SCHOOL OF ENGINEERING

ELECTRICAL AND COMPUTER SYSTEMS ENGINEERING

LABORATORY REPORT MARKING RUBRIC

ECE4053: POWER SYSTEM ANALYSIS

Experiment Number: ______1____

Title of Lab Sheet: Experiment 1(A): The Characteristic of a LineExperiment 1(B): The Voltage Drop of the Line

Group Number: ___________7____

No.	Student ID	Name of Group Members	Total Marks
1	30720230	Loh Jia Quan	100/100
2	30719305	Huan Meng Hui	
3	32259417	Chong Yen Juin	
4	32194471	Tan Jin Chun	

MARKS BREAKDOWN

Area	Total Score	Actual Marks	Scoring Band	Criteria
Format	5	5	4-5	The overall report contents present a clear, presentable, formal, readable and organized format, as per laboratory report guideline. Provide 2 decimal points for each recorded data.
			2-3	The report has most sections which present a clear, presentable, formal, readable and organized format, as per laboratory report guideline. Provide 2 decimal points for each recorded data.
			0-1	Most sections presented in a messy manner and did not follow the laboratory report guideline. Provide 2 decimal points for each recorded data.
Figures and Diagram	5	5	4-5	Extensive figures and diagrams with clear explanation and numbered labels.
			2-3	Extensive figures and diagrams without clear explanation and numbered labels.
			0-1	Insufficient figures and diagrams & without clear explanation and numbered labels.
Objectives and Equipment	5	5	4-5	Detailed description of the objectives and list of all equipment used.
			2-3	Brief description of the objectives and list of all equipment used.
			0-1	Unclear description of the objectives and list of all equipment used.
Results and Discussion	25	25	20 - 25	Comprehensive comparison, evaluation and justification of the results, with clear explanation on the theoretical and experimental/ simulation results.
			11-19	Brief comparison, evaluation and justification of the results, with unclear explanation on the theoretical and experimental/ simulation results.
			0-10	No comparison, evaluation and justification of the results, with unsatisfactory explanation on the theoretical and experimental/ simulation results.
Conclusion and References	10	10	8-10	Clear understanding on the experiment with summarized conclusion. In-text citations and IEEE referencing format is properly done. (3 references)
			4-7	Unclear understanding on the experiment with summarized conclusion, but without the supporting evidence of results. In-text citations and references' format are improperly done. (2 references)
			0-3	Unclear understanding on the experiment without summarized conclusion and the evidence of results. In-text citations and references are absent. (0 – 1 reference)
Total	50	50		

Examiner/ Assessor of ECE 4053: Power System Analysis
Date: 13/8/2023

EXPERIMENT 1A

1. Objectives [3 Marks]

(List the two objectives of this experiment.)

Experiment 1A objective:
Calculate the characteristic data of the line model and compare with a full-scale line

Experiment 1B objective:
Measure the voltage drop on the line to understand the effect of resistive, capacitive and inductive loads on the transmission line

3

2. Equipment used [2 Marks]

(List all of the equipment used in this experiment.)
Experiment 1A:
• Fluke digital multimeter
• Fluke single phase power quality clamp meter
• Terco 3-phase transmission line model
• 3-phase power supply

Experiment 1B:
• Fluke digital multimeter
• Fluke single phase power quality clamp meter
• Terco 3-phase transmission line model
• Terco 3-phase load resistor
• Terco 3-phase load capacitor
• Terco 3-phase load inductor
• 3-phase power supply
• 3-phase reversing switch

2

3. Experimental wiring and experimental setup [5 Marks]

(Insert a photo of your experimental setup and label all of the equipment used.)
Fig. 1 detailed the experimental setup for Experimental 1A short-circuit and no-load test. (Disclaimer: the setup for no-load test was not taken, thus the setup from another group was taken, all values were obtained from Station 1).

Fig. 1 Setup for experiment 1A short circuit test (left) and no-load test (right)

5

4. Results for Experiment 1A [2 Marks]

(Fill in the necessary data/ measurements from the experiment into the table below.)

Experimental Results	Phase (unit)	L1	L2	L3
Part 1	R (Ω)	3.60	3.60	3.50
Part 1	V (V)	31.64	33.13	31.31
Part 1	I (A)	5.04	5.01	4.99
Part 1	P (W)	106.00	115.00	108.00
Part 2	I_C (A)	0.28	0.27	0.29
Part 2	I_{C0} (A)	0.18	0.20	0.19

2

5. Questions

(Answer all of the following questions.)

(i) Calculate Z, R and X by using the values in the result table. Find out the mean value of X. [2 Marks]

(Include your calculation here. Show complete workings.)

L1:

$$Z_1 = \frac{V_{sc,1}}{I_{sc,1}} = \frac{31.64}{5.04} = 6.278\Omega$$

$$R_1 = \frac{P_{sc,1}}{I_{sc,1}^2} = \frac{106}{5.04^2} = 4.173\Omega$$

$$X_1 = \sqrt{Z_1^2 - R_1^2} = \sqrt{6.278^2 - 4.173^2} = 4.69j\Omega$$

L2:

$$Z_2 = \frac{V_{sc,2}}{I_{sc,2}} = \frac{33.13}{5.01} = 6.613\Omega$$
$$R_2 = \frac{P_{sc,2}}{I_{sc,2}^2} = \frac{115}{5.01^2} = 4.582\Omega$$
$$X_2 = \sqrt{Z_2^2 - R_2^2} = \sqrt{6.613^2 - 4.582^2} = 4.77j\Omega$$

L3:

$$Z_3 = \frac{V_{sc,3}}{I_{sc,3}} = \frac{31.31}{4.99} = 6.275\Omega$$
$$R_3 = \frac{P_{sc,3}}{I_{sc,3}^2} = \frac{108}{4.99^2} = 4.337\Omega$$
$$X_3 = \sqrt{Z_3^2 - R_3^2} = \sqrt{6.275^2 - 4.337^2} = 4.53j\Omega$$

Mean Value of X

$$\overline{\mathrm{X}} = \frac{X_1 + X_2 + X_3}{3} = \frac{4.690j + 4.77j + 4.53j}{3} = 4.662j\Omega$$

2

(i) Explain how to transform the mean value of X to a real line value, by using the given impedance scale factor. [1 Marks]

(Include your calculations here. Impedance scale: Bz = 0.35)
To transform the mean value of X to a real line value, it is required to divide the measured impedance values by the impedance scale BZ = 0.35

$$\overline{\mathrm{X}_{\mathrm{real}}} = \frac{X}{0.35} = 13.32j\Omega$$

1

(ii) Calculate the mean value of IC and IC0. [2 Marks]

(Include your calculation here. Show complete workings.)
Mean Value of Ic

$$\overline{\mathrm{I_C}} = \frac{I_{C,1} + I_{C,2} + I_{C,3}}{3} = \frac{0.28 + 0.27 + 0.29}{3} = 0.28A$$

Mean Value of Ic0

$$\overline{\mathrm{I_{C0}}} = \frac{I_{C0,1} + I_{C0,2} + I_{C0,3}}{3} = \frac{0.18 + 0.20 + 0.19}{3} = 0.19A$$

2

(iii) Calculate the mutual capacitance of the real line values and the mutual capacitance per kilometer, C. [2 Marks]

(Include your calculations here using the equation: $I_C = \frac{400}{\sqrt{3}} \cdot 2 \cdot \pi \cdot f \cdot C$ (where 400 is the voltage, $X_C = \frac{1}{\omega C}$)

According to the datasheet of the transmission line model [1], the nominal length of the transmission line model is given as 40km. To calculate the real line mutual capacitance, multiply the line capacitance by the impedance scale Zb = 0.35

Mutual Capacitance of real line values

$$I_c = \frac{400}{\sqrt{3}} * (2\pi f C_{model}) = \frac{400}{\sqrt{3}}(2\pi 50)C_{model} = 0.28$$
$$C_{model} = 3.86\mu F$$

$$C_{real\ line} = C_{model} * 0.35 = 1.35\mu F$$

2

Mutual Capacitance of real line values per kilometer

$$C_{real\ line\ per\ km} = C_{real\ line}/40 = 0.03\mu F/km$$

(iv) Calculate the earth capacitance to real line values and the earth capacitance per kilometer, C_0. [2 Marks]

(Include your calculations here using the equation: $I_C = \frac{400}{\sqrt{3}} \cdot 2 \cdot \pi \cdot f \cdot C$ (where 400 is the voltage, $X_C = \frac{1}{\omega C}$)*)*

According to the datasheet of the transmission line model [1], the nominal length of the transmission line model is given as 40km. To calculate the real line mutual capacitance, multiply the line capacitance by the impedance scale Zb = 0.35

Mutual Capacitance of real line values

$$I_c = \frac{400}{\sqrt{3}} * (2\pi f C_{0,model}) = \frac{400}{\sqrt{3}}(2\pi 50)C_{0,model} = 0.19$$
$$C_{0,model} = 2.62\mu F$$

$$C_{0,real\ line} = C_{0,model} * 0.35 = 0.92\mu F$$

2

Mutual Capacitance of real line values per kilometer

$$C_{0,real\ line\ per\ km} = C_{0,real\ line}/40 = 0.02\mu F/km$$

6. Discussion [2 Marks]

(Discuss your results obtained in Part 1 and Part 2.)
The model used in the lab comes from TERCO produced MV1424 Line Model, we would use the values given by TERCO [1]

Part 1 Short Circuit Test

During this phase of the experiment, a short-circuit test was conducted by connecting the load terminals of the transmission line model, the primary objective of this test is to determine the transmission line's resistance and reactance. When the inductor and capacitor banks are not connected, the resistance value is solely attributed to the resistors connected, and the average resistance per phase after measurement was established to be 3.56Ω. As shown on the nameplate, the theoretical resistance of the resistor is 3.40Ω.

The difference in measured resistance value, and the nameplate value is 3.56Ω - 3.40Ω = 0.16Ω. The discrepancy in values, although closely aligned, might arise from stochastic errors, or equipment generated noise.

Based on the result of Question 5(i), the calculated mean value for the line model's reactance is denoted as $\bar{X} = j4.663\Omega$. Comparing with the nameplate value, where the inductance of the inductor within the transmission line model documented on the nameplate is 15mH, we may obtain the theoretical value of the reactance of the transmission line model

$$X_{model} = j2\pi fL = j2\pi(50Hz)(15mH) = j4.71\Omega$$

The difference in value is $j4.712\Omega - j4.663\Omega = j0.05\Omega$

Although the theoretical reactance value is marginally smaller than the measured value, this disparity could potentially be attributed to the presence of stray inductance and parasitic capacitances introduced by connecting wires, and measurement probes. Hence, the experimentally measured reactance slightly exceeds the theoretical value of reactance of the line model.

Similarly, based on the result of Question 5(i), the measured average resistance, constituting both the resistance and the winding resistance of the inductor is $R_{avg} = \frac{4.690+4.769+4.53}{3} = \frac{13.989}{3} = 4.66\Omega$. The value is taken as the measured per-phase resistance value of the line model. In comparison, the theoretically estimated resistance is 4.70Ω. Within a balanced-3 phase transmission line, any measurement deviations are a consequence of non-ideal hardware traits, such as electrical noise, parasitic capacitances and stray inductances. Notably, the experimentally measured and theoretically resistance per-phase values are very close. The minor variance could potentially arise from errors caused by electrical noise, parasitic capacitances and stray inductances.

Next is Question 5(ii), the empirically measured reactance for the actual line model is $X_{real\ line} = 13.32\Omega$. Meanwhile, the actual value of the nameplate is 15.00Ω. The deviation between the two values is 1.68Ω. The difference in values might be caused by presence of non-ideal circuit traits such as parasitic inductance, capacitance, and electrical noise in the power supply.

Part 2 No Load Test

An open-circuit test was conducted by leaving the load terminals of the transmission line model not in connection. The objective of the no-load test is to determine the mutual capacitance and the earth capacitance of the transmission line model.

Using the result from question 5(iii), the average values of I_C and I_{C0} are computed to be 0.28A and 0.19A respectively. Meanwhile, the results from question 5(iv), which the measured line model's mutual capacitance is $C_{real\ line} = 1.35\mu F$ and the $C_{real\ line\ per\ km} = 0.03377\mu F/km$, whereas the theoretical counterpart stands at $1\mu F$ and $0.025\mu F/km$. Additionally, the earth capacitance to real line value is measured to be $C_{0,real\ line} = 0.917\mu F$ and the $C_{0,real\ line\ per\ km} = 0.0229\mu F/km$. Their theoretical values are $0.60\mu F$ and $15nF/km$.

In all evaluated parameters of interest, the experimental measurements have surpassed the theoretical values. This is because of the presence of parasitic capacitance introduced by the connecting wires and probes. The discrepancies are then propagated in further calculations in mutual/earth capacitance per kilometer, resulting in the difference between the experimentally measured and theoretical values of the real line mutual capacitance per kilometer.

2

s

EXPERIMENT 1B

1. Experimental wiring and experimental setup [5 Marks]

(Insert a photo of your experimental setup and label all of the equipment used.)

Fig. 2 detailed the experimental setup for Experimental 1B Voltage Drop. (Disclaimer: the setup for voltage drop was not taken, thus the setup from another group was taken, all values were obtained from Station 1).

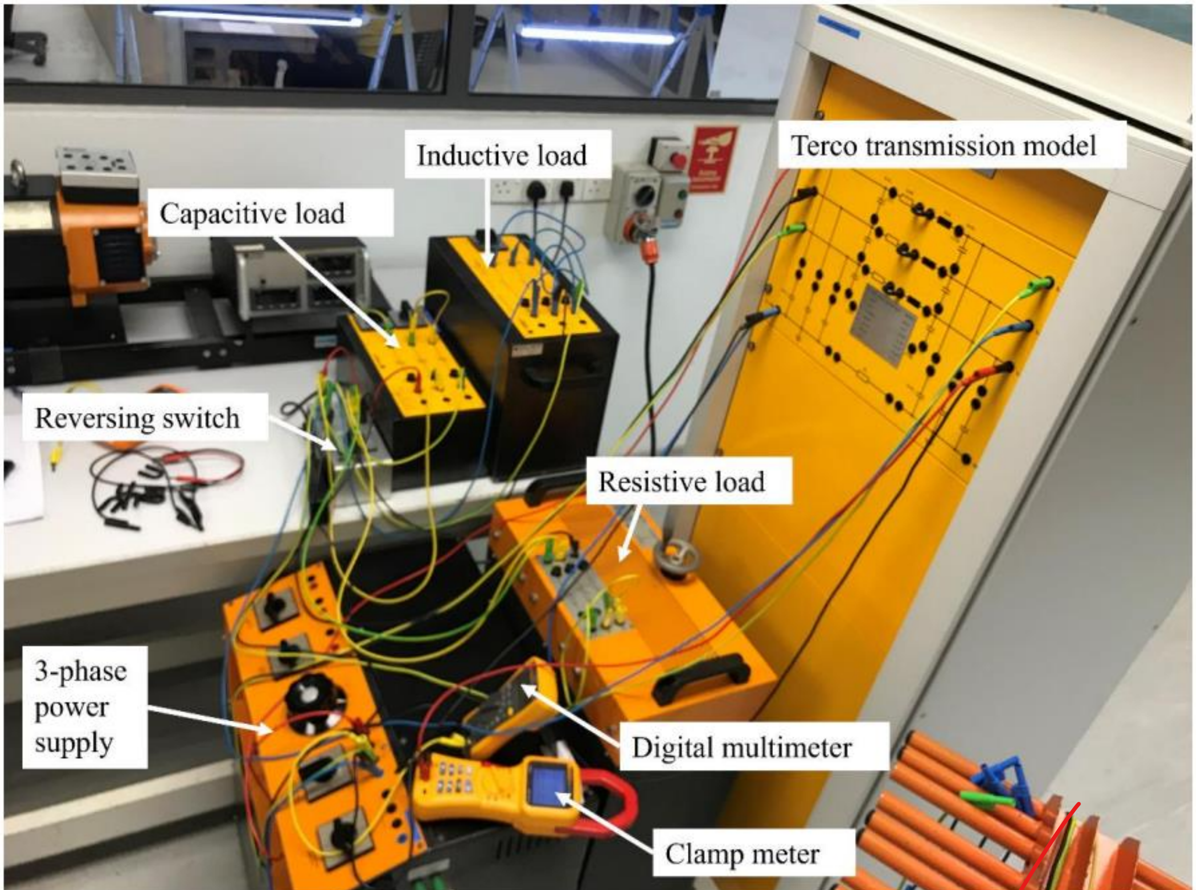


Fig. 2 Setup for experiment 1B

5

2. Results for Experiment 1B [2 Marks]

(Fill in the necessary data/ measurements from the experiment into the table below.)

Types of Loads	Power Factor	Measurement (Unit)	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Resistive Load	1	I_3 (A)	2.00	2.50	3.00	3.50
		V_2 (V)	125.30	122.80	120.60	118.00

Inductive and Resistive Load	± 0.6	I_3 (A)	1.89 (sw2)	2.35 (sw3)	2.91(sw4)	3.37(sw5)
		V_2 (V)	123.80 (0.60 pf)	120.60 (0.50 pf)	117.70 (0.40pf)	115.30 (0.34pf)
Capacitive and Resistive Load	± 0.6	I_3 (A)	1.78 (sw3)	2.14 (sw4)	2.52 (sw5)	2.96 (sw6)
		V_2 (V)	134.80 (0.72pf)	136.30 (0.61pf)	138.10 (0.52pf)	140.10 (0.46pf)

2

3. Questions

(Answer all of the following questions.)

(i) Plot and explain the V-I characteristic for the measured values in procedure Part 1 step 7 and Part 3, step 11. [3 Marks]

(Plot and explain the V-I characteristics.)

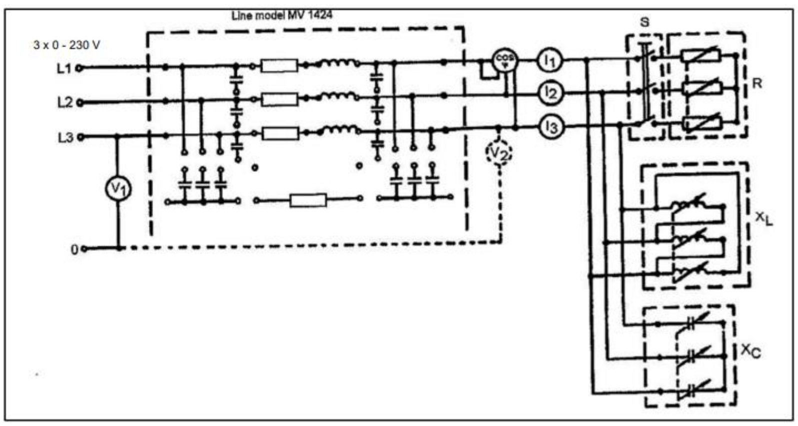


Fig. 3 Experiment 1B Circuit Schematic

Figure 3 shows the experimental setup, which will aid in explanation for the parts below.

V1, V2, R, XL, XC are used in the context of figure 3.

R is used when a component is purely resistive (impedance only contains a real value)
X is used when a component is purely inductive or capacitive (impedance only contains an imaginary value)
Z is used when the impedance contains both a real and imaginary value

Purely Resistive Load:

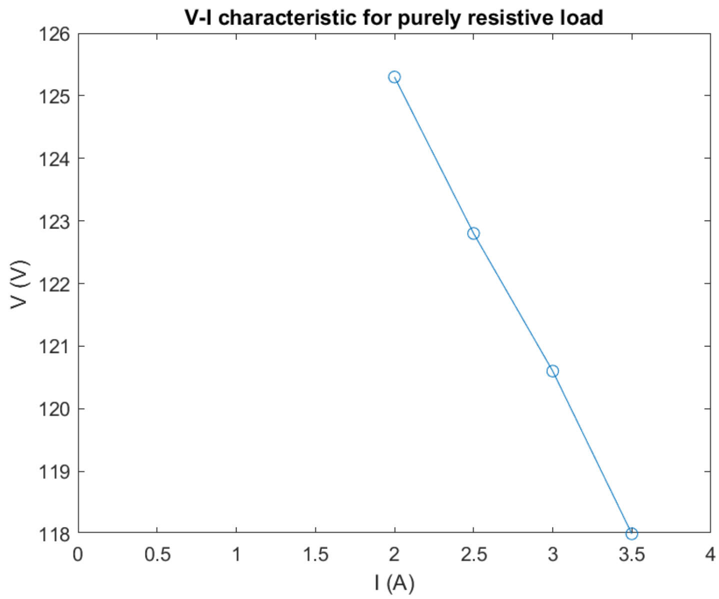


Fig. 4 V-I characteristic of purely resistive load

The output voltage V2 decreases linearly as current increases. The current is increased by decreasing the resistance of the resistive load. According to figure 3, V2 can be expressed as a voltage divider:

$$V_2 = \frac{R}{R + Z_{line}} * V_1$$

As R decreases, the ratio of the load resistance to the total circuit impedance decreases. Which causes V2 to decrease under the assumption that V1 and Zline are constants. This is observed in the trend shown in figure 4.

Inductive and Resistive Load:

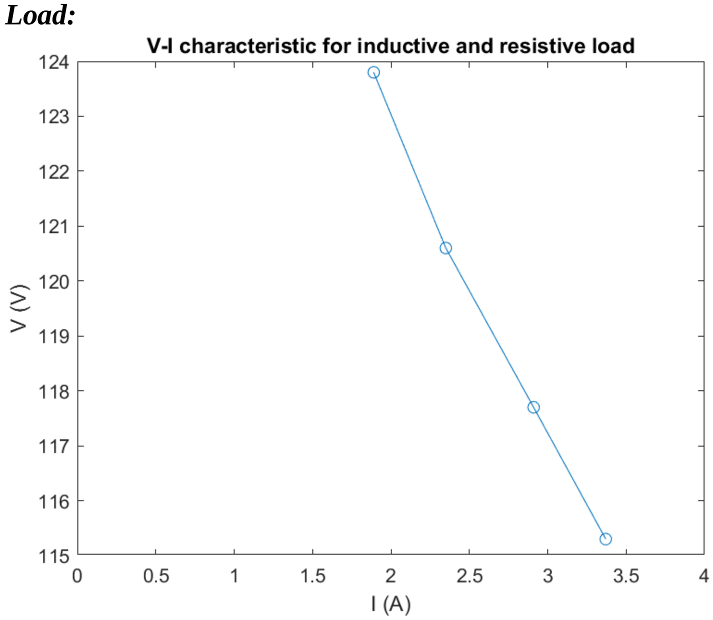


Fig. 5 V-I characteristic of inductive and resistive load

A similar trend is observed for the combined inductive and resistive load, shown in figure 5. The output voltage V2 decreases linearly as current increases. The current is increased by decreasing the impedance of the inductive load. Once again, a voltage divider approach can be used:

$$V_2 = \frac{Z_{RL}}{Z_{RL} + Z_{line}} * V_1$$

Z_{RL} is the equivalent impedance of the combined resistive and inductive load. As the impedance of the inductive load decreases, the ratio of the load impedance to the total impedance decreases. Furthermore, the impedance of an inductor is known to be:

$$X_L = j\omega L$$

Which shows that an inductor's impedance is directly proportional to inductance. Under the assumption that V1 and Zline are constants, V2 will decrease when Z_{RL} decreases.

Capacitive and Resistive Load:

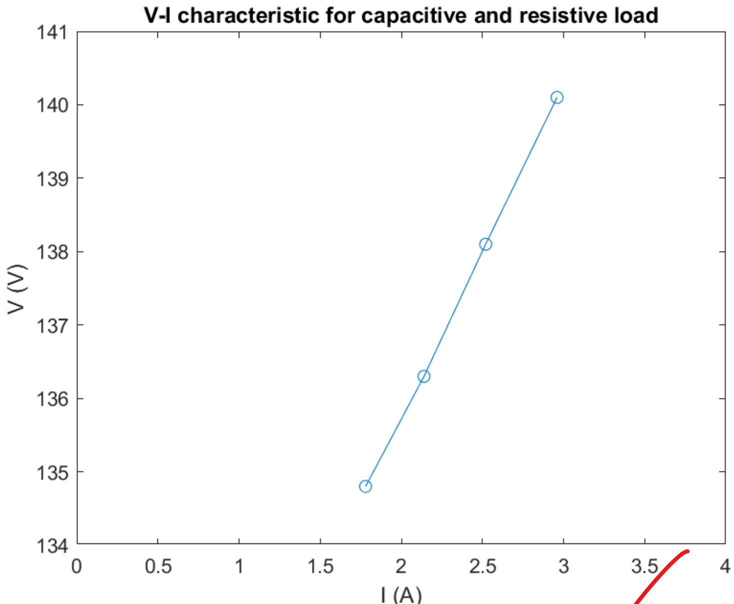


Fig. 6 V-I characteristic of capacitive and resistive load

For the combined capacitive and resistive Load, voltage increases linearly with current. Once again, the current is increased by decreasing the impedance of the capacitive load. The impedance of a capacitor is given by:

$$X_C = \frac{1}{j\omega C} = -\frac{j}{\omega C}$$

A capacitor's impedance is inversely proportional to capacitance. A decrease in impedance indicates an increase in capacitance. Using the voltage divider:

$$V_2 = \frac{Z_{RC}}{Z_{RC} + Z_{line}} * V_1$$

Z_{RC} is the equivalent impedance of the combined resistive and capacitive load. Because of the negative sign in the impedance of a capacitor, a smaller Z_{RC} leads to a larger ratio of the load impedance to the total impedance. This ultimately causes V2 to become larger as well.

3

All three scenarios obey Ohm's law for AC electrical circuits as the relationship between voltage and current are linear (V = IZ).

(ii) Calculate the output voltage for the line model when V1 is 132.8 VPHASE and I = 3.5A, while cos θ = 0.60. Use the calculated values of R and X from the results of experiment 1(A). Compare the theoretical calculation with the experimental measured values. [2 Marks]

(Insert your answer here using the VΔ formula.)

Let pf = 0.60 lagging, then:

$$\theta = cos^{-1}(0.6) = 53.13\, deg$$

From experiment 1(A) results, taking mean values for R and X:
R = 4.36 *Ω*
X = 4.66 j*Ω*
C = 1.35 uF

Equations:

$$I_c = \frac{1}{2}\omega\, C\, V_2$$
$$V_\Delta = IRcos\theta + IX\, sin\theta - X\, I_c$$
$$V_\Delta = V_1 - V_2$$

Substitute:

$$V_1 - V_2 = IRcos\theta + IX\, sin\theta - \frac{1}{2}\, X\, \omega\, C\, V_2$$
$$132.8 - V_2 = (3.5)(4.364)cos(53.13) + (3.5)(4.663)sin(53.13) - 4.663(\frac{1}{2})(2\pi 50)(1.35u)V_2$$
$$V_2 = 110.69 \text{ V}$$

Using MATLAB, a linear regression was done on figure 5, and the equation of the line of best fit is given as **V = −5.6725 I + 134.2687**

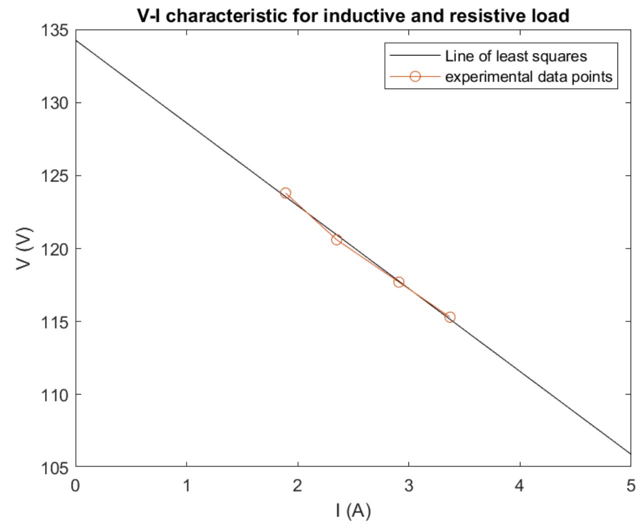


Fig. 7 Linear Regression on V-I characteristic of inductive and resistive load

Therefore, at I = 3.5 A, V2 = 114.415 V

Both values can be considered similar as the percentage error between the two values is 3.26%. The small discrepancy can be due to inaccuracies during measurement and non-ideal characteristics of the lab components such as parasitic capacitance, inductance, and noise.

2

(iii) Justify and elaborate the relationship between the output voltage and line capacitance. [2 Marks]

(Insert your answer here.)

Transmission line capacitance corresponds to the capacitance that exists between two transmission line conductors. The conductor pair is equivalent to a parallel plate of the capacitor, with the open air in between acting as a dielectric medium [2]. A three-phase transmission line is as shown below in figure.

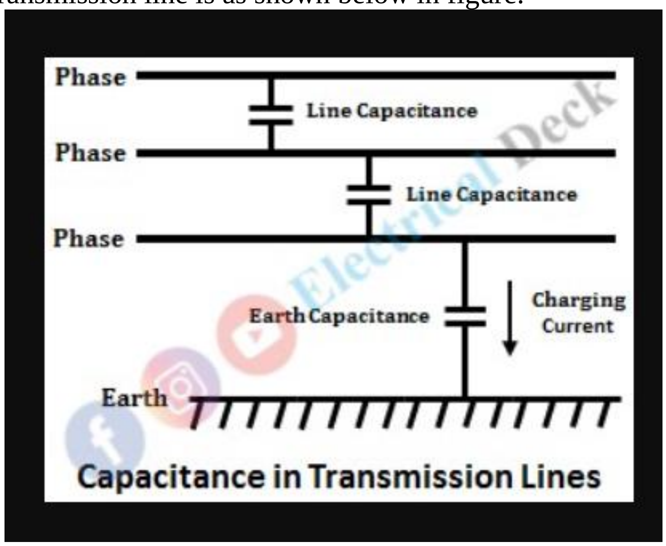


Fig. 8 Transmission Line Model with Line Capacitance

When an alternating potential difference is applied across the transmission line, it draws a current known as a charging current, even when no load is applied, which causes the voltage drop calculated in previous questions. Given a high line capacitance, the line draws more charging current, which compensates the lagging component of an inductive load, hence the resultant current flowing in the line is decreased [3]. This reduction in resultant current flowing in the line results in reduction of line losses and reduction of voltage drop, leading to improvement of voltage regulation.

However, problems may arise when the load is lightly loaded. Under the Ferranti Effect [4] (suitable for long transmission line models, means >250km), no-load and light load conditions make the output voltage greater than the sending end voltage, caused mainly capacitor charging current creating a voltage drop in-phase with the sending end voltage.

2

4. Discussion [3 Marks]

(Discuss your results obtained in Part 1, Part 2 and Part 3)

Part B of the experiment is to try to understand the voltage drop across the transmission line under the influence of resistive, capacitive and inductive loads. In order to comprehend the relationship, the output voltage of the transmission line is measured while varying the current. Then, a V-I graph is plotted to observe the behavior of the output voltage to varying current values.

Part 1 Resistive Load (Without line capacitance connected @ line model)

Part 1 of the experiment is conducted without considering the effects of line capacitance. Instead, it is on how the voltage changes when we adjust the current using the resistive load bank's knob.

The V-I plot shown in Fig. 4 reveals that the output voltage experiences a linear decrease as the current increases. This is due to the increasing current causing a larger voltage drop across the transmission line, which diminishes the output voltage, since $V_2 = V_1 - V_\Delta$, and the only voltage drop is at the resistive components (because power factor is 1 for purely resistive loads). Increasing current would lead to a higher voltage drop in line model, resulting in reducing output voltage.

Part 2 Resistive & Inductive Load

Part 2 of the experiment, the current is varied through adjusting the inductive load bank knob. As shown in Fig. 5, the V-I plot exhibits a linearly decreasing relationship between the output voltage and current, because $V_1 = V_1 - V_\Delta$.

The power factor of 0.6 lagging shows that both the resistance and reactance components of the line model contributed to the voltage drop - since the lagging power factor introduces a positive phase angle θ>0, the value of V_Δ remains positive. Greater current means reduced output voltage as per the relationship shown below.

$$V_\Delta = V_1 - V_2 = \frac{RP + XQ}{V_2} = RI_{in} + XI_{out} = IRcos\theta \ + \ IXsin\theta - XI_C$$

Part 3 Resistive & Capacitive Load

In Part 3 of the experiment, the current is varied through adjusting the capacitive load bank knob. As shown in Fig. 6, the V-I plot demonstrates a linearly increasing relationship between output voltage and current. The higher the current, the less voltage drop across the transmission line. With a leading power factor of 0.6, although both resistance and reactance contributed to the voltage drop, the leading power factor has a negative phase angle, where θ<0. Also, the value of X > R, so according to the relationship shown below,

$$V_\Delta = V_1 - V_2 = IRcos\theta \ + \ IXsin\theta - XI_C$$

where $|IXsin\theta|\ increases\ rapidly, more\ than\ |IRcos\theta|$, because the cosine value is positive, the value of V_Δ becomes negative. As such, increasing current causes voltage drop to decrease.

It is also important to admit that the line capacitance in the transmission line model was omitted during the experiment. The inclusion of line capacitance brings output voltage stability.

3

Conclusion [5 Marks]

(Include your conclusion for experiment 1A and 1B. State the learning outcomes of this experiment.)

The primary objective of Experiment 1(A) is to calculate the characteristic data of the line model and compare it with a full-scale line.

In Experiment 1(A) Part 1, to understand how the line model reacts in this short-circuited condition, several important electrical properties were measured. A short-circuit test was conducted to determine the resistance, current, voltage, power per-phase within the line model.

The measurements are used to calculate phase impedance, resistance, and reactance of the line model. Subsequently, the actual reactance value was determined through averaging the reactance per phase, to produce $\bar{X}$. This scaling is done to convert the average reactance into a value corresponding to the physical characteristics of our line model [5] produced by TERCO [1]. $\bar{X}$ is divided by the impedance scale Z_B=0.35 to find the real reactance value, $X_{real\ line}$.

Subsequently, experiment 1(A) Part 2, we have a no-load test to measure the current flowing through, and to determine the mutual capacitance, earth capacitance per-phase. The average no-load current, I_C , is crucial in quantifying the capacitance characteristics. Hence, we can use it to determine the line model's mutual capacitance, C_{model}. The real mutual capacitance, C_{real} is determined by multiplying the line model's mutual capacitance with the impedance scale Z_B. Since the lab equipment we used has a line length of 40km, the mutual capacitance per kilometer is obtained by dividing C_{real} with 40 km.

Similarly, the I_{C0}, contributes to the calculation of the line model's earth capacitance, $C_{0,\ model}$. The real earth capacitance, $C_{0,\ real}$, is obtained through the product of $C_{0,\ model}$ and the impedance scale Z_B. The earth capacitance per kilometer, C_0, is calculated by dividing $C_{0,real}$ by the line length (40km).

Then, the characteristic data for the line model, $X_{real\ line}$, C_{real}, $C_{real\ per\ km}$, $C_{0,\ real}$, and $C_{0,\ real\ per\ km}$ are compared with their respective theoretical values from the datasheet, which shows small deviations due to non-ideal electrical characteristics.

Meanwhile, Experiment 1(B) is to measure the voltage drop on the line to understand the effect of resistive, capacitive and inductive loads on the transmission line. The data for the output current, and output voltage of the line model are collected by turning the resistive, inductive, and capacitive load banks knob to vary the current. The change in current causes change in output voltage, which obeys the relationship below.

$$V_{\Delta} = V_1 - V_2 = \frac{RP + XQ}{V_2} = RI_{in} + XI_{out} = IRcos\theta \ + \ IXsin\theta - XI_C$$

The voltage drops V_{Δ} across the line model is computed using values of resistance, R, reactance, X, and average no-load current I_C obtained from Experiment 1(A).
From the results of the experiment, as current increases, for resistive load and resistive & inductive load, the output voltage decreases. Conversely, for resistive & capacitive load, due to the negative phase angle, the output voltage increases. In essence, the more resistive and inductive the load is, the higher the output voltage.

5

References [5 Marks]

(Include the references for experiment 1A and 1B here)

[1] *P. Book, "MV1424 Line Model," Terco Technical Education Worldwide. https://www.tercosweden.com/product/mv1424-line-model/?cn-reloaded=1 (accessed Aug. 03, 2023).*

[2] *"What is the Capacitance of a Transmission Line? - Capacitance of Two-wire Line & Symmetrical Three-phase Line," Circuit Globe, May 18, 2016. https://circuitglobe.com/capacitance-of-transmission-line.html*

[3] *What is the Capacitance of a Transmission Line? - Capacitance of Two-wire Line & Symmetrical Three-phase Line," Circuit Globe, May 18, 2016. https://circuitglobe.com/capacitance-of-transmission-line.html*

[4] *"How to Reduce the Ferranti Effect in AC Transmission Lines," resources.system-analysis.cadence.com. https://resources.system-analysis.cadence.com/blog/msa2021-how-to-reduce-the-ferranti-effect-in-ac-transmission-lines*

[5] *B. L. Theraja and A. K. Theraja, A textbook of electrical technology. Ram Nagar, New Delhi, India: S. Chand & Co, 2010.*

5

******** THE END *******

SCHOOL OF ENGINEERING

ELECTRICAL AND COMPUTER SYSTEMS ENGINEERING

LABORATORY REPORT MARKING RUBRIC

ECE4053: POWER SYSTEM ANALYSIS

Experiment Number: ________________2__________________________________

Title of Lab Sheet: _______Three Phase Transformer Connections___________________

Group Number: _______________________7_________________________________

No.	Student ID	Name of Group Members	Total Marks
1	32259417	Chong Yen Juin	92/100
2	30719305	Huan Meng Hui	
3	30720230	Loh Jia Quan	
4	32194471	Tan Jin Chun	

MARKS BREAKDOWN

Area	Total Score	Actual Marks	Scoring Band	Criteria
Format	5	5	4-5	The overall report contents present a clear, presentable, formal, readable and organized format, as per laboratory report guideline. Provide 2 decimal points for each recorded data.
			2-3	The report has most sections which present a clear, presentable, formal, readable and organized format, as per laboratory report guideline. Provide 2 decimal points for each recorded data.
			0-1	Most sections presented in a messy manner and did not follow the laboratory report guideline. Provide 2 decimal points for each recorded data.
Figures and Diagram	5	5	4-5	Extensive figures and diagrams with clear explanation and numbered labels.
			2-3	Extensive figures and diagrams without clear explanation and numbered labels.
			0-1	Insufficient figures and diagrams & without clear explanation and numbered labels.
Objectives and Equipment	5	5	4-5	Detailed description of the objectives and list of all equipment used.
			2-3	Brief description of the objectives and list of all equipment used.
			0-1	Unclear description of the objectives and list of all equipment used.
Results and Discussion	30	26	20 -30	Comprehensive comparison, evaluation and justification of the results, with clear explanation on the theoretical and experimental/ simulation results.
			11-19	Brief comparison, evaluation and justification of the results, with unclear explanation on the theoretical and experimental/ simulation results.
			0-10	No comparison, evaluation and justification of the results, with unsatisfactory explanation on the theoretical and experimental/ simulation results.
Conclusion and References	5	5	4-5	Clear understanding on the experiment with summarized conclusion. ln-text citations and IEEE referencing format is properly done. (3 references)
			2-3	Unclear understanding on the experiment with summarized conclusion, but without the supporting evidence of results. ln-text citations and references' format are improperly done. (2 references)
			0-1	Unclear understanding on the experiment without summarized conclusion and the evidence of results. In-text citations and references are absent. (0 – 1 reference)
Total	50	46		Deductions on pages 4, 8, 9

Examiner/ Assessor of ECE 4053: Power System Analysis
Date: 29/8/23

EXPERIMENT 2

1. Objectives [3 Marks]

(List the three objectives of this experiment.)
The objective of the experiment is to
1. Characterize the primary-to-secondary phase shift of a three-phase transformer
2. Investigate the voltage and current waveform quality
3. Investigate the performance of three-phase transformers under balanced and unbalanced load conditions

3

2. Equipment used [2 Marks]

(List all of the equipment used in this experiment.)
1. Three-phase power supply
2. Single Phase Transformers, 1.0 kVA,220V/110V, 50Hz
3. Three Phase Variac
4. Three Phase Resistive Load Bank
5. Clamp-on AC Voltage/Current/Power meter
6. Digital Multimeter (DMM)
7. Clamp-on Current Probe
8. Differential Voltage Probes (1/500 scale)
9. Digital Storage Oscilloscope (CRO)

2

3. Experimental wiring and experimental setup [5 Marks]

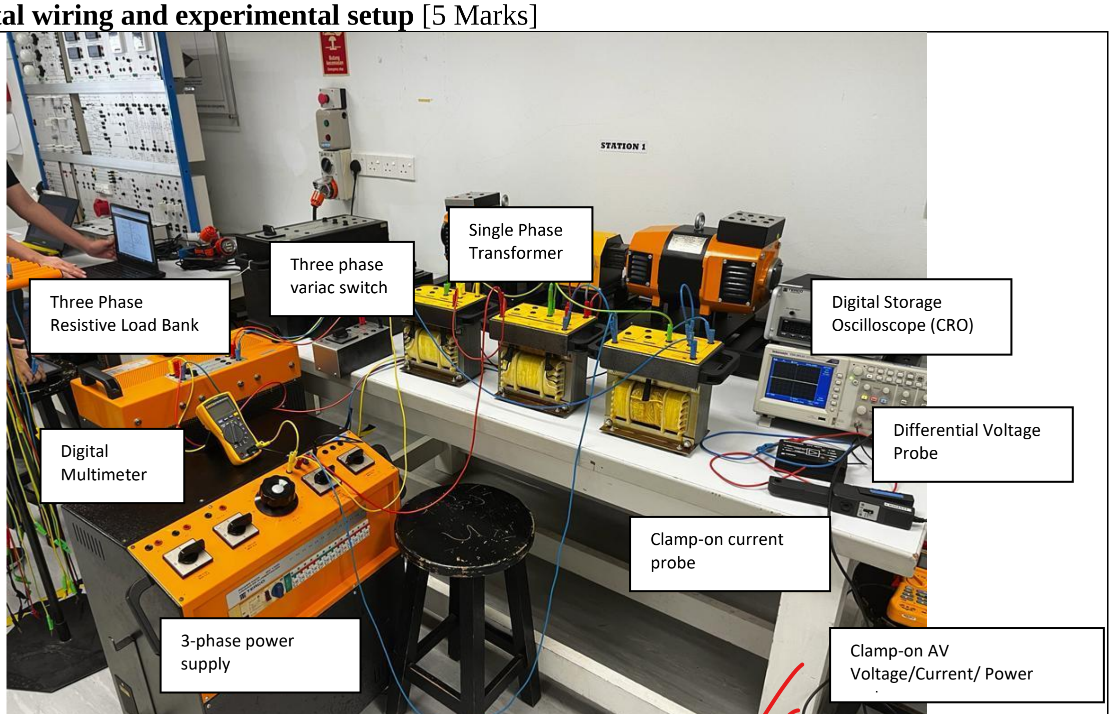


Fig. 1 Experimental Wiring and Setup

5

4. What is the formula used to calculate the voltage and current ratio? [3 Marks]

Real Voltage and Current Ratio
As stated by Wildi[1], the voltage induced in a coil is given as

$$E = 4.44fN\Phi_{max}$$

The voltage ratio is given as $\frac{E_{pri}}{E_{sec}}$.

Thus, the voltage can be expressed as

$$\frac{V_{prim}}{V_{sec}} = \frac{4.44fN_{prim}\Phi_{max}}{4.44fN_{sec}\Phi_{max}}$$

The flux and the frequency within the coil connecting the primary and secondary voltage are the same. Thus, the voltage ratio formula is given as

$$\frac{V_{prim}}{V_{sec}} = \frac{N_{prim}}{N_{sec}} = a$$

However, we are not given the number of turns of the transformer, but we can use the secondary and primary voltage into the transformer windings to find the theoretical voltage ratio.

$$a = \frac{230}{115} = 2$$

The current ratio formula can be found by relating the magnetomotive forces (mmf) created by the primary and secondary windings. The primary current creates an mmf given as $N_{prim}I_{prim}$, which is closely related to the mutual magnetic flux. However, the magnetic flux in the core remains fixed between the primary and secondary coil. Thus, the following relationship has to hold, thus giving us the current ratio formula [1] for the theoretical current ratio.

$$N_{prim}I_{prim} = N_{sec}I_{sec}\,\frac{I_{prim}}{I_{sec}} = \frac{N_{sec}}{N_{prim}} = \frac{1}{a} = \frac{1}{2}$$

2

Experimental Voltage and Current Ratio (from measured values)
However, for this experiment, it is required to obtain the ratios from the measured line-to-line voltages. As this is a **delta-to-wye** transformer, the voltages would have to be converted to the corresponding voltages before applying the voltage ratio.

$$V_{ratio} = \frac{V_{line,prim}}{V_{phase,sec}} = \frac{V_{line,prim}}{\frac{V_{line,sec}}{\sqrt{3}}} = \frac{\sqrt{3}V_{line,prim}}{V_{line,sec}}$$

The current ratio also has the same requirement before the current ratio formula can be applied.

-1m

$$I_{ratio} = \frac{I_{phase,prim}}{I_{phase,sec}} = \frac{\frac{I_{line,prim}}{\sqrt{3}}}{I_{line,sec}} = \frac{I_{line,prim}}{\sqrt{3}I_{line,sec}}$$

Percentage ratio is obtained by multiplying each ratio with 100.

5. Results for Experiment Balanced Three Phase Transformer with Switch Open [4 Marks]

(Fill in the necessary data/ measurements from the experiment into the table below.)

Line-to-Line Voltage	Red - White	White - Blue	Red - Blue
Primary Side	230.10	231.60	232.20
Secondary Side	209.70	208.70 (multiplied with $\sqrt{3}$)	211.10 (multiplied with $\sqrt{3}$)
Voltage Ratio	1.90	1.92	1.91
Percentage Ratio	190.00%	192.00%	191.00%

4

Line Current	Red	White	Blue
Primary Side	0.92	1.18	1.03
Secondary Side	0.42	0.42	0.30
Current Ratio	1.26	1.62	1.98
Percentage Ratio	126.50%	162.20%	198.20%

The discrepancy of the measured and expected current ratios are explained in the discussion.

6. **Capture the primary R-W and secondary R-W voltage waveforms, and the primary and secondary R line current waveforms, using the CRO.** [3 Marks]

(Insert the three waveforms obtained, Primary Voltage – Secondary Voltage, Primary Voltage – Primary Current and Secondary Voltage – Secondary Current.)

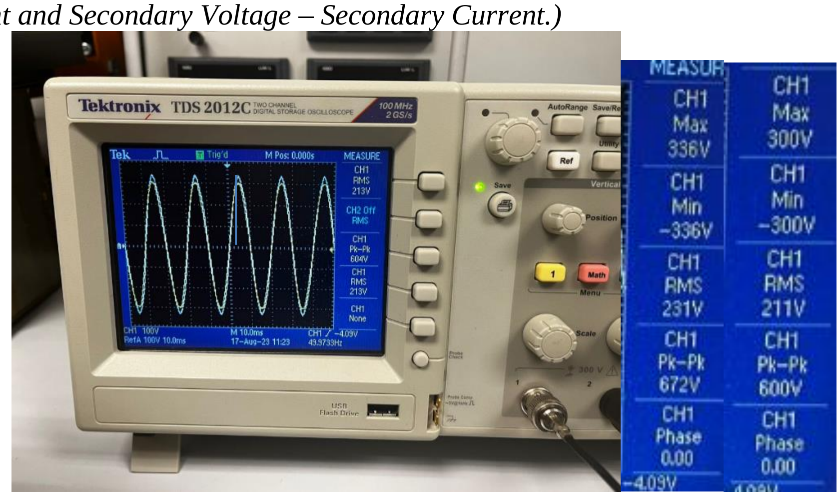


Fig. 2 Primary Voltage-Secondary Voltage waveform and measured parameters (Left: Primary, right: Secondary)

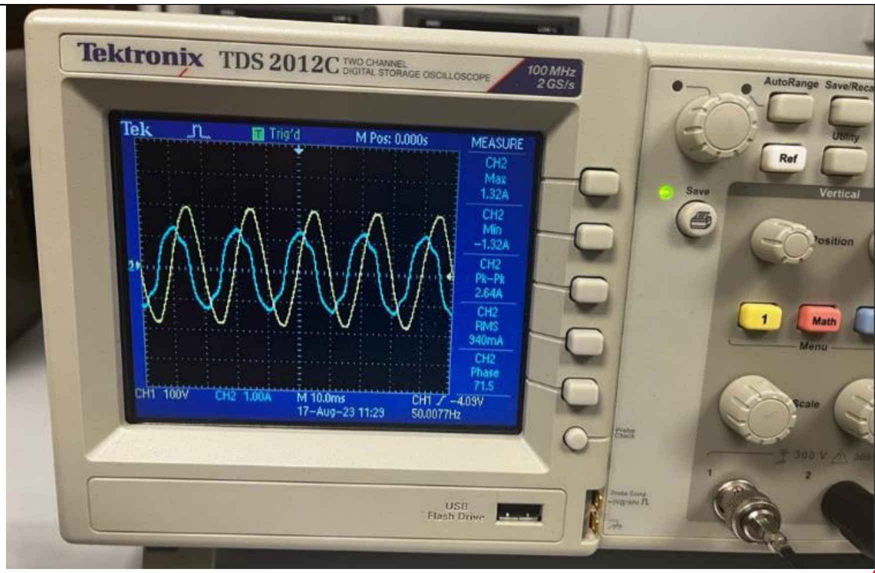
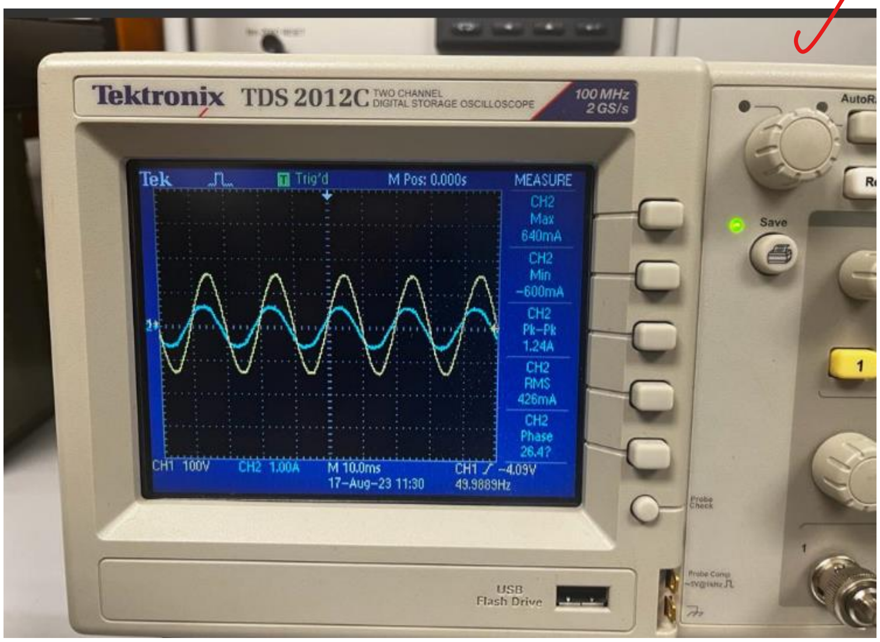


Fig. 3 Primary Voltage-Primary Current waveform and measured parameters (Yellow: Primary voltage, Blue: Primary current)



3

Fig. 4 Secondary Voltage-Secondary Current waveform and measured parameters (Yellow: Secondary voltage, Blue: Secondary current)

7. Is there a phase shift between the primary and secondary side voltages, and also between these voltages and their respective R phase currents? If so, measure these phase shifts and compare it with theory. [5 Marks]

(Fill in the necessary data/ measurements from the experiment into the table below. Justify your answer.)

Measurement 1	Measurement 2	Measured Phase Difference	Theoretical Phase Difference

Primary Voltage	231V	Secondary Voltage	211V	0°	30°
Primary Voltage	231V	Primary Current	0.94A	71.50°	90°
Secondary Voltage	211V	Secondary Current	0.43A	26.40°	30°

Table I. Recorded values for primary and secondary voltages, observed phase difference, and anticipated theoretical phase difference.

Theoretical primary line voltage – secondary line voltage
For a delta-wye connected transformer, there is no phase shift between the primary line-to-line voltage and the secondary phase voltage, thus the secondary phase voltage is given as

$$\frac{V_{prim,line}}{V_{sec,phase}} = \frac{N_1}{N_2}$$

However, we are measuring the secondary line voltage, which is related to the secondary phase voltage by

$$V_{sec,line} = \sqrt{3}\, V_{sec,phase}\angle 30° V_{sec,phase} = \frac{1}{\sqrt{3}} V_{sec,line}\angle -30°$$

$$\frac{V_{prim,line}}{V_{sec,phase}} = \frac{V_{prim,line}}{\frac{1}{\sqrt{3}} V_{sec,line}\angle -30°} = \frac{\sqrt{3}V_{prim,line}}{V_{sec,line}}\angle 30°$$

The primary (delta) line voltage should theoretically lag the secondary (wye) line voltage by 30 degrees.

The measured phase difference of the primary and secondary line voltage is measured to be 0. This could be an estimation error as the primary voltage is captured as a reference, thus the phase difference between the primary and secondary line voltage cannot be measured in real time.

Theoretical primary line voltage – primary line current
A transformer core can be modeled by an ideal inductor. By Faraday's Law and Ohm's Law for an inductor, we can relate the induced voltage towards the current in the inductor using the following formula

$$V = \frac{LdI}{dt}$$

Given a sinusoidal current, we can derive the following relationship [3]

$$V = \frac{Ld(sint)}{dt} = Lcos(t) = Lsin(t + 90)$$

We can observe the theoretical phase difference between the primary line-to-line voltage and primary line current has a phase difference of 90.

The measured phase difference is 71.50 degrees which is relatively close to the theoretical value.

-2m

Theoretical Secondary line voltage– Secondary line current
Given this is a delta-wye transformer, the line current and the phase voltage will be in phase, as the load is a purely resistive load. However, the measured voltage is the line voltage, which leads the phase voltage by 30 degrees, and subsequently the line current by 30 degrees.

also discuss the delta to delta and wye to wye connections

The measured phase difference is 26.40 degrees which is relatively close to the theoretical value.

8. Results for Experiment Balanced Three Phase Transformer with Switch Closed [4 Marks]
(Fill in the necessary data/ measurements from the experiment into the table below.)

Line-to-Line Voltage	Red - White	White - Blue	Red - Blue
Primary Side	230.00	231.80	231.20
Secondary Side	209.80	208.70 (surd 3)	211.00 (surd 3)
Voltage Ratio	1.8988	1.9238	1.8979
Percentage Ratio	189.88%	192.38%	189.79%

4

Line Current	Red	White	Blue
Primary Side	1.26	1.25	1.10
Secondary Side	0.56	0.57	0.57
Current Ratio	0.7698	0.7898	0.8975
Percentage Ratio	76.98%	78.98%	89.75%

9. Explain any differences accounted for from the measurements above. [2 Marks]

(Insert your answer here.)

For the voltage measurements, the voltage percentage ratio fluctuates around 189%; since the transformers banks are connected in delta-wye configuration, the primary side voltage has a line voltage equal to the phase voltage (delta connection), whereas the secondary side voltage has line-line voltage of surd 3 times more than the phase voltage, $V_{line} = \sqrt{3}\, V_{phase}$. The voltage ratio is defined as the ratio of primary voltage to the secondary voltage. The minor differences might be due to electrical noise of the source, systematic errors. This is expected as the three-phase load is balanced.

2

For the current measurements, the blue phase current ratio deviates from the red and white phase current ratio of ~77%. This discrepancy is due to the faults within the transformer windings (causing significant stray capacitance), and the utilization of another type of transformer.

10. Results for Experiment Balanced Three Phase Transformer with Unbalanced Load [2 Marks]
(Fill in the necessary data/ measurements from the experiment into the table below.)

	Primary Current (A)	Secondary Current (A)
Red	1.07	0.48
White	1.29	0.13
Blue	1.00	0.16

2

11. Compare the magnitudes and explain the relationship by considering mmf balance for each set of phase windings. [2 Marks]

(Insert your answer here.)

The primary red current's magnitude appears to be less than that of the white and blue. Additionally, the secondary current for red is significantly greater than its white and blue counterparts. This discrepancy is because only the red transformer is loaded, with the white and blue transformers having their loads disconnected. Given that the red transformer is solely connected to the load and requires more current to power these loads, its secondary current exceeds that of the white and blue transformers. The reduced secondary current in the white and blue transformers results from their connection to the ground.

1

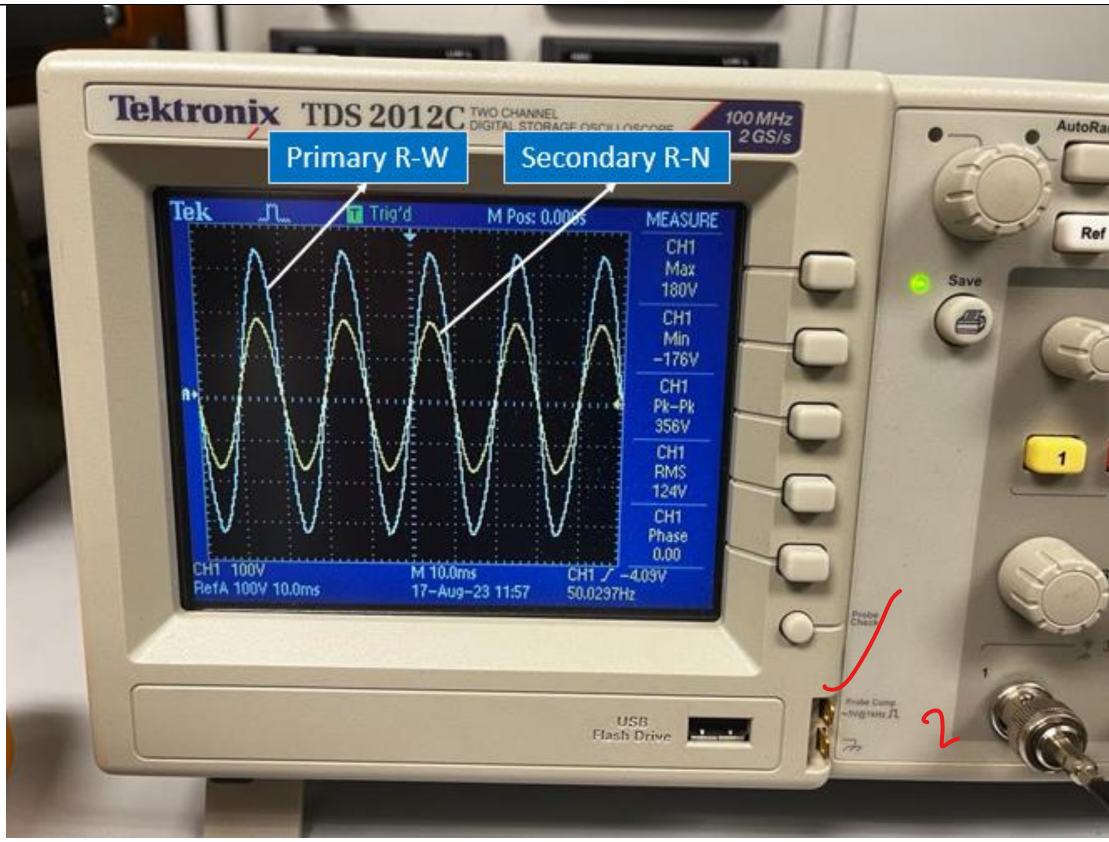
When AC voltage is applied to the primary coil, AC current will flow through the primary winding. The magnetic field created by the AC current cuts across the secondary coil, inducing voltage in the secondary coil. The secondary coil's current generates a magnetomotive force (mmf) that is balanced by the primary side [2].

Due to the unbalanced load, it is expected that the current in each phase is not the same. Since only the Red line is connected to a load on the secondary side, it requires the highest current to drive the load. The White and Blue lines have a lower current for the opposite reason.

how is mmf calculated -1

12. Capture the primary R-W and secondary R-N voltage waveforms using the CRO. [2 Marks]

(Insert the waveforms obtained, Primary R-W and Secondary R-N voltage.)



2

Fig. 5. Primary V_{RW} and secondary V_{RN} plotted against time

The transformer is connected in delta-wye configuration, meaning the delta side (primary voltage) lags the wye side (secondary voltage) by 30 degrees. However, line-to-line voltages in a wye-connected 3 phase system (like the secondary side) lag the line-to-neutral voltage by 30 degrees. Therefore, when the secondary line-to-neutral (VRN) voltage is plotted against the primary line-to-line voltage (VRW), the two waveforms should be in phase, which is observed in the figure above.

13. Results for Experiment Magnitude and Phase Shifts [2 Marks]

(Fill in the necessary data/ measurements from the experiment into the table below.)

	Primary R-W Voltage (V)	Secondary R-W Voltage (V)	Secondary R-N Voltage (V)
Measured	231.30	211.10	121.40
Theoretical	230.00	57.5 x 2 x $\sqrt{3}$ = 199.20	57.5 x 2 = 115.00

/2

14. Capture the secondary R line current waveform and the primary R and W line current waveforms and explain their phase relationship. [3 Marks]

(Insert the waveforms obtained, Secondary R line current -Primary R and W line current. Explain your answer.)

Firstly, comparing the primary R and primary W line currents, we know that in balanced 3 phase systems, each phase should be 120 degrees apart from each other. Based on the figure below, the oscilloscope measured a phase difference of 134 degrees. The deviation is expected and is most likely due to the unbalanced load.

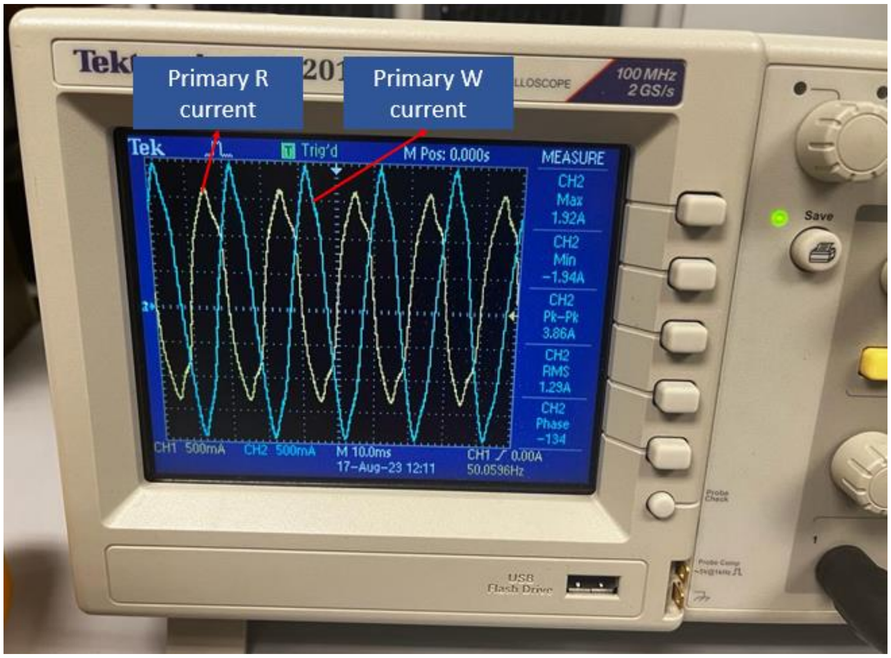


Fig. 6. Primary R and W line currents

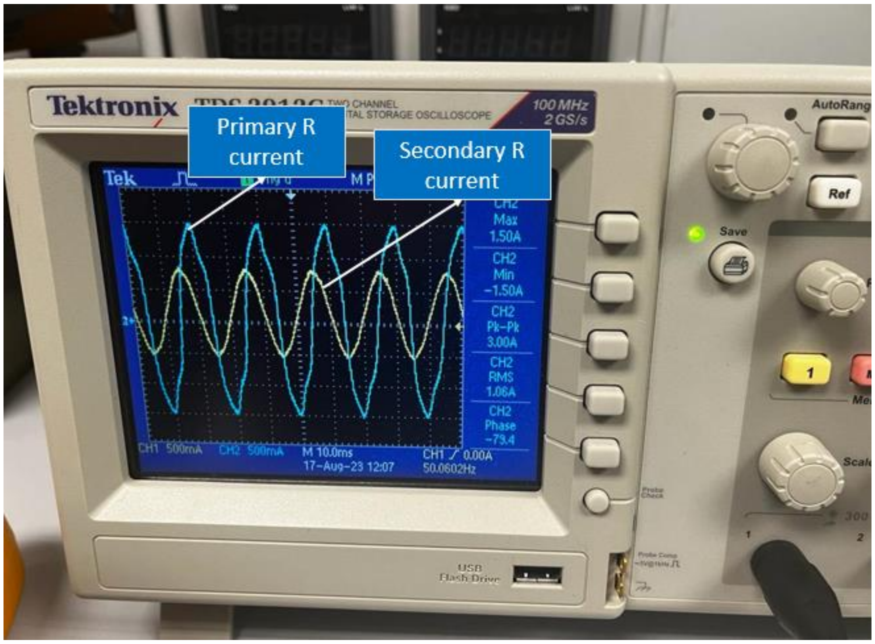


Fig. 7. Primary and Secondary R line currents

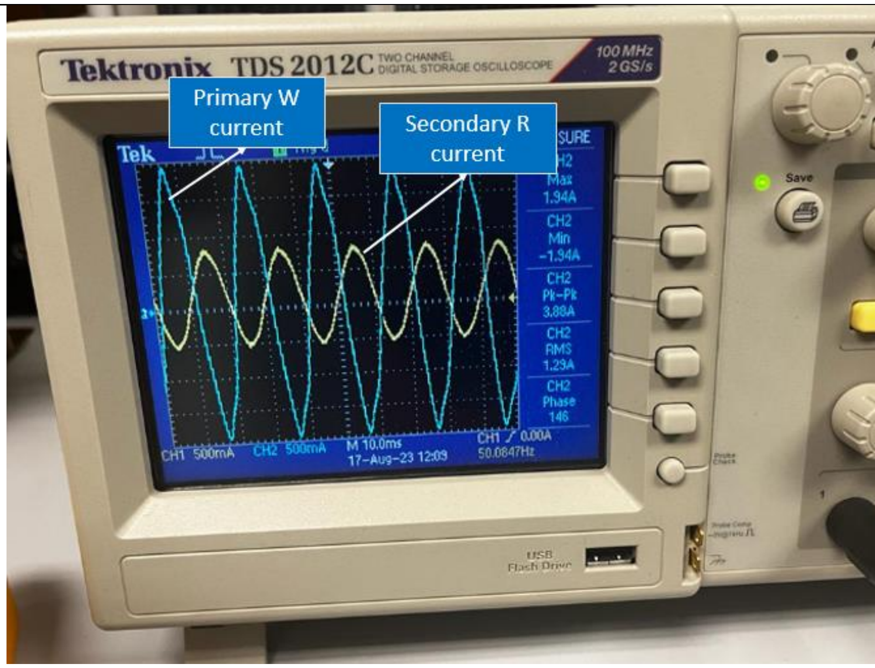


Fig. 8. Primary W and secondary R line currents

Expression	*Measured Phase Difference*
*Primary W **lags** Primary R line current by*	134.00°
*Secondary R **leads** Primary R line current by*	79.40°
*Secondary R **lags** Primary W line current by*	146.00°

Since the transformer is connected in delta-wye fashion, the wye side (secondary) leads the delta side (primary) by 30 degrees. From the table above, the secondary R line current does in fact lead the primary R line current, but by 79.4 degrees.

3

Previously, we have measured that the phase difference between the primary R and W line current is 134 degrees. Therefore, the theoretical phase difference between the **secondary** R and primary W line current is 134 - 30 = 104 degrees. However, the measurement from the oscilloscope is 146 degrees.

For both measurements, the results are on average 45 degrees off. This discrepancy may be due to faulty transformer windings (as we were working with one phase transformer without grounding during the lab), or large stray capacitance and inductance. As the phase measurements were taken using the oscilloscope function, slight vertical offsets in the waveforms may also cause inaccuracies when calculating the phase difference.

15. **Discussion** [3 Marks]

(Discuss your findings based on the results obtained.)

During the initial phase of the lab experiment, the measurements of line-to-line voltages and line currents for both primary and secondary circuits for all 3 phases. This was done to determine the phase differences between primary and secondary voltages, primary voltage, and primary current, then secondary voltages and currents. Among these relationships, the theoretical secondary voltage and current pair exhibited a phase difference of 30°. This is anticipated due to the load's purely resistive nature and its configuration in a wye arrangement.

However, for primary and primary current, the measured phase difference of 18.50° deviated considerably from the anticipated value of 90°. This disparity might be attributed to non-ideal behaviors of the transformer and equipment malfunctions.

The third pair of relations involving secondary voltage and secondary current, the measured phase difference of 26.40° was quite close to the anticipated 30°. Post lab testing and measurements indicated that this discrepancy is caused by the malfunctioning single-phase transformer employed in the Blue-phase connection.

As for the current and voltage ratios, the calculated voltage ratios were able to match closely to the expected voltage ratio, which was calculated to be 2. However, the current ratios were unable to match the expected current ratio of ½. A valid reason would be the transformer was not configured to be operated at rated load, thus the current flowing in the secondary side is not rated, thus the expected current ratio is not able to be obtained.

3

Proceeding to the next part of the experiment, we closed the switch. We have a balanced three-phase delta-wye transformer, coupled with a balanced three-phase resistive load. Our calculated voltage ratio aligned with theoretical expectations, confirming the anticipated $\sqrt{3}$ ratio. However, due to systematic experimental errors associated with the Blue-phase transformer, the line current measured for the 'Blue' phase displayed divergence from that of the 'Red' and 'White' phases.

Ideally, the magnitudes of the line currents should have been comparable, given the balanced nature of both the source and the load.

When it comes to unbalanced loads, the magnetomotive force gives rise to magnetic flux within the system. The presence of the load influences the magnitude and phase of the primary current component. In scenarios of unbalanced loads, the secondary side of the white and blue transformers is disconnected. This disconnection leads to an imbalance in magnetomotive force. Moreover, since the red transformer alone is connected to the load and requires more current to drive the load component, it naturally exhibits a relatively higher secondary current compared to the white and blue transformers.

Conclusion [3 Marks]

(Include your conclusion and state the learning outcomes of this experiment.)

This experiment aimed to achieve the following objectives:
1. Understand the phase shift from primary to secondary in a three-phase transformer.
2. Examine the quality of voltage and current waveforms.

3. Assess the performance of three-phase transformers under both balanced and unbalanced loading conditions.

Our methodology involved measuring line-to-line voltages and currents in both primary and secondary phases **when the loading was at its maximum**. These measurements allowed us to determine the phase differences between primary and secondary voltage, between primary voltage and current, and between secondary voltage and current. We subsequently contrasted our observations with theoretical expectations based on the delta-wye configuration of the transformer, explaining any discrepancies.

3

Furthermore, we compared voltage and current ratios with the secondary star point load/transformer switch connection both opened and closed. Our findings indicated minimal fluctuation in these ratios regardless of the switch's state. This was anticipated due to the balanced nature of the load and the neutrality of the node connecting all three loads and the node linking the three negative transformer terminals in the secondary. The connectivity of these neutral points appeared to have negligible influence on circuit behaviors.

Lastly, we evaluated the transformer's behavior under an unbalanced load. We identified a phase difference of 30° between the primary and secondary R line currents, in line with theoretical projections. Notably, the observed phase difference between the primary R and W line currents might display discrepancies due to potential hardware issues, including unmeasured winding resistance, stray capacitance, or incidental impedance.

References [2 Marks]

(Include the references for this experiment here.)

[1] T. Wildi, "The Ideal Transformer," Electrical Machines, Drives, and Power Systems, 6th ed., ch. 9, pp. 189-202.

[2] "Transformer Connections: Phase Shift and Polarity – Voltage Disturbance," Nov. 27, 2018. https://voltage-disturbance.com/power-engineering/transformer-connections-phase-shift-and-polarity/ (accessed Aug. 17, 2023).

[3] "Inductors and Calculus | Inductors | Electronics Textbook," www.allaboutcircuits.com. https://www.allaboutcircuits.com/textbook/direct-current/chpt-15/inductors-and-calculus/

2

******** THE END *******

MONASH University MALAYSIA

SCHOOL OF ENGINEERING

ELECTRICAL AND COMPUTER SYSTEMS ENGINEERING

LABORATORY REPORT MARKING RUBRIC

ECE4053: POWER SYSTEM ANALYSIS

Experiment Number: 3

Title of Lab Sheet: Load Flow Analysis

Group Number: 7

No.	Student ID	Name of Group Members	Total Marks
1	30720230	Loh Jia Quan	98/100
2	32259417	Chong Yen Juin	
3	30719305	Huan Meng Hui	
4	32194471	Tan Jin Chun	

MARKS BREAKDOWN

Examiner/ Assessor of ECE 4053: Power System Analysis

Area	Total Score	Actual Marks	Scoring Band	Criteria
Format	5	5	4-5	The overall report contents present a clear, presentable, formal, readable and organized format, as per laboratory report guideline. Provide 2 decimal points for each recorded data.
			2-3	The report has most sections which present a clear, presentable, formal, readable and organized format, as per laboratory report guideline. Provide 2 decimal points for each recorded data.
			0-1	Most sections presented in a messy manner and did not follow the laboratory report guideline. Provide 2 decimal points for each recorded data.
Figures and Diagram	5	5	4-5	Extensive figures and diagrams with clear explanation and numbered labels.
			2-3	Extensive figures and diagrams without clear explanation and numbered labels.
			0-1	Insufficient figures and diagrams & without clear explanation and numbered labels.
Objectives and Equipment	3	3	3	Detailed description of the objectives and list of all equipment used.
			2	Brief description of the objectives and list of all equipment used.
			0-1	Unclear description of the objectives and list of all equipment used.
Results and Discussion	34	34	26 - 34	Comprehensive comparison, evaluation and justification of the results, with clear explanation on the theoretical and experimental/ simulation results.
			13-25	Brief comparison, evaluation and justification of the results, with unclear explanation on the theoretical and experimental/ simulation results.
			0-12	No comparison, evaluation and justification of the results, with unsatisfactory explanation on the theoretical and experimental/ simulation results.
Conclusion and References	2	2	2	Clear understanding on the experiment with summarized conclusion. In-text citations and IEEE referencing format is properly done. (3 references)
			1	Unclear understanding on the experiment with summarized conclusion, but without the supporting evidence of results. In-text citations and references' format are improperly done. (2 references)
			0	Unclear understanding on the experiment without summarized conclusion and the evidence of results. In-text citations and references are absent. (0 – 1 reference)
Total	50	49		Deduction on page 7

Date: 10/9/23

EXPERIMENT 3

1. **Objectives** [3 Marks]

(List the three objectives of this experiment.)

Objectives

The objectives of this experiment is to

(a) To carry out load flow studies on a small-scale power system, and determine whether the system is operating within the required performance criteria.

(b) To investigate what corrective measures are appropriate to improve the system performance.

(c) To obtain experience using a commercial power systems simulation tool.

Design Criteria

- supply at 132kV is required to be maintained in the range 0.95 – 1.05 per unit of the nominal 132kV voltage with all lines in service and following the outage of any of the 345kV transmission lines.
- satisfied immediately after the outage before the transformers have had time to tap and after transformer tapping

3

2. Insert the single line diagram with the simulation results for the Base Case Solution. [1 Mark]

(Insert the diagram with the load flow data.)

The transmission lines are:

AC Line 1: from bus 2 to bus 4

AC Line 2: from bus 2 to bus 5

AC Line 3: from bus 4 to bus 5

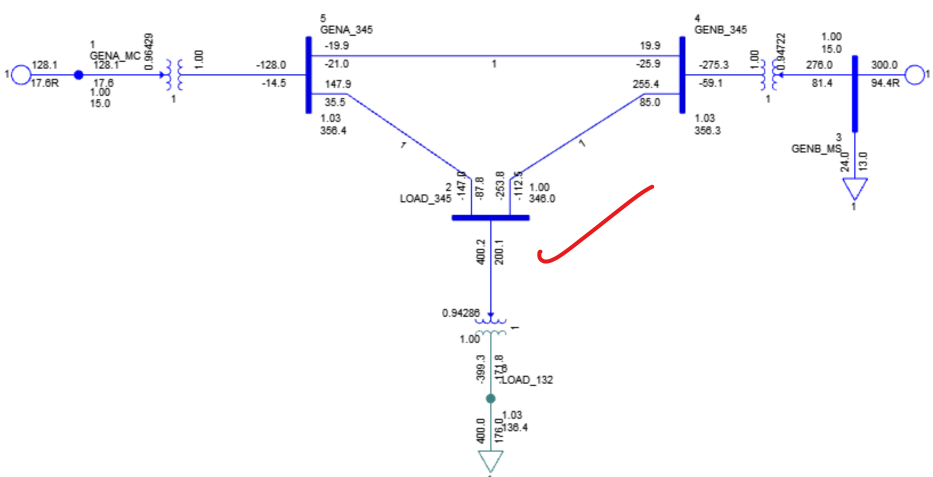


Fig. 1 Single Line Diagram for Base Case

Bus Num	*Bus Name*	*Base kV*	$P_{gen}(MW)$	$P_{max}(MW)$	$P_{min\,(MW)}$	$Q_{gen}(MVAR)$	$Q_{max}(MVAR)$	$Q_{min\,(MVAR)}$
1	GENA_MC	15.00	128.10	400.00	0	17.60	300.00	-160.00

Table 1 Swing Bus Data for Base Case Solution

3. Base Case Solution Experimental Results [2 Marks]

(Complete report of the bus voltages, branch power flows etc. Full report displayed in tables from the Load Flow output.)

FROM BUS			AREA	VOLT		GEN	LOAD	SHUNT
BUS NUM	BUS NAME	BASE kV	ZONE	PU/ KV	ANGLE °	P(MW) Q(MVAR)	P(MW) Q(MVAR)	P(MW) Q(MVAR)
1	GENA_MC	15.000	1 1	1.00 15.00	0.0	128.1 17.6R	0.0 0.0	0.0 -0.0
2	LOAD_345	345.00	1 1	1.0030 346.03	-4.5	0.0 0.0	0.0 0.0	0.0 -0.0
3	GENB_MC	15.000	1 1	1.000 15.000	3.2	300 94.4R	24.0 13.0	0.0 -0.0
4	GENB_345	345.00	1 1	1.0329 356.35	-1.1	0.0 0.0	0.0 0.0	0.0 -0.0
5	GENA_345	345.00	1 1	1.0331 356.41	-1.4	0.0 0.0	0.0 0.0	0.0 -0.0
6	LOAD_132	132.00	1 1	1.0335 136.42	-7.8	0.0 0.0	400.0 176.0	0.0 -0.0

Table 2 Bus Based Report for Base Case Solution

From BUS	TO BUS							TRANSFORMER		RATING	
BUS NUM	BUS NUM	BUS NAME	BASE (kV)	AREA	CIRCUIT	P(MW)	Q(MVAR)	Ratio	°	%	Set
1	5	GENA_345	345	1	1	128.1	17.6	0.964		26	500
2	4 5 6	GENB_345 GENA_345 LOAD_132	345 345 132	1 1 1	1 1 1	-253.8 -147.0 400.2	-112.5 -87.8 200.1	 0.943		23 14 75	1200 1200 600
MISMATCH						0.6	0.3				
3	4	GENB_345	345	1	1	276.0	81.4	0.947		82	350
4	2 3 5	LOAD_345 GENB_MS GENA_345	345 15 345	1 1 1	1 1 1	255.4 -275.3 19.9	85.0 -59.1 -25.9	1.0		22 80 3	1200 350 1200
5	1 2 4	GENA_MC LOAD_345 GENB_345	15 345 345	1 1 1	1 1 1	-128.0 147.9 -19.9	-14.5 35.5 -21.0	1.0		26 12 2	500 1200 1200
6	2	LOAD_345	345	1	1	-399.3	-171.8	1.0		72	600
MISMATCH						-0.7	-4.2				

Table 3 Bus Based Report for Base Case Solution (Continued)

4. Are the network voltages within the desired operating range? [1 Mark]

(Insert your answer here.)

In the Base Case Scenario, all transmission lines are operational. The voltage supply at 132kV should be kept between 0.95 and 1.05 per unit (pu) not only when all lines are in service but also after any 345kV transmission line experiences an outage.

This voltage standard must be met immediately post-outage and during the transformer tapping recovery process. Both Table 2 and Table 3 provide the load flow results, indicating bus voltages when all lines are active. The voltage for LOAD_132 stands at **1.0335pu**, falling within the set operational limits. All other network voltages align with the prescribed range. Additionally, the voltages at bus 1 through bus 5 comply with the 0.95 – 1.05 pu range (desired operating range). Potential discrepancies in the simulation results might stem from computational inaccuracies in the simulation.

5. Insert the single line diagram with the simulation results for the Transformer Taps Locked. [1 Mark]

(Insert the diagram with the load flow data. Tripping Line 1)

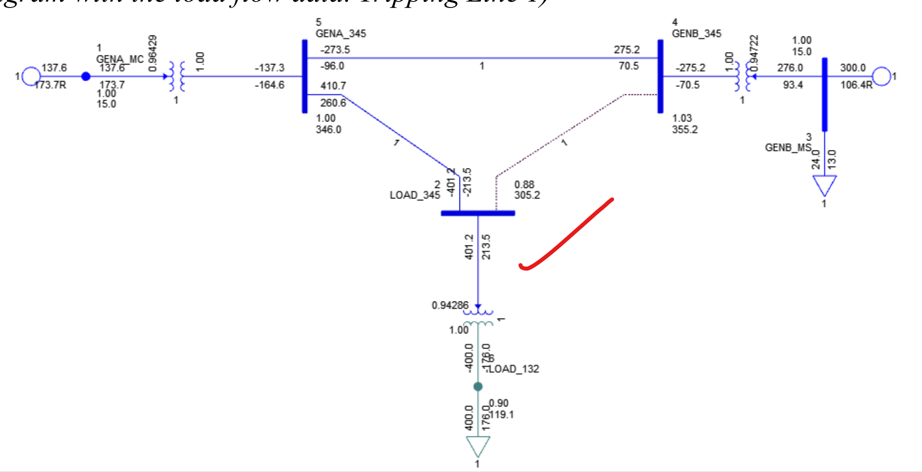


Fig. 2 Transformer Tap Locked Simulation with AC Line 1 Tripped

Bus Num	*Bus Name*	*Base kV*	$P_{gen}(MW)$	$P_{max}(MW)$	$P_{min\ (MW)}$	$Q_{gen}(MVA$	$Q_{max}(MVA$	$Q_{min\ (MVAR)}$
1	GenA_MC	15	137.6	400	0	173.7	300	-160.0

Table 4 Swing Bus Data for Transformer Tap Locked Simulation with AC Line 1 Tripped

6. Generate and print a Bus Based report for the Transformer Taps Locked. [2 Marks]

(Tripping Line 1. Full report displayed in tables from the Load Flow output.)

From BUS					GEN	LOAD	SHUNT
BUS NUM	BUS NAME	BASE kV	PU/ KV	°	P(MW) Q(MVAR)	P(MW) Q(MVAR)	P(MW) Q(MVAR)
1	GENA_MC	15.000	1 15	0.0	137.6 173.7	0.0 0.0	0.0 0.0
2	LOAD_345	345.00	0.8847 305.22	-11.4	0.0 0.0	0.0 0.0	0.0 0.0
3	GENB_MC	15.000	1.0000 15.000	6.6	300 106.4R	24.0 13.0	0.0 0.0
4	GENB_345	345.00	1.0295 355.18	2.3	0.0 0.0	0.0 0.0	0.0 0.0
5	GENA_345	345.00	1.0029 346.01	-1.4	0.0 0.0	0.0 0.0	0.0 0.0
6	LOAD_132	132.00	0.9023 119.1	-15.7	0.0 0.0	400.0 176.0	0.0 0.0

Table 5 Bus Data for Transformer Tap Locked Simulation with AC Line 1 Tripped

From BUS	To BUS					Transformer		Rating	
BUS NUM	BUS NUM	BUS NAME	BASE kV	P(MW)	Q(MVAR)	Ratio	°	%	Set
1	5	GENA_345	345	137.6	173.7	0.964		44	500
2	5 6	GENA_345 LOAD_132	345 132	-401.2 401.2	-213.5 213.5	0.943		43 76	1200 600
3	4	GENB_345	345	276.0	93.4	0.947		83	350
4	3 5	GENB_MS GENA_345	15 345	-275.2 275.2	-70.5 70.5	1.0		81 23	350 1200
5	1 2 4	GENA_MC LOAD_345 GENB_345	15 345 345	-137.3 410.7-273.5	-164.6 260.6 -96.0	1.0		43 40 24	500 1200 1200
6	2	LOAD_345	345	-400	-176	1.0		73	600

Table 6 Swing Bus Data for Transformer Tap Locked Simulation with AC Line 1 Tripped (Continued)

7. Examine the network voltages and determine if they are within the desired operating range. [1 Mark]

(Insert your answer here.)
According to the design criteria, the load voltages at the 132kV supply have to be maintained at 0.95 – 1.05 pu. While Bus 1,3,4 and 5 are able to maintain the voltage within the desired range, Bus 2 and 6 which corresponds to the load voltages were maintained at 0.8847 and 0.9023 pu respectively, which does not fulfill the design criteria. −1 so not within range

8. What has happened to the generator reactive power, and why has this occurred? What has been the impact of adjusting the transformer taps? [1 Mark]

(Insert your answer here.)
What has happened to the generator reactive power, and why has this occurred?
The generators are considered to be connected in parallel before the lines are tripped. This would allow for increase in total system size and increase redundancy. It may also be more cost effective to combine several smaller units in preference to one larger unit [1].

The generator reactive power of GenA_MC and GenB_MC increased from **17.6/94.4** MVAR to **173.7/106.4** MVAR respectively when Line 1 tripped.
When Line 1 tripped, GenB_MC was no longer connected to the load bus. In order to maintain the voltage and power rating at the load, more current is required to flow from GenA_MC through Line 2. The increase in current flow leads to a squared increase in reactive power, due to more current flow in the line with impedance. As GenB_MC is connected to GenA_MC through line 3, it will compensate for the loss in current by also contributing more current to GenA_MC, which is why GenB_MC also experiences a slight increase in reactive power.

What has been the impact of adjusting the transformer taps?
Adjusting the transformer tap ratio, would allow the network voltages to be regulated to the desired PU range when the load voltage falls outside the desired operating range. If the load voltage falls below the desired operating range, the transformer tap ratio will decrease to increase the output voltage, and vice versa if the load voltage is above the desired operating voltage. However, for the simulation, the setting is tap locked to maintain the transformer tap ratio.

9. Insert the single line diagram with the simulation results for the Transformer Taps Locked. [1 Mark]

(Insert the diagram with the load flow data. Tripping Line 2)

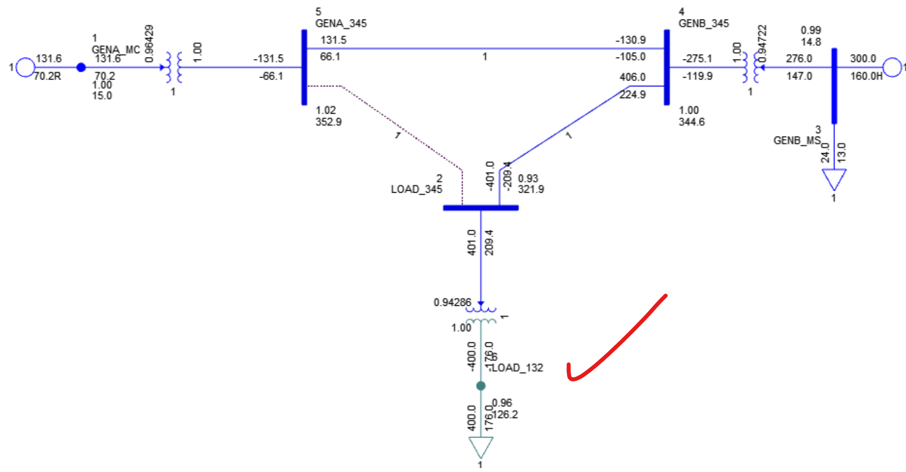


Fig. 3 Transformer Tap Locked Simulation with AC Line 2 Tripped

Bus Num	*Bus Name*	*Base kV*	$P_{gen}(MW)$	$P_{max}(MW)$	$P_{min\,(MW)}$	$Q_{gen}(MVAR)$	$Q_{max}(MVAR)$	$Q_{min\,(MVAR)}$
1	GenA_MC	15	131.6	400	0	70.2	300	-160.0

Table 7 Swing Bus Data for Transformer Tap Locked Simulation with AC Line 2 Tripped

10. Generate and print a Bus Based report for the Transformer Taps Locked. [1 Mark]

(Tripping Line 2. Full report displayed in tables from the Load Flow output.)

From BUS					GEN	LOAD	SHUNT
BUS NUM	BUS NAME	BASE kV	PU/ KV	°	P(MW) Q(MVAR)	P(MW) Q(MVAR)	P(MW) Q(MVAR)
1	GENA_MC	15.000	1.0 15.00	0.0	131.6 70.2	0.0 0.0	0.0 0.0
2	LOAD_345	345.00	0.9330 321.88	-9.0	0.0 0.0	0.0 0.0	0.0 0.0
3	GENB_MC	15.000	0.9859 14.787	1.4	300 160	24.0 13.0	0.0 0.0
4	GENB_345	345.00	0.9988 344.57	3.1	0.0 0.0	0.0 0.0	0.0 0.0
5	GENA_345	345.00	1.0299 352.90	-1.4	0.0 0.0	0.0 0.0	0.0 0.0
6	LOAD_132	132.00	0.9558 126.16	-12.9	0.0 0.0	400.0 176.0	0.0 0.0

Table 8 Bus Data for Transformer Tap Locked Simulation with AC Line 2 Tripped

From BUS	To BUS					Transformer		Rating	
BUS NUM	BUS NUM	BUS NAME	BASE kV	P(MW)	Q(MVAR)	Ratio	°	%	Set
1	5	GENA_345	345	131.6	70.2	0.964		30	500
2	4 6	GENA_345 LOAD_132	345 132	-401 401	-209.4 209.4	0.943		40 75	1200 600
3	4	GENB_345	345	276	147	0.947		89	350
4	2 3 5	LOAD_345 GENB_MS GENA_345	345 15 345	406 -275 -130.9	224.9 -119.9 -105.0	1.0		39 86 14	1200 350 1200
5	1 4	GENA_MC GENB_345	15 345	-131.5 131.5	-66.1 66.1	1.0		29 12	500 1200 1200
6	2	LOAD_345	345	-400	-176.0	1.0		73	600

Table 9 Bus Data for Transformer Tap Locked Simulation with AC Line 2 Tripped (Continued)

11. Examine the network voltages and determine if they are within the desired operating range.
[1 Marks]

(Insert your answer here.)
According to the design criteria, the load voltages at the 132kV supply has to be maintained at 0.95 – 1.05 pu. While Bus 1,3,4 and 5 are able to maintain the voltage within the desired range, and Bus 6 is able to maintain within the range at 0.9558 pu, Bus 2 fails to maintain that desired range when AC Line 2 is tripped at voltage 0.9330 pu.

12. What has happened to the generator reactive power, and why has this occurred? What has been the impact of adjusting the transformer taps? [1 Mark]

(Insert your answer here.)
What has happened to the generator reactive power, and why has this occurred?
The generator reactive power of GenA_MC and GenB_MC increased from **17.6/94.4** MVAR to **70.2/160** MVAR respectively when Line 2 tripped.
When Line 2 tripped, GenA_MC is no longer connected to the load bus. In order to maintain the voltage and power rating at the load, more current is required to flow from GenB_MC through Line 1. The increase in current flow leads to a squared increase in reactive power incurred from the reactive power in the transmission line impedance. As GenA_MC is connected to GenB_MC through line 3, it will compensate for the loss in current by also contributing more current to GenB_MC, which is why GenA_MC also experiences a slight increase in reactive power.

What has been the impact of adjusting the transformer taps?
Adjusting the transformer tap ratio, would allow the network voltages to be regulated to the desired PU range when the load voltage falls outside the desired operating range. If the load voltage falls below the desired operating range, the transformer tap ratio will decrease to increase the output voltage, and vice versa if the load voltage is above the desired operating voltage. However, for the simulation, the setting is tap locked to maintain the transformer tap ratio.

13. Insert the single line diagram with the simulation results for the Transformer Taps Locked. [1 Mark]

(Insert the diagram with the load flow data. Tripping Line 3)

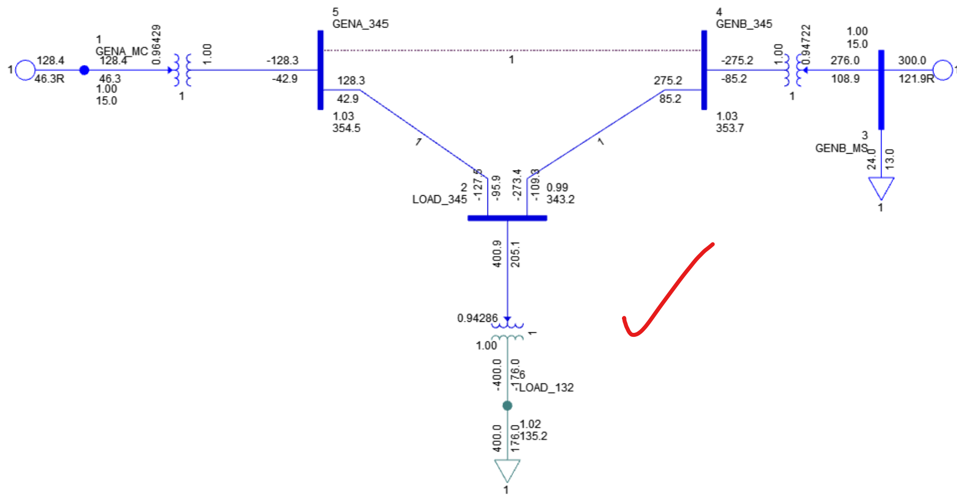


Fig. 4 Transformer Tap Locked Simulation with AC Line 3 Tripped

Bus Num	Bus Name	Base kV	$P_{gen}(MW)$	$P_{max}(MW)$	$P_{min\,(MW)}$	$Q_{gen}(MVA$	$Q_{max}(MVA$	$Q_{min\,(MVAR)}$
1	GenA_MC	15	128.4	400	0	46.3	300	-160.0

Table 10 Swing Bus Data for Transformer Tap Locked Simulation with AC Line 3 Tripped

14. Generate and print a Bus Based report for the Transformer Taps Locked. [1 Mark]

(Tripping Line 3. Full report displayed in tables from the Load Flow output.)

From BUS					GEN	LOAD	SHUNT
BUS NUM	BUS NAME	BASE kV	PU/ KV	°	P(MW) Q(MVAR)	P(MW) Q(MVAR)	P(MW) Q(MVAR)
1	GENA_MC	15.000	1.0 15.00	0.0	128.4 46.3	0.0 0.0	0.0 0.0
2	LOAD_345	345.00	0.9949 343.24	-4.1	0.0 0.0	0.0 0.0	0.0 0.0
3	GENB_MC	15.000	1.0 15.00	4.0	300 121	24.0 13.0	0.0 0.0
4	GENB_345	345.00	1.0251 353.66	-0.3	0.0 0.0	0.0 0.0	0.0 0.0
5	GENA_345	345.00	1.0275 354.5	-1.4	0.0 0.0	0.0 0.0	0.0 0.0
6	LOAD_132	132.00	1.0239 135.16	-7.4	0.0 0.0	400.0 176.0	0.0 0.0

Table 11 Bus Data for Transformer Tap Locked Simulation with AC Line 3 Tripped

From BUS	To BUS					Transformer		Rating	
BUS NUM	BUS NUM	BUS NAME	BASE kV	P(MW)	Q(MVAR)	Ratio	°	%	Set
1	5	GENA_345	345	128.4	46.3	0.964		27	500
2	4 5 6	GENB_345 GENA_345 LOAD_132	345 345 132	-273.4 -127.5 400.9	-109.3 -95.9 205.1	0.943		25 13 75	1200 1200 600
3	4	GENB_345	345	276.0	108.9	0.947		85	350
4	2 3	LOAD_345 GENB_MS	345 15	275.2 -275.2	85.2 -85.2	1.0		23 82	1200 350
5	1 2	GENA_MC LOAD_345	15 345	-128.3 128.3	-42.9 42.9	1.0		27 11	500 1200
6	2	LOAD_345	345	-400	-176.0	1.0		73	600

Table 12 Bus Data for Transformer Tap Locked Simulation with AC Line 3 Tripped (Continued)

15. Examine the network voltages and determine if they are within the desired operating range.
[1 Mark]

(Insert your answer here.)
According to the design criteria, the load voltages at the 132kV supply have to be maintained at 0.95 – 1.05 pu. Bus 2 and Bus 6 are able to be maintained within the desired range at 0.9949 and 1.0239 pu. The other buses are also able to be maintained at the desired range.

16. What has happened to the generator reactive power, and why has this occurred? What has been the impact of adjusting the transformer taps? [1 Mark]

(Insert your answer here.)
What has happened to the generator reactive power, and why has this occurred?
The generator reactive power of GenA_MC and GenB_MC increased from **17.6/94.4** MVAR to **46.3/121.9** MVAR respectively when Line 2 tripped.
Connecting generators in parallel increases the power capacity, control in load management, ease of maintenance, and redundancy. The process involves the physical connection of two or more electric generators, and the synchronization of their outputs [2]. However, when the parallel connections are disconnected, it will cause each generator to be connected to the load without synchronization. The lack of synchronicity between the 2 generators causes it to supply power to the load at unsynchronized rates, thus 2 currents flowing into the load will not be synchronized. The difference in current would cause an imbalance in the load sharing, and thus more current would have to flow from both generators to the load. The increase in current then causes an increase in the reactive power at the generators.

What has been the impact of adjusting the transformer taps?
Adjusting the transformer tap ratio, would allow the network voltages to be regulated to the desired PU range when the load voltage falls outside the desired operating range. If the load voltage falls below the desired operating range, the transformer tap ratio will decrease to increase the output voltage, and vice versa if the load voltage is above the desired operating voltage. However, for the simulation, the setting is tap locked to maintain the transformer tap ratio.

17. Insert the single line diagram with the simulation results for the Installation of Reactive Power. [1 Mark]

(Insert the diagram with the load flow data. Tripping Line 1)

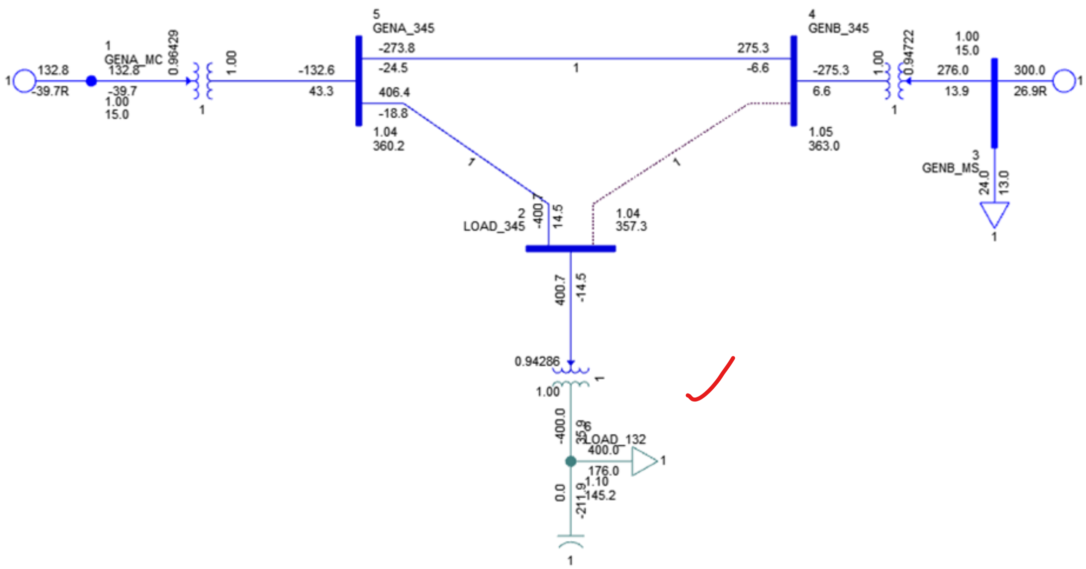


Fig 5: Single Line Diagram (Line 1 Tripped and Fixed Shunt Capacitor Installed)

Bus Num	Bus Name	Base Voltage (kV)	$P_{gen}(MW)$	$P_{max}(MW)$	$P_{min}(MW)$	$Q_{gen}(MVAR)$	$Q_{max}(MVAR)$	$Q_{min}(MVAR)$
1	GENA_MC	15.00	132.80	400.00	0	-39.70	300.00	-160.00

Table 13: Swing Bus Summary (Line 1 Tripped and Fixed Shunt Capacitor Installed)

18. Generate and print a Bus Based report for the Installation of Reactive Power. [2 Marks]

(Tripping Line 1 with a capacitor installed. Full report displayed in tables from the Load Flow output.)

From Bus			**Area**	**Voltage**		**Gen**	**Load**	**Shunt**
No	**Name**	**Base Voltage (kV)**	**Zone**	**PU (kV)**	**Angle**	**P (MW) Q (MVAR)**	**P (MW) Q (MVAR)**	**P (MW) Q (MVAR)**
1	GENA_MC	15.00	1 1	1.00 15.00	0	132.80 -39.70R	0 0	0 -0
2	LOAD_345	345.00	1 1	1.03 357.31	-10.00	0 0	0 0	0 -0
3	GENB_MC	15.00	1 1	1.00 15.00	6.40	300.00 26.90R	24.00 13.00	0 -0
4	GENB_345	345.00	1 1	1.05 362.96	2.20	0 0	0 0	0 -0
5	GENA_345	345.00	1 1	1.04 360.22	-1.40	0 0	0 0	0 -0
6	LOAD_132	132.00	1 1	1.10 145.24	-13.10	0 0	400.00 176.00	0 -211.90

Table 14: Bus Based Report (Line 1 Tripped and Fixed Shunt Capacitor Installed)

From Bus	**To Bus**							**Transformer**		**Rating**	
No	**No.**	**Name**	**Base Voltage (kV)**	**Area**	**Circuit**	**P (MW)**	**Q (MVAR)**	**Ratio**	**Angle**	**%**	**Set**
1	- 5	- GENA_345	- 345.00	- 1	- 1	- 132.80	- -39.70	- 0.964LK		- 28	- 500
2	- 5 6	- GENA_345 LOAD_132	- 345.00 132.00	- 1 1	- 1 1	- -400.70 400.70	- 14.50 -14.50	- 0.943LK		- 32 67	- 1200 600
3	- 4	- GENB_345	- 345.00	- 1	- 1	- 276.00	- 13.90	- 0.947LK		- 79	- 350
4	- 3 5	- GENB_MS GENA_345	- 15.00 345.00	- 1 1	- 1 1	- -275.30 275.30	- 6.60 -6.60	- 1.00UN		- 79 22	- 350 1200
5	- 1 2 4	- GENA_MC LOAD_345 GENB_345	- 15.00 345.00 345.00	- 1 1 1	- 1 1 1	- -132.60 406.40 -273.80	- 43.30 -18.80 -24.50	- 1.00UN		- 28 32 22	- 500 1200 1200
6	- 2	- LOAD_345	- 345.00	- 1	- 1	- -400.00	- 35.9	- 1.00UN		- 67	- 600

Table 15 : Bus Based Report (Line 1 Tripped and Fixed Shunt Capacitor Installed Continued)

19. Examine the network voltages and determine if they are within the desired operating range. What has happened to the generator reactive power, and why has this occurred? What has been the impact of adjusting the transformer taps? [1 Mark]

(Insert your answer here.)

When line 1 trips, a fixed shunt capacitor is added at bus 6. The supply voltage of 132kV must consistently fall between 0.95 and 1.05pu of its standard 132kV value. This standard holds true for all lines in service and even after any line from the 345kV transmission lines faces an outage. The requirement should be met immediately post-outage, both prior to and following transformer tapping recovery.

Load flow results, encompassing bus voltages **when line 1 is tripped** and the shunt capacitor is placed, are presented in Table 14 and Table 15. The voltage for LOAD_132 reads **1.10pu**, exceeding the optimal operational range. Voltages for Buses 1, 2, 3, and 5 stay within the optimal (desired operating) range, but Bus 4's voltage falls outside the 0.95 – 1.05 pu range.

The bus 6 load, denoted as LOAD_132, acts as an inductive load, drawing reactive power. By introducing the shunt capacitor to bus 6, reactive power can be directly supplied to this load. As a result, the generator's reactive power output requirement drops. This change is evident in the reduced reactive power from generator GENA_MC, where its Q shifts from **173.7 MVAR** (when tripping line 1 without the capacitor) to **-39.70 MVAR** (with the capacitor in place during the trip). This drop in Q boosts the power factor, thereby enhancing the system's efficiency and allowing a larger power delivery to the load.

Based on the stated relationship, a decrease in Q leads to an increase in $|VL|$. Installing the shunt capacitor results in a rise in load voltage, evident from the change in load voltage at LOAD_132: from **0.9023pu** (without the shunt capacitor when line 1 trips) to **1.10pu** (with the shunt capacitor when line 1 trips). However, the 1.10pu voltage is outside the preferred 0.95 – 1.05pu range. To bring the load voltage back within the target range, transformer tapping is an option. Despite not being directly connected to the load, the reactive power of generator GENB_MC dropped from **106.4MVAR** (without the shunt capacitor when line 1 trips) to **26.90 MVAR** with the shunt capacitor in place. This reduction in GENB_MC's reactive power is due to the interconnected nature of the network, wherein a voltage alteration in one segment can influence the voltage in other segments.

The transformer tap can be modified using a tap changer, which is designed to set the output voltage within specific limits [1], [2]. This adjustment in the transformer tap modifies the turn ratio incrementally, ensuring that the load voltage stays within 0.95 – 1.05 pu. For this scenario, since the load voltage is outside the preferred range, increasing the turn ratio will help bring down the load voltage into the ideal range. However, the simulation considered locked transformer taps, which simulates a scenario where the taps remain unchanged after an outage caused by the tripping of line 1. As a result, the load voltage remains higher than the set range throughout the simulation.

If tap adjustments were allowed, a dip below the set range would mean decreasing the turn ratio to elevate the load voltage, while a surge above would require increasing the turn ratio to bring it back to the ideal range.

20. Insert the single line diagram with the simulation results for the Installation of Reactive Power. [1 Mark]

(Insert the diagram with the load flow data. Tripping Line 2)

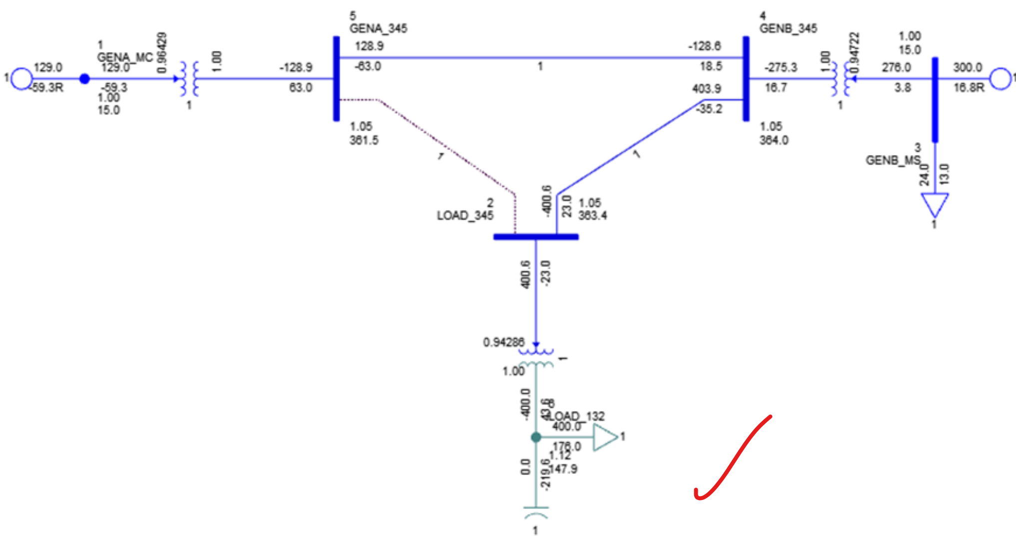


Fig 6: Single Line Diagram (Line 2 Tripped and Fixed Shunt Capacitor Installed)

Bus Num	Bus Name	Base Voltage (kV)	$P_{gen}(MW)$	$P_{max}(MW)$	$P_{min}(MW)$	$Q_{gen}(MVAR)$	$Q_{max}(MVAR)$	$Q_{min}(MVAR)$
1	GENA_MC	15.00	129.00	400.00	0	-59.30	300.00	-160.00

Table 16: Swing Bus Summary (Line 2 Tripped and Fixed Shunt Capacitor Installed)

21. Generate and print a Bus Based report for the Installation of Reactive Power. [2 Marks]

(Tripping Line 2 with a capacitor installed. Full report displayed in tables from the Load Flow output.)

From Bus			Area	Voltage		Gen	Load	Shunt
No.	**Name**	**Base Voltage (kV)**	**Zone**	**PU (kV)**	**Angle**	**P (MW) Q (MVAR)**	**P (MW) Q (MVAR)**	**P (MW) Q (MVAR)**
1	GENA_MC	15.00	1 1	1.00 15.00	0	129.00 -59.3R	0 0	0 -0
2	LOAD_345	345.00	1 1	1.05 363.44	-8.30	0 0	0 0	0 -0
3	GENB_MC	15.00	1 1	1.00 15.00	1.20	300.00 16.80R	24.00 13.00	0 -0
4	GENB_345	345.00	1 1	1.05 363.95	-3.10	0 0	0 0	0 -0
5	GENA_345	345.00	1 1	1.05 361.53	-1.40	0 0	0 0	0 -0
6	LOAD_132	132.00	1 1	1.12 147.87	-11.30	0 0	400.00 176.00	0 -219.60

Table 17: Bus Based Report (Line 2 Tripped and Fixed Shunt Capacitor Installed)

From Bus	To Bus							Transformer		Rating	
No	**No.**	**Name**	**Base Voltage (kV)**	**Area**	**Circuit**	**P (MW)**	**Q (MVAR)**	**Ratio**	**Angle**	**%**	**Set**
1	- 5	- GENA_345	- 345.00	- 1	- 1	- 129.00	- -59.30	- 0.964LK		- 28	- 500
2	- 4 6	- GENB_345 LOAD_132	- 345.00 132.00	- 1 1	- 1 1	- -400.60 400.60	- 23.00 -23.00	- 0.943LK		- 32 67	- 1200 600
3	- 4	- GENB_345	- 345.00	- 1	- 1	- 276.00	- 3.80	- 0.947LK		- 79	- 350
4	- 2 3 5	- LOAD_345 GENB_MS GENA_345	- 345.00 15.00 345.00	- 1 1 1	- 1 1 1	- 403.90 -275.30 -128.60	- -35.20 16.70 18.50	- 1.00UN		- 32 79 10	- 1200 350 1200
5	- 1 4	- GENA_MC GENB_345	- 15.00 345.00	- 1 1	- 1 1	- -128.90 128.90	- 63.00 -63.00	- 1.00UN		- 29 11	- 500 1200
6	- 2	- LOAD_345	- 345.00	- 1	- 1	- -400.00	- 43.60	- 1.00UN		- 67	- 600

Table 18: Bus Based Report (Line 2 Tripped and Fixed Shunt Capacitor Installed)

22. Examine the network voltages and determine if they are within the desired operating range.
[1 Mark]

(Insert your answer here.)
In this section, we will trip line 2 and install a fixed shunt capacitor at bus 6. The goal is to keep the supply at 132kV within a range of 0.95 – 1.05pu from its standard value of 132kV. This range should be maintained under all circumstances: with all lines operational, immediately after any line from the 345kV transmission lines experiences an outage, both before and after any transformer tapping recovery.

Load flow outputs, encapsulated in Table 17 and Table 18, illustrate bus voltages under these conditions. The voltage at LOAD_132 registers at **1.12pu**, which veers outside the optimal operational range. While the voltages for Buses 1, 2, 3, and 5 remain within the target range, the voltage at bus 4 does not, surpassing the 0.95 – 1.05 pu range.

Bus 6's load (LOAD_132) is inductive, consuming reactive power. By installing the shunt capacitor there, it aids in supplying reactive power to this load. Consequently, the generator's burden to provide reactive power lessens. This reduction is evident in the generator GENB_MC's performance: its Q drops from an initial **160 MVAR** (when line 2 is tripped without a shunt capacitor) to **16.80 MVAR** (with the capacitor in place after tripping line 2). This decrease in Q subsequently elevates the power factor, enhancing system efficacy and ensuring more power reaches the load.

As deduced from the aforementioned relationship, a decrease in Q leads to an uptick in $|VL|$. This is evident when the shunt capacitor is installed, causing an escalation in the load voltage at LOAD_132: it shifts from **0.9558pu** (when line 2 is tripped without the capacitor) to **1.12pu** (when line 2 is tripped with the capacitor). Notably, the load voltage value of **1.12 pu** surpasses the preferred range of 0.95 – 1.05pu. One way to rein the load voltage back into the optimal range is through transformer tapping.

It's worth noting that the reactive power of the generator GENA_MC reduced substantially, moving from **70.2MVAR** (without the capacitor during the tripping of line 2) to **-59.3MVAR** (with the capacitor during the tripping). Even though the generator isn't directly linked to the load, this significant reduction in reactive power can be attributed to the interconnected nature of the network. Essentially, a voltage alteration in a specific segment can resonate and influence voltage levels across other parts of the network.

A transformer tap changer is a tool that modulates the output voltage to fit desired ranges, as outlined in references [1] and [2]. This works by tweaking the transformer taps, which in turn alters the turn ratio ($\frac{Nhighvoltage}{Nlowvoltage}$) in stepped increments. The goal is to keep the load voltage within the ideal operating range of 0.95 – 1.05 pu. In the current scenario, where the load voltage surpasses this range, the turn ratio can be augmented to pull the load voltage back into the target range. It's worth noting that during the simulation, the transformer taps are locked. This represents a situation where the transformer hasn't yet reset post the outage caused by the tripping of line 2. As a result, throughout the simulation, the turn ratio remains unchanged, causing the load voltage to stay above the ideal range.

When transformer tap changing is activated, the system becomes dynamic. If the load voltage dips below the target range, the turn ratio can be lowered to elevate the load voltage back into the optimal range. Conversely, if the load voltage soars above the preferred range and transformer taps are active, one can heighten the turn ratio to decrease the load voltage back into the ideal bracket.

23. Insert the single line diagram with the simulation results for the Installation of Reactive Power. [1 Mark]

(Insert the diagram with the load flow data. Tripping Line 3)

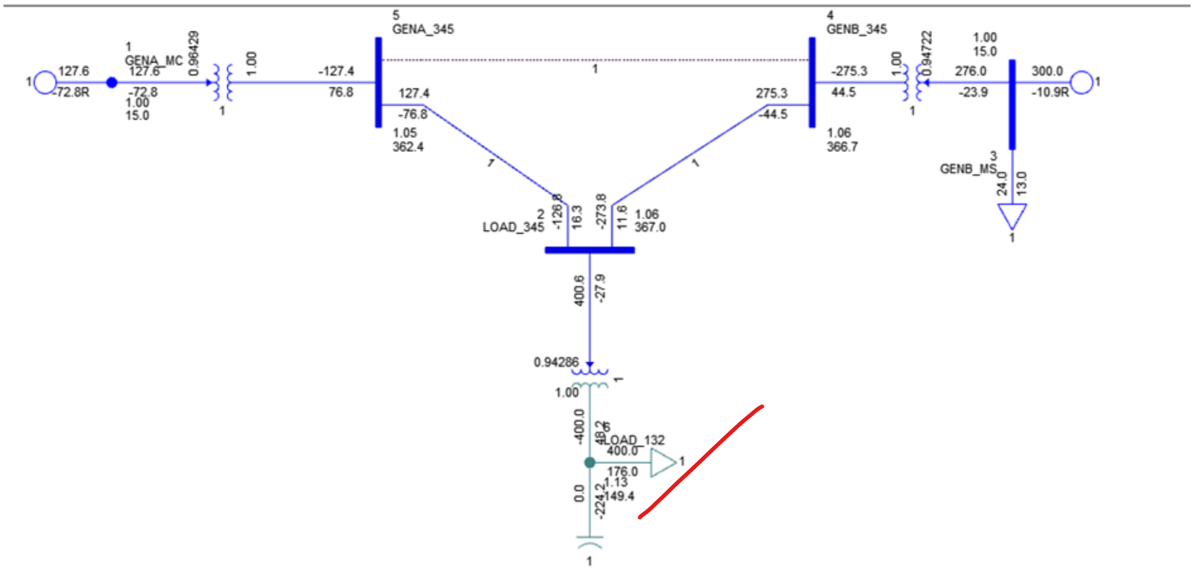


Fig 7: Single Line Diagram (Line 3 Tripped and Fixed Shunt Capacitor Installed)

Bus Num	Bus Name	Base Voltage (kV)	$P_{gen}(MW)$	$P_{max}(MW)$	$P_{min}(MW)$	$Q_{gen}(MVAR)$	$Q_{max}(MVAR)$	$Q_{min}(MVAR)$
1	GENA_MC	15.00	127.60	400.00	0	-72.80	300.00	-160.00

Table 19: Swing Bus Summary (Line 3 Tripped and Fixed Shunt Capacitor Installed)

24. Generate and print a Bus Based report for the Installation of Reactive Power. [2 Marks]

(Tripping Line 3 with a capacitor installed. Full report displayed in tables from the Load Flow output.)

From Bus			Area	Voltage		Gen	Load	Shunt
No.	**Name**	**Base Voltage (kV)**	**Zone**	**PU (kV)**	**Angle**	**P (MW) Q (MVAR)**	**P (MW) Q (MVAR)**	**P (MW) Q (MVAR)**
1	GENA_MC	15.00	1 1	1.00 15.00	0	127.60 -72.8R	0 0	0 -0
2	LOAD_345	345.00	1 1	1.06 366.99	-4.10	0 0	0 0	0 -0
3	GENB_MS	15.00	1 1	1.00 15.00	3.70	300.00 -10.90R	24.00 13.00	0 -0
4	GENB_345	345.00	1 1	1.06 366.67	-0.60	0 0	0 0	0 -0
5	GENA_345	345.00	1 1	1.05 362.43	-1.40	0 0	0 0	0 -0
6	LOAD_132	132.00	1 1	1.13 149.40	-7.00	0 0	400.00 176.00	0 -224.20

Table 20: Bus Based Report (Line 3 Tripped and Fixed Shunt Capacitor Installed)

From Bus	To Bus							Transformer		Rating	
No	No.	Name	Base Voltage (kV)	Area	Circuit	P (MW)	Q (MVAR)	Ratio	Angle	%	Set
1	- 5	- GENA_345	- 345.00	- 1	- 1	- 127.60	- -72.80	- 0.964LK		- 29	- 500
2	- 4 5 6	- GENB_345 GENA_345 LOAD_132	- 345.00 345.00 132.00	- 1 1 1	- 1 1 1	- -273.80 -126.80 400.60	- 11.60 16.30 -27.90	- 0.943LK		- 21 10 67	- 1200 1200 600
3	- 4	- GENB_345	- 345.00	- 1	- 1	- 276.00	- -23.90	- 0.947LK		- 79	- 350
4	- 2 3	- LOAD_345 GENB_MS	- 345.00 15.00	- 1 1	- 1 1	- 275.30 -275.30	- -44.50 44.50	- 1.00UN		- 22 80	- 1200 350
5	- 1 2	- GENA_MC LOAD_345	- 15.00 345.00	- 1 1	- 1 1	- -127.40 127.40	- 76.80 -76.80	- 1.00UN		- 30 12	- 500 1200
6	- 2	- LOAD_345	- 345.00	- 1	- 1	- -400.00	- 48.20	- 1.00UN		- 67	- 600

Table 21: Bus Based Report (Line 3 Tripped and Fixed Shunt Capacitor Installed)

25. Examine the network voltages and determine if they are within the desired operating range. What has happened to the generator reactive power, and why has this occurred? What has been the impact of adjusting the transformer taps? [1 Mark]

(Insert your answer here.)

In this segment, we trip line 3 and position a fixed shunt capacitor at bus 6. The 132kV supply must consistently stay within the 0.95 – 1.05pu range of its standard 132kV value. This standard should be upheld with all transmission lines operational and even after an outage of any line among the 345kV transmission lines. Additionally, this criterion must be met immediately post-outage, both prior to and following any transformer tapping recovery.

Tables 20 and 21 detail the load flow outcomes, inclusive of bus voltages, under the given conditions of a tripped line 3 and the shunt capacitor's installation. The LOAD_132 voltage is measured at **1.13pu** relative to the foundational 132kV voltage, straying beyond the optimal operating bracket. While the voltages at Buses 1, 3, and 5 align with the target range, those at Buses 2 and 4 exceed the 0.95 – 1.05 pu threshold.

Bus 6's load, denoted as LOAD_132, is inductive in nature, demanding reactive power. By installing the shunt capacitor at bus 6, the system can effectively deliver reactive power to this load. Consequently, the generator's obligation to provide reactive power diminishes. This shift is evident in the performance of the generators GENA_MC and GENB_MC. Their reactive power input, initially at **46.3MVAR** and **121.00 MVAR** respectively when line 3 is tripped without the capacitor, shifts to **-72.8MVAR** and **-10.9MVAR** respectively when the capacitor is integrated and line 3 is tripped.

When \(Q \) diminishes, the magnitude of \(VL \) ascends. This correlation is evident upon the introduction of the shunt capacitor. It prompts an uptick in the load voltage at LOAD_132, moving from **1.02 pu** (with line 3 tripped and without the capacitor) to **1.13pu** (with line 3 tripped and with the capacitor in place). Notably, the resulting voltage of **1.13pu** surpasses the preferred 0.95 – 1.05pu range.

To navigate the load voltage back within this optimal spectrum, the mechanism of transformer tapping is employed. With a transformer tap changer – a specialized tool designed to finetune the output voltage within specific bounds [1], [2] – one can amend the transformer taps. These alterations modify the turn ratio, described by ($\frac{Nhighvoltage}{Nlowvoltage}$), systematically ensuring that the load voltage remains tethered to the 0.95 – 1.05pu span. In the given context, as the load voltage overshoots the designated boundary, enhancing the turn ratio helps recalibrate the voltage within the target band.

Yet, the ongoing simulation works under a constraint where transformer taps are immobilized. This mirrors a post-outage scenario after line 3's tripping, wherein the transformer is yet to readjust. Consequently, the turn ratio stays fixed during the simulation, leading the load voltage to overshoot the targeted bounds.

In a dynamic setting where transformer tap modulation is active, varying responses can be elicited based on the load voltage. If it dips below the set bracket, the turn ratio can be scaled down to elevate it back into the range. Conversely, should the load voltage breach the upper limit and the taps remain adjustable, ramping up the turn ratio can bring it back in line with the desired range.

26. Insert the single line diagram with the simulation results for the Second Transmission Line. [1 Mark]

(Insert the diagram with the load flow data. Tripping Line 1)

Fig. 8 illustrates the single line diagram of the power system, where line 1 is tripped, and a 2nd transmission line is added between bus 2 and 4.

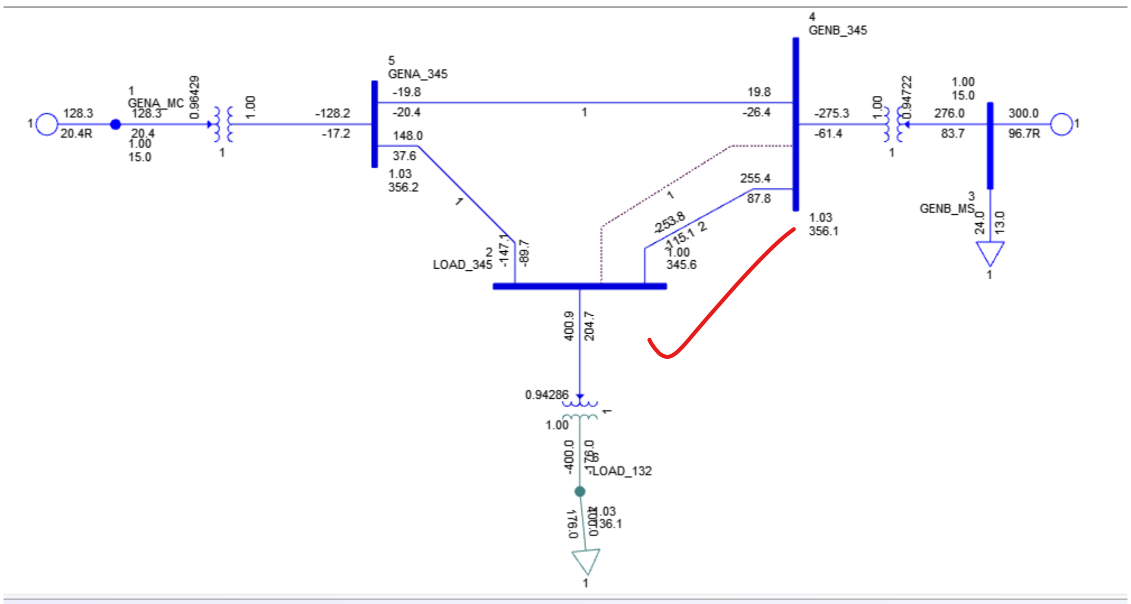


Fig 8: Single Line Diagram (Line 1 Tripped and Second Transmission Line Added)

```
SWING BUS SUMMARY:
  BUS#-SCT X-- NAME --X BASKV      PGEN     PMAX     PMIN      QGEN      QMAX     QMIN
     1      GENA_MC      15.000    128.3    400.0     0.0      20.4     300.0   -160.0
```

Table 22 shows swing bus summary, where line 1 is tripped, and a 2nd transmission line is added between bus 2 and 4.

Bus Num	Bus Name	Base Voltage (kV)	$P_{gen}(MW)$	$P_{max}(MW)$	$P_{min}(MW)$	$Q_{gen}(MVAR)$	$Q_{max}(MVAR)$	$Q_{min}(MVAR)$
1	GENA_MC	15.00	128.30	400.00	0	20.40	300.00	-160.00

Table 22: Swing Bus Summary (Line 1 Tripped and Second Transmission Line Added)

27. Generate and print a Bus Based report for a Second Transmission Line. [2 Marks]

(Tripping Line 1 with Second Transmission Line. Full report displayed in tables from the Load Flow output.)

Table 23, 24 are the bus-based report, where line 1 is tripped, and a 2nd transmission line is added between bus 2 and 4.

From Bus			Area	Voltage		Gen	Load	Shunt
No.	Name	**Base Voltage (kV)**	**Zone**	**PU (kV)**	**Angle**	**P (MW) Q (MVAR)**	**P (MW) Q (MVAR)**	**P (MW) Q (MVAR)**
1	GENA_MC	15.00	1 1	1.00 15.00	0	128.30 20.40R	0 0	0 -0
2	LOAD_345	345.00	1 1	1.00 345.56	-4.50	0 0	0 0	0 -0
3	GENB_MS	15.00	1 1	1.00 15.00	3.20	300.00 96.70R	24.00 13.00	0 -0
4	GENB_345	345.00	1 1	1.03 356.12	-1.10	0 0	0 0	0 -0
5	GENA_345	345.00	1 1	1.03 356.23	-1.40	0 0	0 0	0 -0
6	LOAD_132	132.00	1 1	1.03 136.13	-7.80	0 0	400.00 176.00	0 -0

Table 23: Bus Based Report (Line 1 Tripped and Second Transmission Line Added)

From Bus	To Bus							Transformer		Rating	
No	No.	Name	Base Voltage (kV)	Area	Circuit	P (MW)	Q (MVAR)	Ratio	Angle	%	Set
1	- 5	- GENA_345	- 345.00	- 1	- 1	- 128.30	- 20.40	- 0.964LK		- 26	- 500
2	- 4 5 6	- GENB_345 GENA_345 LOAD_132	- 345.00 345.00 132.00	- 1 1 1	- 2 1 1	- -253.80 -147.10 400.90	- -115.10 -89.70 204.70	- 0.943LK		- 23 14 75	- 1200 1200 600
3	- 4	- GENB_345	- 345.00	- 1	- 1	- 276.00	- 83.70	- 0.947LK		- 82	- 350
4	- 2 3 5	- LOAD_345 GENB_MS GENA_345	- 345.00 15.00 345.00	- 1 1 1	- 2 1 1	- 255.40 -275.30 19.80	- 87.80 -61.40 -26.40	- 1.00UN 		- 22 81 3	- 1200 350 1200
5	- 1 2 4	- GENA_MC LOAD_345 GENB_345	- 15.00 345.00 345.00	- 1 1 1	- 1 1 1	- -128.20 148.00 -19.80	- -17.20 37.60 -20.40	- 1.00UN 		- 26 12 2	- 500 1200 1200
6	- 2	- LOAD_345	- 345.00	- 1	- 1	- -400.00	- -176.00	- 1.00UN		- 73	- 600

Table 24: Bus Based Report (Line 1 Tripped and Second Transmission Line Added)

28. Examine the network voltages and determine if they are within the desired operating range. What has happened to the generator reactive power, and why has this occurred? What has been the impact of adjusting the transformer taps? [1 Mark]

(Insert your answer here.)

In this segment, **line 1 is disconnected**, and an additional transmission line is introduced between bus 2 and bus 4. The 132kV supply must consistently stay within 0.95 – 1.05pu of its standard 132kV value, regardless of any disruptions in the 345kV transmission lines. This stipulation should be met promptly after any outage, both before and after the transformer taps are restored.

Tables 23 and 24 present the load flow results, including the bus voltages, under these conditions. The voltage at LOAD_132 registers at **1.03 pu** of the foundational 132kV voltage, fitting comfortably within the prescribed range. All the other bus voltages also remain within the 0.95 – 1.05 pu bracket.

Interestingly, disconnecting line 1 mirrors the base scenario due to the supplementary transmission line between bus 2 and bus 4. Comparing both instances, the reactive power supplied by generators GENA_MC and GENB_MC reveals a modest surge from **17.60 MVAR** and **81.40 MVAR** (base case) to **20.4 MVAR** and **96.70 MVAR**, respectively. These slight variances could stem from computational discrepancies or the hardware constraints modeled in the PSS/E software.

A transformer tap changer can be employed to fine-tune the transformer taps, thus calibrating the output voltage within set limits [1], [2]. Through such adjustments, the turn ratio is modulated in intervals to ensure the load voltage aligns with the 0.95 – 1.05 pu range. Nonetheless, as the load voltage remains compliant even after the modifications, transformer tap changes aren't necessitated.

Should tap changing be activated, a decline in load voltage below the set range would necessitate a decrease in the turn ratio to realign the voltage. Conversely, if an enabled tap perceives an overshooting voltage, the turn ratio would be elevated to bring the voltage back into the desired range.

29. Insert the single line diagram with the simulation results for the Second Transmission Line. [1 Mark]

(Insert the diagram with the load flow data. Tripping Line 2)

Fig. 9 illustrates the single line diagram of the power system, where line 2 is tripped, and a 2nd transmission line is added between bus 2 and 4.

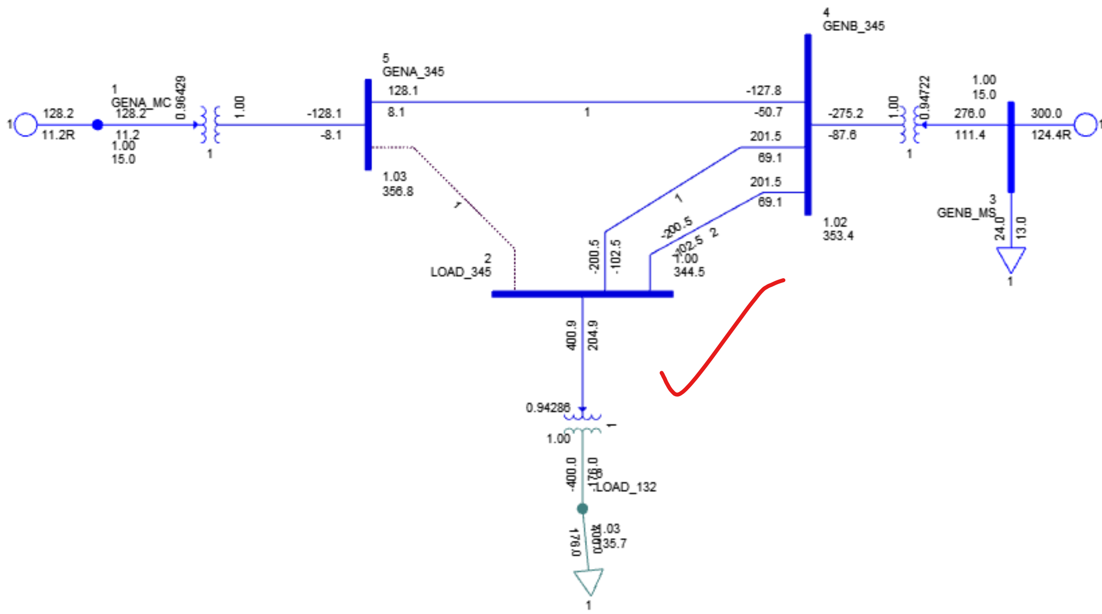


Fig 9: Single Line Diagram (Line 2 Tripped and Second Transmission Line Added)

Table 25 shows swing bus summary, where line 2 is tripped, and a 2nd transmission line is added between bus 2 and 4.

```
SWING BUS SUMMARY:
  BUS#-SCT X-- NAME --X BASKV     PGEN     PMAX    PMIN     QGEN     QMAX    QMIN
     1      GENA_MC      15.000    128.2    400.0    0.0      11.2    300.0  -160.0
```

Bus Num	Bus Name	Base Voltage (kV)	$P_{gen}(MW)$	$P_{max}(MW)$	$P_{min}(MW)$	$Q_{gen}(MVAR)$	$Q_{max}(MVAR)$	$Q_{min}(MVAR)$
1	GENA_MC	15.00	128.20	400.00	0	11.20	300.00	-160.00

Table 25: Swing Bus Summary (Line 2 Tripped and Second Transmission Line Added)

30. Generate and print a Bus Based report for the Second Transmission Line. [2 Marks]

(Tripping Line 2 with Second Transmission Line. Full report displayed in tables from the Load Flow output.)

Table 26, 27 are the bus-based report, where line 2 is tripped, and a 2nd transmission line is added between bus 2 and 4.

From Bus			**Area**	**Voltage**		**Gen**	**Load**	**Shunt**
No.	Name	**Base Voltage (kV)**	**Zone**	**PU (kV)**	**Angle**	**P (MW) Q (MVAR)**	**P (MW) Q (MVAR)**	**P (MW) Q (MVAR)**
1	GENA_MC	15.00	1 1	1.00 15.00	0	128.20 11.20R	0 0	0 -0
2	LOAD_345	345.00	1 1	1.00 344.54	-5.80	0 0	0 0	0 -0
3	GENB_MS	15.00	1 1	1.00 15.00	1.30	300.00 124.40R	24.00 13.00	0 -0
4	GENB_345	345.00	1 1	1.02 353.41	-3.10	0 0	0 0	0 -0
5	GENA_345	345.00	1 1	1.03 356.83	-1.40	0 0	0 0	0 -0
6	LOAD_132	132.00	1 1	1.03 135.70	-9.10	0 0	400.00 176.00	0 -0

Table 26: Bus Based Report (Line 2 Tripped and Second Transmission Line Added)

From Bus	To Bus							Transformer		Rating	
No	No.	Name	Base Voltage (kV)	Area	Circuit	P (MW)	Q (MVAR)	Ratio	Angle	%	Set
1	- 5	- GENA_345	- 345.00	- 1	- 1	- 128.20	- 11.20	- 0.964LK		- 26	- 500
2	- 4 4 6	- GENB_345 GENB_345 LOAD_132	- 345.00 345.00 132.00	- 1 1 1	- 1 2 1	- -200.50 -200.50 400.90	- -102.50 -102.50 204.90	- 0.943LK		- 19 19 75	- 1200 1200 600
3	- 4	- GENB_345	- 345.00	- 1	- 1	- 276.00	- 111.40	- 0.947LK		- 85	- 350
4	- 2 2 3 5	- LOAD_345 LOAD_345 GENB_MS GENA_345	- 345.00 345.00 15.00 345.00	- 1 1 1 1	- 1 2 1 1	- 201.50 201.50 -275.20 -127.80	- 69.10 69.10 -87.60 -50.70	- 1.00UN		- 17 17 83 11	- 1200 1200 350 1200
5	- 1 4	- GENA_MC GENB_345	- 15.00 345.00	- 1 1	- 1 1	- -128.10 128.10	- -8.10 8.10	- 1.00UN		- 26 10	- 500 1200
6	- 2	- LOAD_345	- 345.00	- 1	- 1	- -400.00	- -176.00	- 1.00UN		- 73	- 600

Table 27: Bus Based Report (Line 2 Tripped and Second Transmission Line Added)

31. Examine the network voltages and determine if they are within the desired operating range. What has happened to the generator reactive power, and why has this occurred? What has been the impact of adjusting the transformer taps? [1 Mark]

(Insert your answer here.)

In this segment, **line 2 is disconnected**, and an additional transmission line is introduced between bus 2 and bus 4. The 132kV supply must consistently stay within 0.95 – 1.05pu of its standard 132kV value, regardless of any disruptions in the 345kV transmission lines. This stipulation should be met promptly after any outage, both before and after the transformer taps are restored.

Tables 26 and 27 present the load flow results, including the bus voltages, under these conditions. The voltage at LOAD_132 registers at **1.03 pu** of the foundational 132kV voltage, fitting comfortably within the prescribed range. All the other bus voltages also remain within the 0.95 – 1.05 pu bracket.

The reactive power output of generator "GenB_ms" diminished from **160 MVAR** (under the condition of line 2 disconnection without any supplementary line) to **124.4 MVAR** (upon tripping line 2 with an additional line). The introduction of the 2nd transmission line introduces an effective line impedance in parallel configuration between bus 2 and 4. The equivalent line impedance experiences a reduction, leading to a decrease in the reactive power consumption along the line spanning from bus 2 to bus 4. Applying the principle of power conservation, the reactive power consumed by both transmission lines and the load remains equivalent to the reactive power supplied by the generators, denoted as

$$Qgen = Qline + Qload$$

While maintaining Qload at a constant level, the reduction in Qline consequently induces a decrease in Qgen, thereby having the observed decline in the reactive power by generator "GenB_ms."

The reactive power output of generator "GenA_mc" increased from **70.2 MVAR** (in the scenario of line 2 disconnection without any supplementary line) to **11.2 MVAR** (upon tripping line 2 with an additional line), despite its lack of direct connection to the load.

Transformer tap adjustments are facilitated through the utilization of a transformer tap changer, an apparatus employed for regulating the output voltage within specified ranges [1], [2]. This manipulation of transformer taps instigates modifications to the turn ratio in incremental steps, thereby ensuring the maintenance of load voltage within the designated operational range of 0.95 to 1.05 per unit (pu). It is noteworthy, that in situations where the load voltage remains within the operational range despite the occurrence of line 2 tripping and the installation of an additional transmission line, the status of the transformer taps would remain unaltered, even in cases where tap adjustment is enabled.

32. Insert the single line diagram with the simulation results for the Second Transmission Line. [1 Mark]

(Insert the diagram with the load flow data. Tripping Line 3)

Fig. 10 illustrates the single line diagram of the power system, where line 3 is tripped, and a 2nd transmission line is added between bus 2 and 4.

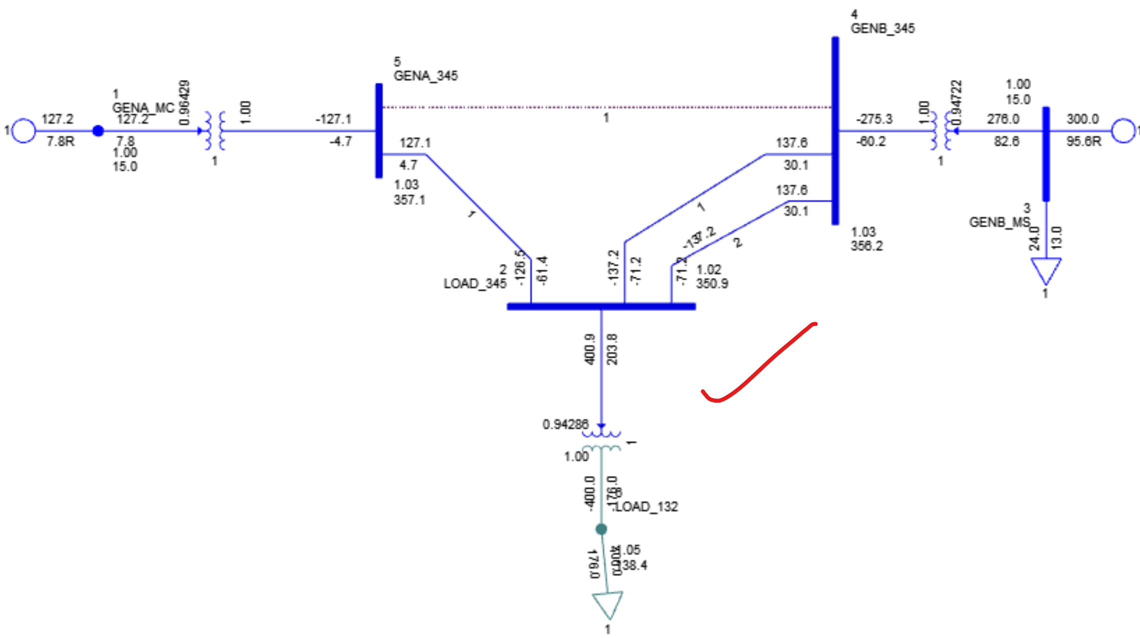


Fig 10: Single Line Diagram (Line 3 Tripped and Second Transmission Line Added)

Table 28 shows swing bus summary, where line 3 is tripped, and a 2nd transmission line is added between bus 2 and 4.

```
SWING BUS SUMMARY:
  BUS#-SCT X-- NAME --X BASKV      PGEN     PMAX    PMIN      QGEN     QMAX    QMIN
     1      GENA_MC      15.000    127.2    400.0    0.0       7.8     300.0  -160.0
```

Bus Num	Bus Name	Base Voltage (kV)	$P_{gen}(MW)$	$P_{max}(MW)$	$P_{min}(MW)$	$Q_{gen}(MVAR)$	$Q_{max}(MVAR)$	$Q_{min}(MVAR)$
1	GENA_MC	15.00	127.20	400.00	0	7.80	300.00	-160.00

Table 28: Swing Bus Summary (Line 3 Tripped and Second Transmission Line Added)

33. Generate and print a Bus Based report for the Second Transmission Line. [2 Marks]

(Tripping Line 3 with Second Transmission Line. Full report displayed in tables from the Load Flow output.)

Table 29, 30 are the bus-based report, where line 3 is tripped, and a 2nd transmission line is added between bus 2 and 4.

From Bus			**Area**	**Voltage**		**Gen**	**Load**	**Shunt**
No.	Name	**Base Voltage (kV)**	**Zone**	**PU (kV)**	**Angle**	**P (MW) Q (MVAR)**	**P (MW) Q (MVAR)**	**P (MW) Q (MVAR)**
1	GENA_MC	15.00	1 1	1.00 15.00	0	127.20 7.80R	0 0	0 -0
2	LOAD_345	345.00	1 1	1.02 350.93	-4.00	0 0	0 0	0 -0
3	GENB_MS	15.00	1 1	1.00 15.00	2.10	300.00 95.60R	24.00 13.00	0 -0
4	GENB_345	345.00	1 1	1.03 356.24	-2.20	0 0	0 0	0 -0
5	GENA_345	345.00	1 1	1.04 357.06	-1.40	0 0	0 0	0 -0
6	LOAD_132	132.00	1 1	1.05 138.38	-7.20	0 0	400.00 176.00	0 -0

Table 29: Bus Based Report (Line 3 Tripped and Second Transmission Line Added)

From Bus	To Bus							Transformer		Rating	
No	No.	Name	Base Voltage (kV)	Area	Circuit	P (MW)	Q (MVAR)	Ratio	Angle	%	Set
1	- 5	- GENA_345	- 345.00	- 1	- 1	- 127.20	- 7.80	- 0.964LK		- 25	- 500
2	- 4 4 5 6	- GENB_345 GENB_345 GENA_345 LOAD_132	- 345.00 345.00 345.00 132.00	- 1 1 1 1	- 1 2 1 1	- -137.20 -137.20 -126.50 400.90	- -71.20 -71.20 -61.40 203.80	- 0.943LK		- 13 13 12 75	- 1200 1200 1200 600
3	- 4	- GENB_345	- 345.00	- 1	- 1	- 276.00	- 82.60	- 0.947LK		- 82	- 350
4	- 2 2 3	- LOAD_345 LOAD_345 GENB_MS	- 345.00 345.00 15.00	- 1 1 1	- 1 2 1	- 137.60 137.60 -275.30	- 30.10 30.10 -60.20	- 1.00UN		- 11 11 81	- 1200 1200 350
5	- 1 2	- GENA_MC LOAD_345	- 15.00 345.00	- 1 1	- 1 1	- -127.10 127.10	- -4.70 4.70	- 1.00UN		- 25 10	- 500 1200
6	- 2	- LOAD_345	- 345.00	- 1	- 1	- -400.00	- -176.00	- 1.00UN		- 73	- 600

Table 30: Bus Based Report (Line 3 Tripped and Second Transmission Line Added)

34. Examine the network voltages and determine if they are within the desired operating range. What has happened to the generator reactive power, and why has this occurred? What has been the impact of adjusting the transformer taps? [1 Mark]

(Insert your answer here.)

In this segment, **line 3 is disconnected**, and an additional transmission line is introduced between bus 2 and bus 4. The 132kV supply must consistently stay within 0.95 – 1.05pu of its standard 132kV value, regardless of any disruptions in the 345kV transmission lines. This stipulation should be met promptly after any outage, both before and after the transformer taps are restored.

Tables 29 and 30 present the load flow results, including the bus voltages, under these conditions. The voltage at LOAD_132 registers at **1.05 pu** of the foundational 132kV voltage, fitting comfortably within the prescribed range. All the other bus voltages also remain within the 0.95 – 1.05 pu bracket.

The reactive power output of generator "GenB_ms" diminished from **121 MVAR** (under the condition of line 2 disconnection without any supplementary line) to **95.60 MVAR** (upon tripping line 3 with an additional line). The introduction of the 2nd transmission line introduces an effective line impedance in parallel configuration between bus 2 and 4. The equivalent line impedance experiences a reduction, leading to a decrease in the reactive power consumption along the line spanning from bus 2 to bus 4. Applying the principle of power conservation, the reactive power consumed by both transmission lines and the load remains equivalent to the reactive power supplied by the generators, denoted as

$$Qgen = Qline + Qload$$

While maintaining Qload at a constant level, the reduction in Qline consequently induces a decrease in Qgen, thereby having the observed decline in the reactive power by generator "GenB_ms."

The reactive power output of generator "GenA_mc" increased from **46.3 MVAR** (in the scenario of line 3 disconnection without any supplementary line) to **7.80 MVAR** (upon tripping line 3 with an additional line), despite its lack of direct connection to the load.

Transformer tap adjustments are facilitated through the utilization of a transformer tap changer, an apparatus employed for regulating the output voltage within specified ranges [1], [2]. This manipulation of transformer taps instigates modifications to the turn ratio in incremental steps, thereby ensuring the maintenance of load voltage within the designated operational range of 0.95 to 1.05 per unit (pu). It is noteworthy, that in situations where the load voltage remains within the operational range despite the occurrence of line 3 tripping and the installation of an additional transmission line, the status of the transformer taps would remain unaltered, even in cases where tap adjustment is enabled.

35. Insert the single line diagram with the simulation results for the Second Transmission Line. [1 Mark]

(Insert the diagram with the load flow data. Tripping Line 4)

Fig. 11 illustrates the single line diagram of the power system, where line 4 is tripped, and a 2nd transmission line is added between bus 2 and 4.

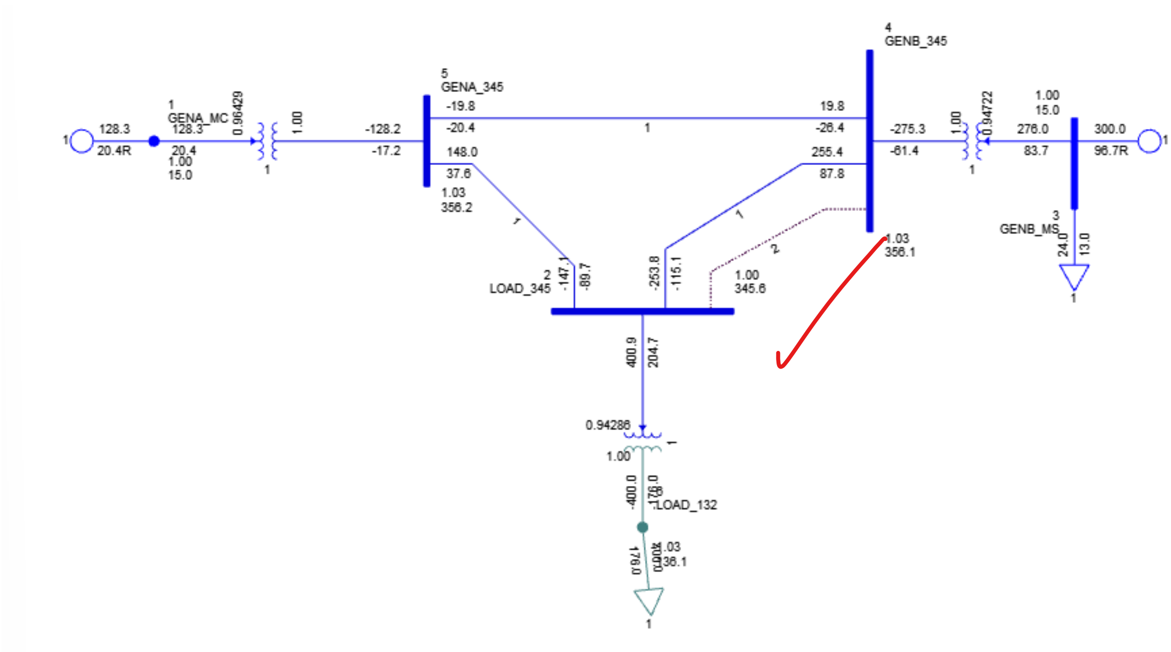


Fig 11: Single Line Diagram (Line 4 Tripped and Second Transmission Line Added)

Table 31 shows swing bus summary, where line 4 is tripped, and a 2nd transmission line is added between bus 2 and 4.

```
SWING BUS SUMMARY:
  BUS#-SCT X-- NAME --X BASKV      PGEN     PMAX    PMIN      QGEN     QMAX    QMIN
     1      GENA_MC      15.000    128.3    400.0     0.0     20.4    300.0  -160.0
```

Bus Num	Bus Name	Base Voltage (kV)	$P_{gen}(MW)$	$P_{max}(MW)$	$P_{min}(MW)$	$Q_{gen}(MVAR)$	$Q_{max}(MVAR)$	$Q_{min}(MVAR)$
1	GENA_MC	15.00	128.30	400.00	0	20.40	300.00	-160.00

Table 31: Swing Bus Summary (Line 3 Tripped and Fixed Shunt Capacitor Installed)

36. Generate and print a Bus Based report for the Second Transmission Line. [2 Marks]

(Tripping Line 4 with Second Transmission Line. Full report displayed in tables from the Load Flow output.)

Table 32, 33 are the bus-based report, where line 4 is tripped, and a 2nd transmission line is added between bus 2 and 4.

From Bus			**Area**	**Voltage**		**Gen**	**Load**	**Shunt**
No.	Name	**Base Voltage (kV)**	**Zone**	**PU (kV)**	**Angle**	**P (MW)** **Q (MVAR)**	**P (MW)** **Q (MVAR)**	**P (MW)** **Q (MVAR)**
1	GENA_MC	15.00	1 1	1.00 15.00	0	128.30 20.40R	0 0	0 -0
2	LOAD_345	345.00	1 1	1.00 345.56	-4.50	0 0	0 0	0 -0
3	GENB_MS	15.00	1 1	1.00 15.00	3.20	300.00 96.70R	24.00 13.00	0 -0
4	GENB_345	345.00	1 1	1.03 356.12	-1.10	0 0	0 0	0 -0
5	GENA_345	345.00	1 1	1.03 356.23	-1.40	0 0	0 0	0 -0
6	LOAD_132	132.00	1 1	1.03 136.13	-7.80	0 0	400.00 176.00	0 -0

Table 32: Bus Based Report (Line 4 Tripped and Second Transmission Line Added)

From Bus	To Bus							Transformer		Rating	
No	No.	Name	Base Voltage (kV)	Area	Circuit	P (MW)	Q (MVAR)	Ratio	Angle	%	Set
1	-	-	-	-	-	-	-	-		-	-
	5	GENA_345	345.00	1	1	128.30	20.40	0.964LK		26	500
2	-	-	-	-	-	-	-	-		-	-
	4	GENB_345	345.00	1	1	-253.80	-115.10			23	1200
	5	GENA_345	345.00	1	1	-147.10	-89.70			14	1200
	6	LOAD_132	132.00	1	1	400.90	204.70	0.943LK		75	600
3	-	-	-	-	-	-	-	-		-	-
	4	GENB_345	345.00	1	1	276.00	83.70	0.947LK		82	350
4	-	-	-	-	-	-	-	-		-	-
	2	LOAD_345	345.00	1	1	255.40	87.80			22	1200
	3	GENB_MS	15.00	1	1	-275.30	-61.40	1.00UN		81	350
	5	GENA_345	345.00	1	1	19.80	-26.40			3	1200
5	-	-	-	-	-	-	-	-		-	-
	1	GENA_MC	15.00	1	1	-128.20	-17.20	1.00UN		26	500
	2	LOAD_345	345.00	1	1	148.00	37.60			12	1200
	4	GENB_345	345.00	1	1	-19.80	-20.40			2	1200
6	-	-	-	-	-	-	-	-		-	-
	2	LOAD_345	345.00	1	1	-400.00	-176.00	1.00UN		73	600

Table 33: Bus Based Report (Line 4 Tripped and Second Transmission Line Added)

37. Examine the network voltages and determine if they are within the desired operating range. What has happened to the generator reactive power, and why has this occurred? What has been the impact of adjusting the transformer taps? [1 Mark]

(Insert your answer here.)

In this segment, **line 3 is disconnected**, and an additional transmission line is introduced between bus 2 and bus 4. The 132kV supply must consistently stay within 0.95 – 1.05pu of its standard 132kV value, regardless of any disruptions in the 345kV transmission lines. This stipulation should be met promptly after any outage, both before and after the transformer taps are restored.

Tables 32 and 33 present the load flow results, including the bus voltages, under these conditions. The voltage at LOAD_132 registers at **1.03 pu** of the foundational 132kV voltage, fitting comfortably within the prescribed range. All the other bus voltages also remain within the 0.95 – 1.05 pu bracket.

Similar to the scenario involving the tripping of line 1 followed by the introduction of an additional transmission line. The act of tripping line 4 aligns with the baseline condition. This alignment can be attributed to the presence of a supplementary transmission line bridging between bus 2 and bus 4. Upon contrasting these two scenarios, a marginal increase is discerned in the reactive power contributions from generators.

`GenA_mc" increased from **17.6 MVAR** to **20.40 MVAR**; and "GenB_ms," shifting from **94.4 MVAR** to **96.70 MVAR**, upon tripping line 4 in conjunction with the second transmission line. With the introduction of a second transmission line, the outcomes for the event of tripping line 4 converge to coincide with those of tripping line 1, substantiated by the fact that both line 1 and line 4 establish connections between bus 2 and bus 4. These slight divergences might emanate from potential simulation discrepancies or intrinsic hardware imperfections embedded within the PSS/E software.

Transformer tap adjustments are facilitated through the utilization of a transformer tap changer, an apparatus employed for regulating the output voltage within specified ranges [1], [3]. This manipulation of transformer taps instigates modifications to the turn ratio in incremental steps, thereby ensuring the maintenance of load voltage within the designated operational range of 0.95 to 1.05 per unit (pu). It is noteworthy, that in situations where the load voltage remains within the operational range despite the occurrence of line 4 tripping and the installation of an additional transmission line, the status of the transformer taps would remain unaltered, even in cases where tap adjustment is enabled.

Conclusion [1 Mark]

(Include your conclusion and state the learning outcomes of this experiment.)

To sum up, we conducted load flow analyses on a small-scale power system. The system's performance was assessed based on a 5% tolerance, specifically within an operating range of 0.95-1.05 per unit for the 132kV base voltage at the load substation. By adjusting the transformer taps iteratively, we evaluated each network scenario.

Initially, we assessed the base case solution involving 3 transmission lines, all of which were active. Despite slight discrepancies in the simulation outcomes (potentially caused by software computation errors), the base case was valuable for contrasting with subsequent experiments wherein the lines underwent individual tripping.

In the next phase, we explored the consequences of tripping transmission lines sequentially. Upon tripping lines 1 and 2, the load bus voltage fell below the preferred range, an outcome of disconnecting generators directly from the load bus. Additionally, the generators' reactive power surged due to an uptick in reactive power consumed by the active lines, amplifying the network's overall reactive power consumption.

In the third segment, we introduced shunt capacitors at the load bus. These capacitors served as reactive power sources, diminishing the need for generator-supplied reactive power. In some instances, they even provided reactive power back to the generators, causing them to operate in an under excited state. These capacitors can also modulate the voltage at the load by tweaking the reactive power. Nevertheless, a voltage surge beyond the acceptable range was observed, primarily because the simulations didn't employ transformer tapping. Incorporating an on-load tap changer might keep the voltage within the 0.95 – 1.05pu range.

Lastly, the experiment focused on integrating a secondary transmission line between GENB_MC (bus 4) and the load bus (bus 2). With this arrangement, tripping individual lines still maintained load bus voltages within the desired range, possibly owing to the newly-added line's voltage regulation. This setup also safeguards against a single point of failure between buses 2 and 4. With both lines active, the line impedance between these buses lessens, cutting down power usage across the network's transmission lines. This, in turn, reduces the reactive power generators need to furnish, as evidenced by our simulations.

In summary, the objectives of this experiment were successfully met. We explored the impact of line tripping, investigated the significance of shunt capacitors, and delved into the implications of adding more transmission lines. Without enabling tap changing and in the absence of a secondary transmission line between bus 2 and bus 4, the network falls short of upholding the design specifications to keep the load voltage within the 5% margin (0.95 – 1.05pu). To guarantee compliance with these criteria, we emphatically suggest the deployment of a shunt capacitor at the load to minimize the reactive power supplied by the generator. Additionally, introducing a secondary transmission line can thwart single points of failure, while enabling tap changing is crucial for effective voltage regulation at the load bus.

References [1 Mark]

(Include the references here)

[1] Charlie," What are generators in parallel? Why use generators in parallel? How do you get generators in parallel? " Welland Power, 24th August 2023, https://support.wellandpower.net/hc/en-us/articles/360001993337-What-are-generators-in-parallel-Why-use-generators-in-parallel-How-do-you-get-generators-in-parallel-#:~:text=while%20generally%20unlikely.-,Why%20use%20generators%20in%20parallel%3F,preference%20to%20one%20%20large%20%20unit.

[2] anon, "▷ Paralleling of Generators and Synchronization," Electrical Equipment, Sep. 01, 2016. https://engineering.electrical-equipment.org/electrical-distribution/paralleling-generators-synchronization.html#:~:text=Connecting%20generators%20in%20parallel%20increases (accessed Aug. 24, 2023).

[3] Inst Tools. "What is a Transformer Tap Changer?" instrumentationtools.com. Accessed: Sep. 2, 2023. [Online]. Available: https://instrumentationtools.com/transformer-tap-changer/

******** THE END *******

SCHOOL OF ENGINEERING

ELECTRICAL AND COMPUTER SYSTEMS ENGINEERING

LABORATORY REPORT MARKING RUBRIC

ECE4053: POWER SYSTEM ANALYSIS

Experiment Number: ____________________4_________________________________

Title of Lab Sheet: _________________System Stability__________________________

Group Number: _________________________7_________________________________

No.	Student ID	Name of Group Members	Total Marks
1	30720230	Loh Jia Quan	96/100
2	32259417	Chong Yen Juin	
3	30719305	Huan Meng Hui	
4	32194471	Tan Jin Chun	

MARKS BREAKDOWN

Area	Total Score	Actual Marks	Scoring Band	Criteria
Format	5	5	4-5	The overall report contents present a clear, presentable, formal, readable and organized format, as per laboratory report guideline.
			2-3	The report has most sections which present a clear, presentable, formal, readable and organized format, as per laboratory report guideline.
			0-1	Most sections presented in a messy manner and did not follow the laboratory report guideline.
Figs and Diagram	5	5	4-5	Extensive Figs and diagrams with clear explanation and numbered labels.
			2-3	Extensive Figs and diagrams without clear explanation and numbered labels.
			0-1	Insufficient Figs and diagrams & without clear explanation and numbered labels.
Objectives and Equipment	5	5	3	Detailed description of the objectives and list of all equipment used.
			2	Brief description of the objectives and list of all equipment used.
			0-1	Unclear description of the objectives and list of all equipment used.
Results and Discussion	25	23	20 - 25	Comprehensive comparison, evaluation and justification of the results, with clear explanation on the theoretical and experimental/ simulation results.
			11-19	Brief comparison, evaluation and justification of the results, with unclear explanation on the theoretical and experimental/ simulation results.
			0-10	No comparison, evaluation and justification of the results, with unsatisfactory explanation on the theoretical and experimental/ simulation results.
Conclusion and References	10	10	8-10	Clear understanding on the experiment with summarized conclusion. ln-text citations and IEEE referencing format is properly done. (3 references)
			4-7	Unclear understanding on the experiment with summarized conclusion, but without the supporting evidence of results. ln-text citations and references' format are improperly done. (2 references)
			0-3	Unclear understanding on the experiment without summarized conclusion and the evidence of results. In-text citations and references are absent. (0 – 1 reference)
Total	50	48		Deductions on pages 14, 17

Examiner/ Assessor of ECE 4053: Power System Analysis
Date: 25/9/23

EXPERIMENT 4

1. Objectives [5 Marks]

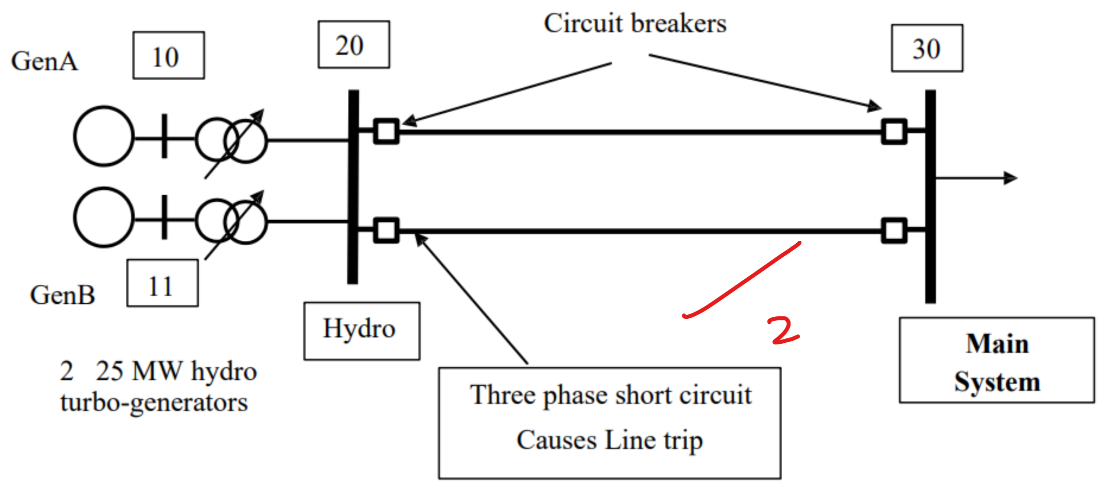
(List the three objectives of this experiment.)

(a) To carry out stability studies on a small-scale power system, and determine whether the system is operating within the required performance criteria.
(b) To investigate what corrective measures are appropriate to improve the system dynamic performance
(c) To gain experience using PSSE - a commercial power systems simulation software

5

2. Insert the single line simulation diagram for 50MW Installation. [2 Marks]

(Insert the single line diagram with the data.)



2

Fig 1. Single Line Simulation Diagram for 50MW Installation

3. 50MW Installation plots for the longest stable fault clearance time and the first unstable result. [4 Marks]

(Insert your graphical results.)

When the fault clearance time is 1.08s

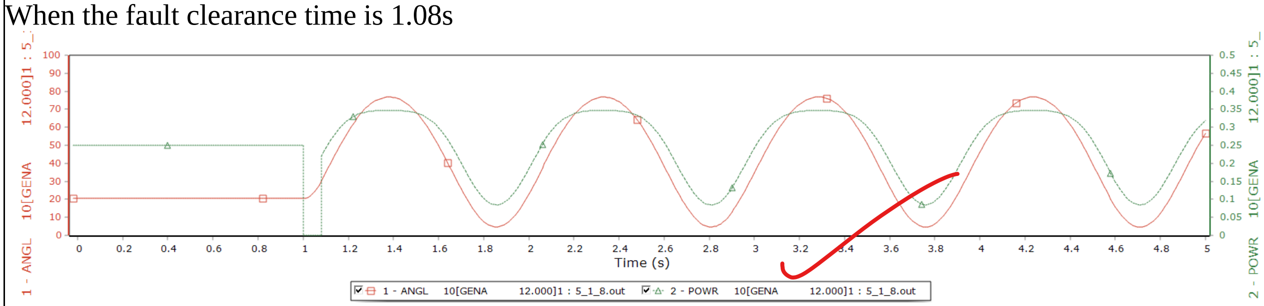


Fig 2. Power (Green) and Angle (Red) plots for the shortest stable fault clearance time for 50 MW installation

When the fault clearance time is 1.12s

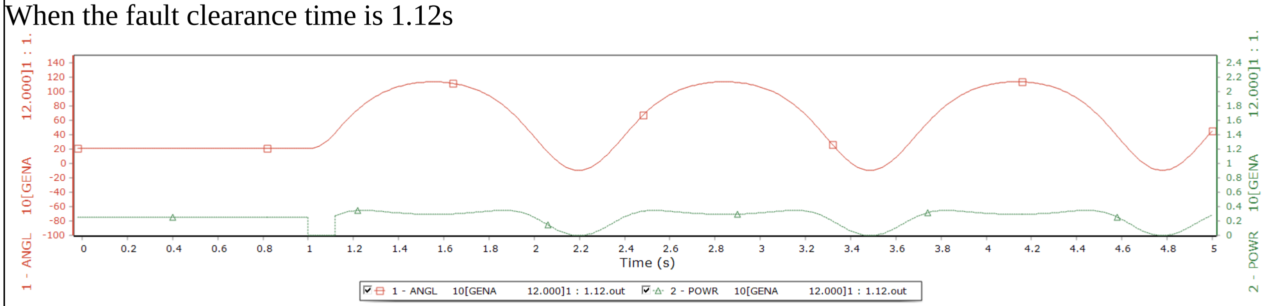


Fig 3. Power (Green) and Angle (Red) plots for the longest stable fault clearance time for 50 MW installation

When the fault clearance time is 1.13s

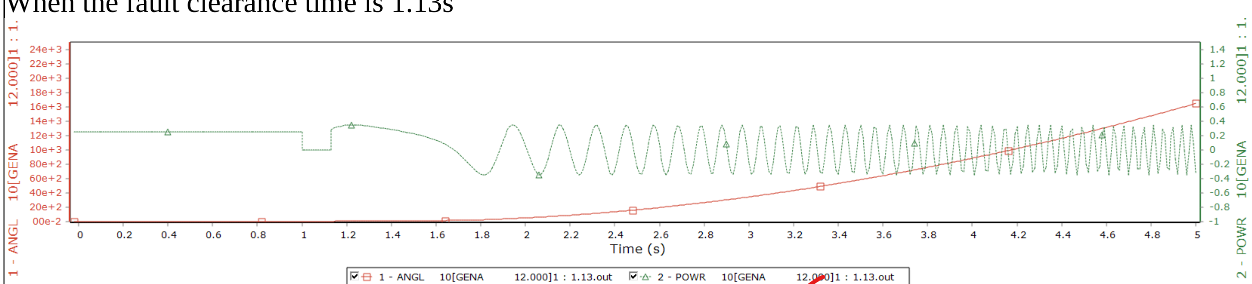


Fig 4. Power (Green) and Angle (Red) plots for the first unstable fault clearance time for 50 MW installation

4

4. Is the system stable for a fault cleared by the installed protection and circuit breakers? (Explain using the power angle graph). [3 Marks]

(Insert your answer here.)

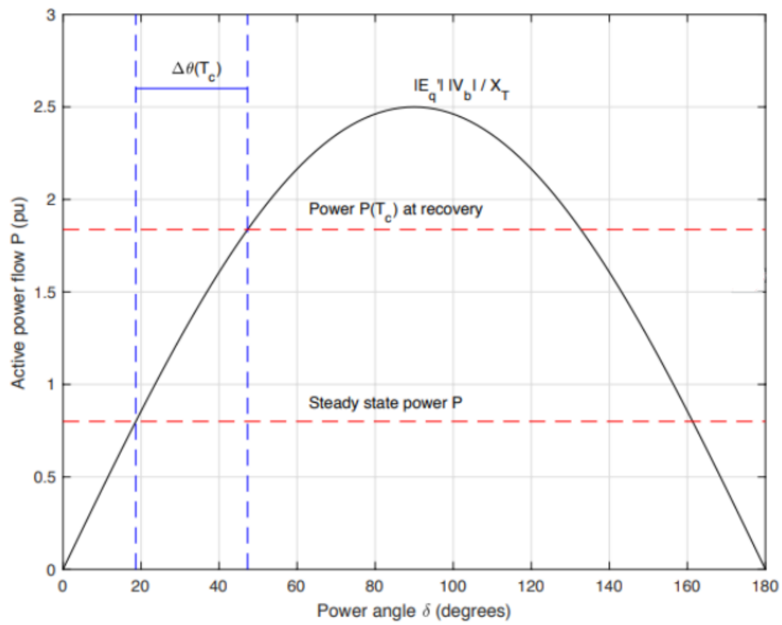


Fig 5: The Power Angle Relation Graph

This analysis is aimed at determining the system's transient stability under various fault clearance time scenarios. When the system is subjected to meticulous testing with a resolution of 0.01 seconds, it is observed that the system exhibits stability if the fault clearance time is equal to or less than 1.12 seconds. As the fault clearance time increases beyond this threshold of 1.12 seconds, the transient stability of the system diminishes.

Within a two-bus power network, the active power P generated can be approximated using the given equation [1]:

$$P = \frac{|E'_q||V_b|}{X_T} \sin\delta$$

E_q' signifies the transient electromotive force (EMF), V_b represents the infinite bus voltage, X_T is the transmission line reactance, and δ denotes the phase angle of E_q' (the machine q-axis) relative to the infinite bus.

If a short-circuit fault arises at the machine terminal at time t=0, the estimated power flow during the recovery phase becomes [1]:

$$P(T_C) = \frac{|E'_q||V_b|}{X_T} \sin\delta(T_C)$$

T_C represents the fault clearance time.

The power-angle relationship within a two-bus network and the impact of angle variation during a fault are depicted in Fig 5. The equal-area criterion is useful in assessing the stability of a power grid following the occurrence and clearance of a fault. This criterion is grounded in the power-angle relationship graph, and it serves two crucial purposes [2,3]:

1. Estimating Power Angle Movement (δ) during Recovery from a Fault:
    a. The first function of the equal-area criterion is to provide an estimate of the total angular movement, denoted as δ, that the power system experiences during the recovery phase following a fault. This is essential because during and after a fault, the power angles within the grid can deviate significantly from their initial values.
2. Determining Transient Stability Conditions:
    a. The second function of the equal-area criterion is to determine the conditions under which transient stability is achieved or, conversely, when transient instability or pole slipping occurs. These terms are related to the ability of the power system to maintain a stable operation following a disturbance like a fault. Here's what these conditions mean:
    b. Transient Stability: This condition refers to the ability of the power system to recover to a steady-state operation after experiencing a disturbance. In the context of the equal-area criterion, it implies that the power angle (δ) returns to a stable, constant value once the system has undergone transient oscillations.
    c. Transient Instability/Pole Slipping: On the other hand, transient instability occurs when the power angle does not return to a stable value but continues to deviate uncontrollably. This is often referred to as pole slipping because the angle moves away from a stable operating point, potentially leading to further instability and potential equipment damage.

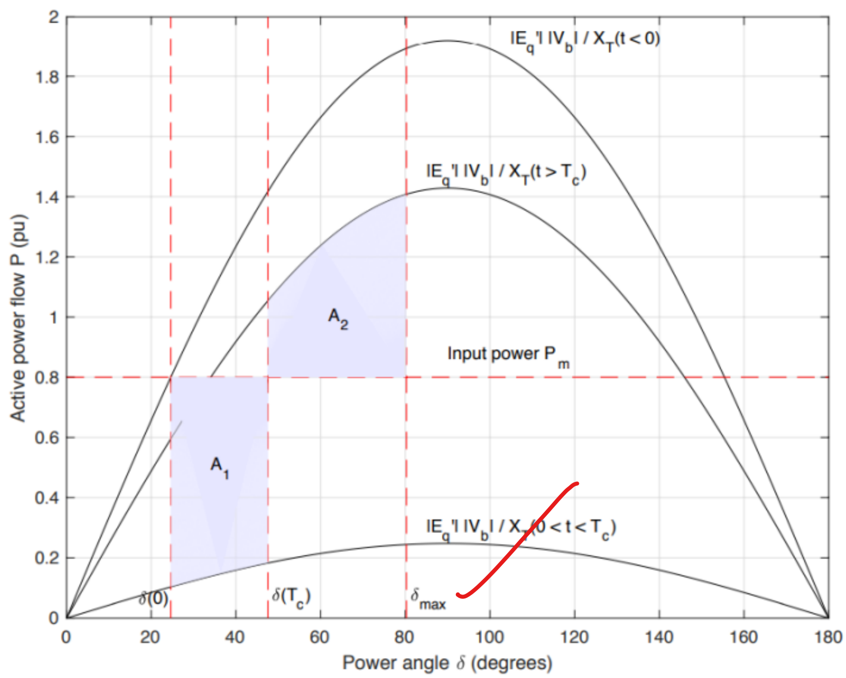


Fig 6. Line fault, equal-area criterion [1]; the highest line is the network before fault, the middle line is the network after fault, and the lowest line is the network during fault

The relationship is trivial, where an increase in power would increase δ_{max} as they are proportional. The area under the power angle diagram is given as $A = \int_{\delta_1}^{\delta_2} (P_m - P(\delta))\, d\delta$.

According to the equal-area criterion, for the system to remain stable following a fault cleared by the protection and circuit breakers, it is imperative that A1 equals A2. Consequently, the fault clearance time (T_C) must be sufficiently short to prevent $\delta(T_C)$ from surpassing the critical angle, thereby allowing A2 to be equal to A1. For a 50 MW installation, the fault clearance time T_C must be less than or equal to 1.12 seconds to fulfill the equal-area criterion. As TC increases, $\delta(T_C)$ and A1, the accelerating energy, increase concurrently. This elevated A1, indicative of an increased $\delta(T_C)$, leaves a smaller margin for A2.

However, when A1 increases, A2 needs to span a larger area to maintain equilibrium with A1. Consequently, an increase in TC diminishes the transient stability of the network, as the likelihood of meeting the equal area criterion diminishes.

In our experimental analysis, for a 50 MW installation, an escalation in the fault clearance time leads to a critical clearing time breach when T_C = 1.13 seconds. At this specific T_C value, δ_{max} is undefined as $\delta(T_C)$ has exceeded a critical angle threshold and the expansion of A1 is excessively substantial, making it infeasible for A2 to match A. This situation corresponds to the occurrence of transient instability when T_C = 1.13 seconds for the 50MW installation.

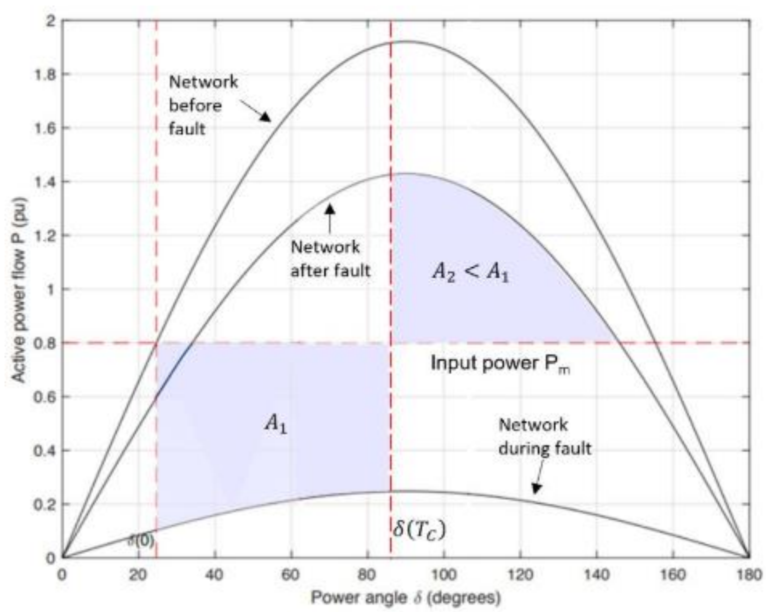
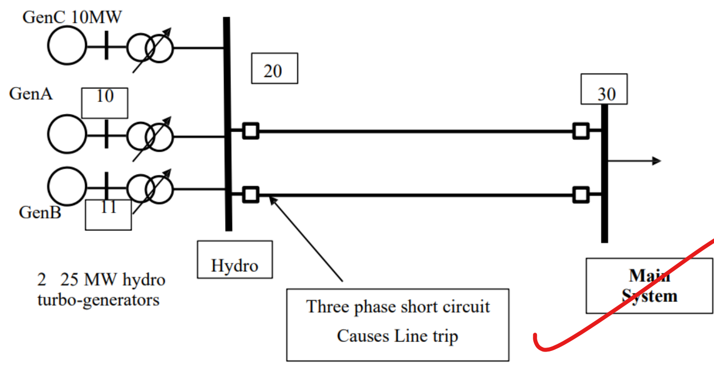


Fig 7. Scenario where equal-area criterion cannot be fulfilled [2]

3

5. Insert the single line simulation diagram for 60MW Generation Installation. [2 Marks]

(Insert the single line diagram with the data.)



2

Fig 8. Single Line Simulation Diagram for 60 MW installation

6. 60MW Generation Installation plots for the longest stable fault clearance time and the first unstable result. [4 Marks]

(Insert your graphical results.)

When the fault clearance time is 1.08s

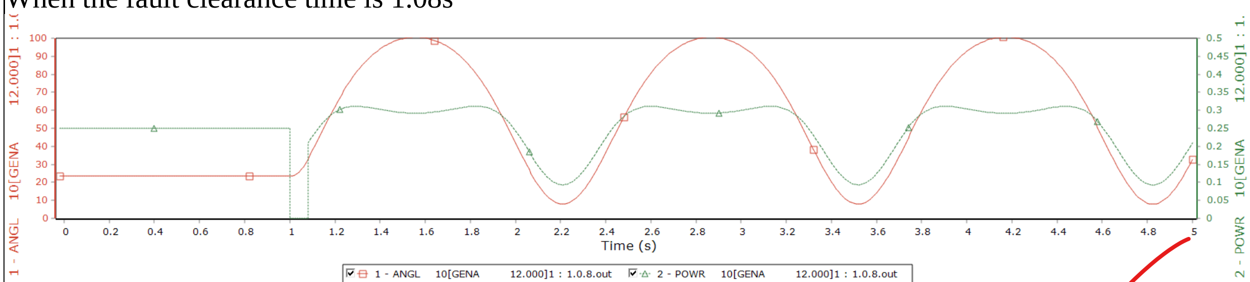


Fig 9. Power (Green) and Angle (Red) plots for the first and longest stable fault clearance time for 60 MW installation

When the fault clearance time is 1.09s

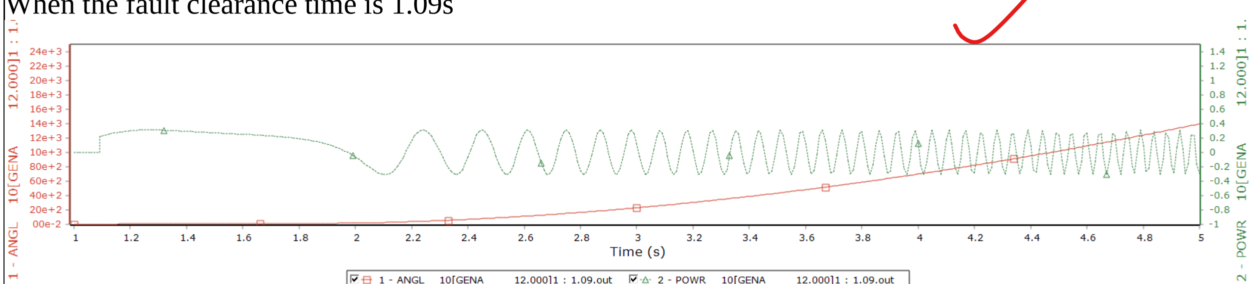


Fig 10. Power (Green) and Angle (Red) plots for the first and longest stable fault clearance time for 60 MW installation

4

7. Is the system stable for a fault cleared by the installed protection and circuit breakers? (Explain using the power angle graph). [3 Marks]

(Insert your answer here.)

This analysis is aimed at determining the system's transient stability under various fault clearance time scenarios after the addition of a 10MW Generator. When the system is subjected to testing with a resolution of 0.01 seconds, it is observed that the system exhibits stability if the fault clearance time is equal to or less than 1.08 seconds, decreasing from 1.13 second from the previous experiment. As the fault clearance time increases beyond this threshold of 1.08 seconds, the transient stability of the system diminishes.

Within a two-bus power network, the active power P generated can be approximated using the given equation [1]:

$$\boldsymbol{P(t) = \frac{|E_q||V_b|}{X_T} sin\ \delta(t)}$$

E_q' signifies the transient electromotive force (EMF), V_b represents the infinite bus voltage, X_T is the transmission line reactance, and δ denotes the phase angle of E_q' (the machine q-axis) relative to the infinite bus.

If a short-circuit fault arises at the machine terminal at time t=0, the estimated power flow during the recovery phase becomes [1]:

$$\boldsymbol{P(T_C) = \frac{|E_q||V_b|}{X_T} sin\ \delta(T_C)}$$

T_C represents the fault clearance time.

The relationship is trivial, where an increase in power would increase δ_{max} as they are proportional. The area under the power angle diagram is given as $A = \int_{\delta_1}^{\delta_2} (P_m - P(\delta))\ d\delta$. As the generator is added to the network, P_m rises. This increase in P_m has a direct impact on area, A. A higher P_m leads to a larger area under the power-angle curve.

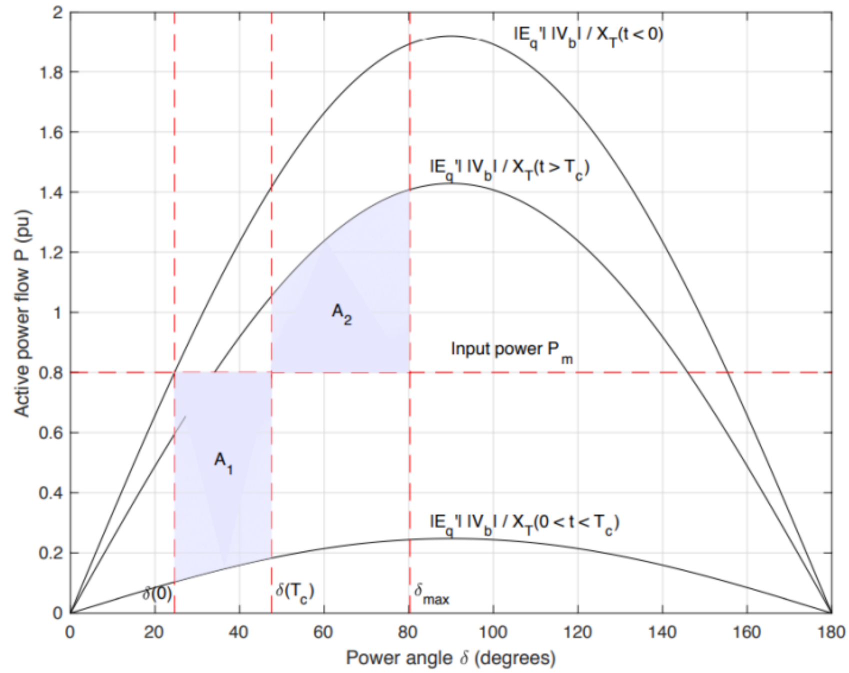


Fig 11. Line fault, equal-area criterion [1]; the highest line is the network before fault, the middle line is the network after fault, and the lowest line is the network during fault; Before increased in input power

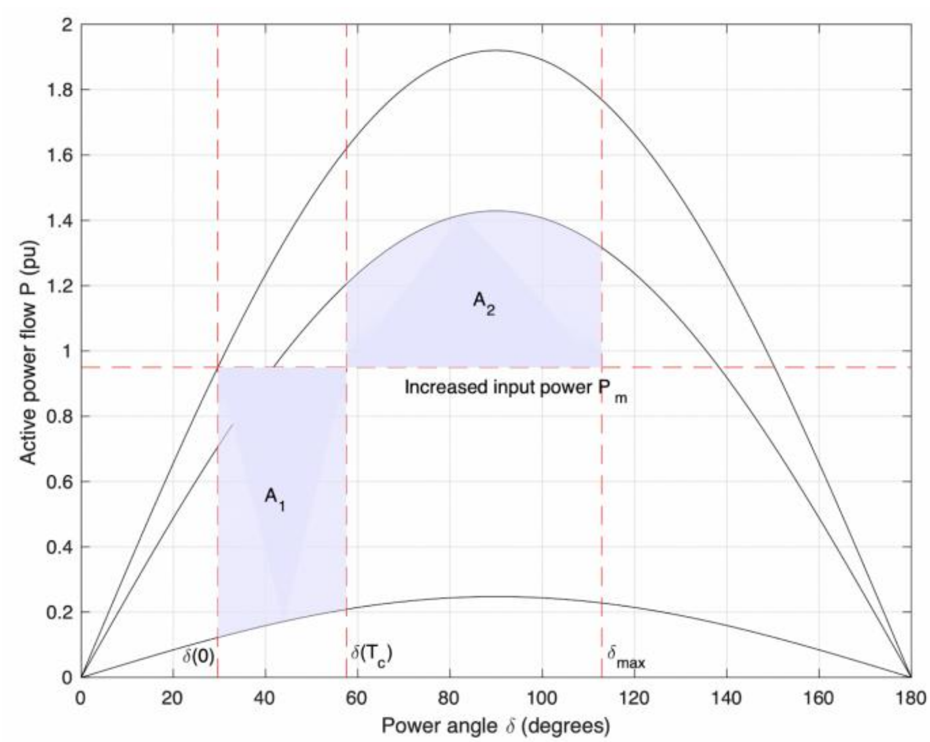


Fig 12. Line fault, equal-area criterion [1]; the highest line is the network before fault, the middle line is the network after fault, and the lowest line is the network during fault; After increased in input power [2]

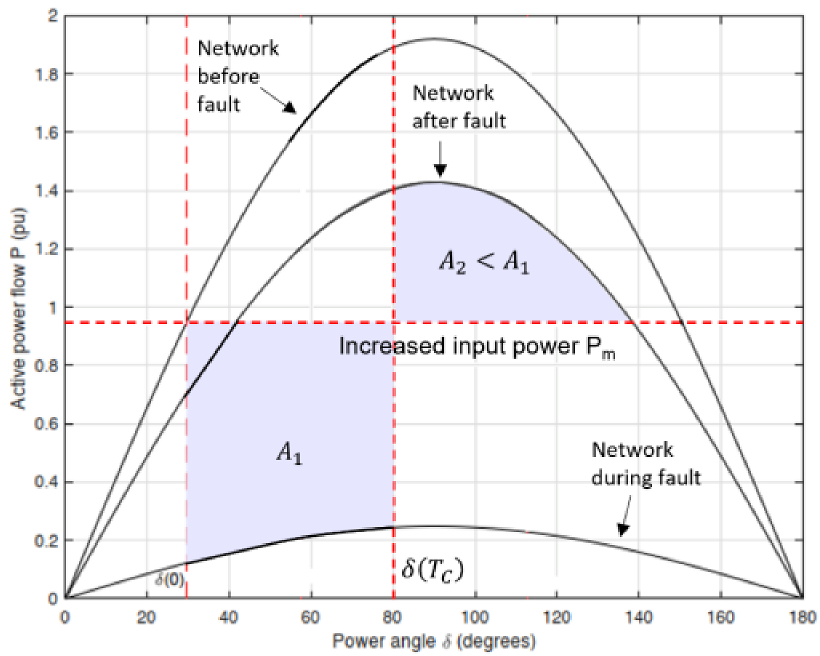


Fig 13. Power Angle Relation Graph (Equal-Area Criterion Cannot be Met) [2]

Fig 11 illustrates the application of the equal-area criterion to a power network with a sufficiently low fault clearance time. Three distinct curves are presented: the curve with the highest peak power corresponds to the network's pre-fault condition (pre-contingent steady state), the second-highest peak power curve represents the network during the recovery phase after the fault, and the curve with the lowest peak power reflects the network's configuration during the fault itself. Two critical energy components, A1 and A2, are identified within this framework. A1 signifies the accelerating energy, responsible for increasing speed deviation, while A2 represents the decelerating energy, which serves to decrease speed deviation. According to the equal-area criterion, for the system to maintain stability following the clearance of a fault by the installed protection and circuit breakers, we assert that A1 equals A2. Consequently, the fault clearance time (TC) must be sufficiently short to prevent the power angle (δ) at TC from surpassing the critical angle, thereby allowing A2 to be equal to A1. In the case of a 60 MW installation, the fault clearance time, TC, must be less than or equal to 1.08 seconds to satisfy the equal-area criterion.

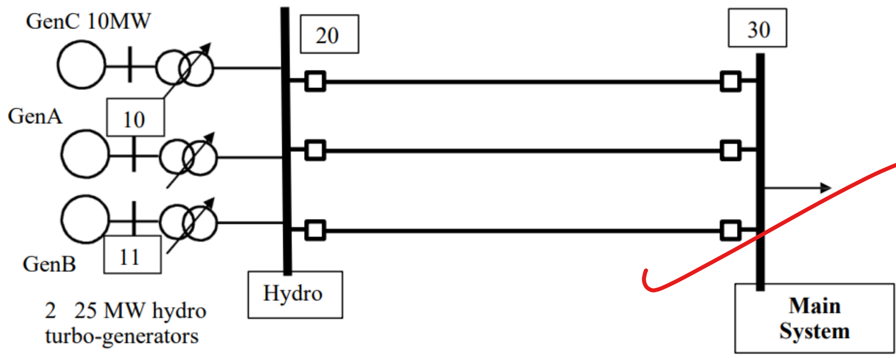
In Fig 12, it is observed that an increase in input power (Pm) from 50MW (the previous installation) to 60MW (the current installation) results in a higher value of A1, representing the accelerating energy. This increase in A1 reduces the available margin for A2, as depicted in the same figure. However, as A1 increases, A2 must span a larger area to maintain equality with A1. Consequently, an increase in TC degrades the transient stability of the network, as indicated by the lower critical clearance time for the 60MW installation. Specifically, the critical clearing time reduced from 1.12 seconds for the 50MW installation to 1.08 seconds for the 60MW installation.

Furthermore, when the fault clearance time TC equals 1.09 seconds, which exceeds the critical clearance time of 1.08 seconds, the expansion of A1 becomes too substantial, as depicted in Fig 13. In this scenario, the equal-area criterion cannot be met, indicating the occurrence of transient instability.

3

8. Insert the single line simulation diagram for 60MW Generation and Additional Line. [2 Marks]

(Insert the single line diagram with the data.)



2

Fig 14. The Single Line Simulation Diagram for 60 MW Generation and Additional Line

9. 60MW Generation and Additional Line plot for the fault clearance time at T = 1.1s. [3 Marks]

(Insert your graphical results.)

When the fault clearance time is 1.10s

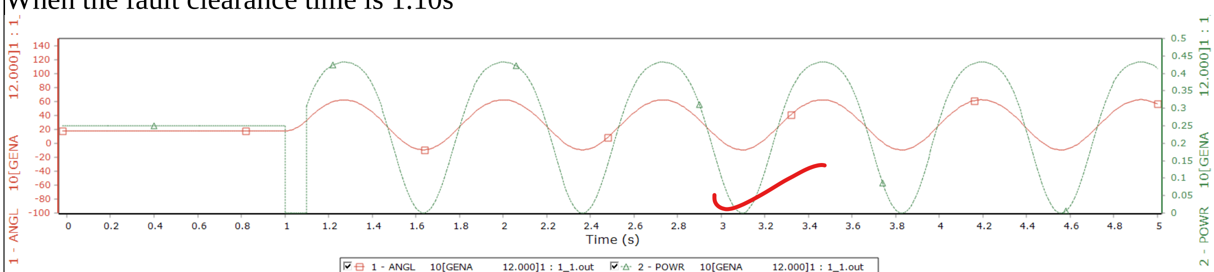
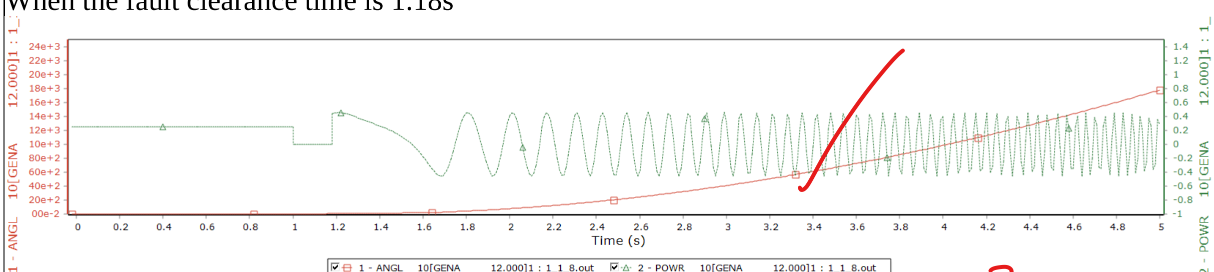


Fig 15. Power (Green) and Angle (Red) plots for the first and longest stable fault clearance time for 60 MW installation and additional line

When the fault clearance time is 1.18s



3

Fig 16. Power (Green) and Angle (Red) plots for the first and longest stable fault clearance time for 60 MW installation and additional line

10. Is the system stable for a fault cleared by the installed protection and circuit breakers? (Explain using the power angle graph). [3 Marks]

(Insert your answer here.)

When evaluated with a precision of 0.01s, the system remains stable if a fault is cleared within a time frame of 1.17s by the integrated protection and circuit breakers. This suggests that as the fault clearance time increases, transient stability diminishes. Should the fault clearance time extend to 1.18s, surpassing the 1.17s stability threshold, the system exhibits instability for cleared faults. The critical clearance time has been extended from 1.08s in the prior setup (60MW without an extra line) to 1.17s in the latest arrangement (60MW with an extra line), indicating an enhancement in transient stability due to the added line.

Multiple techniques exist to enhance the transient stability of a power system. One can achieve this by elevating the power-angle curves associated with the post-fault network configuration. This involves boosting its peak value, determined using the given formula [1]:

$$P(\frac{\pi}{2}) = \frac{|E_q^{'}|\,|V_b|}{X_T}$$

The equation suggests that decreasing X_T can enhance transient stability. By introducing a new line between the infinite bus and the generator-connected bus, one can effectively lower the transmission network's impedance during its recovery phase. As depicted in Fig. 17, let's consider Z_N as the impedance of the added line. If the lower line with impedance Z_2 encounters a fault and is subsequently isolated, the impedance of the remaining transmission lines becomes $(Z_1 \parallel Z_N)$ instead of solely (Z_1). When Z_N matches Z_1, the impedance (and consequently, the line reactance) during recovery is effectively cut by half.

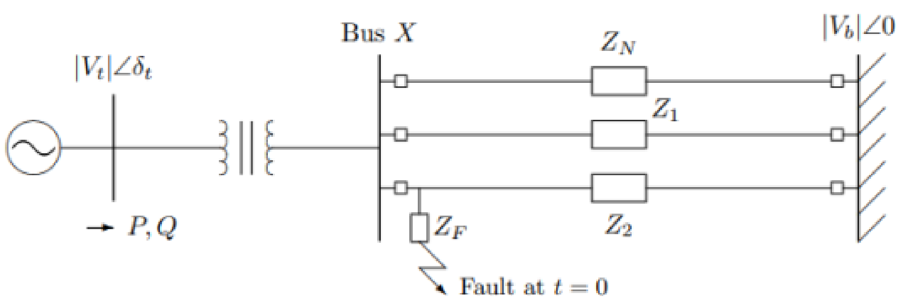


Fig 17. The Single Line Diagram with Additional Line, ZN [2]

The inclusion of an extra line amplifies the peak value of the post-fault curve ($t > TC$) compared to the peak of the pre-fault curve ($t < 0$). Conversely, the peak value of the during-fault curve ($0 < t < TC$) diminishes relative to the pre-fault curve's peak ($t < 0$). The impact of this added line on the power-angle relation curves is illustrated in the figure below.

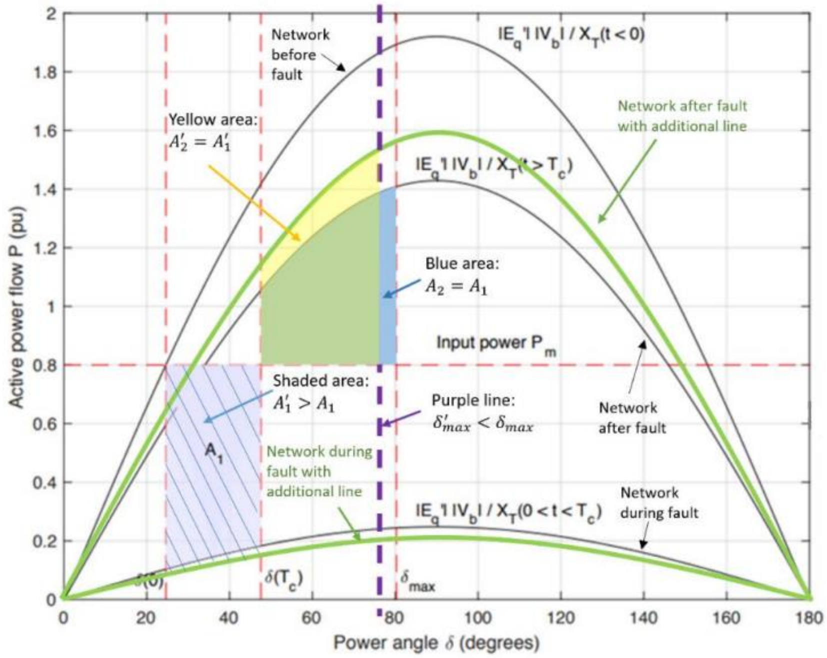


Fig 18. Power-Angle Relation Curve with the Effect of an Additional Line [2]

In the figure above, the peak of the post-fault curve for $(t > TC)$ rises, aligning with the depicted green curve. Elevating this post-fault curve causes the area spanned by $A2$ to grow notably for the same power angle range from $\delta(TC)$ to $\delta(max)$. While the during-fault curve $0 < (t < TC)$ has a diminished peak and appears lower—represented by the green curve in the figure above—its power reduction is marginal due to scaling. Consequently, the growth from $A1$ to $A1'$ is minimal. The sizable increase in $A2$ for the same power angle range is more noteworthy than the slight rise in $A1$. In fact, $A2$ can match the area of $A1$ at a reduced δmax compared to the scenario without the extra line $\delta max' < \delta max$. The visual in the figure above illustrates the area difference for scenarios with $A1'$ and $A2'$ and without $A1$ and $A2$ the added line. Evidently, the augmented area of $A2$ provides a more generous buffer for fault clearance time before system instability. This means that TC can be extended in comparison to setups lacking the extra line, up until $A2$ is smaller than $A1$ and can no longer satisfy the equal-area criterion. Our experimental data corroborates this, showing the critical clearing time for the updated setup (60MW with an extra line) is 1.17s—greater than its predecessor (60MW without the extra line) which stood at 1.08s. 2

electrical and mechanical output impacts -1

11. Insert the single line simulation diagram for 60MW Generation and Series Capacitors.
[3 Marks]

(Insert the single line diagram with the data.)

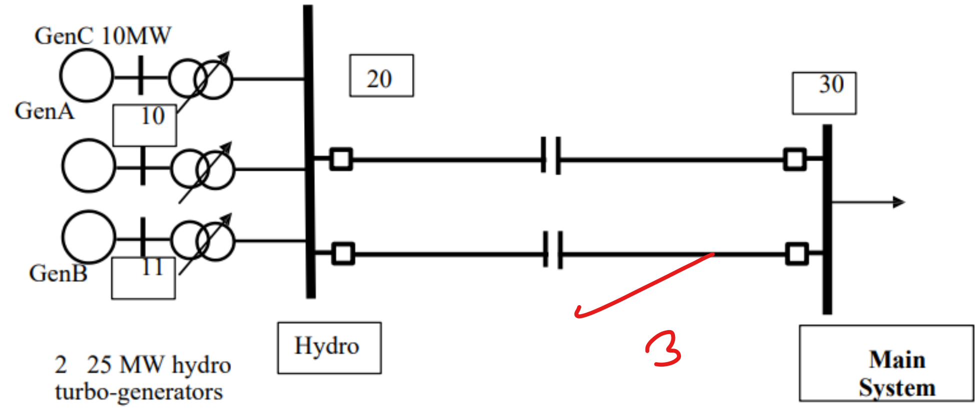


Fig 19. Single line diagram for 60MW installation with series capacitor

12. 60MW Generation and Series Capacitors plot for the fault clearance time at T = 1.1s.
[3 Marks]

(Insert your graphical results.)
Fig. 20 shows the power (green) and angle (red) plots for the longest stable fault clearance time tested (1.10s) for 60MW installation and series capacitor.

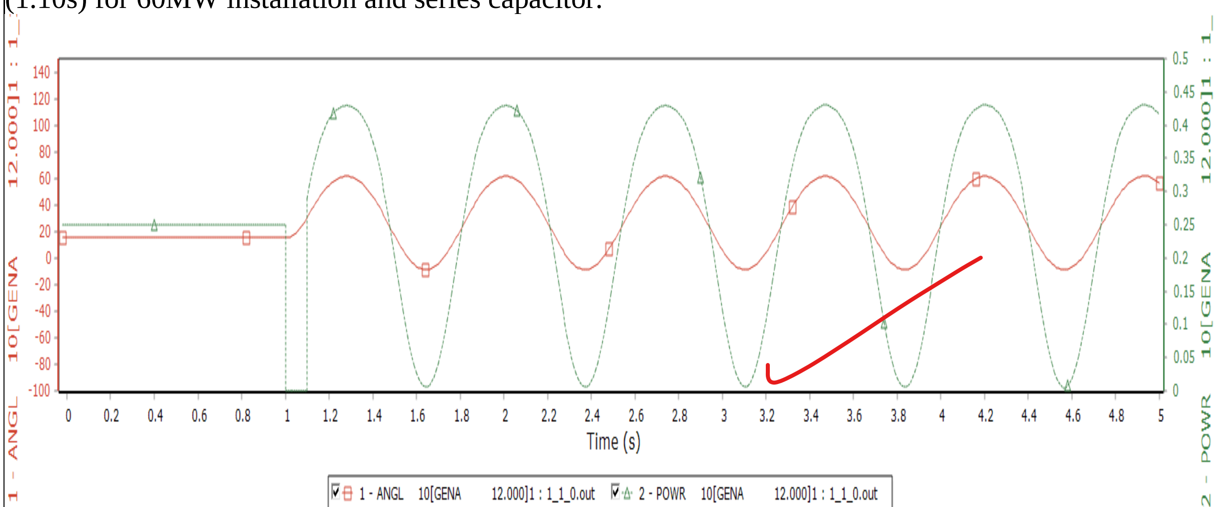


Fig 20. Power (green) and angle (red) plots for longest stable fault clearance time (1.10s) for 60MW installation and Series Capacitor

Fig. 21 shows the power (green) and angle (red) plots for the first unstable fault clearance time tested (1.18s) for 60MW installation and series capacitor.

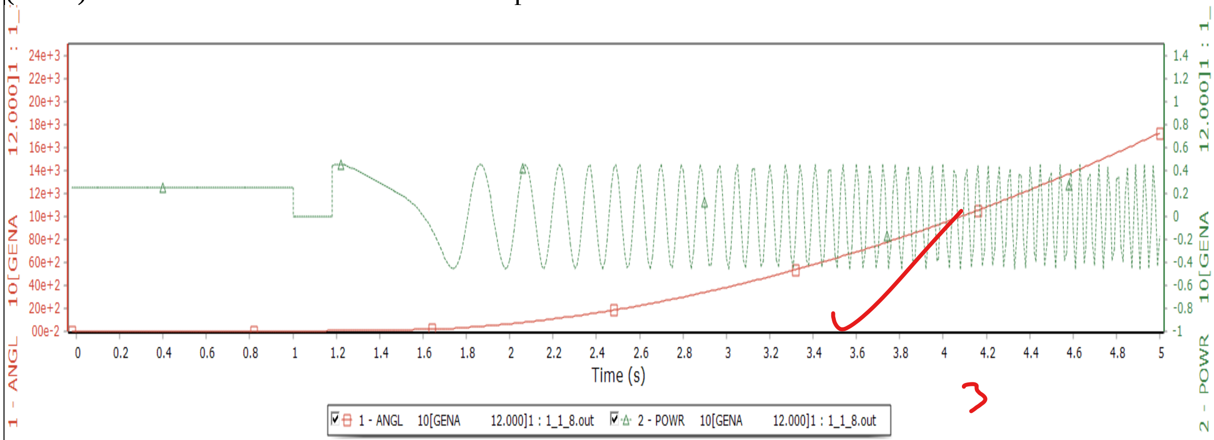


Fig 21. Power (green) and angle (red) plots for first unstable fault clearance time (1.18s) for 60MW installation

13. Is the system stable for a fault cleared by the installed protection and circuit breakers? [3 Marks]

(Insert your answer here.)
The system is stable with fault is cleared within 1.17s with the installation of protection (series capacitors) and circuit breakers. However, the protection and circuit breaker have a limited stability range of up to 1.17s, in which if a fault is cleared after 1.18s or more, instability would occur for the system. The critical fault clearance time has increased from 1.08s to 1.18s with the installation of series capacitors compared to the system without a series capacitor, indicating an improvement in transient stability.

To improve the transient stability of the system, the approach employed in this section is to raise the power angle curve, achieved by increasing the peak value.

$$P\left(\frac{\pi}{2}\right) = \frac{|E_q'||V_b|}{X_T}$$

More specifically, we increase the peak value with the addition of a series capacitor to the transmission line between the hydro generator bus and the system bus. The series capacitor reduces the reactance of the system, effectively reducing X_T, leading to series compensation.
Assuming that without the series capacitor, the transmission line impedance is given as

$$Z_{system} = Z_{generator} + \frac{1}{\frac{1}{Z_{line,1}} + \frac{1}{Z_{line,2}}} = Z_{generator} + \frac{Z_{line,1}Z_{line,2}}{Z_{line,1}+Z_{line,2}}$$

The addition of the series capacitance, $Z_c = -\frac{1}{\omega_0 C}j$, reduces $Z_{line,1}$ and $Z_{line,2}$ altogether, leading to a smaller Z_{system}, and subsequently smaller X_T.

We can evaluate the stability using the equal area criterion.

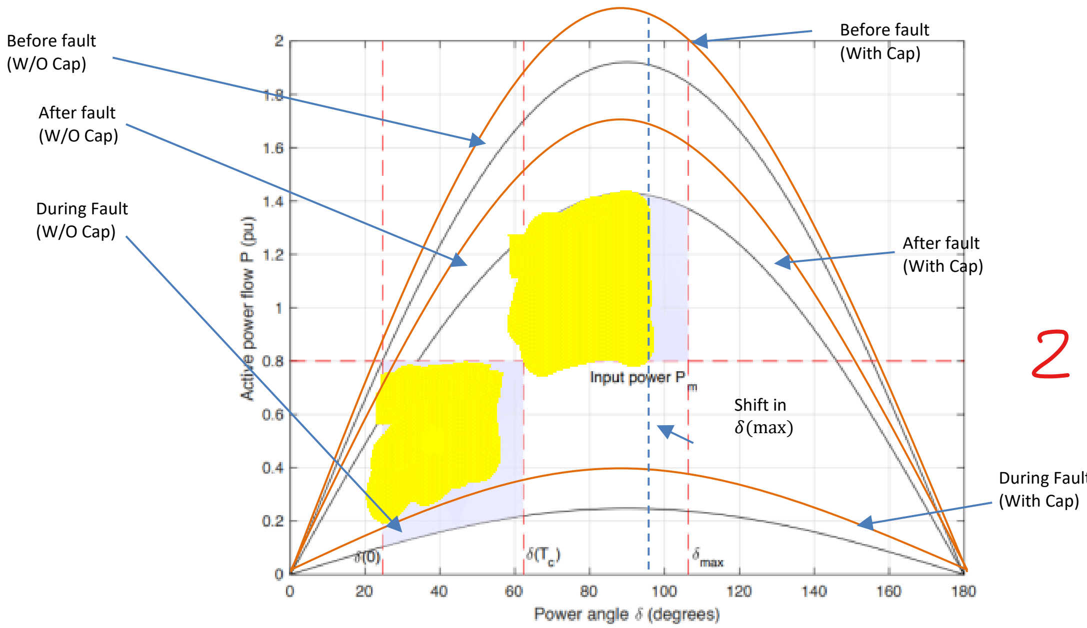


Fig 22. Effect of adding series capacitor on power angle relation curve [2]

2

With the increase in the peak value, we can see that the shaded area between the input mechanical power and the power curve during fault, A_1', became smaller, while the shaded area between the input mechanical power and the power curve after fault, A_2', became larger, being able to cover more area than it previously was able to before reaching the critical angle. Once A_2' is able to increase past A_1's area, the system is indicated to have reached stability and the δ_{max} would have shifted to the left.

capacitor is used to boost voltage to improve stability

-1

Conclusion [5 Marks]

(Include your conclusion and state the learning outcomes of this experiment.)

In summary, we delved into the transient stability of a compact power system, gauging its stability post-fault with a baseline fault clearance time of 100ms. All designs tested in this study—including the 50MW, 60MW, 60MW with an extra line, and 60MW with a series capacitor—met the design criteria.

The stability assessment was conducted using two distinct techniques. First, by plotting power and angle against time, we discerned the system's stability status. An unstable network exhibits an angle graph that rises indefinitely over time, while a stable one showcases a bounded sinusoidal angle graph. Additionally, by applying the power-angle relation graphs and the equal area criterion, we assessed the system's resilience. When acceleration energy aligns with deceleration energy, the criterion is met and the network can recuperate post-fault for the given fault clearance time. Otherwise, recovery is unattainable. Using these methodologies, we assessed the stability following various fault clearance intervals after tripping a 3-phase line.

In our initial assessment, we focused on a 50MW generation network. It could handle a fault clearance time up to 1.12s, but faltered at 1.13s. When power generation was ramped up to 60MW, the maximum fault clearance time dropped to 1.08s, and at 1.09s, the system lost its synchrony post-fault.

We then explored the impact of integrating additional components—extra transmission lines and series capacitors. These inclusions diminished the network's overall reactance, expanding the fault clearance time window. Empirical data for a 60MW generation showed an extension from 1.08s (sans additions) to 1.17s (with added components). This suggests that these components bolster the network's stability by prolonging the crucial fault clearance interval.

Overall, this experiment achieved its objectives. We executed dynamic studies, pinpointing the network's stability. For all four design cases—50MW, 60MW, 60MW with an added line, and 60MW with a series capacitor—the design criteria were met. Notably, as power generation surged, the fault clearance time shrank. Given this, to augment the fault clearance time frame, particularly for high-power generation networks, it's advisable to integrate more transmission lines and capacitors.

5

References [5 Marks]

(Include the references here)

[1] Monash University. (2022). Power System Transient Stability [PDF]. Available: https://lms.monash.edu/course/view.php?id=141931&section=14

5

[2] A. Morton. (2022). Power System Transient Stability [PDF]. Available: https://lms.monash.edu/course/view.php?id=141931&section=14

[3] M. Pavella, D. Ernst, and D. Ruiz-Vega, "Appendix A THE EQUAL-AREA CRITERION," in Transient Stability of Power Systems. New York, NY, USA: Kluwer, 2000, pp. 207-213.

******** THE END *******

MONASH University
MALAYSIA

SCHOOL OF ENGINEERING

ELECTRICAL AND COMPUTER SYSTEMS ENGINEERING

LABORATORY REPORT MARKING RUBRIC

ECE4053: POWER SYSTEM ANALYSIS

Experiment Number: 5

Title of Lab Sheet: Three Phase Fault Calculations

Group Number: 7

No.	Student ID	Name of Group Members	Total Marks
1	30720230	Loh Jia Quan	90/100
2	32259417	Chong Yen Juin	
3	30719305	Huan Meng Hui	
4	32194471	Tan Jin Chun	

MARKS BREAKDOWN

Area	Total Score	Actual Marks	Scoring Band	Criteria
Format	5	5	4-5	The overall report contents present a clear, presentable, formal, readable and organized format, as per laboratory report guideline. Provide 2 decimal points for each recorded data.
			2-3	The report has most sections which present a clear, presentable, formal, readable and organized format, as per laboratory report guideline. Provide 2 decimal points for each recorded data.
			0-1	Most sections presented in a messy manner and did not follow the laboratory report guideline. Provide 2 decimal points for each recorded data.
Figures and Diagram	5	5	4-5	Extensive figures and diagrams with clear explanation and numbered labels.
			2-3	Extensive figures and diagrams without clear explanation and numbered labels.
			0-1	Insufficient figures and diagrams & without clear explanation and numbered labels.
Objectives and Equipment	5	5	4-5	Detailed description of the objectives and list of all equipment used.
			2-3	Brief description of the objectives and list of all equipment used.
			0-1	Unclear description of the objectives and list of all equipment used.
Results and Discussion	25	20	20 - 25	Comprehensive comparison, evaluation and justification of the results, with clear explanation on the theoretical and experimental/ simulation results.
			11-19	Brief comparison, evaluation and justification of the results, with unclear explanation on the theoretical and experimental/ simulation results.
			0-10	No comparison, evaluation and justification of the results, with unsatisfactory explanation on the theoretical and experimental/ simulation results.
Conclusion and References	10	10	8-10	Clear understanding on the experiment with summarized conclusion. In-text citations and IEEE referencing format is properly done. (3 references)
			4-7	Unclear understanding on the experiment with summarized conclusion, but without the supporting evidence of results. In-text citations and references' format are improperly done. (2 references)
			0-3	Unclear understanding on the experiment without summarized conclusion and the evidence of results. In-text citations and references are absent. (0 – 1 reference)
Total	50	45		Deductions on pages 6, 8, 12

Examiner/ Assessor of ECE 4053: Power System Analysis

Date: 18/10/23

EXPERIMENT 5

1. Objectives [3 Marks]

(List the three objectives of this experiment.)
1. Identify the per unit impedance values of a simple model grid network.
2. Measure the fault currents flowing and fault voltages under various fault conditions.
3. Match the measured fault currents and voltages to the values predicted by the measured impedances of the network elements

3

2. Equipment used [2 Marks]

(List all the equipment used in this experiment.)
3 x Single Phase Step-down Transformers (1 kVA, 230V/4 x 57.5V, 50Hz)
1 x Three Phase self/mutual line impedance network
1 x Three Phase Resistive Load Bank
1 x Clamp-on AC Voltage/Current/Power meter
1 x Digital Multimeter (DMM)
1 x Switch

2

3. Experimental wiring and experimental setup [5 Marks]

(Insert a photo of your experimental setup and label all of the equipment used.

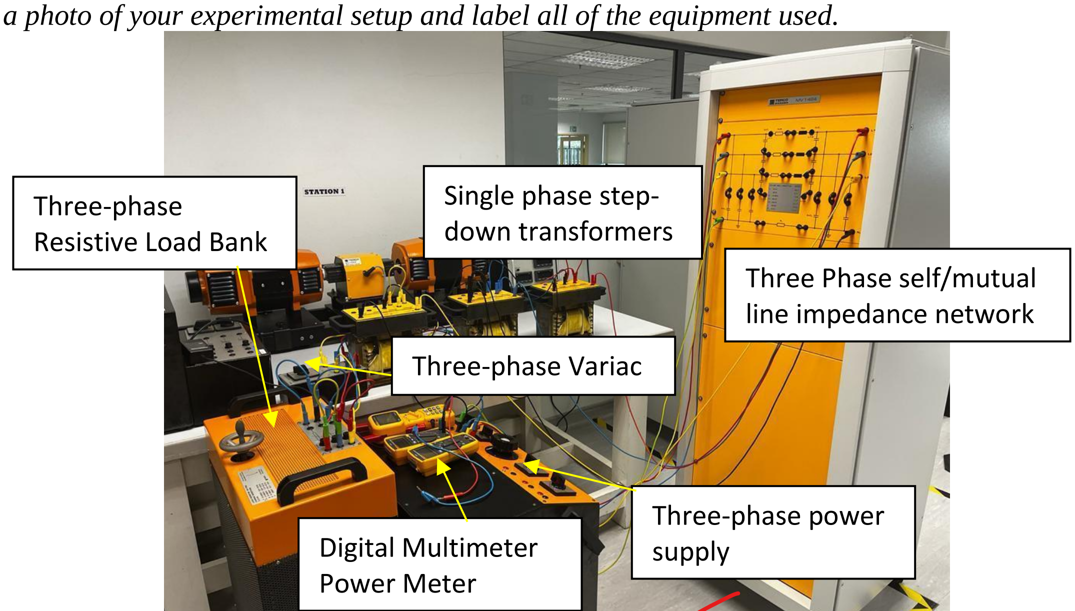


Fig 1. Labeled Experimental Wiring and Experimental Setup

5

4. Results for Phase A, B and C Voltage & Current Measurements for no-load Condition [2 Marks]
(Fill in the necessary data/ measurements from the experiment into the table below.)

	Phase Voltages (V)			**Phase Current (A)**		
	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
Source	131.9	132.7	133.7	0.16	0.16	0.16
Transformer (Primary Winding)	130.9	132.9	131.7	0.29	0.28	0.30
Transformer (Secondary Winding) [1st one measure from GND, 2nd one measure from Neutral]	68.9	70.0	69.5	0.24	0.28	0.22
Load	0.009	0.012	0.13	0.3	0.3	0.34

2

5. Results for Fault Condition (Phase Current and Phase Voltage) [4 Marks]
(Fill in the necessary data/ measurements from the experiment into the table below.)

Faults	I_A (A)	I_b (A)	I_c (A)
Single Line-to -Ground	15.01	0.45	0.47
Line-to-Line	15.73	15.94	0.55
Double Line-to-Ground	13.92	19.28	0.49
Balanced	18.30	18.04	18.31

Faults	V_A (A)	V_b (A)	V_c (A)
Single Line-to -Ground	0.31	87.30	65.70
Line-to-Line	34.56	34.85	69.20
Double Line-to-Ground	0.28	0.31	81.30
Balanced	1.14	1.14	1.17

4

6. Questions

(Answer all of the following questions.)

(i) Calculate all network element impedances, in p.u. unit. [5 Marks]

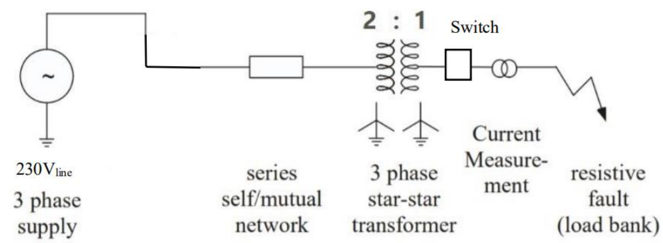


Fig 2. Single Line Diagram of Model Grid Network

Fig 3. Transformer Nameplate

Base Values
Zone 1

$$S_{base1,1\phi} = 1kVA, V_{base1,LN} = 230V, I_{base1} = \frac{S_{base1,1\phi}}{V_{base1,LN}} = 4.35A, Z_{base1} = \frac{V_{base1,LN}}{I_{base1}} = 52.90\Omega$$

Zone 2

$$S_{base2,1\phi} = 1kVA$$

As we are using a 2 to 1 turns ratio, the base voltage at Zone 2 is given as

$$V_{base2,LN} = 115V, I_{base2} = \frac{S_{base2,1\phi}}{V_{base2,LN}} = 8.70A, Z_{base2} = \frac{V_{base2,LN}}{I_{base2}} = 13.22\Omega$$

Zone 1 is the primary side, also known as the high voltage (HV) side, while zone 2 is the secondary side, also referred to as the low voltage (LV) side.

Given that the fault is at the load end, the base impedance region corresponds to the secondary winding of the transformer. Therefore, for sequence impedance calculations, Z_{base} is 13.22 Ω.

Network Impedance

Element Impedance	Theoretical		
	Z_a	Z_b	Z_c
Transmission Line	$\frac{\lvert Source\rvert \; - \; \lvert Primary\ Transformer\rvert}{I_{phase}}$ $= \frac{\lvert 131.9\rvert - \lvert 130.9\rvert}{0.16}$ = 6.25j	$= \frac{\lvert 132.7\rvert - \lvert 132.9\rvert}{0.16}$ = -1.25j	$= \frac{\lvert 133.7\rvert - \lvert 131.7\rvert}{0.16}$ = 12.50j
	Average $Z_{TH} = \frac{6.25j \; - 1.25j + 12.5j}{3}$ = 5.83j Ω $Z_a = Z_b = Z_c$ = 5.83j Ω $\frac{5.833j}{52.9} \; = \; 0.11j\ pu$		
Load Bank	Measured Value: Z = 271.95∠0 Ω $= \frac{271.95}{13.22}$ = 20.57 pu (Y-Connected)		

was this measured @ the load ?

$Z_{load} : \frac{V_b - V_c}{I_b}$

Assumption Made:
The assumption made is that the reactance of the transformer and generator has been neglected. Therefore, the current is likely to surge significantly.

Transformer impedance ?

-2

3

Theoretical Fault Current Calculation

<table>
<tr><th>Sequence Network Construction</th><th>Thevenin Equivalent at Load</th></tr>
<tr><td>Positive Sequence

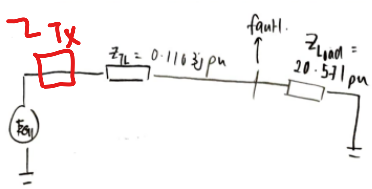



Fig 4. Equivalent Circuits for Positive Sequence Network</td><td>$Z_{TH} = 20.571 \mid\mid 0.1103j$
$= 0.1103 \angle 89.69$ pu
$= 0.11j$
$Z_{TH} = (Z_{line} + Z_{TX}) \mid\mid Z_{Load}$</td></tr>
<tr><td>Negative Sequence

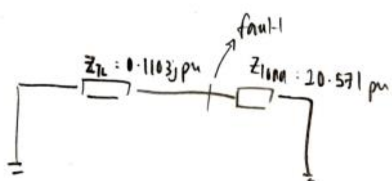



Fig 5. Equivalent Circuits for Negative Sequence Network</td><td>$Z_{TH} = 20.571 \mid\mid 0.1103j$
$= 0.1103 \angle 89.69$ pu
$= 0.11j$</td></tr>
<tr><td>Zero Sequence

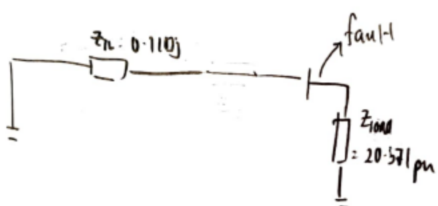



Fig 6. Equivalent Circuits for Zero Sequence Network</td><td>$Z_{TH} = 20.571 \mid\mid 0.1103j$
$= 0.1103 \angle 89.69$ pu
$= 0.11j$</td></tr>
<tr><td colspan="2">Prefault Voltage
$$Z_f = \frac{\frac{131.9 + 132.7 + 133.7}{3}}{230}$$
$$= \frac{132.77}{230}$$
$= 0.577$ pu</td></tr>
</table>

(ii) Compute the measured fault currents for each fault type, in p.u. Unit. [10 Marks]

(Insert your calculations here)

Single Line-to-Ground Fault:

For the SLG fault, only Phase A is connected to the ground, leading it to be grounded. In contrast, Phases B and C are open-circuited, resulting in no current flow. Thus, only Phase A exhibits a fault current, while Ibf and Icf remain at zero.

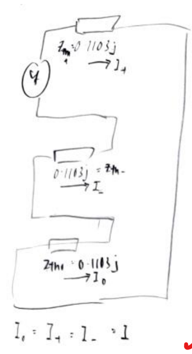


Fig 7. Single Line-to-Ground Fault Circuit

$$\boldsymbol{I_0} = \boldsymbol{I_+} = \boldsymbol{I_-} = \mathbf{I}$$

$$\boldsymbol{I_+} = \frac{\boldsymbol{V_f}}{\mathbf{0.1103}\boldsymbol{j} * \mathbf{3}}$$

$$= \mathbf{-1.7437\ pu}$$

$$= \boldsymbol{I_{base,2}} = \mathbf{8.6957}$$

$$= \mathbf{-15.1629j\ A}$$

−2

$V_f = 1$ pu

always ideal

as it would be

avg line Volt or

line volt

avg phase volt

phase volt

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} I_0 \\ I_+ \\ I_- \end{bmatrix}$$

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} -15.1629i \\ 11 \\ 11 \end{bmatrix}$$

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 45.49\angle -90 \\ 0 \\ 0 \end{bmatrix}$$

Line-to-line Fault:

In a line-to-line fault, two lines, in this case Phase A and Phase B, are interconnected with an impedance Z_f between them. Due to this connection, the fault currents are such that $I_a{}^f = -I_b{}^f$. As Phase C is not involved in the fault, its fault current, $I_c{}^f$ is zero.

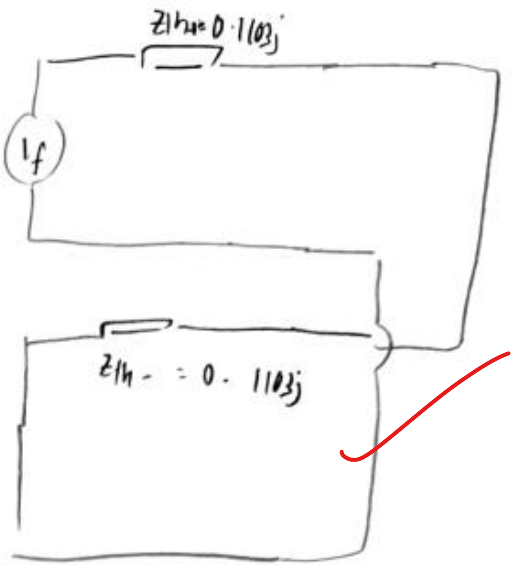


Fig 8. Line-to-Line Fault Circuit

$$I_+ = -I_- = \mathrm{I}\,,\ I_1 = 0$$

$$I\ =\ \frac{V_f}{0.1103j*2} = \frac{0.577}{0.1103j*2} = -2.6156j = -22.74j\ \mathrm{A}$$

$$I_+ = 2.6156j = 22.74j\ \mathrm{A}$$

$$I_0 = 0\ \mathrm{A}$$

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} 0 \\ -22.74j \\ 22.74j \end{bmatrix}$$

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 0 \\ -39.39j \\ 39.39j \end{bmatrix}$$

Double Line-to-Ground Fault:

In a double line-to-ground fault, only Phases A and B are connected to the ground, rendering them grounded. Conversely, Phase C is open-circuited, resulting in no current flow through it. Consequently, fault current is present only in Phases A and B. $I_c{}^f$ is zero, and $I_a{}^f$ equals $I_b{}^f$ because both represent two SLG faults with identical sequence impedances.

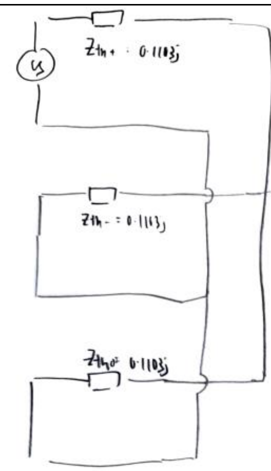


Fig 9. Double Line-to-Ground Fault Circuit

$$\boldsymbol{I_+} = \frac{\boldsymbol{V_s}}{\boldsymbol{Z_{TH+}} + \boldsymbol{Z_{TH-}} \mid\mid \boldsymbol{Z_{TH0}}}$$

$$= \frac{\mathbf{0.577}}{\mathbf{0.1103}\boldsymbol{j} + \mathbf{0.05515}\boldsymbol{j}}$$

= 3.487j = -30.32j A

$$\boldsymbol{I_-} = -\boldsymbol{I_+} * \frac{\mathbf{0.1103}\boldsymbol{j}}{\mathbf{0.1103}\boldsymbol{j} + \mathbf{0.1103}\boldsymbol{j}} = 1.74j = 15.17j \text{ A}$$

$$\boldsymbol{I_0} = 1.74j = 15.17j \text{ A}$$

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} -30.32j \\ 15.17j \\ 15.17j \end{bmatrix}$$

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 0 \\ -45.49j \\ -45.49j \end{bmatrix}$$

Balanced Fault:

In the event of a balanced fault, all three phases are short-circuited, resulting in their connection to a common node.

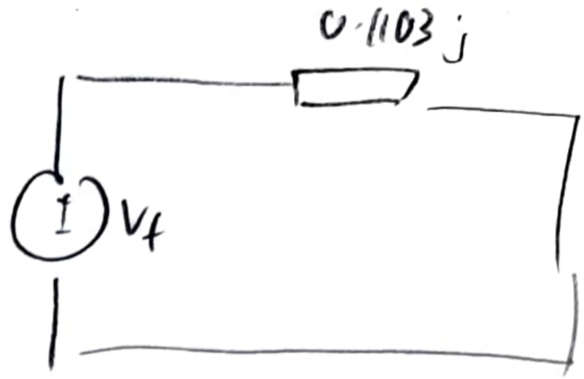


Fig 10. Balanced Fault Circuit

$$I_+ = \frac{0.577}{0.1103j} = -5.231j = -45.49j \text{ A}$$

$$I_0 = 0 \text{ A}$$

$$I_- = 0 \text{ A}$$

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} -45.49j \\ 0 \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} -45.49j \\ -45.49j \\ -45.49j \end{bmatrix}$$

Summary of the values calculated (Theoretical)

Fault Type	**Theoretical**		
	IA	IB	IC
Single Line-to -Ground	45.49 ∠ -90	0	0
Line-to-Line	0	-39.39	39.39
Double Line-to-Ground	0	-45.485j	-45.485j
Balanced	-45.49j	-45.49j	-45.49j

8

(iii) Compare all the measured fault currents with the calculated/ predicted fault currents. [5 Marks]

Fault Type	Theoretical			Actual / Measured		
	IA	IB	IC	IA	IB	IC
Single Line-to - Ground	45.49 ∠ -90	0	0	15.01	0.45	0.47
Line-to-Line	0	-39.39	39.39	15.73	15.94	0.55
Double Line-to-Ground	0	-45.485j	-45.485j	13.92	19.28	0.49
Balanced	-45.49j	-45.49j	-45.49j	18.30	18.04	18.31

-1

(Fill in the calculated and measured data from the experiment into the table below.)

actual fault current should reflect correctly on the phase with no fault

4

(
In the single line-to-ground fault scenario, the observed values for $I_b{}^f$ and $I_c{}^f$ closely approach the theoretical value of 0. In contrast, the measured $I_a{}^f$ is about a third of its expected value. Such a difference arises primarily because calculations for the theoretical value disregard the generator and wire sequence impedances. Furthermore, elements like device aging, the non-ideal behavior of components like transformers and the line model may display sequence impedances that differ from datasheet specifications. It's also worth noting that the resistance value utilized for computations was derived from earlier lab sessions, which might not align perfectly with the resistance in this experiment. These combined discrepancies elevate the actual sequence impedances over their theoretical counterparts. Given that fault current is inversely related to these impedances, the real-world fault current is consequently lower.

In the line-to-line fault, the measured $I_c{}^f$ is almost identical to its theoretical zero value. However, both $I_a{}^f$ and $I_b{}^f$ readings are approximately a third of what theory predicts. The variances between the observed and expected values mirror the explanations provided for the single line-to-ground fault.

The double line-to-ground fault displays similar patterns, with $I_c{}^f$ aligning nearly perfectly with the theoretical zero and both $I_a{}^f$ and $I_b{}^f$ being around a third of their expected values. Again, the underlying reasons for these differences echo those of the single line-to-ground fault.

Lastly, for the balanced fault, the real fault currents are about a third of their anticipated values, primarily attributed to overlooked impedances, notably those from generators and wire sequences.

7. Discussion [4 Marks]

(Discuss the results obtained in this experiment.)

In the conducted experiment, two types of faults were identified: symmetrical and unsymmetrical faults. Symmetrical faults encompass L-L-L-G and L-L-L faults, while three types of symmetrical faults were tested: L-G, L-L, and double L-G [1]. During symmetrical faults, all three phase currents surged, whereas unsymmetrical faults affected one or two phases.

In the event of a single line-to-ground fault, the faulted line experienced lower voltage (near 0V) but higher current compared to other phases. Line-to-line faults exhibited lower voltage on the faulty lines (however, the voltage is substantially higher than 0V in this case) but higher current than the normal functioning line. Double-line-to-ground faults resulted in lower voltage (near to 0V) on the faulted lines and greater current. Current values during balanced faults were significantly higher than during normal operation. The voltages and currents of all three phases are similar during a balanced fault, however, the current values are higher than normal operating conditions.

In the case of a single line-to-ground fault, measured ${I_b}^f$ and ${I_c}^f$ closely match the theoretical value of 0A. However, the measured ${I_a}^f$ is only approximately half of the theoretical value. This disparity is expected because the theoretical calculation does not account for generator and wire sequence impedances. Additionally, factors such as aging and non-ideal devices like transformers and the line model can result in higher actual sequence impedances than indicated in datasheets. Moreover, the load resistance used in calculations, derived from previous lab work, may deviate from the actual load resistance employed in the current experiment. These factors collectively lead to higher actual sequence impedances compared to theoretical values, resulting in lower actual fault currents due to their inverse relationship.

4

For the line-to-line fault, measured ${I_c}^f$ almost aligns with the theoretical value of 0A. However, measured ${I_a}^f$ and ${I_b}^f$ are approximately half of their respective theoretical values. The reasons for these discrepancies are the same as those observed in the single line-to-ground fault. For a double line-to-ground fault, measured ${I_c}^f$ also closely approximates the theoretical value of 0A, Similar to the single line-to-ground fault, the reasons behind these differences remain consistent.

Measured fault currents deviated from theoretical values due to factors such as sequence impedances, aging, non-ideal devices, and load resistance. Symmetrical faults occurred 2% to 5% of the time [2], whereas unsymmetrical faults, including line-to-line faults (65% to 75%) and double-line-to-ground faults (15% to 20%), were more common in real-world electrical systems [3].

To safeguard electrical system components, swift fault clearing is necessary. Various protection devices like fuses, circuit breakers, and protective relays have been developed for this purpose [2].

Conclusion [5 Marks]

(Include your conclusion and state the learning outcomes of this experiment.)

In conclusion, this experiment accurately identified per unit impedance values (positive, negative, and zero sequence impedances) for a simple model grid network. Furthermore, the experiment measured and documented fault currents and voltages under various fault conditions, including both balanced and unbalanced faults. Lastly, the experiment facilitated a comparison between the measured and predicted (theoretical) impedance values, thereby showing the limitations of this experiment.

Electrical faults can stem from factors such as insulation breakdown in transmission lines, attributed to aging, accidents, or natural events like lightning strikes. Fault currents may cause equipment damage, power outages, and even pose risks to personnel and public safety. By understanding fault currents, operators could implement safety measures and fault clearing protection devices to mitigate these risks.

5

This experiment highlights the significance of fault analysis for determining fault currents across various fault types. The process involves applying symmetrical component theory to ensure accurate calculations. The resulting calculations are then compared against measured currents to identify discrepancies and their respective causes. Generally, single-line equivalent circuit representation falls short in fault analysis, requiring the use of symmetrical component computation. This method proves to be effective in networks with minimal impedance imbalance at select points, while maintaining balanced source voltage. To determine network phase voltage at the fault location under any fault condition, Thevenin equivalent source voltage is employed.

References [5 Marks]

(Include the references here)

[1] Electronics Hub. "Types of Faults in Electrical Power Systems." electronicshub.org. Accessed: Oct. 9, 2023. [Online.] Available: https://www.electronicshub.org/types-of-faults-in-electrical-power-systems/

[2] D. Prajapat. “Faults and Effects in Electrical Power System.” Madhav University. Accessed: Oct. 9, 2023. [Online.] Available: https://madhavuniversity.edu.in/faults-and-effects-in-electrical-power-system.html

[3] Electronics, Projects, Focus. "Types of Faults and Effects in Electrical Power Systems." elprocus.com. Accessed:Oct.9,2023.[Online].Available:https://www.elprocus.com/what-are-the-different-types-of-faults-in-electrical-power-systems/

5

******** THE END *******