Improving Power Systems Stability using Reactive Power Compensation

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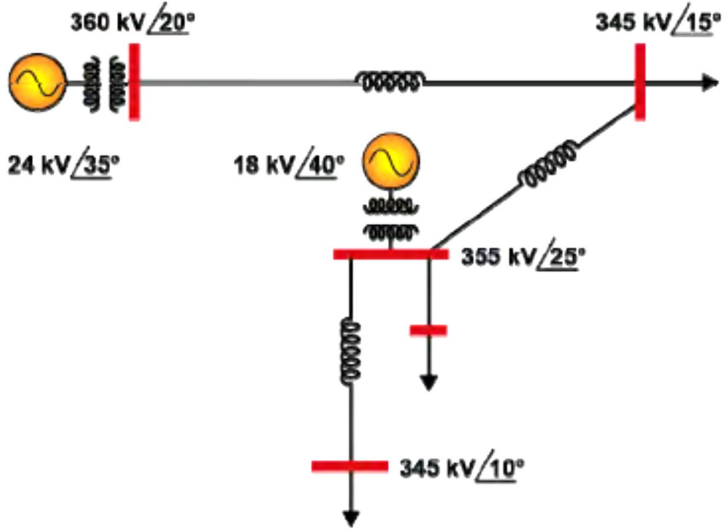
Unitec Research Symposium Auckland, New Zealand
8-9 December 2022

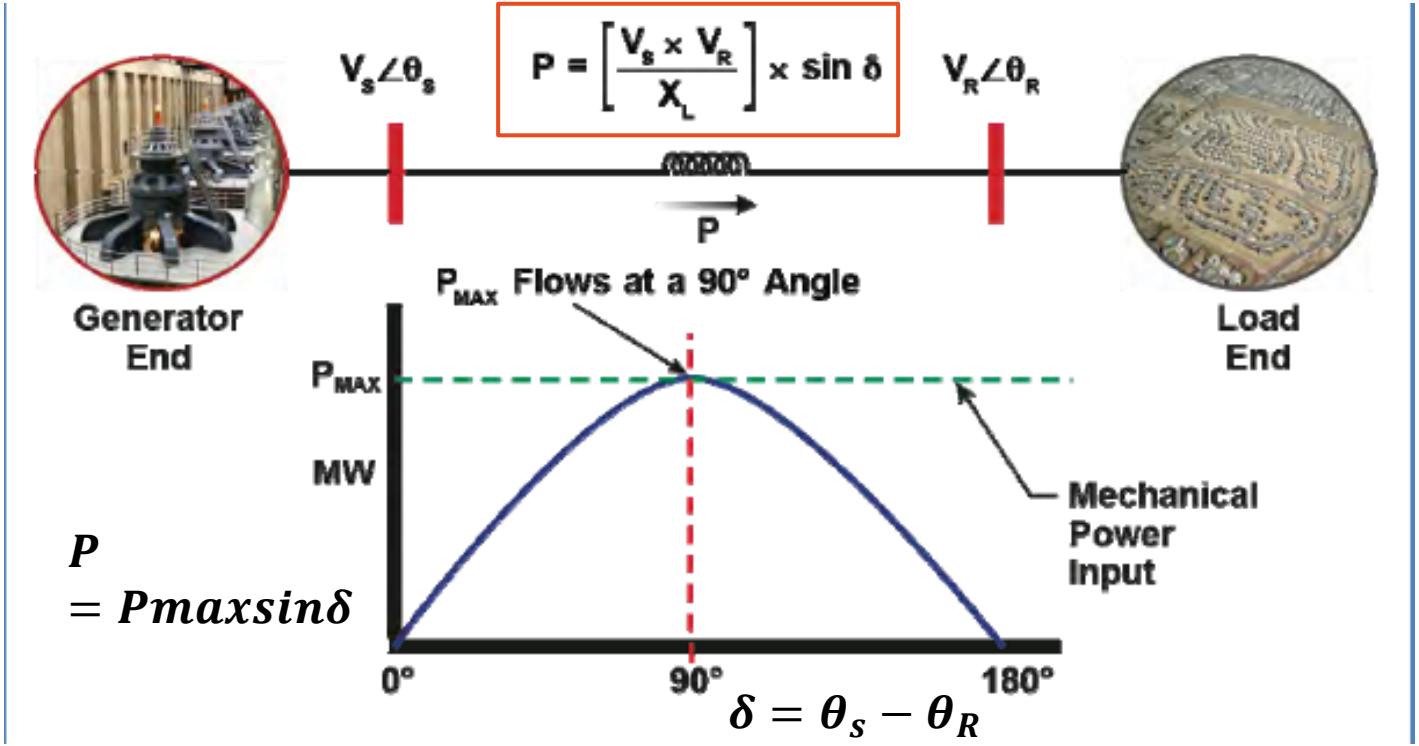
Introduction to Angle Stability

- Angle stability is related to the **phase angle separation** between power system buses.
- In a stable power system voltage magnitudes and angle differences have acceptable magnitudes and are controllable.
- The angular separation of the voltages (power angles) in this figure is small, ranging from 5° to 15°. This is typical for a high voltage transmission system.
- When a power system is angle stable it has sustained power angles of less than 90°.
- When a system is angle unstable, power angles grow beyond 90°, up to 180° and larger.
- System operators lose control of both MW and Mvar flows in an angle unstable system



Reference: EPRI 2008, "EPRI Power System Dynamics Tutorial", report 1016295

Active Power & the Power-Angle Curve



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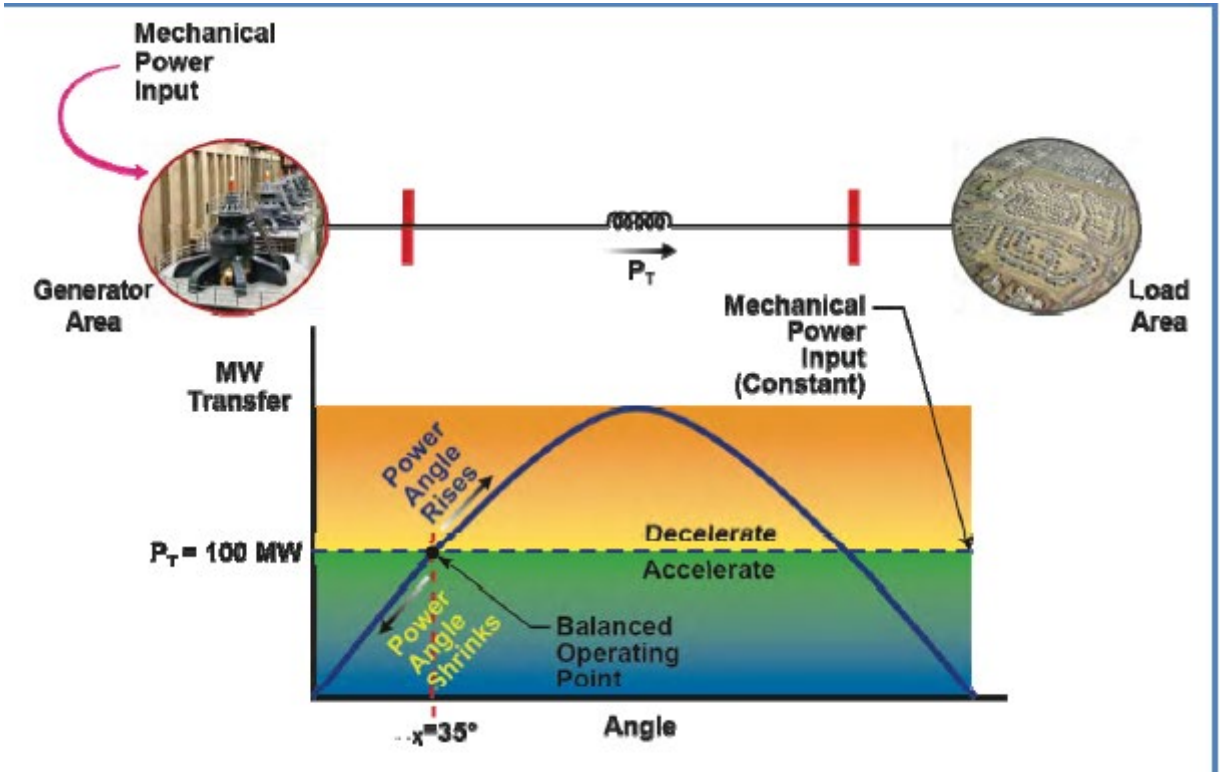
Active Power & the Power-Angle Curve



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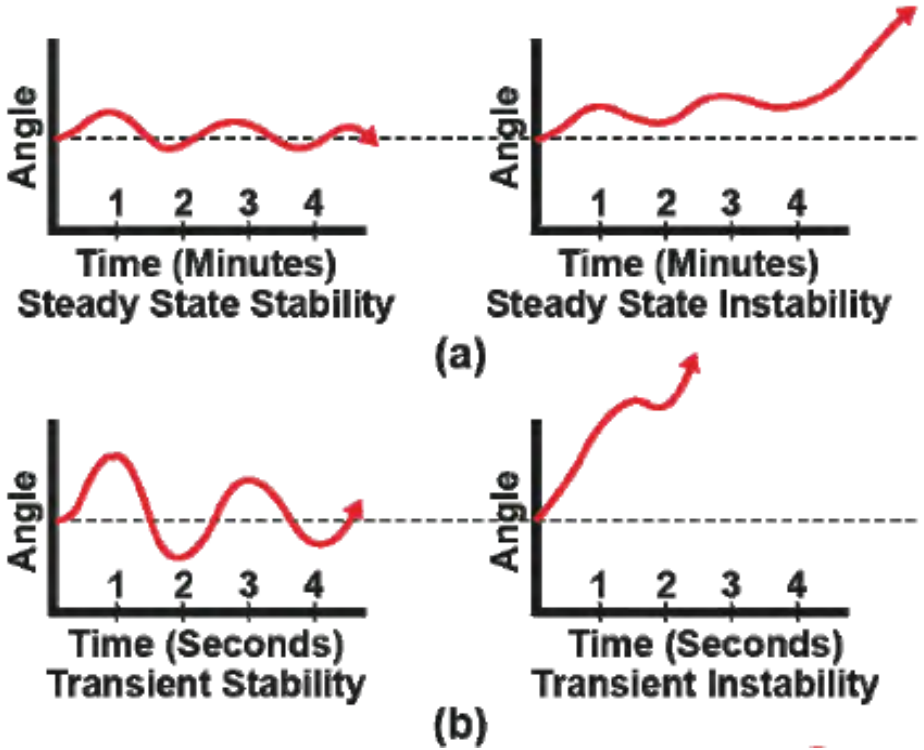
Types of Angle Stability



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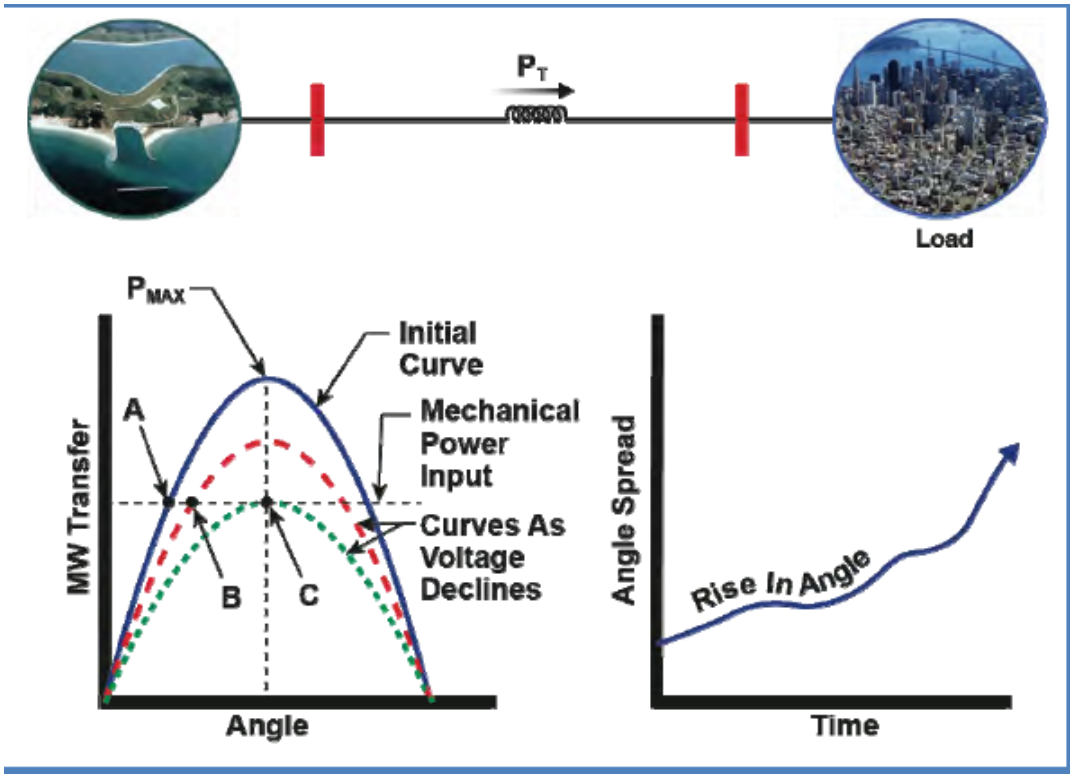
Example of Steady State Instability

$$P = \frac{V_S V_R}{X} sin\delta$$

$$P_{max} = \frac{V_S V_R}{X}$$



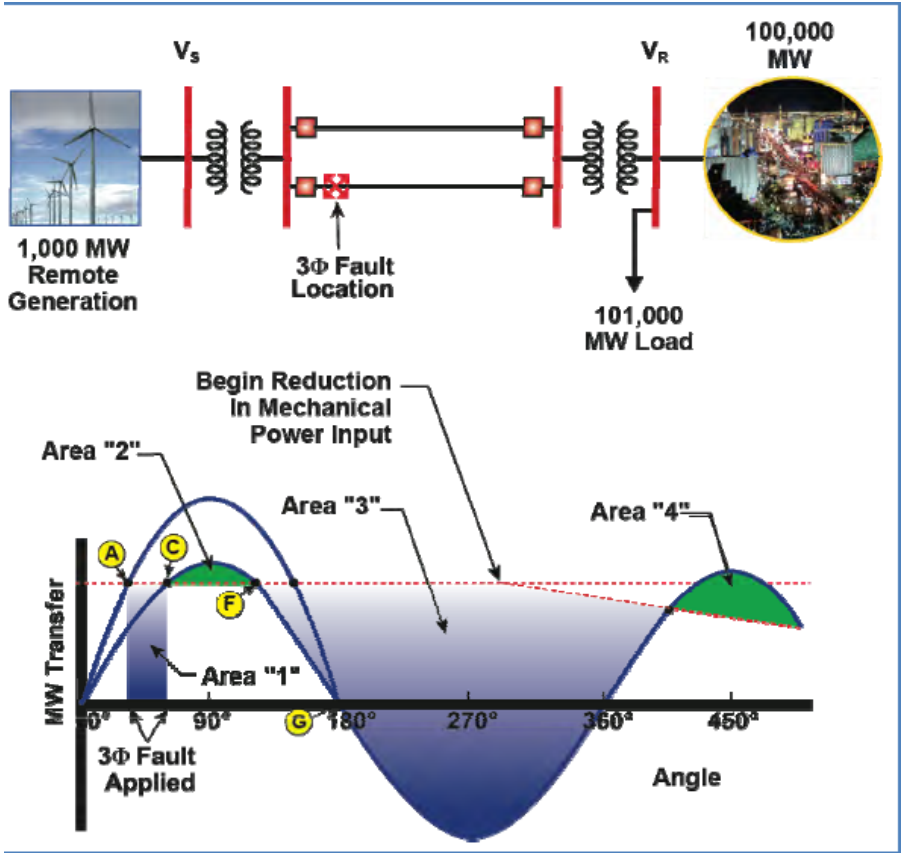
Reducing the Operating Angle will improve the Steady State Stability

Reference: EPRI 2008, “EPRI Power System Dynamics Tutorial”, report 1016295

Example of Transient Instability

$$P = \frac{V_S V_R}{X} sin\delta$$

$$P_{max} = \frac{V_S V_R}{X}$$



Reducing the Operating Angle will improve the Transient Stability

Reference: EPRI 2008, "EPRI Power System Dynamics Tutorial", report 1016295

Improving Angle Stability

- Reducing the power angle δ by increasing the line capacity $P_{max} = \frac{V_S V_R}{X}$

$$P = P_{max} sin\delta \rightarrow \delta = sin^{-1}(\frac{P}{P_{max}})$$

- Line capacity can increase by reducing the line reactance X
- This can be achieved by series compensation using series capacitors:

$$X = X_L - X_C$$

- Two issues:
  - Increasing the Short Circuit Capacity
  - Sub-Synchronous Resonance (SSR)

Shunt compensation may be a solution

Methodology

- The Theory
- Verification by simulation
- Validation by laboratory tests

The Theory

- The voltage at the midpoint of the transmission line is fixed using reactive compensation
- The line with reactance X is split into two lines each $\frac{X}{2}$
- The angle separation for each half of the line will be $\frac{\delta}{2}$:

$$P = \frac{V_S V_R}{\frac{X}{2}} \sin\frac{\delta}{2} \longrightarrow P = \frac{2V_S V_R}{X} \sin\frac{\delta}{2} \longrightarrow P = 2P_{max} \sin\frac{\delta}{2}$$

After compensation: $\delta = 2\sin^{-1}(\frac{P}{2P_{max}})$

Before compensation: $\delta = \sin^{-1}(\frac{P}{P_{max}})$

Examples

Example 1: P=0.4 P_{max} $(Small\ \delta)$

Before compensation: $\boldsymbol{\delta = sin^{-1}\left(\frac{P}{P_{max)}}\right) = sin^{-1}(0.4) = 23.579^o}$

After compensation: $\boldsymbol{\delta = 2sin^{-1}(\frac{P}{2P_{max}})=2\ sin^{-1}(0.2) = 2 \times 11.537^o = 23.074^o}$

Example 2: P=0.8 P_{max} $(Large\ \delta)$

Before compensation: $\boldsymbol{\delta = sin^{-1}\left(\frac{P}{P_{max)}}\right) = sin^{-1}(0.8) = 53.130^o}$

After compensation: $\boldsymbol{\delta = 2sin^{-1}(\frac{P}{2P_{max}})=2\ sin^{-1}(0.4) = 2 \times 23.579^o = 47.156^o}$

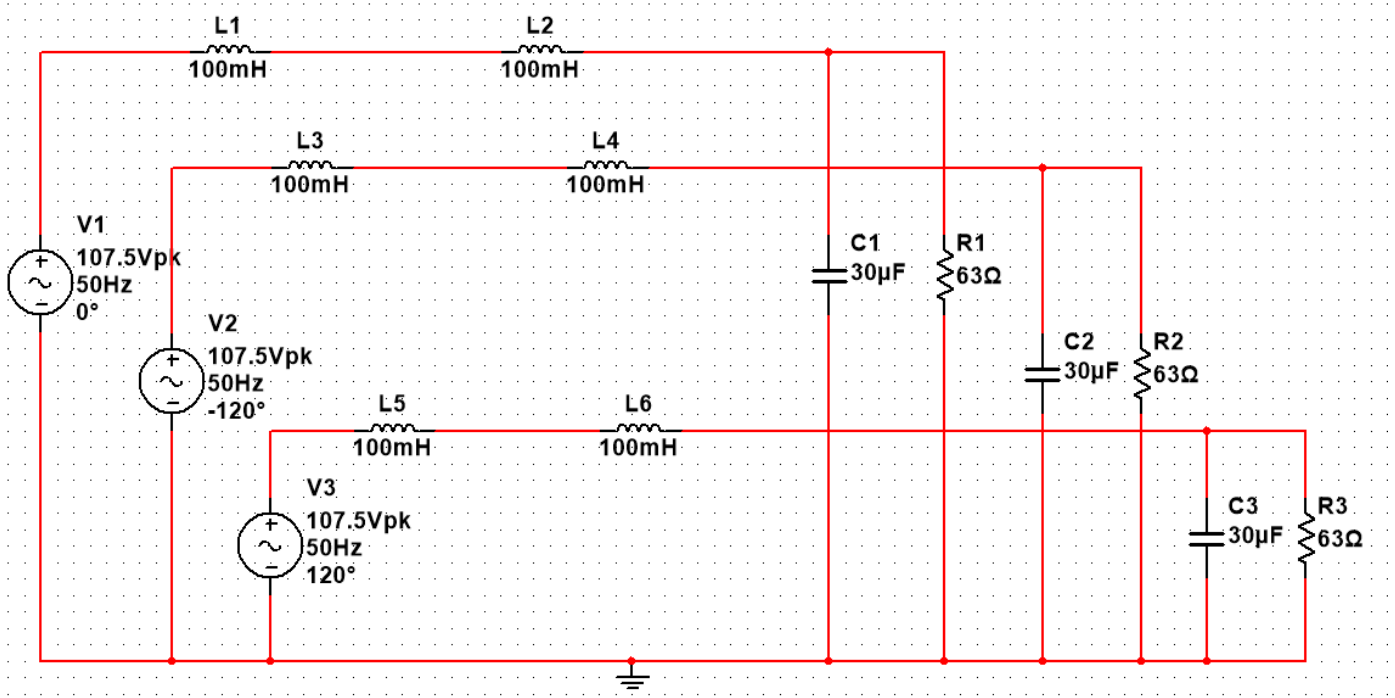
Simulation: Python Code Results

```
v_load_capa((76,0),0.2,63,30*pow(10,-6))
```

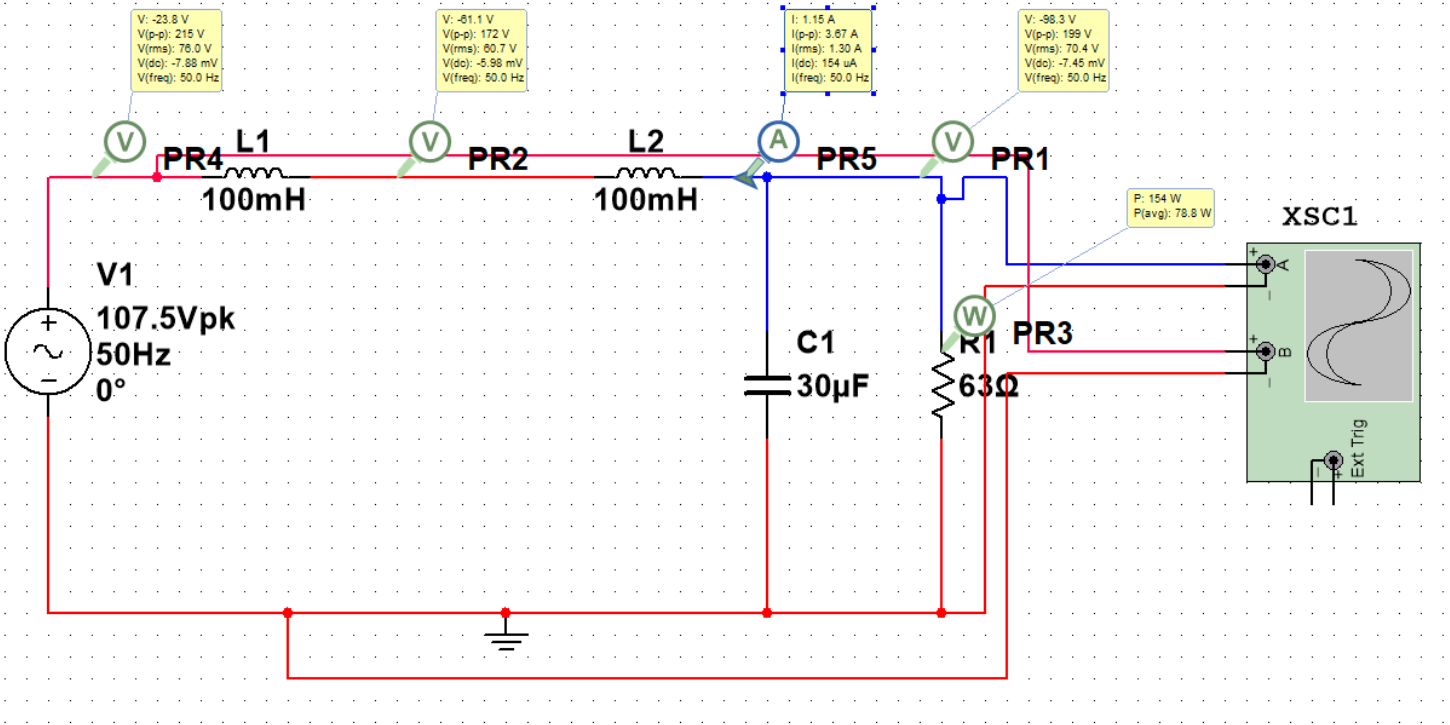
```
Transmission Line Simulation
voltage of source:(76, 0) V
inductance of transmission line: 0.2 H
load: 63 ohm
load current: (1.302, -0.647) A
load voltage: (70.52, -1.183) V
load active power: 78.943 W
load reactive power: -46.892 VAR
load apparent power: (91.82,-0.536) VA
voltage at the middle of transmission line: (60.839, -0.566) V
difference angle between the source and load voltages: 1.183 radian = 67.781 degree
```

Without midpoint compensation

Simulation: Circuit without midpoint compensation

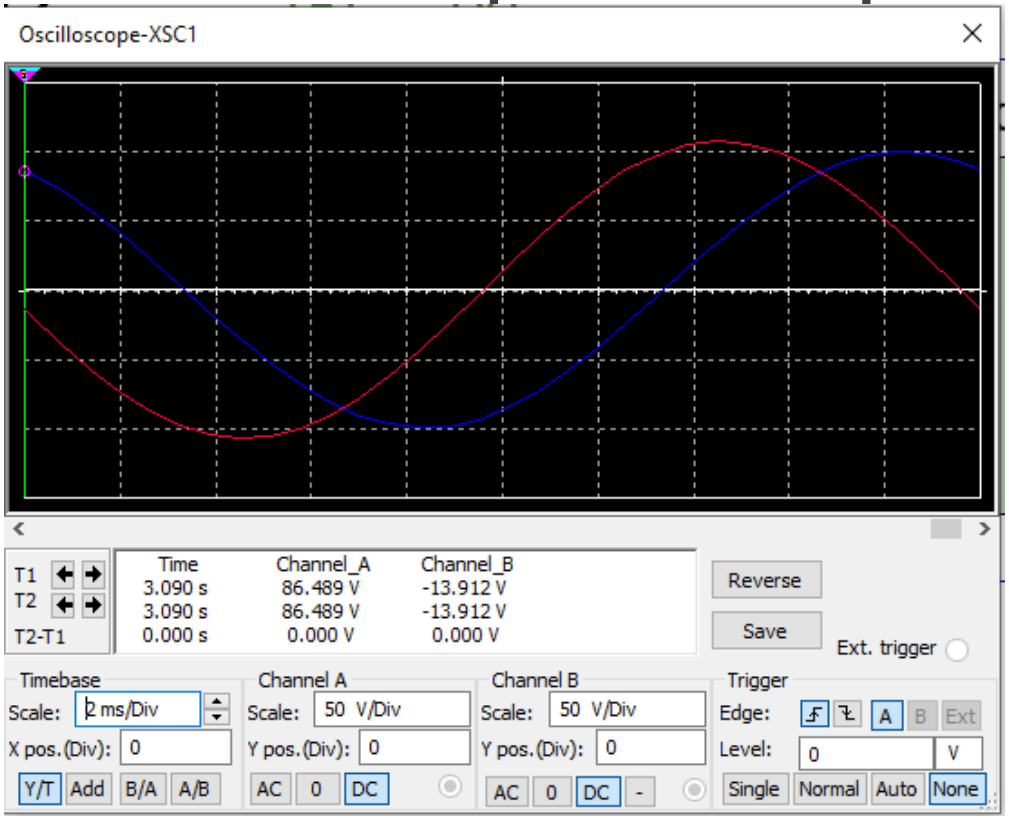


Multisim Simulation



Readings: without midpoint compensation

Simulation: No midpoint compensation



Power Angle δ=9.5/50×360≅68°

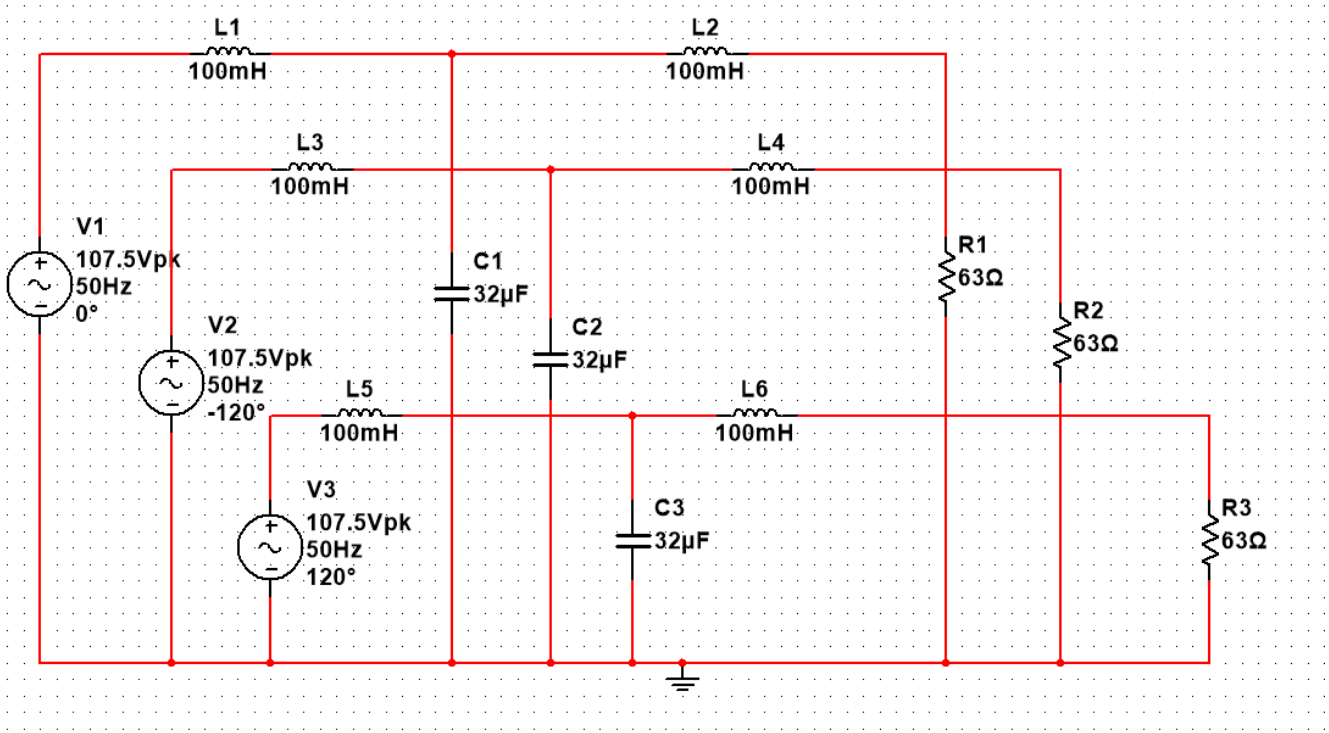
Simulation: Python Code Results

```
v_load_stabilized((76,0),0.1,32*pow(10,-6),0.1,63)
```

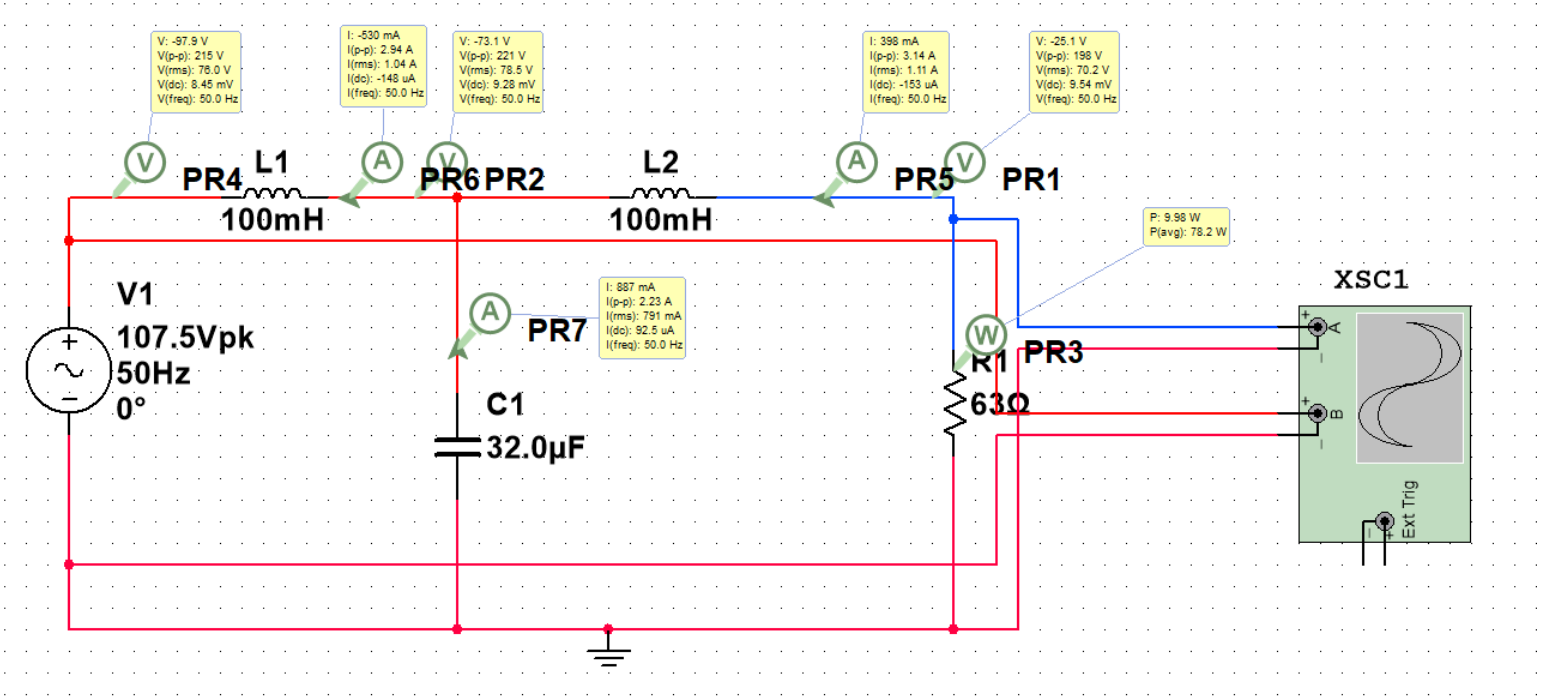
```
Transmission Line Simulation with Stabilizer
voltage of source:(76, 0) V
inductance of the first section of the transmission line: 0.1 H
capacitance in the middle of the transmission line: 3.2e-05 farad
inductance of the second section of the transmission line: 0.1 H
load: 63 ohm
current of source: (1.038, -0.141) A
load voltage: (70.146, -0.888) V
load current: (1.113, -0.888) A
load active power: 78.103 W
load reactive power: 0.0 VAR
load apparent power: (78.103, 0.0) VA
voltage at the middle of transmission line: (78.374, -0.424) V
difference angle between the source and load voltages: 0.888 radian = 50.867 degree
```

With midpoint compensation

Simulation: Circuit with midpoint compensation

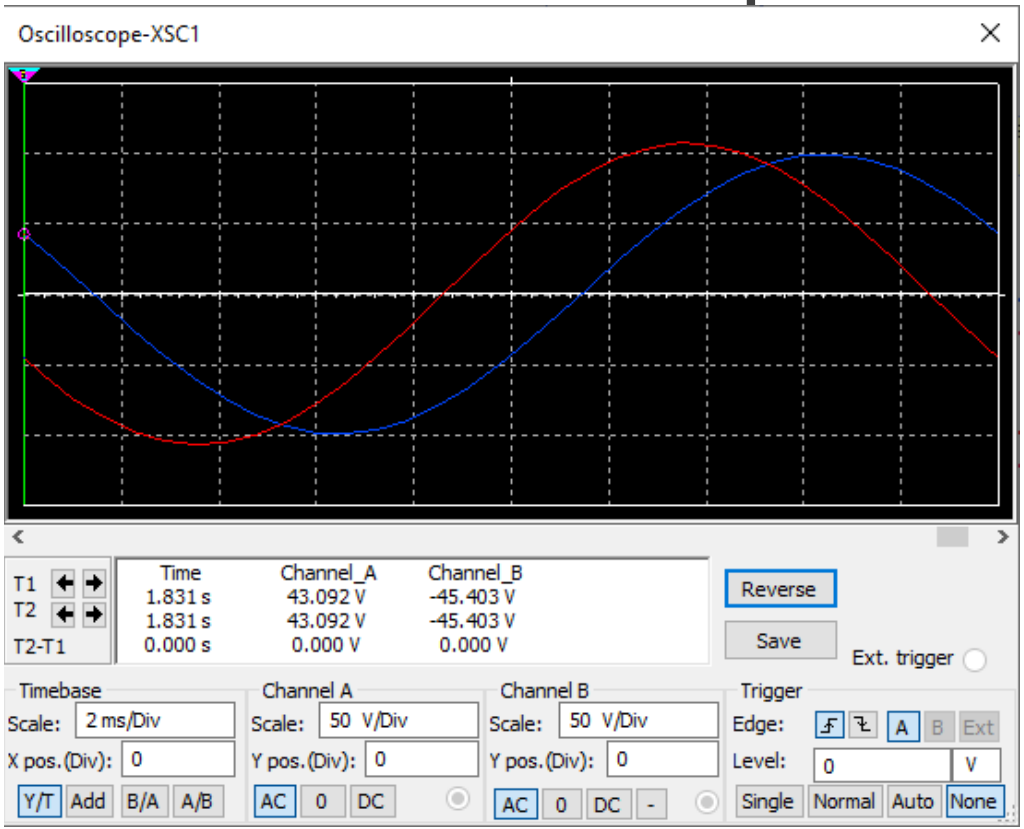


Multisim Simulation



Readings: with midpoint compensation

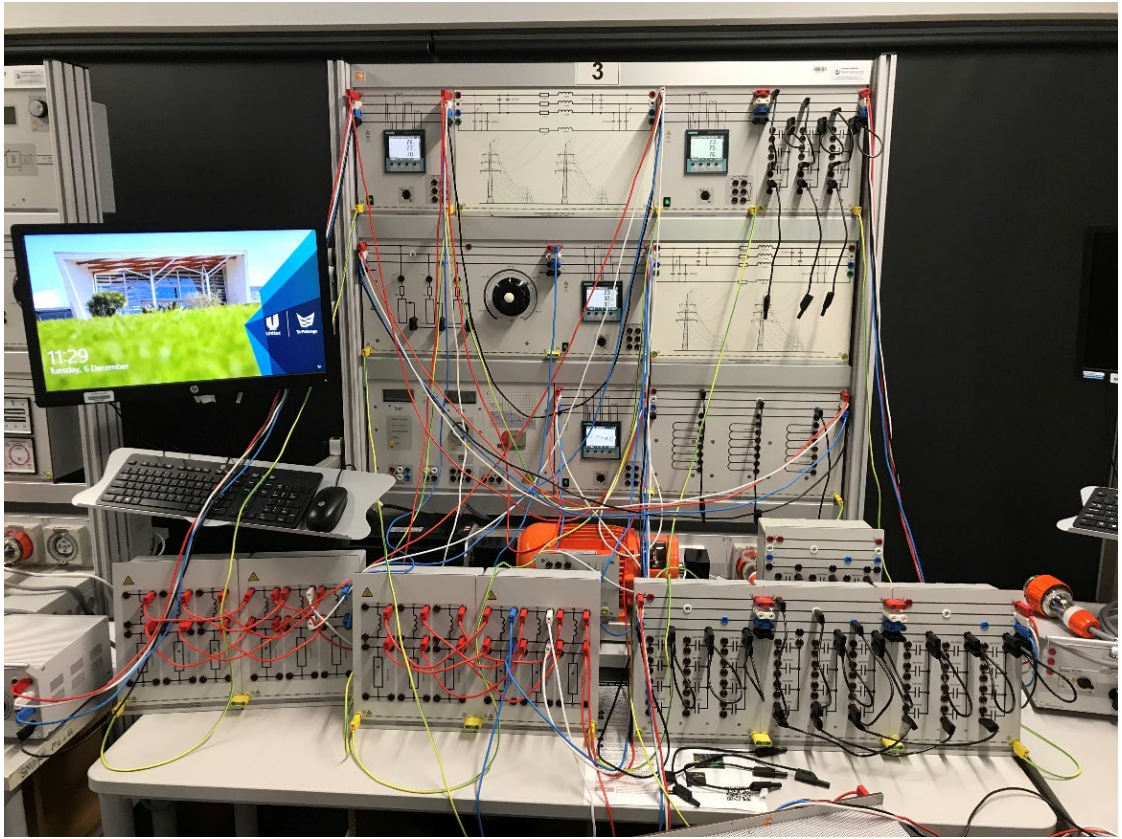
Simulation: midpoint compensation



Power Angle $\delta = 7/50 \times 360 \cong 50.4°$

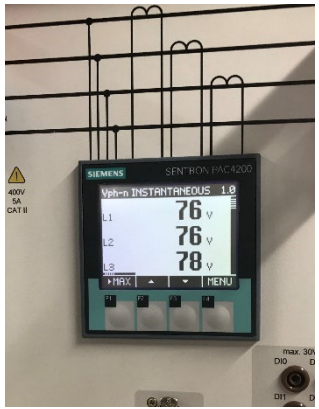
The angle difference decreases from $68°$ to $50.4°$ due to the reactive power compensation.

Validation: Power Lab Test Bench

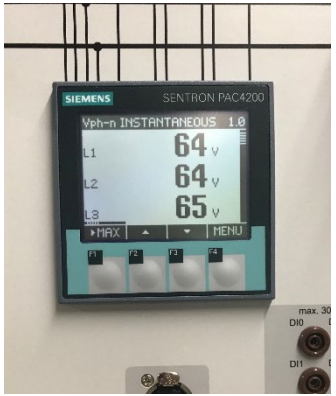


Validation: Power Lab Test

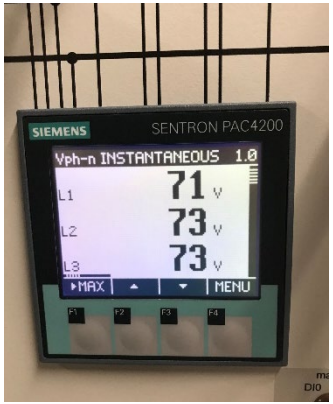
Before Midpoint Compensation:



Source Voltage

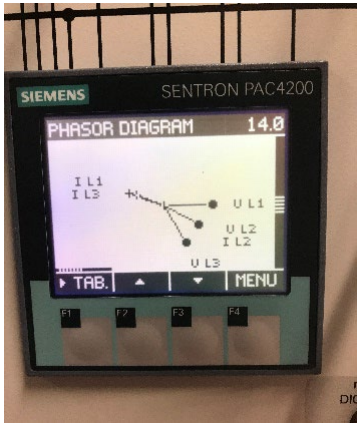


Midpoint Voltage



Load Voltage

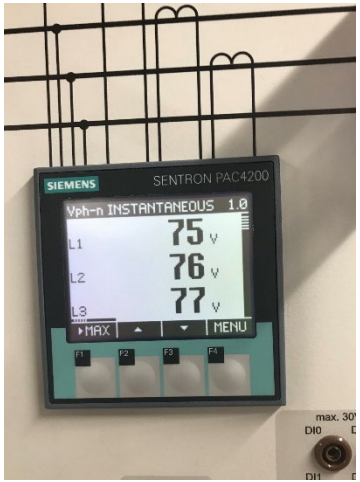
Load Power



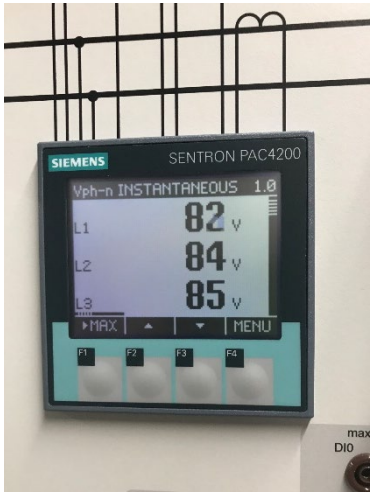
Angle Difference

Validation: Power Lab Test

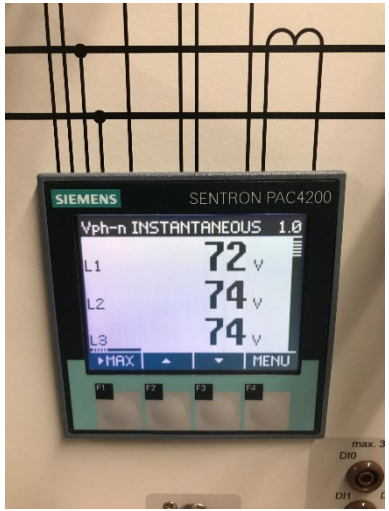
With Midpoint Compensation:



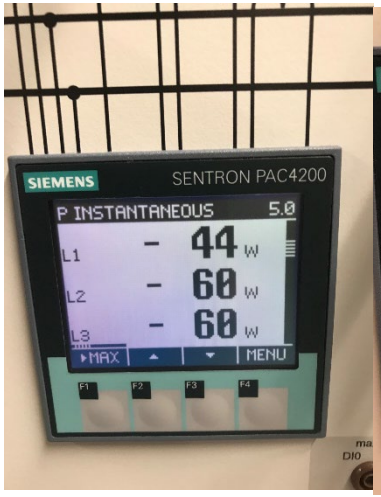
Source Voltage



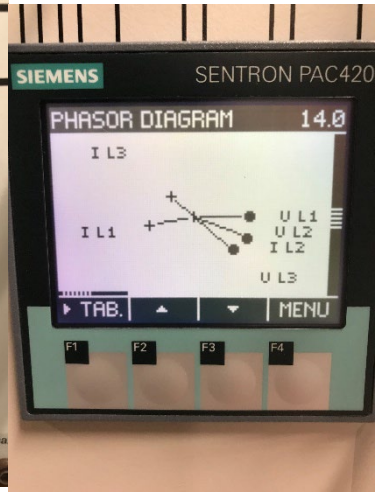
Midpoint Voltage



Load Voltage

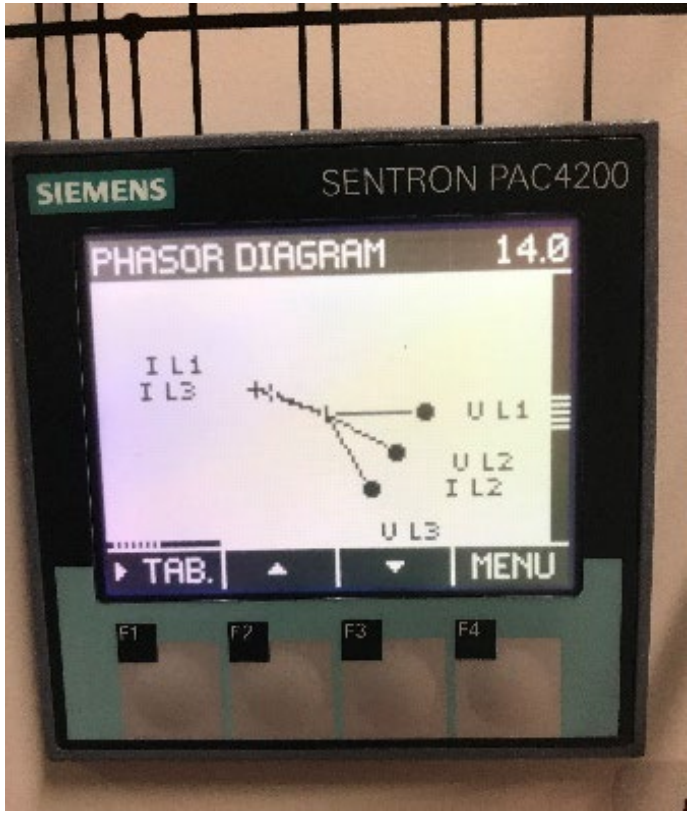


Load Power

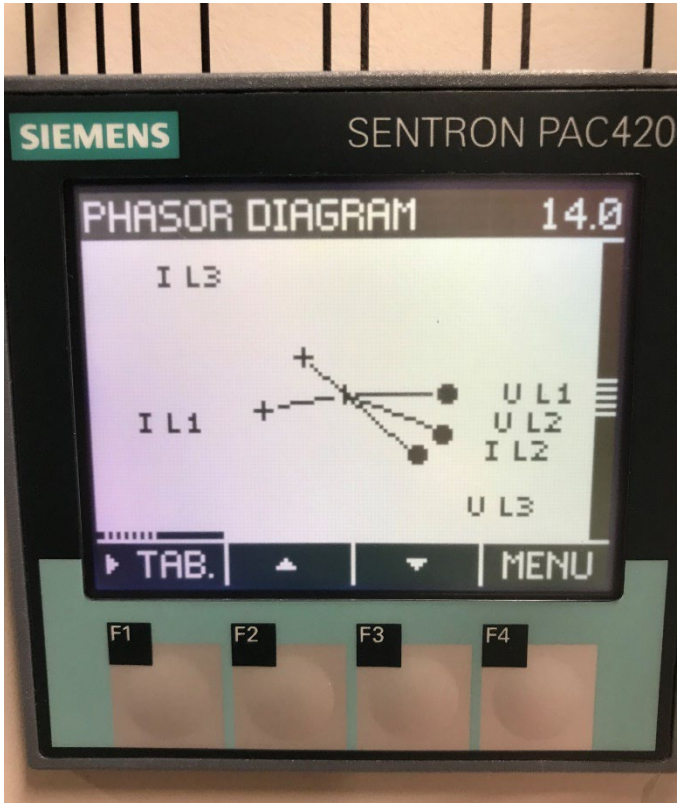


Angle Difference

Angle Differences Comparison



Without Midpoint Compensation



With Midpoint Compensation

Conclusion

- The main objective of this research was improving power system angle stability
- It was shown that the line midpoint voltage control can be used to decrease the power angle
- Mutlisim simulations were used to verify the proposed theory
- The findings were validated using the Lucas Nuelle Power Equipment
- The future work will be on the impact of the proposed method on the relays settings

Thank You