# IGEE 402 Power System Analysis – Fall 2024

Experiment 1 Lab Report– Transmission Line Steady-State Operation

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## Objective:

This experiment was aim to get us familiar with the steady-state operation of transmission lines in a power system, focusing on modeling and analyzing the performance of parallel transmission lines. By simulating a 600 km network consisting of 765 kV and 345 kV lines, the study examines key parameters such as impedance, surge impedance loading, and power stability limits. Through a series of simulations, the experiment evaluates the effects of different loading conditions, parallel line operation, and series compensation on power transfer, voltage profiles, and active power losses, providing insights into optimal transmission line operation.

# I. Introduction

In this experiment, we explore how transmission lines work in a steady state within power systems. The goal is to create accurate models of these lines, understand how they behave when operating in parallel, and learn how to improve their performance using compensation techniques. We will simulate different scenarios to see how these lines handle power transfer, voltage changes, and energy losses under various conditions.

# II. Experiment and Analysis

## Part 1 *Preliminary Calculations*

### 1.1 The series impedance of the two lines in p.u and SI units.

$$Z_{p.u} = \frac{Z}{Z_{base}} \rightarrow Z_{base} = \frac{(V_{base})\text{^}2}{S_{base}}$$

In 765 KV line

$$(SI)Z_{765} = (r + jx)l = (0.016 + j0.330)600km = 9.6 + j198\ \Omega$$

$$Z_{765\ base} = \frac{(765 * 10^3)\text{^}2}{2000 * 10^6} = 292.52\Omega$$

$$(p.u)Z_{765} = \frac{9.6+j198}{292.52} = 0.0329 + j0.6767\Omega$$

In 345 KV Line

$$(SI)Z_{345} = (r + jx)l = (0.032 + j0.35)600km = 19.2 + j210\ \Omega$$

$$Z_{345\ base} = \frac{(345 * 10^3)\text{^}2}{2000 * 10^6} = 59.5125\Omega$$

$$(p.u)Z_{345} = \frac{19.2 + j210}{59.5125} = 0.03226 + j3.53\Omega$$

1.2 Surge Impedance loading of two Lines

In 765 KV Line

$$Z_c = \sqrt{\frac{z}{y}} = \sqrt{\frac{0.016 + j0.33}{j4.5 * 10^{-6}}} = 267.92 - j6.49\Omega$$

$$SIL = \frac{(V_{base})^\wedge 2}{|Z_c|} = \frac{(765 * 10^3)^\wedge 2}{\sqrt{(267.92^2) + (6.49^2)}} = 2183.7MW$$

In 345 KV Line

$$Z_c = \sqrt{\frac{z}{y}} = \sqrt{\frac{0.032 + j0.35}{j4.2 * 10^{-6}}} = 288.98 - j13.18\Omega$$

$$SIL = \frac{(V_{base})^\wedge 2}{|Z_c|} = \frac{(345 * 10^3)^\wedge 2}{\sqrt{(288.98^2) + (13.18^2)}} = 411.5MW$$

1.3 The Steady-State power stability limits of the individual line using the short lossless line model.

$P_s = P_r = \frac{V_s V_r}{X} sin\delta$, The limit reaches when $\sin\delta = 1$

In 765 KV Line

$$X = 0.6767p.u \rightarrow P_{max} = \frac{1.0 * 1.0}{0.6767} = 1.479\ p.u$$

$$(SI)P_{max} = 1.479\ \times 2000\ \times\ 10^6 = 2958\ MW$$

In 345 KV Line

$$X = 3.53p.u \rightarrow P_{max} = \frac{1.0 * 1.0}{3.53} = 0.2837p.u$$

$$(SI)P_{max} = 0.2837\ \times 2000\ \times\ 10^6 = 567.4\ MW$$

**Part 2 *Experimental Procedures***

2.1 Operation of the 765kV Line

2.1.2 The approximately experimental surge impedance loading (SIL) of the Line

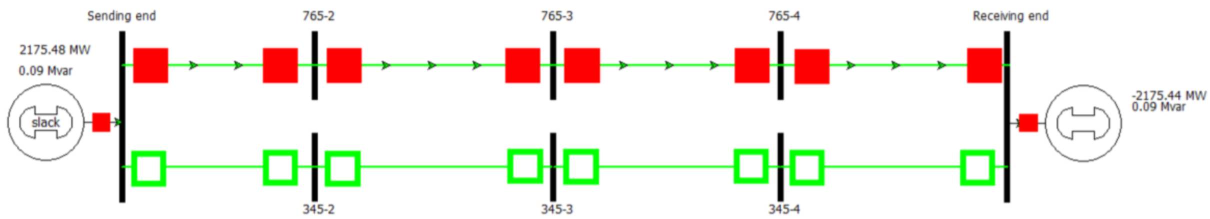


*Figure 1 The Experimental Surge Impedance Loading*

Open all segments of the 345 kV line. To ensure the line is lossless for surge impedance loading, we set the value of resistance of each segment on Line 765KV to 0 and the Active Power at the receiving end to the -2183.7 MW which is the value we calculated in the preliminary session. Although there is still reactive power present, adjusting the active power to -2175.44 MW brings the reactive power closer to zero, indicating the surge impedance loading condition. In practical experiments, factors such as the line's reactance can influence the results, leading to deviations from the calculated values.

2.1.3 The experimental steady-state stability limit of the Line.

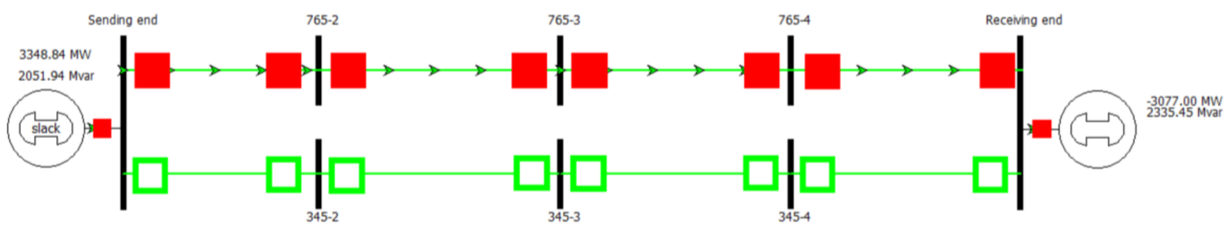


*Figure 2 The Steady-State Stability limit of the Line*

After reintroducing the line resistance into the model, each segment of the 765 kV transmission line now includes its respective resistance. The team then set the active power at the receiving end to 2958 MW, which corresponds to the value calculated during the preliminary sessions. The line can still function without reporting errors. Steady-state stability is achieved when the line reaches its maximum active power limit. To find this limit, we continued increasing the active power until it reached 3077 MW, which is the highest value before the system reported an error. This value represents the experimental steady-state stability limit. It is important to note that calculations often use simplified models that assume ideal conditions, such as perfect sinusoidal voltages, linear behavior, and the absence of losses. In contrast, real-world experiments encounter non-idealities like non-linearities, harmonics, and losses, which can impact the stability limit.

2.1.4 Simulation for 10, 20, 40, 60, 80 and 99%of the maximum active power loading found previously are performed. The results are shown in the figure below.

| | Sending End | | Receiving End | | | | |
|---|---|---|---|---|---|---|---|
| | Active Power(S) MW | Reactive Power(S) Mvar | Active Power(R) MW | active absolute value | Reactive Power R (Mvar) | Angle (R) | Ploss |
| 10% | 312.75 | -842.92 | -307.7 | 307.7 | -815.3 | -5.53 | 5.05 |
| 20% | 624.49 | -811.28 | -615.4 | 615.4 | -765.57 | -11.11 | 9.09 |
| 40% | 1256.84 | -648.95 | -1231 | 1231 | -539.18 | -22.74 | 25.84 |
| 60% | 1903.13 | -324.47 | -1846.2 | 1846.2 | -159.05 | -35.63 | 56.93 |
| 80% | 2572.63 | 257.97 | -2461.8 | 2461.8 | 480.09 | -51.47 | 110.83 |
| 99% | 3282.25 | 1648.53 | -3046.2 | 3046.2 | 1927.74 | -79.51 | 236.05 |

*Figure 3 Data Recorded for Different Conditions*

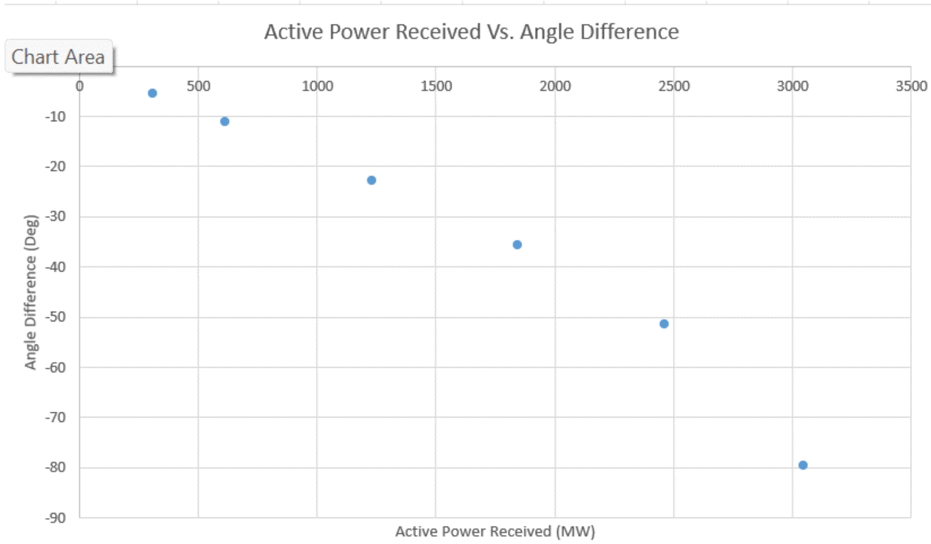


*Figure 0 Active Power Received against the Voltage Angle Difference*

The magnitude of the active power received against voltage angle difference plot is shown above. As more active power received, magnitude of voltage angle difference increases. When the transmitted power increases, the system operates closer to the stability limit, leading to a larger phase angle difference.

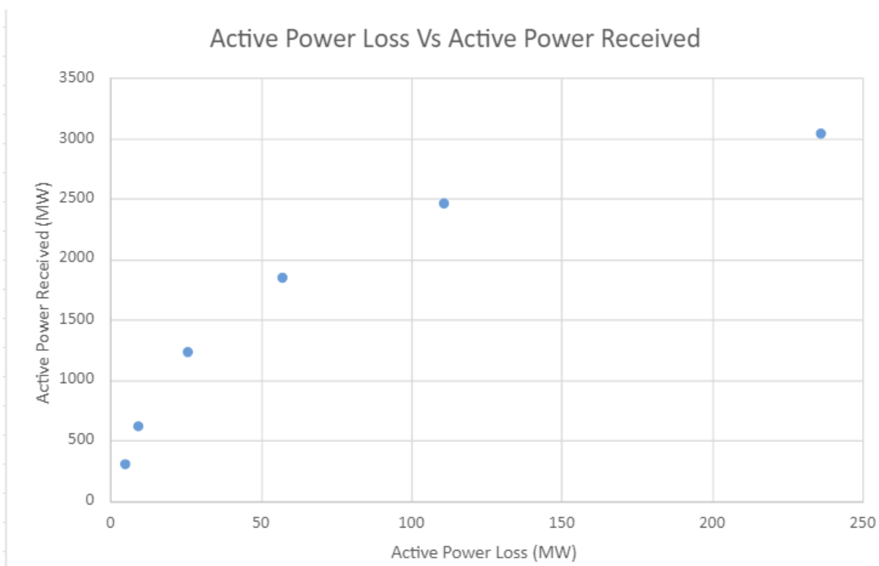


*Figure ❶Active Power Losses against the Active Power Received*

The active power loss against the active power received plot is shown in the figure above. As more power transmitted, the current increases, which in turn increases the loss. As power loss increases, the active power received increases. The relationship is non-linear, losses increase more sharply close to stability limits.

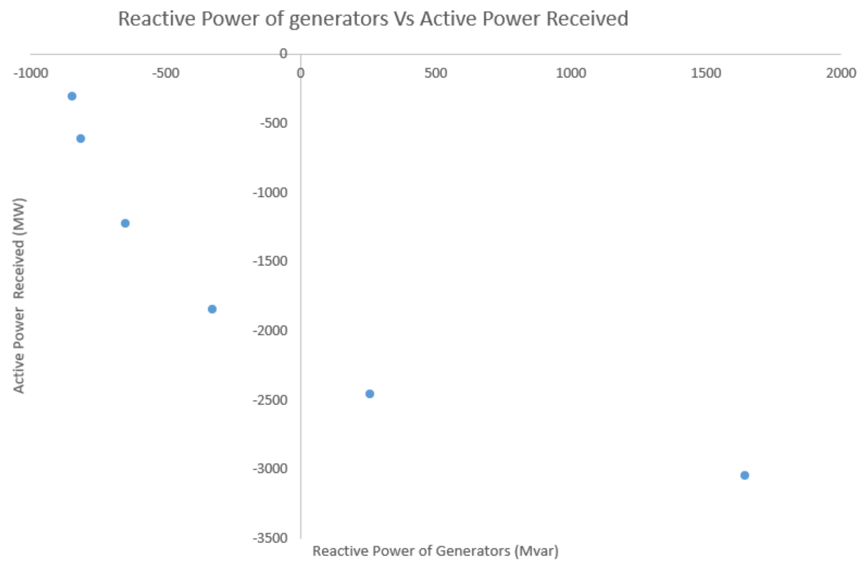


*Figure ❷Reactive Power generated by the Generators against the Active power Received*

The reactive power generated by the generators against the active power received is shown in the figure above. As the active power received increases, the reactive power supplied by the generators starts from a very large negative values and moves towards a less negative value, eventually becoming positive at high power levels. When the active power received is low, generators need to supply a large negative reactive power to maintain voltage stability. As active power received increases, generator's reactive output becomes positive, indicating existence of power compensation at sending end to support voltage stability for maximum power transfer. The system is heavily loaded at 99% showing that is super close to the maximum power limit. Generators need to inject reactive power to the network actively to ensure voltage levels required for active power transfer.

### 2.1.5 Evidence of the voltage profiles across the length of the line

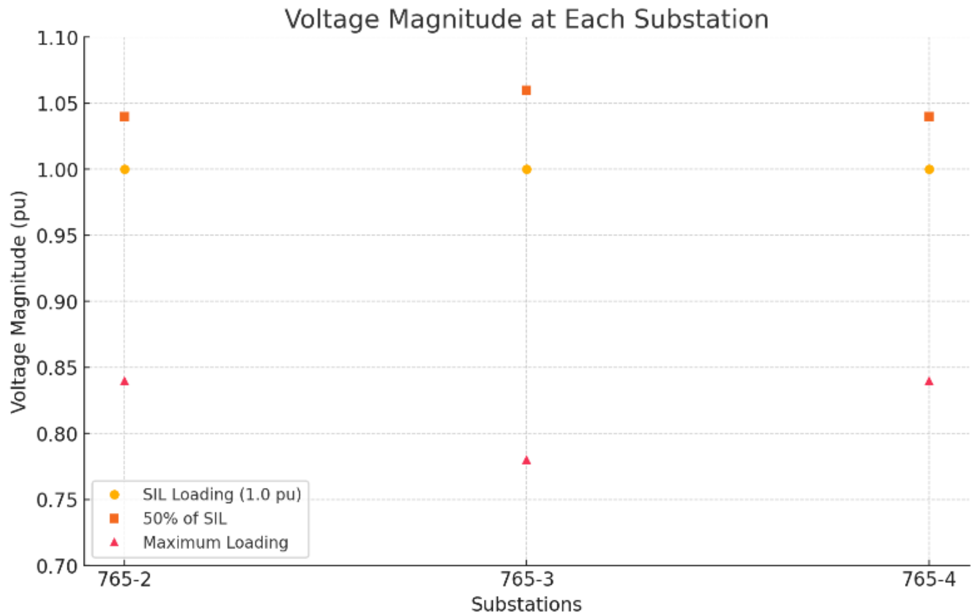


*Figure 7 Voltage Profile Across the Length of Line*

At SIL loading, the voltage across all substations remains at 1.0 p.u. We have a flat voltage profile. At 50% SIL loading, the voltage slightly increased at each substation, with a noticeable peak at 765-3. At maximum loading, voltage drops significantly, indicating the line is operating near capacity.

## 2.2 Parallel operation of the 765 and 345 kV lines

### 2.2.2 Flow on each line when receiving end of the system consume 3000MW

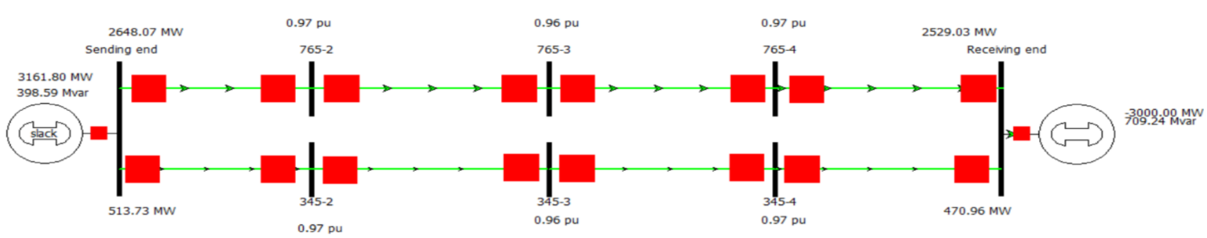


*Figure 8 The power carry on each line*

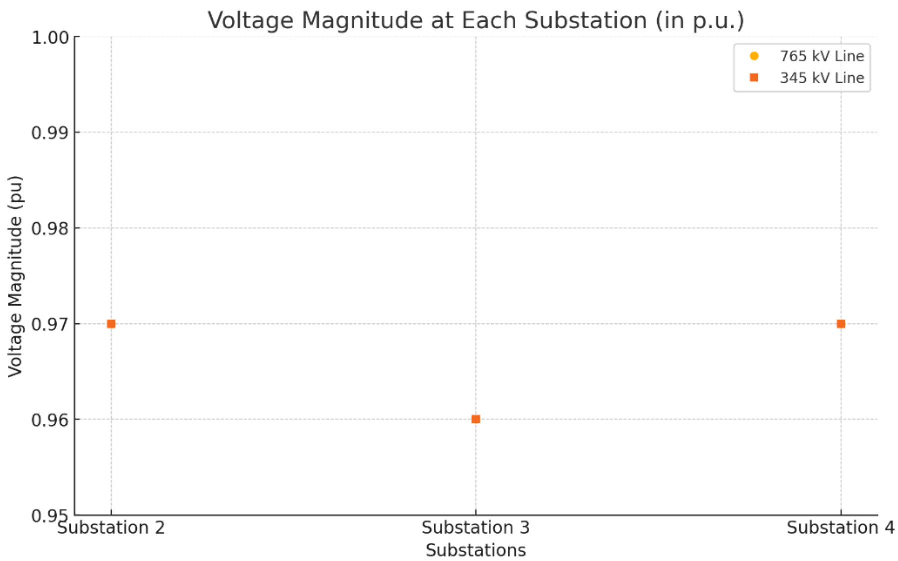


*Figure 9 The voltage profile across each section line*

Two lines exhibit the same voltage profile which these two points overlap each other. The voltage flow in p.u is same that across each same section line in 347kV and 765kV respectively, while as it times the base voltage, the value would be different. The voltage has a slightly drop in the middle due to the line impedance and power losses over the distance.

2.2.3 The system with series compensation is shown below.

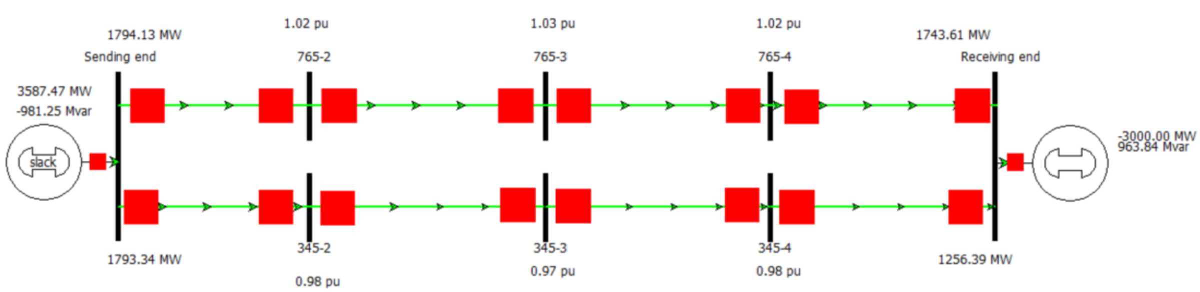


*Figure 10 The active power transfer with series compensation*

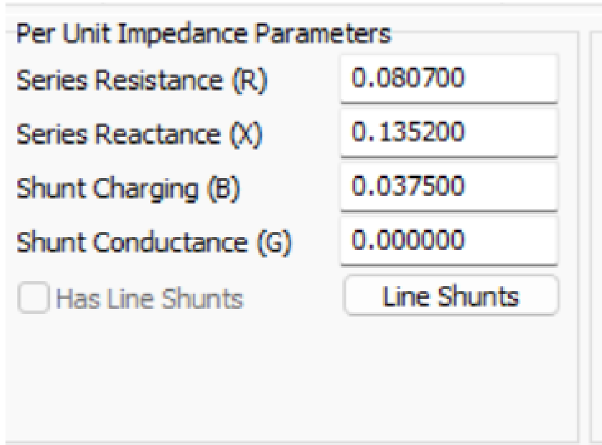


*Figure 11 The compensation setting*

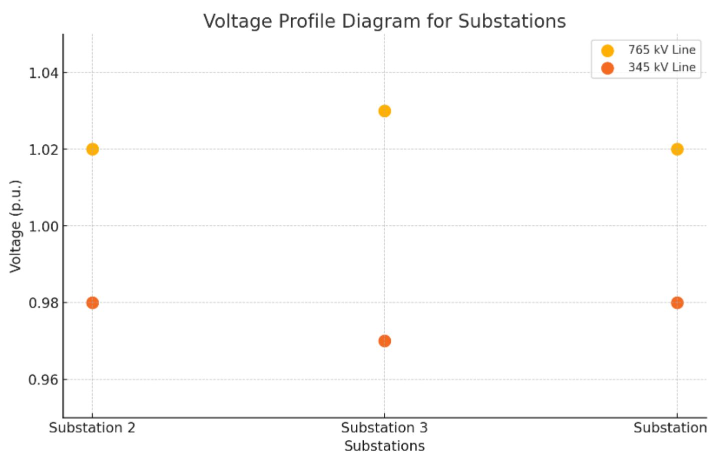


*Figure 12 Voltage profile of System with Compensation*

We reduced the series reactance from 0.8820 to 0.1352 by decreasing the reactance by approximately 84.5% on each 345 kV line to achieve the desired series compensation. As a result, the sending-end power of the 345 kV line and the 765 kV line are now approximately equal. The overall impedance has been reduced allowing for greater power transfer capability. It can be reflected through the improved voltage profiles.

## Part 3 *Question and Analysis*

1. By changing the length of line, how Surge impedance loading, steady-state stability limit, active power losses for a given line loading, and active power losses for a given line loading are presented under the table below.

| Performance | 800 km Line | 100 km Line | Justification |
|---|---|---|---|
| (a) Surge impedance loading | Smaller | Bigger | The surge impedance will be larger than in the 100km long line and smaller than in the 800km line. Because based on formula:$P_{SIL} = \frac{V^2}{Z_c}, where\ Z_c = \sqrt{\frac{z}{y}} = \sqrt{\frac{x}{b}}$, the SIL is inversely proportional to the line length. The longer lines have higher inductive reactance which reducing the SIL, and shorter lines have higher SIL as the lines have lower reactance. |
| (b) Steady-state stability limit | Smaller | Bigger | The steady-state stability limit is greater than in 100kM and smaller than in 800kM line. Based on the formula $P_s = P_r = \frac{V_s V_r}{X} sin\delta$, the stability limit decreases with the increased line length due to higher impedance, which limits the power transfer capability. Shorter lines have lower impedance and hence higher stability limits. |
| (c) Active power losses for a given line loading | Bigger | Smaller | The active power losses are larger in the 800kM line and smaller than in the 100kM. Because active power is proportional to the resistance. Longer lines have greater resistances which results more active power losses. Conversely, shorter lines have less resistance and experience lower power losses. |
| (c) Active power losses for a given line loading | Bigger | Smaller | As longer lines have higher reactive power due to greater inductive and capacitive effects. The shorter lines require less reactive power compensation. |

2. Discuss why operating transmission lines near surge impedance loading is desirable. Use evidence generated through the experiment to support your claims.

During the experiment, when the reactive impedance was adjusted to operate the system around the SIL, the voltage magnitude remained relatively stable. This stability occurs because the reactive power generated by the line's capacitance balances the reactive power consumed by the line's inductance. This behavior minimizes reactive power flows, leading to an optimal voltage profile. As a result, reactive power flows are minimized, which in turn reduces losses and limits voltage regulation issues.

3. Discuss the mechanism by which series compensation can be used to control the flow of active power between parallel lines.

Series compensation is used to reduce the impedance of a transmission line by inserting capacitors in series with the line. This reduction in impedance allows more active power to flow through the line, increasing its power transfer capability. When there are parallel transmission lines, series compensation can be used to control power flow. By lowering the impedance of one line through series compensation, more active power tends to flow through that line, thereby optimizing the load distribution between the parallel lines.

## III. Conclusion

The Lab provides us further understanding about the steady-state stability of the transmission lines by modeling and optimizing their performance under different loading conditions. Through the simulation, we observe how the 345 kV and 765kV lines behave in terms of their impedance ,surge impedance loading and power stability limit.