بِسْمِ ٱللَّهِ ٱلرَّحْمَٰنِ ٱلرَّحِيمِ

(وَفَوْقَ كُلِّ ذِي عِلْمٍ عَلِيمٌ)

صدق الله العظيم

Tuesday , March, 24 ,2020
9.00 AM

Electrical Test (4)

Experiment

Power Line Series Compensation Demonstrator

Presenter:

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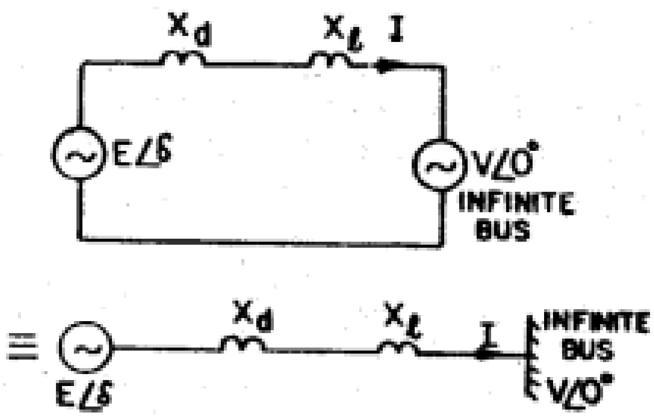
Power flow

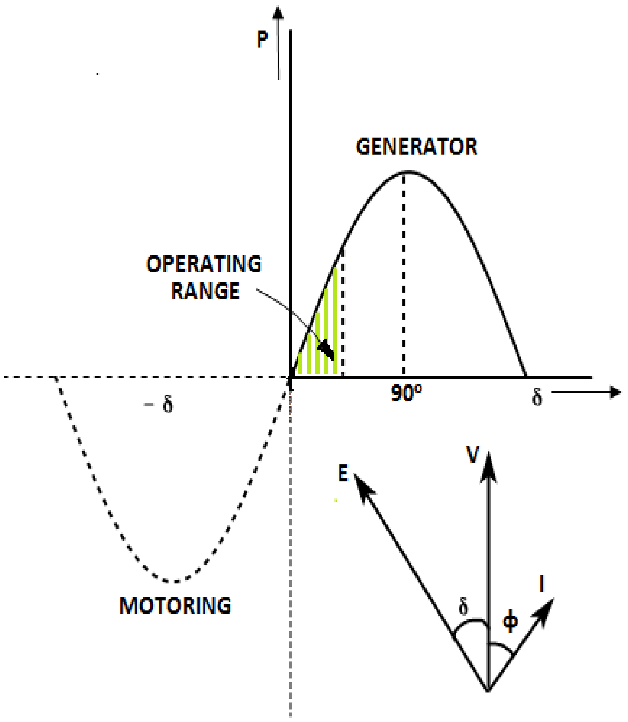


Active power transferred to the system

$$P_e = \frac{EV}{X} \sin \delta$$

The reactive power transferred to the system

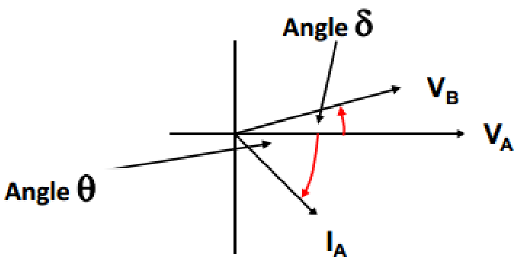
$$Q_e = \frac{EV}{X} \cos \delta - \frac{V^2}{X}$$



Real power flow

- Real Power (P_R) flow between two buses is obtained by:

$$P_R = \frac{V_S \times V_R}{X} \times \sin\delta$$



Where,

- P = Real power in MW
- V_S = Sending-end voltage
- V_R = Receiving-end voltage
- X = Line impedance between buses
- δ = Angle delta between bus voltages

Electrical Test (4)

Real power flow

- Increasing impedance results in a decrease in real power transfer.
- Increasing the phase angle difference increases real power transfer.
- Neither increasing or decreasing voltage magnitudes has a significant effect on the flow of real power.
- If impedances of parallel lines are equal, power flow is equally distributed.
- If impedances of parallel lines are different, real power flow is inversely proportional to line impedance.

Electrical Test (4)

Reactive power flow

- Reactive Power (P_Q) flow on a transmission line is a result of the inductive reactance of the load requirement and is obtained by:

$$P_Q = \frac{V_S \times \Delta V}{X} \times \cos\delta$$

Where,

Q = Reactive Power in MVAR

V_S = Sending-end voltage

ΔV = Difference between bus voltages V_S and V_R

X = Line Impedance between buses

δ = Phase angle between VS and VR

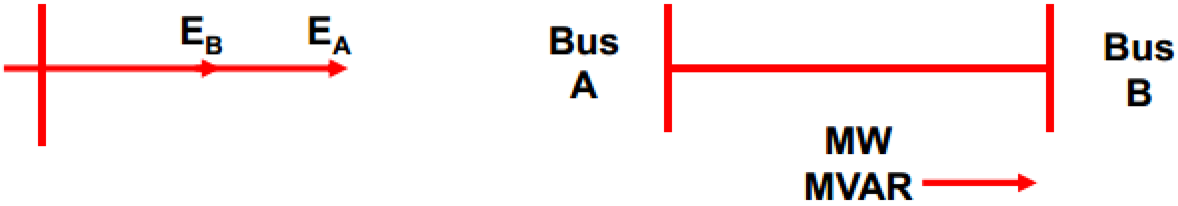
Reactive power flow

- Increasing the voltage magnitude at the sending end increases the reactive power flow toward the receiving end.
- Increasing the voltage magnitude at the receiving end decreases the reactive power flow toward the receiving end.
- Increasing the path impedance between the two buses decreases the reactive power flow towards the receiving end.

Different Scenarios of power flow

Scenario 1

- Voltages are in-phase; Bus A voltage > Bus B voltage

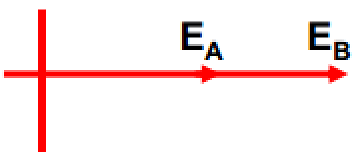


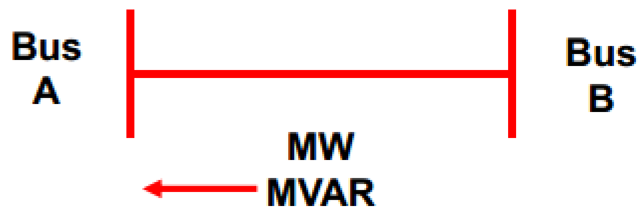
- No MW flow; no phase angle difference
- VAR's flow from Bus A to Bus B

Different Scenarios of power flow

Scenario 2

- Voltages are in-phase; Bus A voltage < Bus B voltage



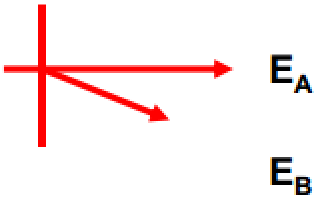


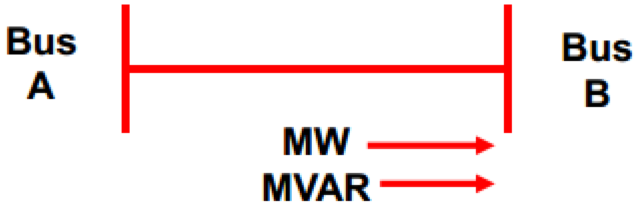
- No MW flow; no phase angle difference
- VAR's flow from Bus B to Bus A

Different Scenarios of power flow

Scenario 3

- Voltages are not in-phase; Bus A voltage > Bus B voltage



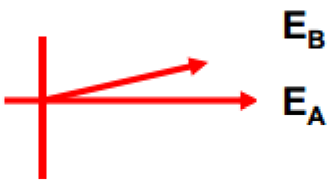


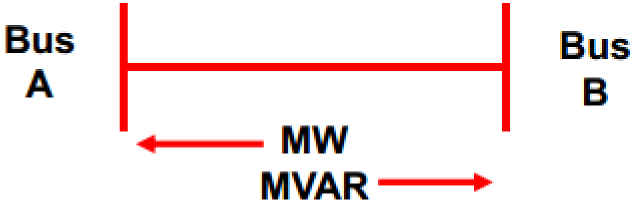
- MW flow; Bus B voltage is lagging Bus A voltage
- VAR's flow from Bus A to Bus B

Different Scenarios of power flow

Scenario 4

- Voltages are not in-phase; Bus A voltage > Bus B voltage



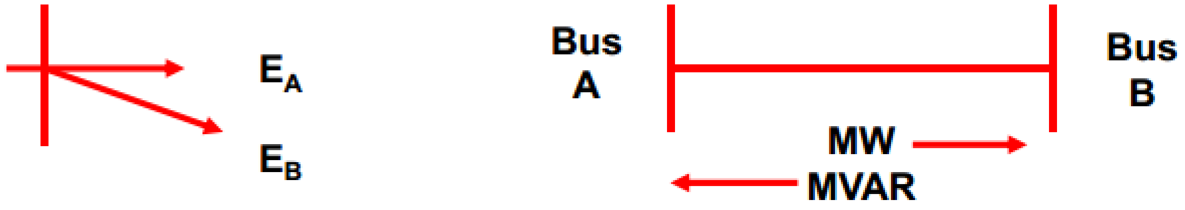


- MW flow; Bus A voltage is lagging Bus B voltage
- VAR's flow from Bus A to Bus B

Different Scenarios of power flow

Scenario 5

- Voltages are not in-phase; Bus A voltage < Bus B voltage

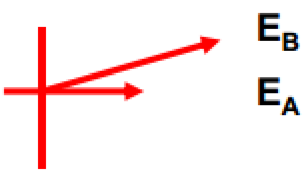


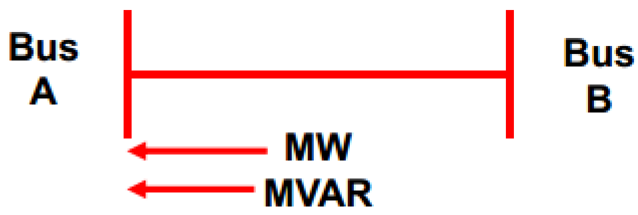
- MW flow; Bus B voltage is lagging Bus A voltage
- VAR's flow from Bus B to Bus A

Different Scenarios of power flow

Scenario 6

- Voltages are not in-phase; Bus A voltage < Bus B voltage





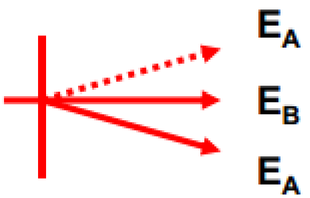
- MW flow; Bus A voltage is lagging Bus B voltage
- VAR's flow from Bus B to Bus A

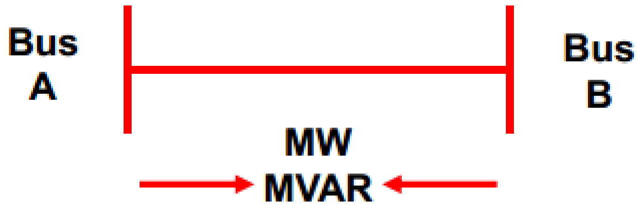
Electrical Test (4)

Different Scenarios of power flow

Scenario 7

- Voltages are not in-phase; Bus A voltage = Bus B voltage





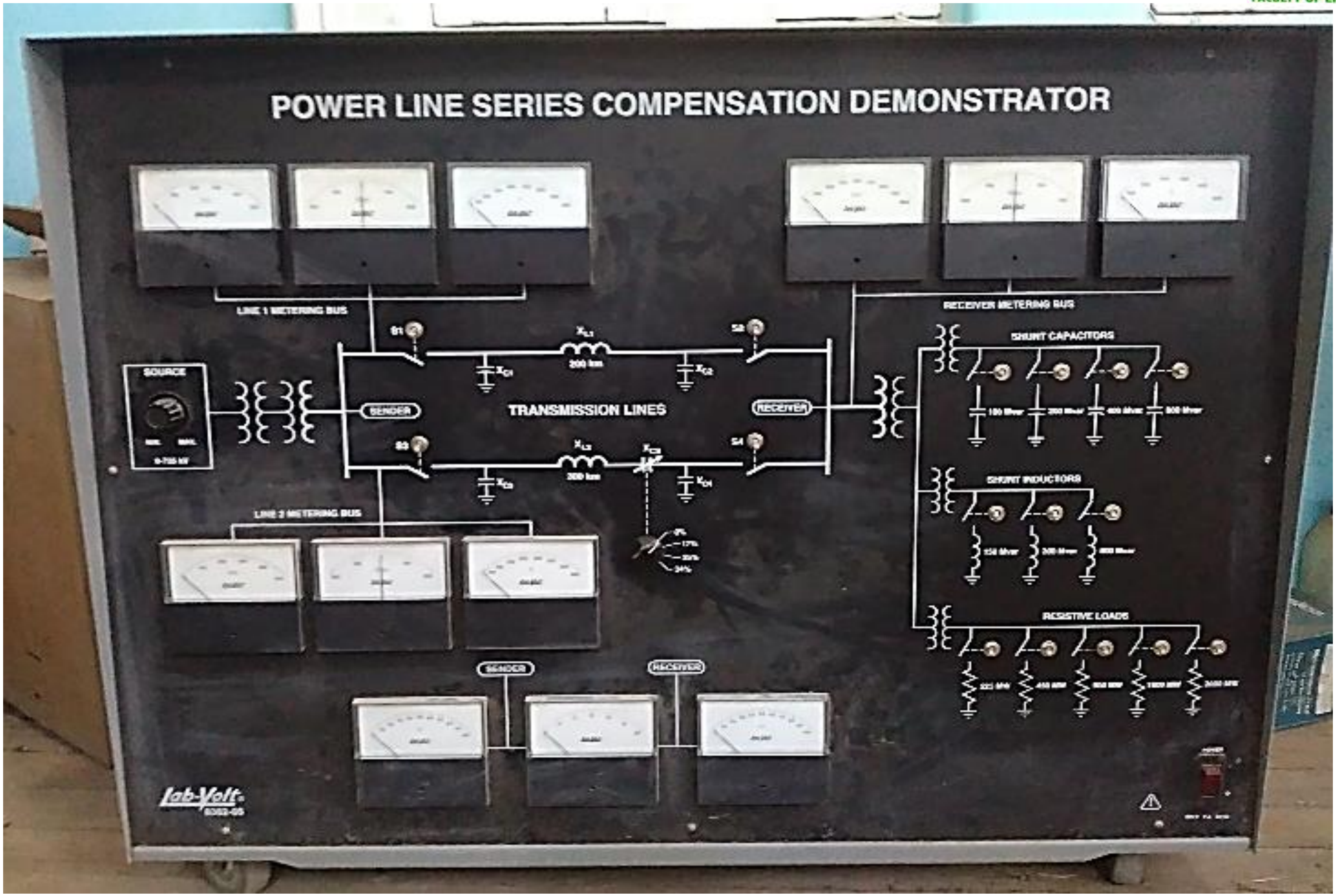
- MW flow
  - Bus A voltage lags Bus B voltage, MW flow into Bus A
  - Bus B voltage lags Bus A voltage, MW flow out of Bus A
- VAR's flow from Bus B and from Bus A into the line

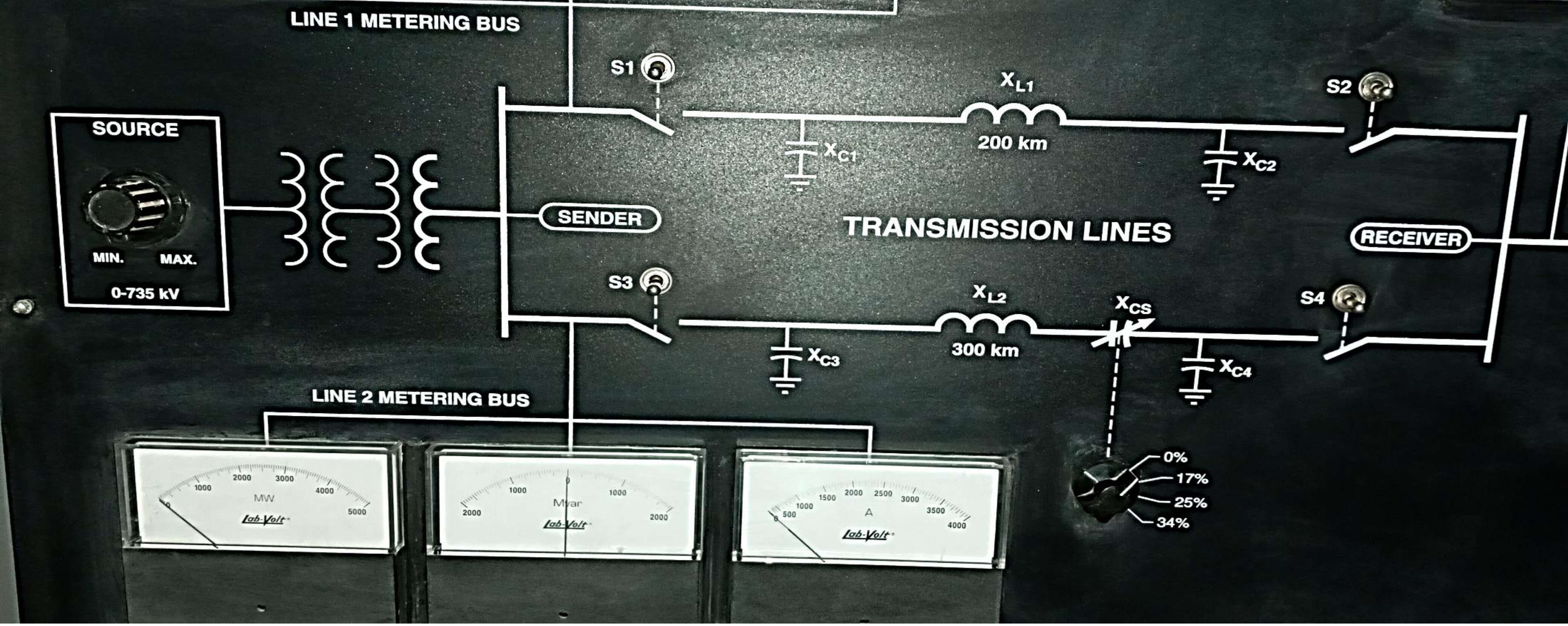
Difference between series and shunt compensation

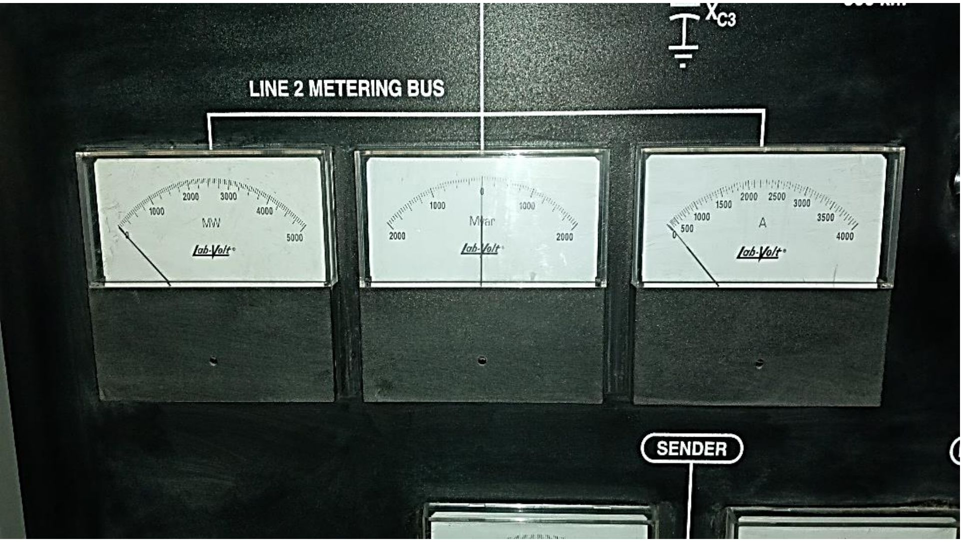
	Shunt compensation	Series compensation
Advantages	❑ Control the reactive power at load. ❑ The power factor improves and increases active power output which is available from the source.	❑ Increase power transfer capability and stability. ❑ Improve the power factor. ❑ Reduce transmission lines losses. ❑ Improve voltage regulation.
Disadvantages	➢ The Shunt capacitors does not affect current or power factor beyond their point of application. ➢ The reactive power which is supplied by the shunt capacitor banks is directly proportional to bus voltage. ➢ When the reactive power is required less on light load the capacitor bank output will be high.	➢ Increase in fault current. ➢ Mal operation of distance relay if the degree of compensation and location is not proper.

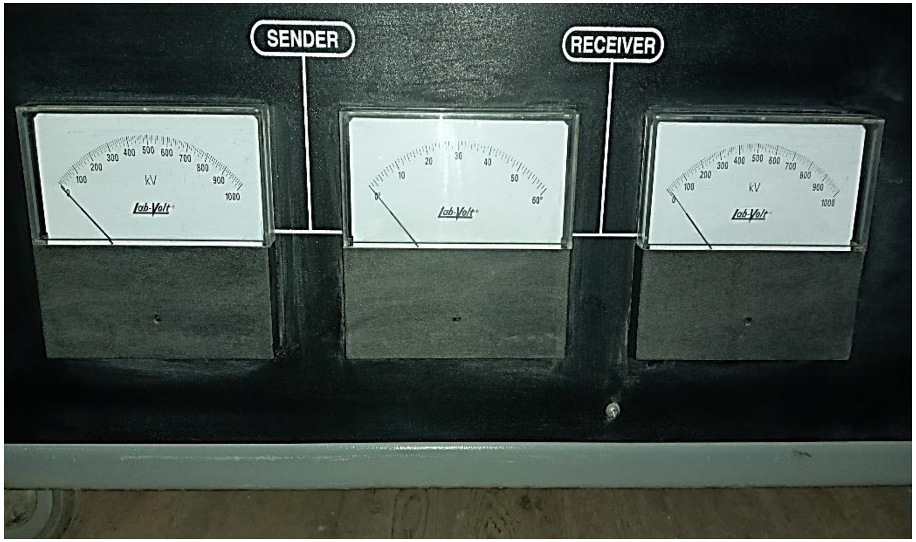
Power Line Series Compensation Demonstrator

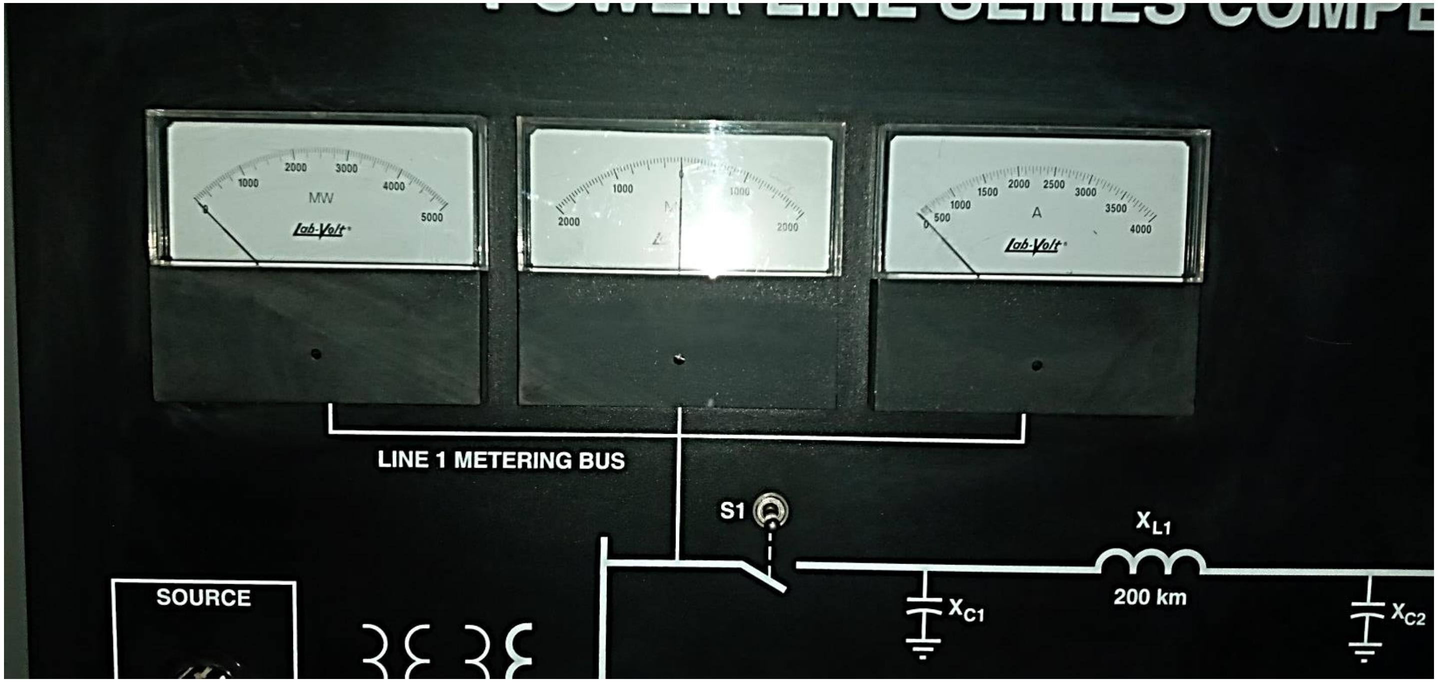
Electrical Test (4)

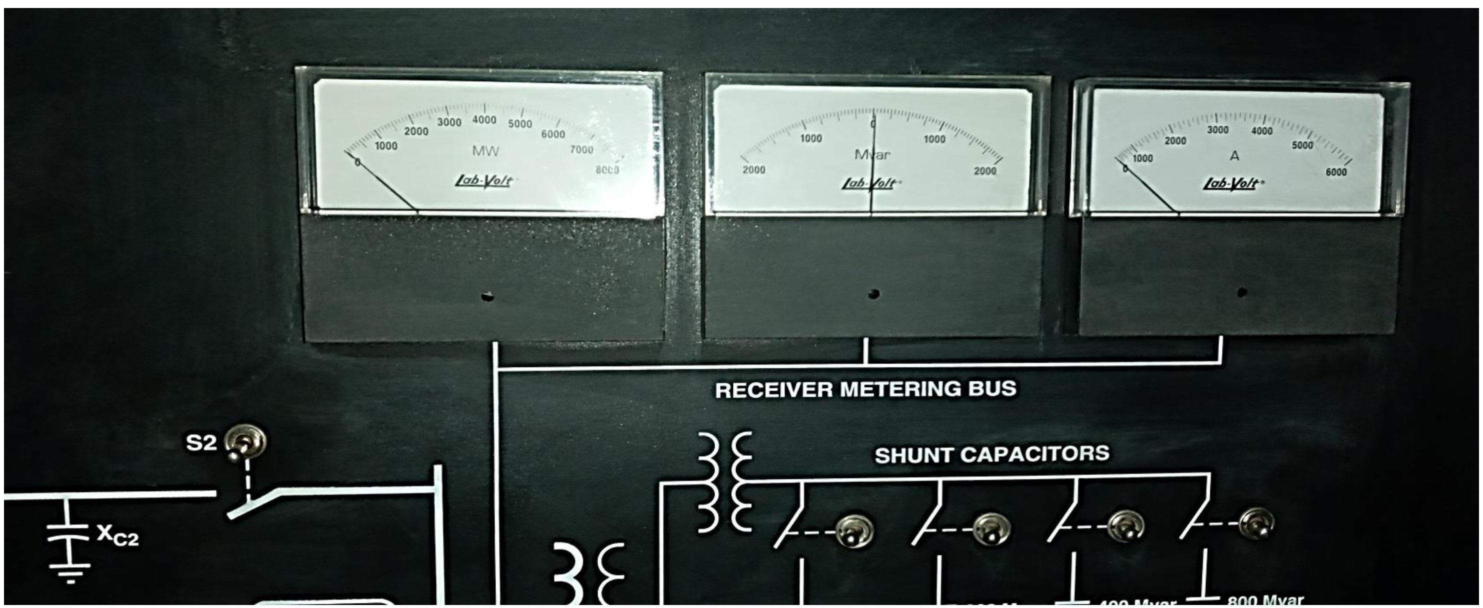


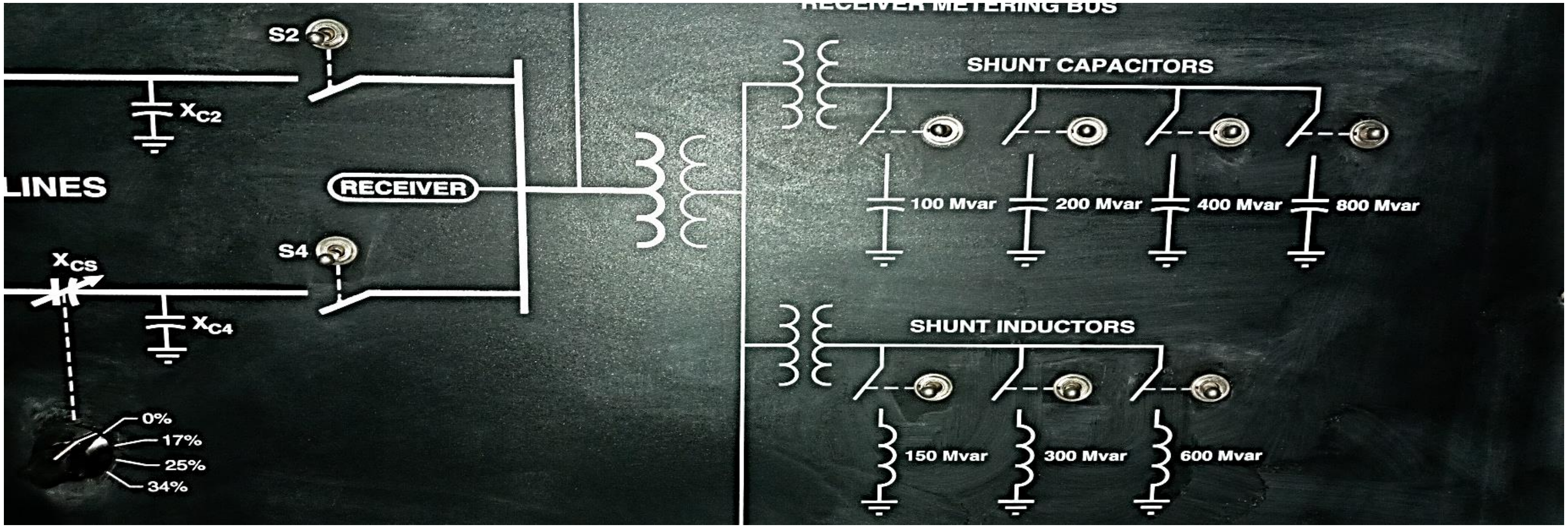

LINE 1 METERING BUS
SOURCE
MIN.
MAX.
0-735 kV
SENDER
S1
S2
S3
S4
X_{L1}
200 km
X_{C1}
X_{C2}
TRANSMISSION LINES
RECEIVER
X_{L2}
300 km
X_{CS}
X_{C3}
X_{C4}
LINE 2 METERING BUS
0%
17%
25%
34%
MW
Mvar
A
Lab-Volt

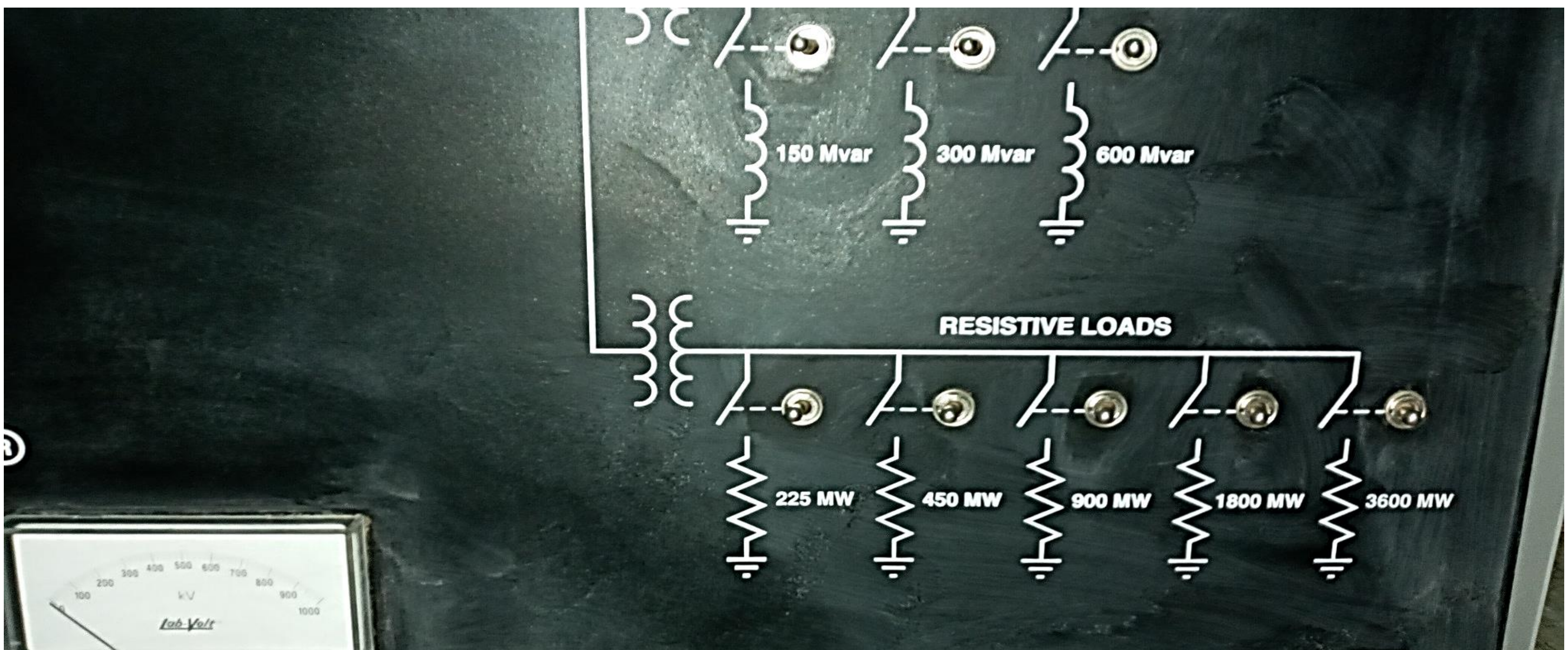

X_{C3}
LINE 2 METERING BUS
MW
Mvar
A
Lab-Volt
SENDER


SENDER
RECEIVER
kV
Lab-Volt


LINE 1 METERING BUS
S1
X_{L1}
200 km
SOURCE
X_{C1}
X_{C2}


RECEIVER METERING BUS
S2
SHUNT CAPACITORS
X_{C2}


RECEIVER METERING BUS
S2
X_{C2}
LINES
RECEIVER
S4
X_{CS}
X_{C4}
0%
17%
25%
34%
SHUNT CAPACITORS
100 Mvar
200 Mvar
400 Mvar
800 Mvar
SHUNT INDUCTORS
150 Mvar
300 Mvar
600 Mvar


150 Mvar
300 Mvar
600 Mvar
RESISTIVE LOADS
225 MW
450 MW
900 MW
1800 MW
3600 MW
kV
Lab-Volt
POWER

Electrical Test (4)

Parameter	Value
Power Requirement	
Current	2 A
Protection	Circuit breaker
Service Installation	Standard single-phase ac outlet
Line 1	
Simulation lengthy	200 km
Simulated Nominal Power	4500 MW
Line 2	
Simulation lengthy	300 km
Simulated Nominal Power	3000 MW
Compensation	17 %, 25 %, and 34 %
Front Panel Meters	
Ammeters	0-6000 A (1)
Phasemeter	0-60°
Varmeters	0-±2000 (3)
Voltmeters	0-1000 kV (2)

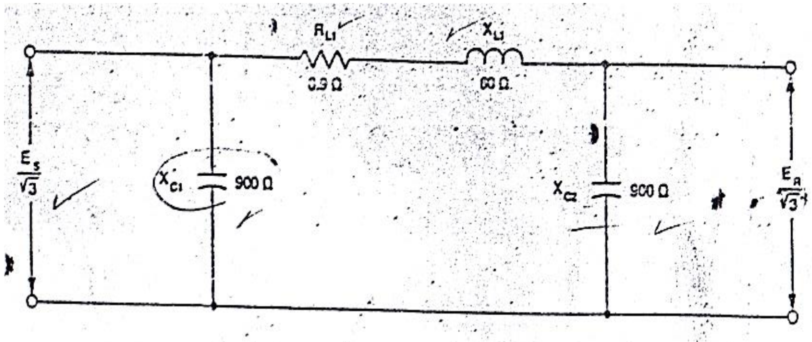
Electrical Test (4)

Transmission line 1 (non compensated)

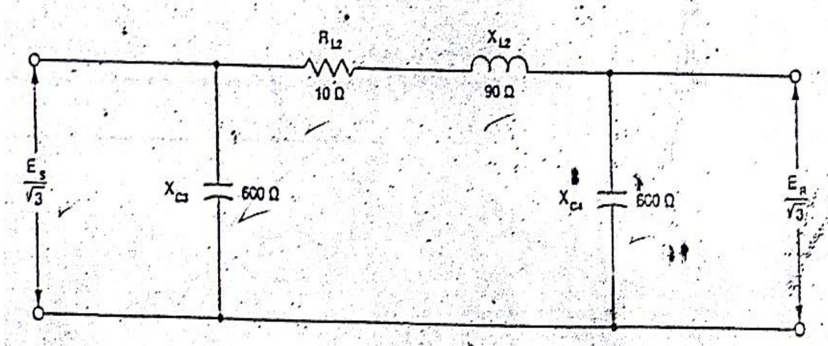
- Simulated length .... 200 km
- Impedance
  - R_{L1} .... 8.9 Ω
  - X_{L1} .... 60 Ω
  - X_{C1} .... 900 Ω
  - X_{C2} .... 900 Ω

Transmission line 2 (compensable)

- Simulated length .... 300 km
- Impedance
  - R_{L2} .... 10 Ω
  - X_{L2} .... 90 Ω
  - X_{C3} .... 600 Ω
  - X_{C4} .... 600 Ω



a) TRANSMISSION LINE 1 (200 km)



a) TRANSMISSION LINE 2 (300 km)

Electrical Test (4)

Power Transfer Capability of a Transmission Line (1)

Power transfer capability of transmission line 1 (200 km)

- ☐ 1. Open all the demonstrator switches. Put transmission line 1 in service by closing both switches S1 and S2.
- ☐ 2. Adjust the sender voltage to 735 kV using the SOURCE adjustment.
- ☐ 3. Connect a resistive load of 900 MW to line 1.
- ☐ 4. Observe that the receiver voltage exceeds the sender voltage due to reactive power being generated in excess by line capacitance X_{C2}.
- ☐ 5. Compensate line 1 so that the sender and receiver voltages are equal. To do so, connect the required shunt inductor (about 450 Mvar) across the load in order for the receiver voltage to be as close as possible to the sender voltage of 735 kV.
- ☐ 6. On the phasemeter, observe the phase shift between the sender and receiver voltages. The phase shift is about 6°, which is much less than 30°. Therefore, the power demand is well below the power transfer capability of line 1.
- ☐ 7. Increase the load on line 1 to 1800 MW.

Electrical Test (4)

8. Readjust the shunt inductor across the load so that the receiver voltage is as close as possible to the sender voltage of 735 kV. The required shunt inductor should be around 150 Mvar.

9. The phase shift now observed on the phasemeter is about 12°, which is less than 30°. Therefore, the power demand is still below the power transfer capability of line 1.

10. Further increase the load on line 1 to 3600 MW.

11. Compensate line 1 so that the sender and receiver voltages are equal. First disconnect the shunt inductor from the load. Then connect the required shunt capacitor (around 800 Mvar) across the load in order for the receiver voltage to be as close as possible to the sender voltage of 735 kV.

12. The phase shift now observed on the phasemeter is about 25°. Therefore, the power transfer capability of line 1 has not been reached yet.

13. Further increase the load on line 1 to 4500 MW.

14. Readjust the shunt capacitor across the load so that the receiver voltage is as close as possible to the sender voltage of 735 kV. The required shunt capacitor should be about 1500 Mvar.

15. The phase shift now observed is about 30°. Therefore, the power transfer capability of line 1 has been reached and is 4500 MW.

Note: *If the displayed phase angle differs from 30° by more than 3°, you may want to readjust the load on line 1 in order to accurately measure its power transfer capability at 30°.*

Electrical Test (4)

Power Transfer Capability of a Transmission Line (2)

Power transfer capability of transmission line 2 (300 km)

- ☐ 16. Open all the demonstrator switches.
- ☐ 17. Put transmission line 2 in service by closing switches S3 and S4. Set the series-compensation selector to 0%.

	MW	Mvar
Line (1)	4500 MW	1500 Mvar
Line (2) at zero compensation	2925 MW	400 Mvar

☐ 18. Connect a resistive load of 1800 MW to line 2.

☐ 19. Compensate line 2 so that the sender and receiver voltages are equal. To do so, connect the required shunt inductor (about 300 Mvar) across the load in order for the receiver voltage to be as close as possible to the sender voltage of 735 kV.

☐ 20. On the phasemeter, observe the phase shift between the sender and receiver voltages. The phase shift is about 17°, which is much less than 30°. Therefore, the power demand is below the power transfer capability of line 2.

☐ 21. Increase the load on line 2 to 3600 MW.

☐ 22. Compensate line 2 so that the sender and receiver voltages are equal. First disconnect the shunt inductor from the load. Then connect the required shunt capacitor (about 1000 Mvar) across the load in order for the receiver voltage to be as close as possible to the sender voltage of 735 kV.

☐ 23. The phase shift now observed on the phasemeter is about 38°, which is much more than 30°. Therefore, the power demand exceeds the power transfer capability of line 2.

☐ 24. Decrease the load on line 2 to 2925 MW.

☐ 25. Readjust the shunt capacitor across the load so that the receiver voltage is as close as possible to the sender voltage of 735 kV. The required shunt capacitor should be about 400 Mvar.

☐ 26. The phase shift now observed is about 30°. Therefore, the power transfer capability of line 2 is 2925 MW.

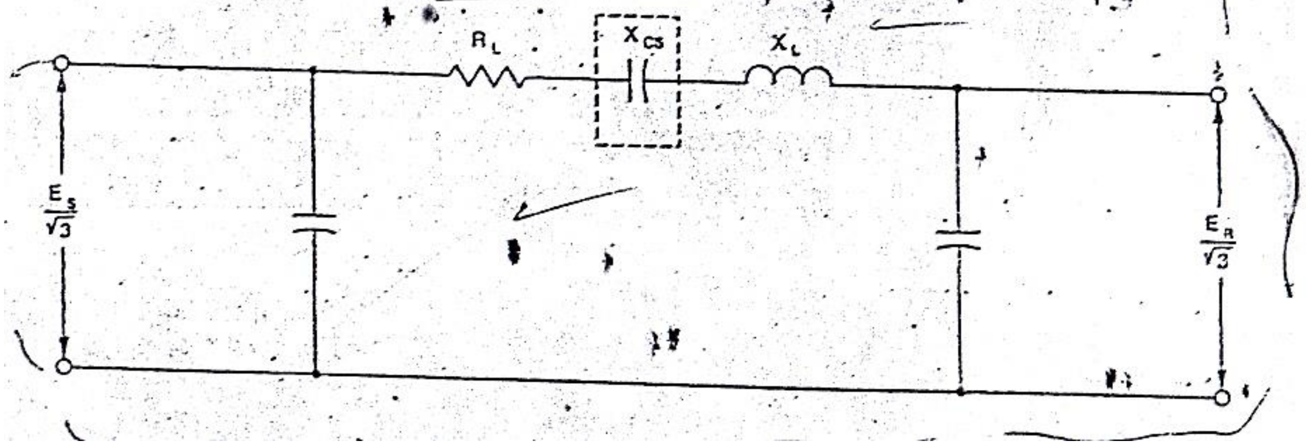
Note: *If the displayed phase shift differs from 30° by more than 3°, you may want to readjust the load on line 2 in order to accurately measure its power transfer capability at 30°.*

Effects of Series Compensation on Power Transfer Capability and System Stability

... through the line becomes

$$P_T = \frac{E_S \times E_R}{X_L - X_{CS}} \times \sin\theta$$

where
- P_T is the transferred power (W)
- E_S is the line-to-line sender voltage (V)
- E_R is the line-to-line receiver voltage (V)
- X_L is the reactance of the line (Ω)
- X_{CS} is the reactance of the series capacitor (Ω)
- θ is the phase shift between the sender and receiver voltages (°)



Electrical Test (4)

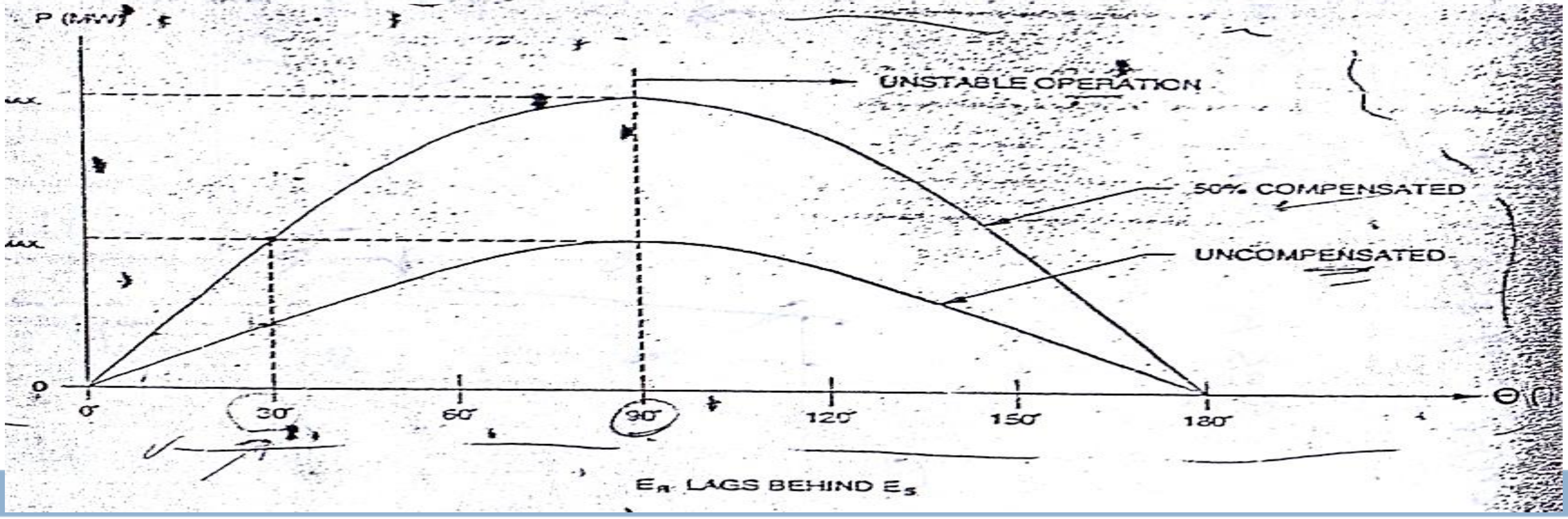
The decrease in line reactance created by series compensation is named compensation factor, k. The value of k, as a percentage, is given by

$$k_{(\%)} = \frac{X_{CS}}{X_L} \times 100$$

The power transfer capability of a line increases as the compensation factor is increased. The increase in power transfer capability for a given compensation factor is given by

$$\text{Increase}_{(\%)} = \frac{k}{(1-k)} \times 100$$

If, for example, the line is compensated 34%, the increase in power transfer capability will be 51.5%. Compensation factors between 20 and 70% are generally used, thereby providing an increase in power transfer capability between 25 and 233%.



PROCEDURE

☐ 1. Open all the demonstrator switches.

☐ 2. Put transmission line 2 in service by closing switches S3 and S4. Set the series-compensation selector to 0%.

☐ 3. Adjust the sender voltage to 735 kV.

☐ 4. Connect a load of 2925 MW to line 2. This corresponds to the power transfer capability of line 2 without series compensation, as previously found in Exercise 1.

☐ 5. Connect the required shunt capacitor across the load in order for the receiver voltage to be as close as possible to the sender voltage of 735 kV. The phase shift should now be about 30°.

☐ 6. Set the series-compensation selector to 17%.

☐ 7. Observe that the phase shift has decreased from 30° to about 24°. The power demand on line 2, however, is still 2925 MW. Therefore, series compensation has decreased the phase shift required to transfer the same amount of power, which, in turn, has improved the stability of the system.

☐ 8. Increase the load on line 2 to 3600 MW.

☐ 9. Readjust the shunt capacitor across the load so that the receiver voltage is as close as possible to the sender voltage of 735 kV.

☐ 10. The phase shift now observed is about 31°. Therefore, the 17%-series compensation has increased the power transfer capability of line 2 by

$$\frac{3600\ \text{MW} - 2925\ \text{MW}}{2925\ \text{MW}} \times 100 = 23\%$$

☐ 11. Set the series-compensation selector to 34%.

Electrical Test (4)

12. Observe that the phase shift has decreased from 31° to about 25°. The power demand on line 2, however, is still 3600 MW. Therefore, the increase in compensation factor has improved the stability of the system.

13. Increase the load on line 2 to 4500 MW.

14. Readjust the shunt capacitor across the load so that the receiver voltage is as close as possible to the sender voltage of 735 kV.

15. The phase shift now observed is about 32°. Therefore, the 34%-series compensation has increased the power transfer capability of line 2 by

$$\frac{4500\ \text{MW} - 2925\ \text{MW}}{2925\ \text{MW}} \times 100 \quad 54\%$$

Line (2)	MW	δ	Increase % $\left(\frac{P_{new}-P_{old}}{P_{old}}\right)$ 100%
zero compensation	2925 MW	$30°$	—
17% compensation	3600 MW	$31°$	23%
34% compensation	4500 MW	$32°$	54%

Electrical Test (4)

Effect of Series Compensation on Regulation of the Receiver Voltage

PROCEDURE

- ☐ 1. Open all the demonstrator switches.
- ☐ 2. Put transmission line 2 in service by closing both S3 and S4. Set the series-compensation selector to 0%.
- ☐ 3. Adjust the sender voltage to 735 kV.
- ☐ 4. Connect a load of 2925 MW to line 2.
- ☐ 5. Connect the required shunt capacitor across the load in order for the receiver voltage to be as close as possible to the sender voltage of 735 kV. The phase shift should now be about 30°.

☐ 6. Decrease the load on line 2 by disconnecting the 900-MW load from this line.

☐ 7. Observe that, due to disconnection of the 900-MW load from line 2, the receiver voltage has increased by about 8%.

$$\text{Increase}_{(\%)} = \frac{E_R - E_S}{E_S} \times 100$$

☐ 8. Reconnect the 900-MW load to line 2.

☐ 9. Set the series-compensation selector to 34%.

☐ 10. Readjust the shunt capacitor across the load so that the receiver voltage is as close as possible to the sender voltage of 735 kV.

☐ 11. Decrease the load on line 2 by disconnecting the 900-MW load from this line.

☐ 12. Observe that the receiver voltage has increased by about 4.5% due to disconnection of the 900-MW load from line 2. This increase was about 8% without series compensation. Therefore, series compensation has significantly reduced the increase in receiver voltage.

Line (2)	Full load voltage E_s	no load voltage E_R	Regulation % $\left(\frac{E_R - E_s}{E_s}\right)$ 100%
0% compensation	735 kV	810 kV	10.2%
34% compensation	735 kV	780 kV	6.12%

Electrical Test (4)

Reduction of Transmission Losses on Parallel Lines Using Series Compensation

- ❑ Transmission losses due to line resistance (RL) =3 $\times R_L \times I_L^2$
- ❑ Efficiency % = $\frac{P_{receiver}}{P_{sender}}$ 100%
- ❑ When two transmission lines of unequal efficiency are connected in parallel, the sharing or power between these lines may not be optimum;
- ✓ Highest efficiency will be less than maximum capacity
- ✓ Lower efficiency will be at maximum capacity
- ❑ Series compensation leads, highest efficiency line operates at maximum capacity.
- ❑ The overall efficiency of lines are optimum when both lines have equal resistance to reactance ratio. $\frac{R_{L1}}{X_{L1}} = \frac{R_{L2}}{X_{L2}}$

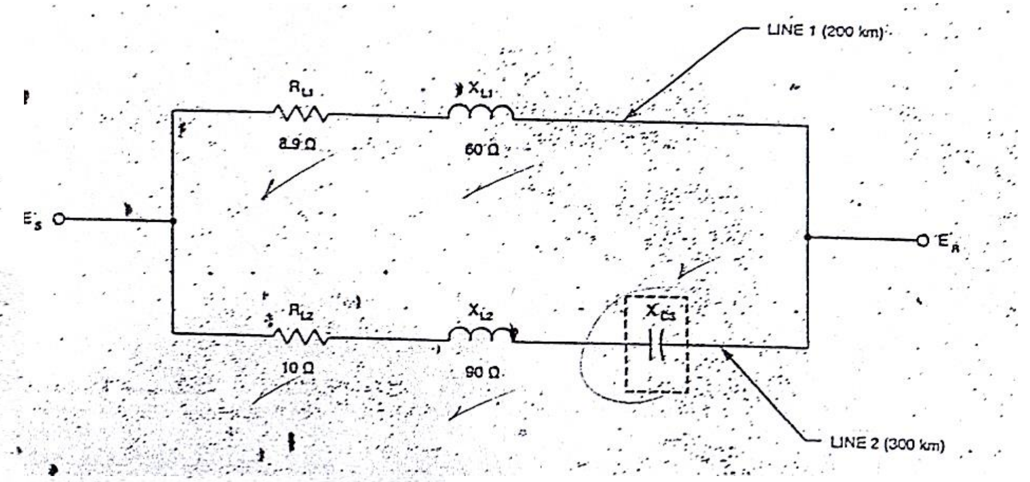
According to the previous ratio, line 1 is highest ratio so it has lowest efficiency (loaded).

- ❑ By using the series compensation, the power sharing is optimized and losses are reduced.

Calculating the required series compensation factor

be reduced to minimum by reducing the reactance of line 2 with a series capacitor X_{CS} so that

$$\frac{R_{L1}}{X_{L1}} = \frac{R_{L2}}{X_{L2} - X_{CS}}$$



This equation can be rewritten as

$$X_{L2} - X_{CS} = \frac{R_{L2} \times X_{L1}}{R_{L1}}$$

which leads to

$$X_{CS} = X_{L2} - \frac{R_{L2} \times X_{L1}}{R_{L1}}$$

and then to

$$X_{CS} = \frac{(X_{L2} \times R_{L1}) - (X_{L1} \times R_{L2})}{R_{L1}}$$

According to Figure 4-1, the required series capacitor would be

$$X_{CS} = \frac{(90\,\Omega \times 8.9\,\Omega) - (60\,\Omega \times 10\,\Omega)}{8.9\,\Omega}$$

$$= 22.6\,\Omega$$

which corresponds to a compensation factor of

$$\frac{22.6\,\Omega}{90\,\Omega} \times 100 = 25.1\%$$

Electrical Test (4)

Procedure

- 1. Open all the demonstrator switches.
- 2. Put both lines 1 and 2 in service by closing S1, S2, S3, and S4.
- 3. Adjust the sender voltage to 735 kV.
- 4. Set the series-compensation selector to 0%.
- 5. Connect a load of 6975 MW to lines 1 and 2.
- 6. Connect the required shunt capacitor across the load in order for the receiver voltage to be as close as possible to the sender voltage of 735 kV. The phase shift should now be about 29°.
- 7. Observe that the active power at the sender end of line 1 is about 4550 MW, while the active power at the sender end of line 2 is about

3000 MW. Therefore, line 1 is sending 1.5 times more active power than line 2.

- ☐ 8. Measure and record below the current carried by lines 1 and 2. Then calculate the total current, I_T, carried by these lines.

  I_1 = 3950 A $P = 4250$

  I_2 = 2650 A $P = 2800$

  I_T = 6600 A

- ☐ 9. Based on the I_1 and I_2 currents recorded in step 8, calculate the transmission losses in lines 1 and 2. Then, calculate the overall losses in these lines.

  Note: *Assume the resistance of line 1 to be 8.9 Ω and that of line 2 to be 10 Ω.*

  Transmission losses in line 1 = ______ MW

  Transmission losses in line 2 = ______ MW

  Overall transmission losses = ______ MW

- ☐ 10. Set the series-compensation selector to 25%.

- ☐ 11. If necessary, readjust the shunt capacitor across the load so that the receiver voltage is as close as possible to the sender voltage of 735 kV.

- ☐ 12. Observe that the active power at the sender end of line 1 has decreased to about 4000 MW, while the active power at the sender end of line 2 has increased to about 3450 MW. This means line 1 is now sending only 1.16 times more power than line 2.

  at Compensation

- ☐ 13. Measure and record below the current carried by lines 1 and 2. Then calculate the total current, I_T, carried by these lines.

  I_1 = 3500 A $P_1 = 3750$

  I_2 = 3200 A $P_2 = 3500$

  I_T = 6700 A

☐ 14. Compare the currents I_T found in steps 8 and 13. Theoretically, these currents should be equal; however, due to the uncertainty of measurement of currents I_1 and I_2 resulting from ammeter accuracy, you may find that the currents I_T are slightly unequal. If so, compensate for the measurement uncertainty by correcting the values of currents I_1 and I_2 in step 13 using the equations below:

$$I_{1\,(corrected)} = \frac{I_{1\,(step\ 13)} \times I_{T\,(step\ 8)}}{I_{T\,(step\ 13)}} \qquad I_{2\,(corrected)} = \frac{I_{2\,(step\ 13)} \times I_{T\,(step\ 8)}}{I_{T\,(step\ 13)}}$$

$I_{1\,(corrected)}$ = 3497.75 A

$I_{2\,(corrected)}$ = 3152.23 A

$$I_{corrected} = \frac{I_{compensated} - I_{T\,uncompensated}}{I_{T\,compensated}}$$

☐ 15. Based on the corrected currents I_1 and I_2 obtained in step 14 (or on the currents recorded in step 13 if correction was unnecessary), calculate the transmission losses in lines 1 and 2. Then, calculate the overall losses in these lines.

Transmission losses in line 1 = ______ MW

Transmission losses in line 2 = ______ MW

Overall transmission losses = ______ MW

☐ 16. Compare the overall transmission losses obtained with and without series compensation (from steps 9 and 15). You should observe that series compensation reduces the losses by several megawatts. Though this reduction may not seem to be significant, it should be kept in mind that reducing the transmission losses by as little as 1% will still result in appreciable energy cost savings.

Part 2

Electrical Test (4)

Feedback

Email: hossam.herzallah7@gmail.com

Email subject: Series Compensation Feedback

Reference

- https://blog.oureducation.in/effect-of-series-and-shunt-compensation-on-voltage-stability/
- https://learn.pjm.com/~/media/training/nerc-certifications/gen-exam-materials/bet/20160104-basics-of-elec-power-flow-on-ac.ashx

Thanks