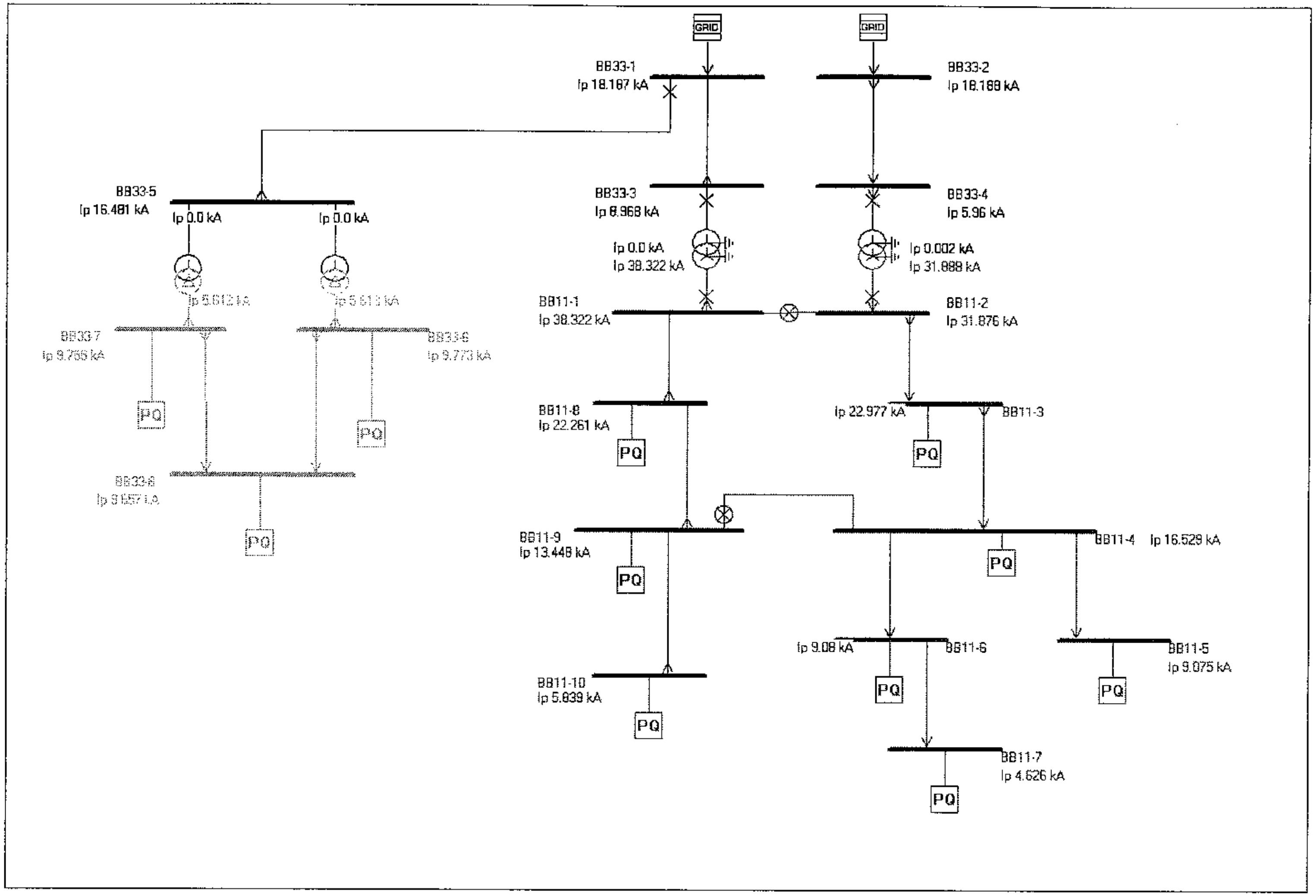

Figure 17 :Three Phase Fault Survey

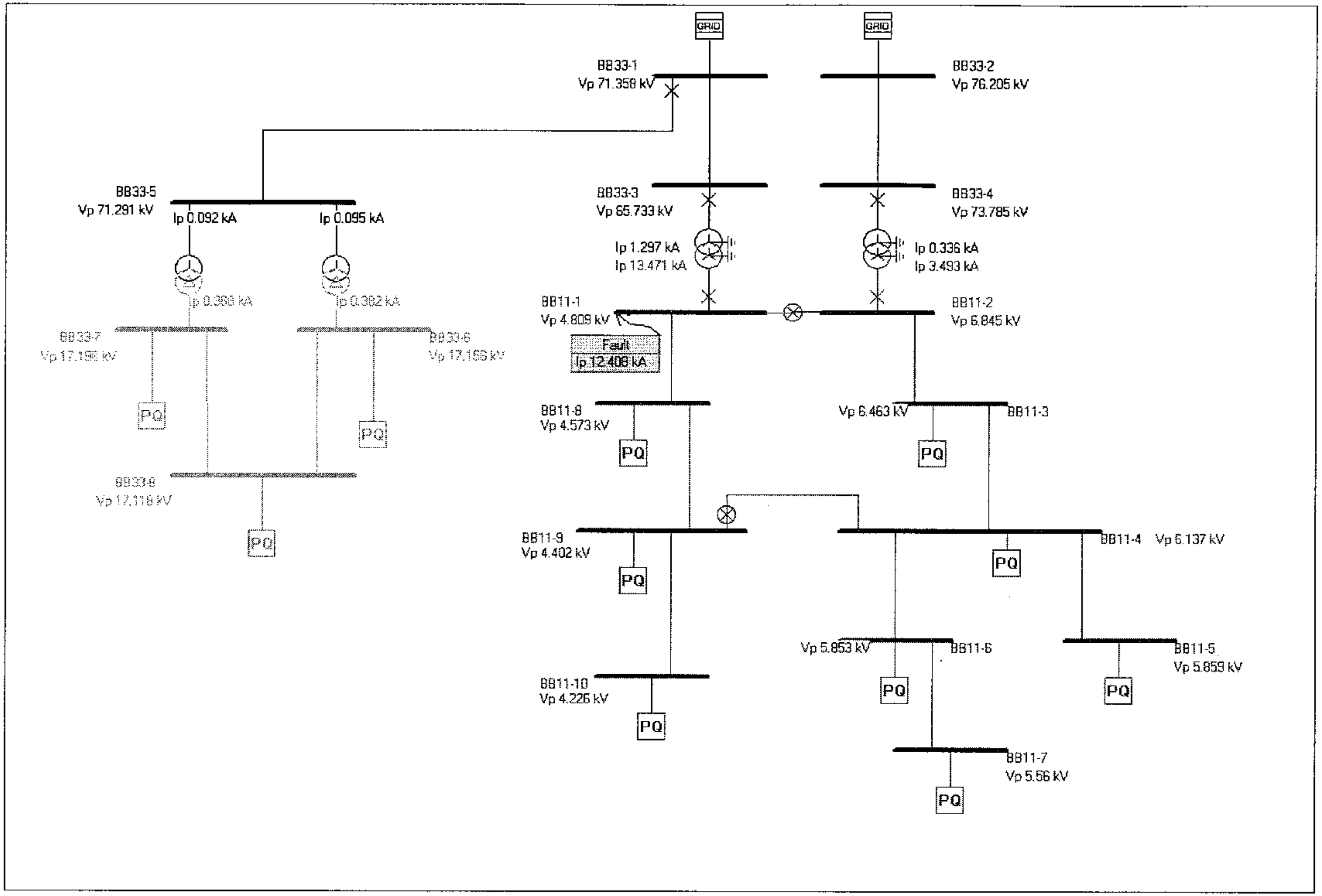

Figure 18 :Single Phase to Earth Fault Survey (at BB11-1)

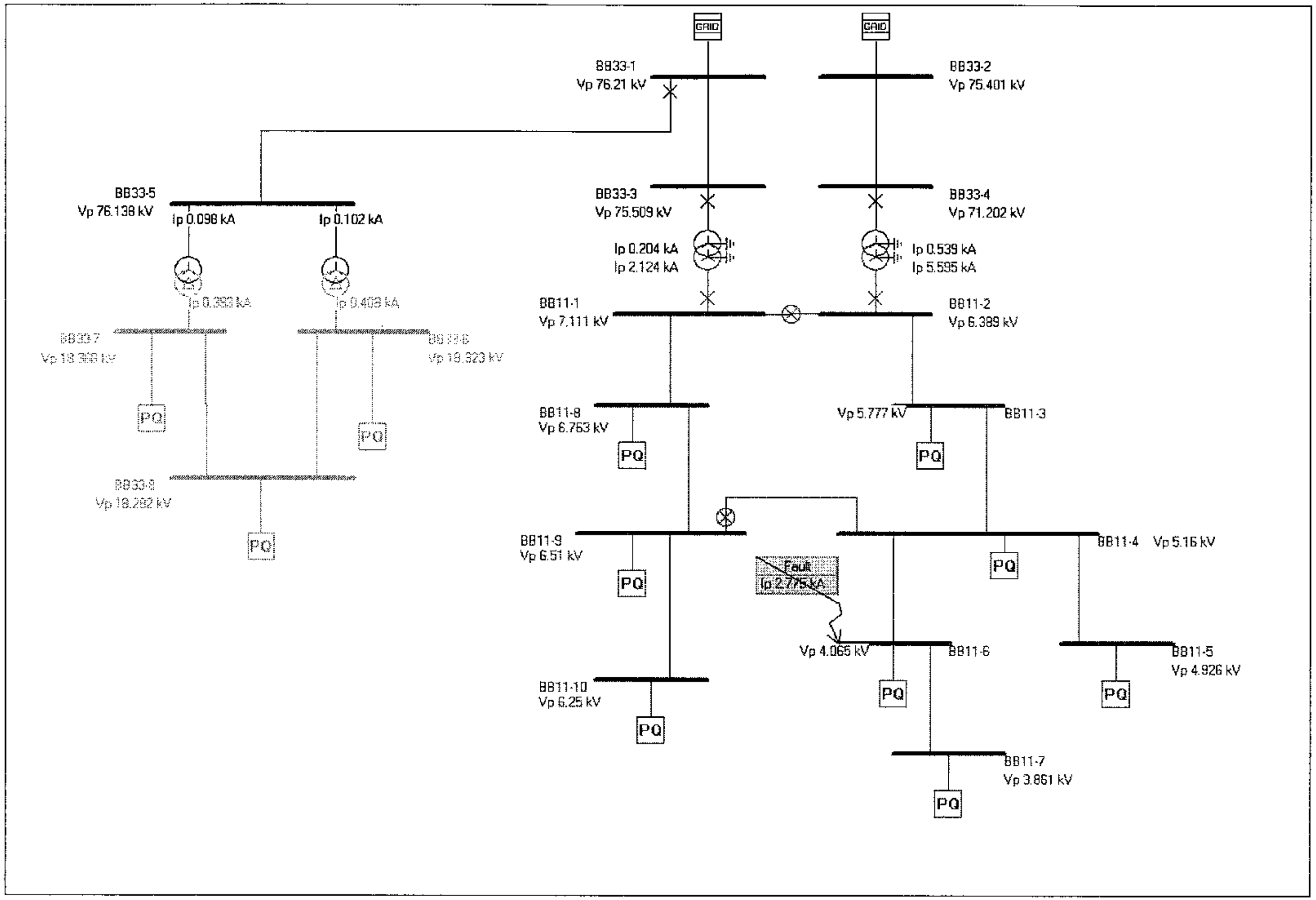

Figure 19 : Single Phase to Earth Fault Survey (at BB11-6)

4.2 LoadFlow Simulation

According to the simulation results shown in Figure 14, the total generated real power is 133.95 MW while the total generated reactive power is 97.213 MVAr. Total power flowing in the lines amounts to 123.4 MW and 87.678 MVAr. A total of 10.545 MW and 9.54 MVAr of power losses occur in the lines.

The first incoming feeder supplying the residential consumers takes 58.59 MW of the total supply. 36.70 MW flows through the second incoming feeder while the feeder supplying the industrial consumers carries 37.60 MW of power. The real and reactive power load of each PQ load is calculated based on the input MVA and power factor.

Based on results in Figure 15, the voltage level at the secondary side of the 132/11 transformer is 12.317kV. This is an automatically calculated figure based on the allowed tap rating of the transformer, which was set at 10%. The software calculated a 6.64% increase from the original rating of 11.55 kV. This voltage rating allows the voltage at all the receiving ends to stay above 80% of the distribution voltage. This is essential because ERACS does not allow the receiving-end voltage to be less than 80% of the sending-end voltage.

Figure 16 shows the voltage rating at all busbars. The highest voltage ratings are generally at the sending-end of the network. For the residential network, the highest voltage is at busbar BB11-1 while the lowest is at busbar BB11-6.

Losses in the network depend on the magnitude of current flowing, the resistance, reactance and capacitance in the lines. At the 11kV side of the system, losses are higher than those on the 132 kV side.

4.3 Fault Studies

The three phase fault survey calculated the three phase fault at all busbars. ERACS calculates the fault current at all the busbars and displays them to each busbar. In the single phase-to-earth simulation, the fault rating at BB11-1 and BB11-6 was calculated to be 12.408 kA and 2.775 kA respectively.

4.4 Power System Study Using MATLAB

4.4.1 Voltage Regulation of Transmission Line

Because of the impedance in the line, the receiving end voltage of the transmission line varies with the load even if the input voltage remains constant. To conveniently compare transformers in this respect, it is customary to define the voltage regulation. Usually, it is good practice to have as small a voltage regulation as possible. For an ideal transformer, voltage regulation is 0 percent. Table 4 compares the voltage regulation of the transmission line at different loads.

Load	Voltage regulation
40 MVA lagging load	3.441%
40 MVA leading load	-0.106%
60 MVA lagging load	5.191%
60 MVA leading load	-1.419%

Table 4: Comparison of voltage regulation at various loads

The results show a common trend where lagging loads produce a positive voltage regulation in the line while leading loads produce negative voltage regulation. This is because for lagging loads, the receiving end voltage is less than the sending end voltage. The reverse is true for leading loads. Another observable trend is that as the load increases, so does the voltage regulation, regardless of whether the load is leading or lagging.

4.5 Synchronous Generator Phasor Model

After entering the input data as shown in Appendix A, the "**phasor.m**" program was run. It calculated the vector parameters and produced phasor diagrams, illustrating the vectors of Ea, Ia, V_{ϕ}, IaXa and IaRa.

4.5.1 40 MVA lagging load

The graph obtained for a lagging load of 40 MVA resembles the theoretical graph shown in Figure 2. Based on the graph in Figure 19 which was produced by MATLAB, it is demonstrated that the magnitude of terminal voltage, V_{ϕ}, is smaller than the internal voltage, Ea.

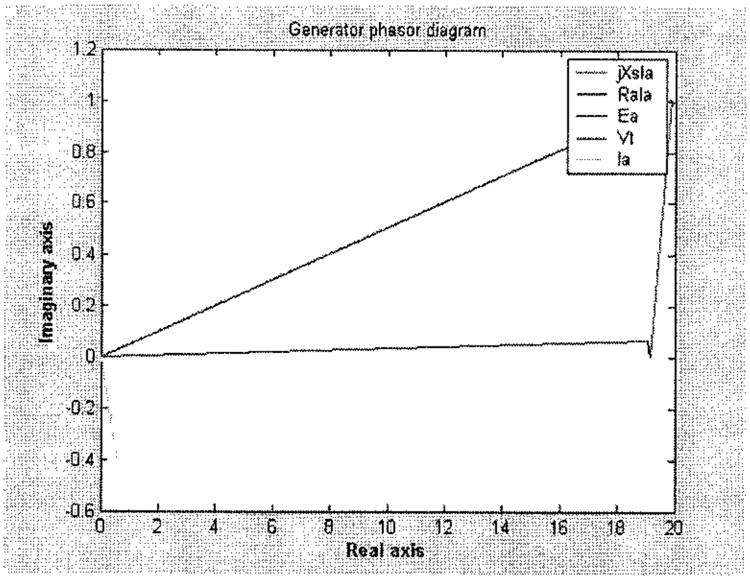

Figure 20 : Phasor diagram for 40 MVA lagging load

4.5.2 40 MVA leading load

For a leading load, the opposite is proven true, where the magnitude of terminal voltage, V_ϕ, exceeds the internal voltage, Ea.

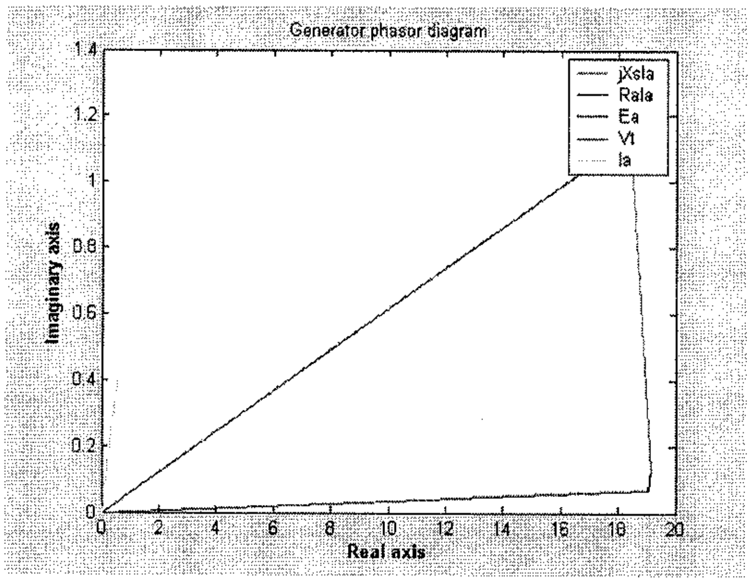

Figure 21 : Phasor diagram for 40 MVA leading load

4.5.3 60 MVA lagging load

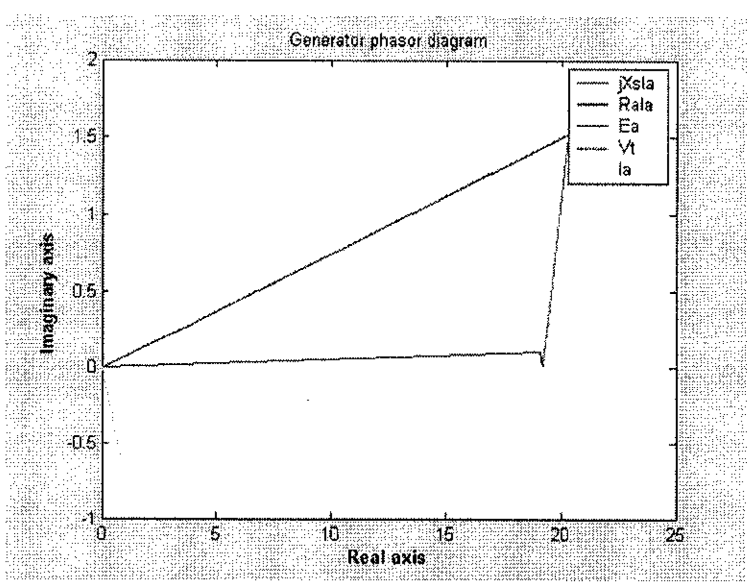

Figure 22 :Phasor diagram for 60 MVA lagging load

4.5.4 60 MVA leading load

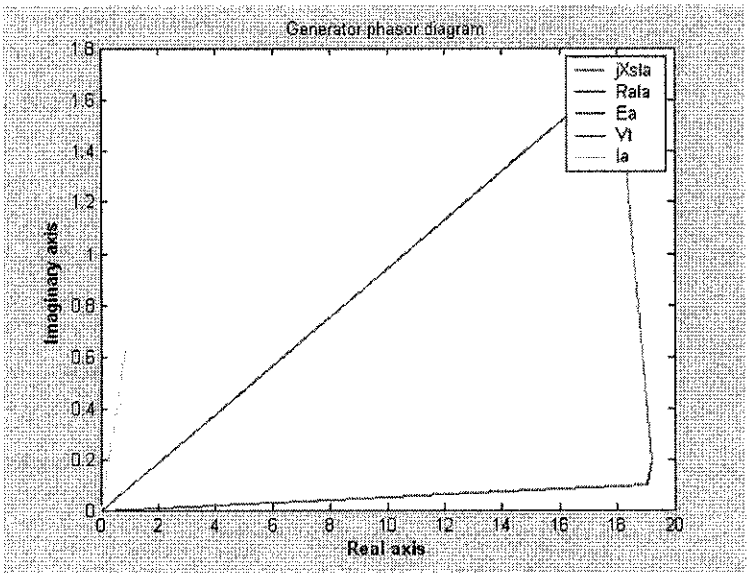

Figure 23 :Phasor diagram for 60 MVA leading load

4.6 Effect of Load Changes on Synchronous Generator Operating Alone

Ia (kA)	Vt (kV)	Ea (kV)	Ea change in percent	Voltage drop (kV)
0.69982	19.06579	19.93109	0.00000	0.86529
0.76980	19.06579	20.01995	0.44585	0.95416
0.83978	19.06579	20.10921	0.44588	1.04342
0.90976	19.06579	20.19888	0.44587	1.13308
0.97975	19.06579	20.28893	0.44583	1.22313
1.04973	19.06579	20.37937	0.44575	1.31357
1.11971	19.06579	20.47018	0.44564	1.40439
1.18969	19.06579	20.56138	0.44550	1.49559
1.25967	19.06579	20.65295	0.44533	1.58715
1.32966	19.06579	20.74488	0.44513	1.67908

Figure 24 :Effect of increasing load on Ea (lagging load)

Figure 23 shows the effect of increasing Ia in 10% steps. According to Equation 1, this will cause V_ϕ to drop. Since the objective is to maintain V_ϕ at a constant level which is at 19.06kV, Ea needs to be increased. According to the calculations performed by "phasor.m", for each 10% increase in the Ia, Ea needs to be increased by 0.445% to compensate.

Ia	Vt	Ea	Ea change in percent	Voltage drop
(kA)	(kV)	(kV)		(kV)
0.69982	19.06579	18.42892	0.00000	-0.63687
0.76980	19.06579	18.36880	-0.32621	-0.69699
0.83978	19.06579	18.30936	-0.32360	-0.75643
0.90976	19.06579	18.25060	-0.32093	-0.81519
0.97975	19.06579	18.19253	-0.31819	-0.87326
1.04973	19.06579	18.13515	-0.31538	-0.93064
1.11971	19.06579	18.07848	-0.31251	-0.98731
1.18969	19.06579	18.02251	-0.30957	-1.04328
1.25967	19.06579	17.96726	-0.30657	-1.09853
1.32966	19.06579	17.91273	-0.30350	-1.15306

Figure 25 Effect of increasing load on Ea (leading load)

For leading loads, the effect is the opposite of lagging loads. For each increase in Ia, Ea must be decreased between 0.32% to 0.30% to compensate. The negative sign in the fourth column shows a decrease in Ea.

CHAPTER 5
CONCLUSION AND RECOMMENDATION

5.1 Conclusion

Overall, it can be concluded that simulation studies are crucial in the design of power systems. Simulation improves the quality of routine design and allows the engineer to assess the performance of the power system not only during the design stages, but also when the system is already operating.

One of the disadvantages of the ERACS simulation is that it is not as flexible as the MATLAB program. Its functions such as Loadflow are already built-into the program. MATLAB, however, provides the user with options to expand the program to include extra functions. This can be done by changing the program source code according to requirements. However, ERACS still maintains an advantage, since it is a graphical user interface based program and is more user-friendly than MATLAB. It also simplifies the simulation process, since it is a powerful tool which takes numerous input data into account. This makes ERACS more accurate and reliable than MATLAB.

5.1.1 MATLAB simulation

It can be concluded that a working simulation program was successfully produced using MATLAB. This program was verified using the ERACS software. The program can be used to conduct various studies on power systems, since it emulates the LoadFlow feature in ERACS, albeit on a smaller and simpler scale. With this program, a better understanding of the characteristics of the main components of a power system was obtained.

5.1.2 Voltage regulation

It was proven using MATLAB that lagging loads produce a positive voltage regulation in the line while leading loads produce negative voltage regulation.

5.1.3 Synchronous Generator Phasor Model

Terminal voltage variations in synchronous generators are corrected by varying the magnitude of Ea to compensate for changes in the load. For lagging and unity loads, Ea must be increased to keep V_{ϕ} constant. For leading loads, Ea must be decreased.

5.2 Recommendations

5.2.1 Improvements on ERACS simulation

The occurrence of voltage drop along transmission and distribution lines is common in electrical power systems. It is essential that the voltage at the consumer's terminals be within narrow limits, for the consumer's appliances are sensitive to voltage. Thus a rise of voltage may burn out lamps and heaters, and a drop will cause unsatisfactory operation. The simulation should be extended to test the effects of adding shunt capacitors and synchronous generators to improve voltage at the receiving end of the distribution line.

5.2.2 Improvements on MATLAB program

The MATLAB program can be modified to include a function for calculating the required shunt capacitor Mvar for a specified load. This is to create added functionality for the program and broaden the scope of simulations that can be performed. Besides that, a function can be added to calculate the required tap rating of the transformer based on the required voltage rating at the receiving-end. The study of a power system can be further expanded by exploring the options in reducing or managing voltage drop at the receiving end of a transmission line.

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APPENDIX A

INPUT DATA AND RESULTS OF POWER SYSTEM MODEL SIMULATION USING MATLAB

20 MVA LAGGING LOAD

Load data

Load MVA : 11.148

Load Power Factor

+ for leading loads and - for lagging loads : -0.8

Load terminal voltage in volts(kV) : 11

Transformer 2 data

Primary voltage in volts(kV) : 33

Series branch resistance ref. to HV side : 0.0545

Series branch inductance ref. to HV side : 1.6335

Transmission line data

Resistance per unit length : 0.1234

Inductance per unit length(mH) : 0.2523

Line Length(km) : 40

Supply Frequency(Hz) : 50

Transformer 1 data

Primary voltage in volts(kV) : 11

Generator data

Armature Resistance, Ra : 3.2

Synchronous Reactance, Xs : 1.8

==

Generator model results

==

Armature resistance = 3.200 Ohm

Synchronous reactance = 1.800 Ohm

Internal generated voltage = 8.485 kV(per phase) at -1.658 degrees

= 14.697 kV(L-L) at -1.658 degrees

Terminal voltage = 6.352 kV (per phase)
= 11.002 kV(L-L)
Armature current = 585.129 A at -36.870 degrees

==

Transformer 1 model results

==

Primary input voltage = 6.352 kV (per phase)
= 11.002 kV (L-L)
Secondary voltage = 20.206 kV (per phase)
= 34.997 kV (L-L)
Secondary current = 195.043 A at -36.870 degrees
Current ref. to primary = 585.129 A at -36.870 degrees
Voltage regulation = 0.020 percent

==

Line performance model

==

Sending end voltage = 20.206 kV (per phase)
= 34.997 kV (L-L)
Receiving end voltage = 19.066 kV (per phase)
= 33.023 kV (L-L)
SENDING END===
Real power = 9.375 MW Reactive power = 7.204 Mvar
RECEIVING END===
Real power = 8.919 MW Reactive power = 6.689 Mvar
POWER LOSS==
Real power = 0.456 MW Reactive power = 0.515 Mvar
Receiving end current = 0.195 kA at -36.870ø PF = 0.800 lagging
Voltage Regulation = 5.979 percent
Transmission line efficiency = 95.131 percent

==

Transformer 2 model results

==

Primary input voltage = 19.066 kV (per phase)
= 33.023 kV (L-L)
Secondary load voltage = 6.351 kV (per phase)

= 11.000 kV (L-L)

Secondary load current = 585.129 A at -36.870 degrees

Current ref. to primary = 195.043 A at -36.870 degrees

Voltage regulation = 0.070 percent

===

Load model

===

Load terminal voltage = 6.351 kV (per phase)

= 11.000 kV (L-L)

Real power = 8.919 MW

Reactive power = 6.689 Mvar

40 MVA LAGGING LOAD

Load data

Load MVA : 40

Load Power Factor

+ for leading loads and - for lagging loads : -0.8

Load terminal voltage in volts(kV) : 33

Transformer 2 data

Primary voltage in volts(kV) : 132

Series branch resistance ref. to HV side : 1.2

Series branch inductance ref. to HV side : 6

Transmission line data

Resistance per unit length : 0.15

Inductance per unit length(mH) : 1.32623

Line Length(km) : 40

Supply Frequency(Hz) : 50

Transformer 1 data

Primary voltage in volts(kV) : 33

Generator data

Armature Resistance, Ra : 0.15

Synchronous Reactance, Xs : 1.8

==

Generator model results

==

Armature resistance = 0.150 Ohm

Synchronous reactance = 1.800 Ohm

Internal generated voltage = 19.931 kV(per phase) at 2.906 degrees

= 34.522 kV(L-L) at 2.906 degrees

Terminal voltage = 19.066 kV (per phase)

= 33.023 kV(L-L)

Armature current = 699.819 A at -36.870 degrees

==

Transformer 1 model results

==

Primary input voltage = 19.066 kV (per phase)

= 33.023 kV (L-L)

Secondary voltage = 79.057 kV (per phase)

= 136.931 kV (L-L)

Secondary current = 174.955 A at -36.870 degrees

Current ref. to primary = 699.819 A at -36.870 degrees

Voltage regulation = 0.069 percent

==

Line performance model

==

Sending end voltage = 79.057 kV (per phase)

= 136.931 kV (L-L)

Receiving end voltage = 76.427 kV (per phase)

= 132.376 kV (L-L)

SENDING END===

Real power = 32.309 MW Reactive power = 26.037 Mvar

RECEIVING END===

Real power = 32.000 MW Reactive power = 24.000 Mvar

POWER LOSS==

Real power = 0.309 MW Reactive power = 2.037 Mvar

Receiving end current = 0.175 kA at -36.870ø PF = 0.800 lagging

Voltage Regulation = 3.441 percent

Transmission line efficiency = 99.045 percent

==

Transformer 2 model results

==

Primary input voltage = 76.427 kV (per phase)
= 132.376 kV (L-L)
Secondary load voltage = 19.053 kV (per phase)
= 33.000 kV (L-L)
Secondary load current = 699.819 A at -36.870 degrees
Current ref. to primary = 174.955 A at -36.870 degrees
Voltage regulation = 0.285 percent

==

Load model

==

Load terminal voltage = 19.053kV
Real power = 32.000 MW
Reactive power = 24.000 Mvar

40 MVA LEADING LOAD

Load data

Load MVA	: 40
Load Power Factor	
+ for leading loads and - for lagging loads	: 0.8
Load terminal voltage in volts(kV)	: 33

Transformer 2 data

Primary voltage in volts(kV)	: 132
Series branch resistance ref. to HV side	: 1.2
Series branch inductance ref. to HV side	: 6

Transmission line data

Resistance per unit length	: 0.15
Inductance per unit length(mH)	: 1.32623
Line Length(km)	: 40
Supply Frequency(Hz)	: 50

Transformer 1 data

Primary voltage in volts(kV) : 33

Generator data

Armature Resistance, Ra : 0.15

Synchronous Reactance, Xs : 1.8

==

Generator model results

==

Armature resistance = 0.150 Ohm

Synchronous reactance = 1.800 Ohm

Internal generated voltage = 18.429 kV(per phase) at 3.535 degrees

= 31.920 kV(L-L) at 3.535 degrees

Terminal voltage = 19.066 kV (per phase)

= 33.023 kV(L-L)

Armature current = 699.819 A at 36.870 degrees

==

Transformer 1 model results

==

Primary input voltage = 19.066 kV (per phase)

= 33.023 kV (L-L)

Secondary voltage = 75.617 kV (per phase)

= 130.973 kV (L-L)

Secondary current = 174.955 A at 36.870 degrees

Current ref. to primary = 699.819 A at 36.870 degrees

Voltage regulation = 0.069 percent

==

Line performance model

==

Sending end voltage = 75.617 kV (per phase)

= 130.973 kV (L-L)

Receiving end voltage = 76.427 kV (per phase)

= 132.376 kV (L-L)

SENDING END===

Real power = 32.970 MW Reactive power = -22.095 Mvar

RECEIVING END==

Real power = 32.000 MW Reactive power = -24.000 Mvar

POWER LOSS==

Real power = 0.970 MW Reactive power = 1.905 Mvar

Receiving end current = 0.175 kA at 36.870ø PF = 0.800 leading

Voltage Regulation = -1.060 percent

Transmission line efficiency = 97.059 percent

==

Transformer 2 model results

==

Primary input voltage = 76.427 kV (per phase)
= 132.376 kV (L-L)

Secondary load voltage = 19.053 kV (per phase)
= 33.000 kV (L-L)

Secondary load current = 699.819 A at 36.870 degrees

Current ref. to primary = 174.955 A at 36.870 degrees

Voltage regulation = 0.285 percent

==

Load model

==

Load terminal voltage = 19.053kV

Real power = 32.000 MW

Reactive power = -24.000 Mvar

60 MVA LAGGING LOAD

Load data

Load MVA	: 60
Load Power Factor	
+ for leading loads and - for lagging loads	: -0.8
Load terminal voltage in volts(kV)	: 33

Transformer 2 data

Primary voltage in volts(kV)	: 132
Series branch resistance ref. to HV side	: 1.2
Series branch inductance ref. to HV side	: 6

Transmission line data

Resistance per unit length	: 0.15
Inductance per unit length(mH)	: 1.32623
Line Length(km)	: 40
Supply Frequency(Hz)	: 50

Transformer 1 data

Primary voltage in volts(kV)	: 33

Generator data

Armature Resistance, Ra	: 0.15
Synchronous Reactance, Xs	: 1.8

==

Generator model results

==

```
Armature resistance        =  0.150 Ohm
Synchronous reactance      =  1.800 Ohm
Internal generated voltage =  20.388 kV(per phase)  at  4.263 degrees
                           =  35.314 kV(L-L)  at  4.263 degrees
Terminal voltage           =  19.072 kV (per phase)
                           =  33.035 kV(L-L)
Armature current           =  1049.728 A  at  -36.870 degrees
```

==

Transformer 1 model results

==

```
Primary input voltage   =  19.072 kV (per phase)
                        =  33.035 kV (L-L)
Secondary voltage       =  80.515 kV (per phase)
                        =  139.456 kV (L-L)
Secondary current       =  262.432 A  at  -36.870 degrees
Current ref. to primary =  1049.728 A  at  -36.870 degrees
Voltage regulation      =  0.105 percent
```

==

Line performance model

==

Sending end voltage = 80.515 kV (per phase)
= 139.456 kV (L-L)
Receiving end voltage = 76.541 kV (per phase)
= 132.574 kV (L-L)
SENDING END===
Real power = 48.694 MW Reactive power = 40.584 Mvar
RECEIVING END===
Real power = 48.000 MW Reactive power = 36.000 Mvar
POWER LOSS==
Real power = 0.694 MW Reactive power = 4.584 Mvar
Receiving end current = 0.262 kA at -36.870ø PF = 0.800 lagging
Voltage Regulation = 5.191 percent
Transmission line efficiency = 98.574 percent

==
Transformer 2 model results
==
Primary input voltage = 76.541 kV (per phase)
= 132.574 kV (L-L)
Secondary load voltage = 19.053 kV (per phase)
= 33.000 kV (L-L)
Secondary load current = 1049.728 A at -36.870 degrees
Current ref. to primary = 262.432 A at -36.870 degrees
Voltage regulation = 0.434 percent

==
Load model
==
Load terminal voltage = 19.053kV
Real power = 48.000 MW
Reactive power = 36.000 Mvar

60 MVA LEADING LOAD

Load data

Load MVA : 60
Load Power Factor
+ for leading loads and - for lagging loads : 0.8
Load terminal voltage in volts(kV) : 33

Transformer 2 data

Primary voltage in volts(kV)	: 132
Series branch resistance ref. to HV side	: 1.2
Series branch inductance ref. to HV side	: 6

Transmission line data

Resistance per unit length	: 0.15
Inductance per unit length(mH)	: 1.32623
Line Length(km)	: 40
Supply Frequency(Hz)	: 50

Transformer 1 data

Primary voltage in volts(kV)	: 33

Generator data

Armature Resistance, Ra	: 0.15
Synchronous Reactance, Xs	: 1.8

==

Generator model results

==

Armature resistance	= 0.150 Ohm
Synchronous reactance	= 1.800 Ohm
Internal generated voltage	= 18.145 kV(per phase) at 5.390 degrees
	= 31.428 kV(L-L) at 5.390 degrees
Terminal voltage	= 19.072 kV (per phase)
	= 33.035 kV(L-L)
Armature current	= 1049.728 A at 36.870 degrees

==

Transformer 1 model results

==

Primary input voltage	= 19.072 kV (per phase)
	= 33.035 kV (L-L)
Secondary voltage	= 75.401 kV (per phase)
	= 130.599 kV (L-L)
Secondary current	= 262.432 A at 36.870 degrees

Current ref. to primary = 1049.728 A at 36.870 degrees
Voltage regulation = 0.105 percent

==

Line performance model

==

Sending end voltage = 75.401 kV (per phase)
= 130.599 kV (L-L)
Receiving end voltage = 76.541 kV (per phase)
= 132.574 kV (L-L)

SENDING END===

Real power = 50.182 MW Reactive power = -31.714 Mvar

RECEIVING END===

Real power = 48.000 MW Reactive power = -36.000 Mvar

POWER LOSS==

Real power = 2.182 MW Reactive power = 4.286 Mvar

Receiving end current = 0.262 kA at 36.870ø PF = 0.800 leading

Voltage Regulation = -1.490 percent

Transmission line efficiency = 95.652 percent

==

Transformer 2 model results

==

Primary input voltage = 76.541 kV (per phase)
= 132.574 kV (L-L)
Secondary load voltage = 19.053 kV (per phase)
= 33.000 kV (L-L)
Secondary load current = 1049.728 A at 36.870 degrees
Current ref. to primary = 262.432 A at 36.870 degrees
Voltage regulation = 0.434 percent

==

Load model

==

Load terminal voltage = 19.053kV
Real power = 48.000 MW
Reactive power = -36.000 Mvar

APPENDIX B

MATLAB SOURCE CODE FOR POWER SYSTEM MODEL

powersys.m

```
fprintf('\n');
fprintf('========================================\n');
fprintf('Load data\n');
fprintf('========================================\n');
SL = input('Please enter load MVA                              : ');
fprintf('Please enter Load Power Factor\n')
pf = input('+ for leading loads and - for lagging loads        : ');
V2LLpol2 = input('Please enter load terminal voltage in volts(kV)  : ');          %Load voltage


fprintf('\n\n========================================\n');
fprintf('Transformer 2 data\n');
fprintf('========================================\n');
V1LLnl = input('Please enter primary voltage in volts(kV)          : ');          %Transformer
primary no load voltage
RZe = input('Series branch resistance ref. to HV side          : ');
LZe = input('Series branch inductance ref. to HV side          : ');


theta = acos(abs(pf));
if(pf>0)
    theta = -theta;
    [x,y] = pol2cart(theta, SL);
else
    [x,y] = pol2cart(theta, SL);
end

SL = x + j*y;   %Creating a cartesian form of the SL variable

V2p = V1LLnl/sqrt(3);       %Secondary phase voltage referred to primary side

V2LLpol1 = V2LLpol2/sqrt(3);
ILcart = (conj(SL)*1000)/(3*V2LLpol1);                       %Secondary load current
[IL_theta, ILpol]  = cart2pol(real(ILcart), imag(ILcart));
IL_theta = 180*IL_theta/pi;                                          %Converting radians into
degrees

Icart  = (conj(SL)*1000)/(3*V2p);                            %Current referred to primary
[I_theta, Ipol]  = cart2pol(real(Icart), imag(Icart));
```

```
I_theta = 180*I_theta/pi;

Ze = RZe + j*LZe;

V1p = V2p + Ipol*Ze/1000;

V1LLcart = V1p*sqrt(3);

V1LLpol1 = abs(V1p);
V1LLpol2 = V1LLpol1*sqrt(3);                              %Primary input voltage

Voltreg_Trans = (V1LLpol2 - V1LLnl)*100/V1LLnl;


fprintf('\n\n========================================\n');
fprintf('Transmission line data\n');
fprintf('========================================\n');
r = input('Please enter Resistance per unit length          : ');
L = input('Please enter Inductance per unit length(mH)      : ');
l = input('Please enter Line Length(km)                     : ');
f = input('Please enter Supply Frequency(Hz)                : ');

L = L/1000;
Z = (r + j*2*pi*f*L)*l;

VrLLcart = V1LLcart;                %Passing the receiving end voltage from transformer model
to transmission line model
Vrp = VrLLcart/sqrt(3);             %Phase Voltage in units of kV

Sr3cart = SL;
IR = Icart/1000;                    %Passing the current per phase from transformer model to
transmission line model and converting to kA

Vsp = Vrp + Z*IR;                   %Sending End Phase Voltage in kV

VsLLcart = Vsp*sqrt(3);             %Line Sending Voltage in kV

Ss3cart = 3*Vsp*conj(IR);           %Apparent Sending End Power in units of MVA

[alpha,VsLLpol2] = cart2pol(real(VsLLcart), imag(VsLLcart)); %Obtaining the polar form and
magnitude of VsLL

[beta,VrLLpol2] = cart2pol(real(VrLLcart), imag(VrLLcart)); %Obtaining the polar form and
magnitude of VrLL

VsLLpol1 = VsLLpol2/sqrt(3);
VrLLpol1 = VrLLpol2/sqrt(3);
```

```
VoltReg_Line = (VsLLpol2 - VrLLpol2)*100/VrLLpol2;

Efficiency = real (Sr3cart) * 100 / real(Ss3cart);


fprintf('\n\n========================================\n');
fprintf('Transformer 1 data\n');
fprintf('========================================\n');
V1LLAnl = input('Please enter primary voltage in volts(kV)          : ');          %Transformer primary no load voltage
a1 = V1LLAnl/V1LLnl;

RZeA = RZe*a1^2;
LZeA = LZe*a1^2;

V2LLApol2 = VsLLpol2;     %Sending end voltage of transmission line equals secondary voltage of transformer
V2LLApol1 = V2LLApol2/sqrt(3);
VsLLpol1 = V2LLApol1;      %Sending end phase voltage of transmission line equals secondary phase voltage of transformer

SL2 = Ss3cart;   %Load on the transformer

V2Ap = V1LLAnl/sqrt(3);           %Secondary phase voltage referred to primary side

ZeA = RZeA + j*LZeA;

V1Ap = V2Ap + Ipol*ZeA/1000;

V1LLAcart = V1Ap*sqrt(3);

V1LLApol1 = abs(V1Ap);
V1LLApol2 = V1LLApol1*sqrt(3);                                  %Primary input voltage in line to line form


Igenpol = Ipol/a1;
Voltreg_TransA = (V1LLApol2 - V1LLAnl)*100/V1LLAnl;


fprintf('\n\n========================================\n');
fprintf('Generator data\n');
fprintf('========================================\n');
Ra = input('Please enter Armature Resistance, Ra             : ');
Xs = input('Please enter Synchronous Reactance, Xs           : ');

Ia = V1LLnl * Icart/V1LLAnl;
```

```
Xs_Iacart = Xs*Ia;          %Vector for XsIa


%this is the angle of the vector Ia in radian

Ia_theta = I_theta*pi/180;

RaIacart = Ra * Ia/1000;


Vtcart = V1Ap;                          %terminal voltage of Transformer equals terminal phase
voltage of generator

Vtpol = abs(Vtcart);


V = j*Xs_Iacart/1000;       %vector for jXsIa


Eacart = Vtcart + RaIacart + V;

[Ea_theta,Eapol1] = cart2pol(real(Eacart), imag(Eacart));

Eapol2 = Eapol1*sqrt(3);            %converting Eapol to line to line voltage


Ea_theta = Ea_theta*180/pi;



fprintf('\n\n====================================================================\n');

fprintf('Generator model results\n');

fprintf('====================================================================\n');

fprintf('Armature resistance          =  '), fprintf('%1.3f',Ra), fprintf(' Ohm\n');

fprintf('Synchronous reactance        =  '), fprintf('%1.3f',Xs), fprintf(' Ohm\n');

fprintf('Internal  generated  voltage     =    '),  fprintf('%1.3f',Eapol1),  fprintf('  kV'),
fprintf('(per phase)'), fprintf('  at'), fprintf('  %1.3f',Ea_theta), fprintf(' degrees\n');

fprintf('                                 =  '), fprintf('%1.3f',Eapol2), fprintf(' kV'),
fprintf('(L-L)'), fprintf('  at'), fprintf('  %1.3f',Ea_theta), fprintf(' degrees\n');

fprintf('Terminal  voltage                =  '), fprintf('%1.3f',V1LLApol1), fprintf(' kV'),
fprintf(' (per phase)\n');

fprintf('                                 =  '), fprintf('%1.3f',V1LLApol2), fprintf(' kV'),
fprintf('(L-L)\n');

fprintf('Armature current             =  '), fprintf('%1.3f',Igenpol), fprintf(' A'), fprintf('
at'), fprintf('  %1.3f',I_theta), fprintf(' degrees\n');



fprintf('\n\n====================================================================\n');

fprintf('Transformer 1 model results\n');

fprintf('====================================================================\n');

fprintf('Primary  input  voltage       =    '),  fprintf('%1.3f',V1LLApol1),  fprintf('  kV  (per
phase)\n');

fprintf('                           =  '), fprintf('%1.3f',V1LLApol2), fprintf(' kV (L-L)\n');

fprintf('Secondary  voltage              =    '),  fprintf('%1.3f',V2LLApol1),  fprintf('  kV  (per
phase)\n');

fprintf('                           =  '), fprintf('%1.3f',V2LLApol2), fprintf(' kV (L-L)\n');

fprintf('Secondary current          =  '), fprintf('%1.3f',Ipol), fprintf(' A'), fprintf('  at'),
fprintf('  %1.3f',IL_theta), fprintf(' degrees\n');

fprintf('Current ref. to primary   =   '), fprintf('%1.3f',Igenpol), fprintf(' A'), fprintf('
at'), fprintf('  %1.3f',I_theta), fprintf(' degrees\n');

fprintf('Voltage  regulation               =    '),  fprintf('%1.3f',Voltreg_TransA),  fprintf('
percent\n');
```

```
fprintf('\n\n=================================================================\n');
fprintf('Line performance model\n');
fprintf('=================================================================\n');
fprintf('Sending end voltage   = '), fprintf('%1.3f',VsLLpol1), fprintf(' kV (per phase)\n');
fprintf('                      = '), fprintf('%1.3f',VsLLpol2), fprintf(' kV (L-L)\n');
fprintf('Receiving end voltage = '), fprintf('%1.3f',VrLLpol1), fprintf(' kV (per phase)\n');
fprintf('                      = '), fprintf('%1.3f',VrLLpol2), fprintf(' kV (L-L)\n');
fprintf('SENDING END=====================================================\n');
fprintf('Real power            = '), fprintf('%1.3f',real(Ss3cart)), fprintf(' MW'), fprintf('
Reactive power = '), fprintf('%1.3f',imag(Ss3cart)), fprintf(' Mvar\n');
fprintf('RECEIVING END===================================================\n');
fprintf('Real power            = '), fprintf('%1.3f',real(Sr3cart)), fprintf(' MW'), fprintf('
Reactive power = '), fprintf('%1.3f',imag(Sr3cart)), fprintf(' Mvar\n');
fprintf('POWER LOSS======================================================\n');
fprintf('Real power            = '), fprintf('%1.3f',(real(Ss3cart)-real(Sr3cart))), fprintf('
MW'), fprintf('       Reactive power = '), fprintf('%1.3f',(imag(Ss3cart)-imag(Sr3cart))),
fprintf(' Mvar\n');
fprintf('Receiving end current = '), fprintf('%1.3f',abs(IR)), fprintf(' kA'), fprintf(' at '),
fprintf('%1.3f',I_theta), fprintf('ø   PF = '), fprintf('%1.3f',abs(pf));
if (pf < 0)
    fprintf(' lagging\n');
else
    fprintf(' leading\n');
end
fprintf('Voltage Regulation = '), fprintf('%1.3f', VoltReg_Line), fprintf(' percent\n');
fprintf('Transmission line efficiency = '), fprintf('%1.3f', Efficiency), fprintf('
percent\n');



fprintf('\n\n=================================================================\n');
fprintf('Transformer 2 model results\n');
fprintf('=================================================================\n');
fprintf('Primary input voltage    = '), fprintf('%1.3f',V1LLpol1), fprintf(' kV (per
phase)\n');
fprintf('                         = '), fprintf('%1.3f',V1LLpol2), fprintf(' kV (L-L)\n');
fprintf('Secondary load voltage   = '), fprintf('%1.3f',V2LLpol1), fprintf(' kV (per
phase)\n');
fprintf('                         = '), fprintf('%1.3f',V2LLpol2), fprintf(' kV (L-L)\n');
fprintf('Secondary load current   = '), fprintf('%1.3f',ILpol), fprintf(' A'), fprintf('
at'), fprintf('  %1.3f',IL_theta), fprintf(' degrees\n');
fprintf('Current ref. to primary  = '), fprintf('%1.3f',Ipol), fprintf(' A'), fprintf('  at'),
fprintf('  %1.3f',I_theta), fprintf(' degrees\n');
fprintf('Voltage regulation       = '), fprintf('%1.3f',Voltreg_Trans), fprintf(' percent\n');



fprintf('\n\n=================================================================\n');
fprintf('Load model\n');
fprintf('=================================================================\n');
fprintf('Load terminal voltage  = '), fprintf('%1.3f',V2LLpol1), fprintf('kV\n');
```

```
fprintf('Real power                = '), fprintf('%1.3f',real(Sr3cart)), fprintf(' MW\n');
fprintf('Reactive power            = '), fprintf('%1.3f',imag(Sr3cart)), fprintf(' Mvar\n');
```

APPENDIX C

MATLAB SOURCE CODE FOR SYNCHRONOUS GENERATOR CASE STUDY

phasor.m

```
Igencart = Icart/a1;
Ia = Igencart/1000;

Xs_Iacart = Xs*Ia;          %Vector for XsIa

%this is the angle of the vector Ia in radian
Ia_theta = I_theta*pi/180;
RaIacart = Ra * Ia;

Vtcart = V1Ap;                    %terminal voltage of Transformer equals terminal phase
voltage of generator
Vtpol = abs(Vtcart);

V = j*Xs_Iacart;       %vector for jXsIa

Eacart = Vtcart + RaIacart + V;
[Ea_theta,Eapol] = cart2pol(real(Eacart), imag(Eacart));

Ea_theta = Ea_theta*180/pi;

X = RaIacart + Vtcart;

f = real(X) + real(V);
g = imag(X) + imag(V);
Y = f + j*g;

Vt_V = [0 Vtcart];                %plotting the vector of the generator terminal voltage
RaIa_V = [Vtcart X];
XsIa_V = [X Y];
Ia_V = [0 Ia];
Ea_V = [0 Y];

h = plot(real(XsIa_V), imag(XsIa_V), 'g', real(RaIa_V), imag (RaIa_V), '', real(Ea_V),
imag(Ea_V), 'r', real(Vt_V), imag(Vt_V), real(Ia_V), imag(Ia_V), 'y');

legend(h, 'jXsIa', 'RaIa', 'Ea', 'Vt', 'Ia');

%adding labels
```

```
xlabel('Real axis', 'Fontweight', 'Bold');
ylabel('Imaginary axis', 'Fontweight', 'Bold');
title('Generator phasor diagram');


n = 0;
Ia_t = Ia;  %passing the value of Ia to a temporary variables
fprintf('\n      Ia         Vt          Ea       Ea change  Voltage \n')
fprintf('                                              in percent     drop    \n')
fprintf('      (kA)       (kV)        (kV)                         (kV)\n')

while n ~= 100;
        Ea0 = Eapol1;
        Ia_t = Ia * (n + 100)/100;  %increase Ia in 10% steps

        Xs_Iacart = Xs*Ia_t;           %Vector for XsIa

        %this is the angle of the vector Ia in radian
        Ia_theta = I_theta*pi/180;
        RaIacart = Ra * Ia_t;

        Vtcart = V1Ap;                          %terminal voltage of Transformer equals terminal
phase voltage of generator
        Vtpol = abs(Vtcart);

        V = j*Xs_Iacart;       %vector for jXsIa

        Eacart = Vtcart + RaIacart + V;
        [Ea_theta,Eapol1] = cart2pol(real(Eacart), imag(Eacart));

        Ea_theta = Ea_theta*180/pi;

        inc = (Eapol1 - Ea0) * 100/Ea0;
        VD = Eapol1 - Vtpol;
        n = n + 10;
        fprintf('%10.5f %10.5f %10.5f %10.5f %10.5f\n', abs(Ia_t), Vtpol, Eapol1, inc, VD);
        end;
```

APPENDIX D
TNB SHORT CIRCUIT RATINGS

As a guide, the maximum fault levels to the various voltage systems are as follows. All equipment proposed to be installed and connected to TNB supply must comply with the stated short circuit ratings:

	System	Short circuit rating
i.	500kV	50kA at 550 kV
ii.	275kV	40kA at 300 kV
iii.	132kV	31.5 kA at 145 kV
iv.	66kV	20 kA at 72 kV
v.	33kV	25 kA at 36 kV
vi.	22kV	20 kA at 24 kV
vii.	11kV	20 kA at 12 kV
viii.	6.6kV	20 kA at 7.2 kV
ix.	415/240V	42 MVA

APPENDIX E

INPUT DATA FOR ERACS SIMULATION

i) **Grid Infeed (Inc-1 and Inc-2)**

Three phase

Fault Infeed (MVA)	:	4158
Fault X/R Ratio	:	10
+/- Sequence Resistance (pu)	:	0.1
+/- Sequence Reactance (pu)	:	0.995

Single phase

Fault Infeed (MVA)	:	4158
Fault X/R Ratio	:	10
+/- Sequence Resistance (pu)	:	0.1
+/- Sequence Reactance (pu)	:	0.995

ii) **All 132kV Busbars**

Voltage Rating (kV)	:	132
Frequency (Hz)	:	50
Three Phase Fault Rating (MVA)	:	1500
Single Phase Fault Rating (MVA)	:	2000

All 33kV Busbars

Voltage Rating (kV)	:	33
Frequency (Hz)	:	50
Three Phase Fault Rating (MVA)	:	500
Single Phase Fault Rating (MVA)	:	700

All 11kV Busbars

Voltage Rating (kV)	:	11
Frequency (Hz)	:	50
Three Phase Fault Rating (MVA)	:	500
Single Phase Fault Rating (MVA)	:	700

iii) **132/11 kV Transformers**

Winding 1

Off Load Tap Changer (%)	:	0
Rating (MVA)	:	110
Voltage Rating (kV)	:	132
Winding Connection	:	Grounded Star
Angle (degrees)	:	0
+/- Sequence Resistance (pu)	:	0.25
+/- Sequence Reactance (pu)	:	4.25

Winding 2

Off Load Tap Changer (%)	:	10
Rating (MVA)	:	110
Voltage Rating (kV)	:	11.55
Winding Connection	:	Grounded Star
Angle (degrees)	:	+30
+/- Sequence Resistance (pu)	:	0.25
+/- Sequence Reactance (pu)	:	4.25

iv) **132/33 kV Transformers**

Winding 1

Off Load Tap Changer (%)	:	0
Rating (MVA)	:	45
Voltage Rating (kV)	:	132
Winding Connection	:	Star
Angle (degrees)	:	0
+/- Sequence Resistance (pu)	:	0.3195
+/- Sequence Reactance (pu)	:	6

Winding 2

Off Load Tap Changer (%)	:	0

Rating (MVA)	:	45
Voltage Rating (kV)	:	33
Winding Connection	:	Delta
Angle (degrees)	:	+30
+/- Sequence Resistance (pu)	:	0.3195
+/- Sequence Reactance (pu)	:	6