For the simple 2 bus system shown in the figure look at steady-state reactive compensation

Define Constants

Sending and Receiving End Voltages

\[ V_{1L} := 132kV \quad V_{1p} := \frac{V_{1L}}{\sqrt{3}} \quad V_{1p} = 76.21\text{-kV} \]

\[ V_{2L} := 132kV \quad V_{2p} := \frac{V_{2L}}{\sqrt{3}} \quad V_{2p} = 76.21\text{-kV} \]

Sending and Receiving End Angles

\[ \theta_1 := 0\text{deg} \quad \theta_2 := -20.14\text{deg} \]

Line Reactance

\[ X_{\text{line}} := 10\text{ohm} \]

Define Unit for MVAr

\[ \text{MVAr} := \text{MW} \]

(a) Compute \( P_{12} \)

\[ P_{12} := \left( \frac{3 \cdot V_{1p} \cdot V_{2p}}{X_{\text{line}}} \right) \cdot \sin(\theta_1 - \theta_2) \]

\[ P_{12} = 599.93\text{-MW} \quad \text{For all intensive purposes: 600 MW} \]
(b) Next increase $P_{12}$ to 700 MW. Consider the following options to do so. Give a written evaluation of each form of compensation

**A. Add series capacitance.** What size capacitor is needed? What is the percent compensation? If the max compensation is 60%, what is $P_{12_{\text{max}}}$?

\[
X_{\text{total}} := \frac{3 \cdot V_{1p} \cdot V_{2p} \cdot \sin(\theta_1 - \theta_2)}{700 \text{MW}} \quad X_{\text{total}} = 8.57 \text{ ohm}
\]

\[
X_{\text{cap}} := X_{\text{line}} - X_{\text{total}} \quad X_{\text{cap}} = 1.43 \text{ ohm}
\]

\[
\text{PercentCompensation} := \frac{X_{\text{cap}}}{X_{\text{line}}} \quad \text{PercentCompensation} = 14.3 \%
\]

\[
\text{Cap} := \frac{1}{2 \cdot \pi \cdot 60 \text{Hz} \cdot X_{\text{cap}}} \quad \text{Cap} = 1855.6 \mu \text{F}
\]

\[
X_{c_{\text{max}}} := 0.6 \cdot X_{\text{line}}
\]

\[
P_{12_{\text{max}}} := \frac{3 \cdot V_{1p} \cdot V_{2p} \cdot \sin(\theta_1 - \theta_2)}{X_{\text{line}} - X_{c_{\text{max}}}} \quad P_{12_{\text{max}}} = 1499.84 \text{ MW}
\]

**Advantages**
1) Effective way to increase power transfer
2) Can vary compensation by switching multiple banks in series/parallel combinations
3) Insensitive to location
4) Relatively inexpensive (compared to other options)
5) Doesn't result in overvoltages at either bus when line lightly loaded

**Disadvantages**
1) Potential series resonance problems
2) Possible subsynchronous resonance (SSR)
3) Stepwise variation in compensation only
4) Slow response if need to change $X_c$ (can't damp slow oscillations)
5) Overvoltage protection needed for capacitor in event of fault on line
6) Impact on distance protection schemes
B. Instead of series compensation add phase angle control. What phase, $\alpha$ does the compensator need to produce? Lets say that $\alpha_{\text{max}}=30^\circ$, what is $P_{12\text{max}}$?

$$\begin{align*}
\text{Bus 1} & \quad \text{Bus 2} \\
\mid V_1 \mid &= 132 \text{ kV (line to line)} \\
& \text{at an angle of 0 degrees} \\
\mid V_2 \mid &= 132 \text{ kV (line to line)} \\
& \text{at an angle of -20.1} \\
\end{align*}$$

$$\begin{align*}
\text{TotalAngle} := \text{asin} \left( \frac{700\text{MW} \cdot X_{\text{line}}}{3 \cdot V_{1p} \cdot V_{2p}} \right) \\
&= 23.69 \text{ deg} \\
\alpha := \text{TotalAngle} - (\theta_1 - \theta_2) \\
&= 3.55 \text{ deg} \\
\alpha_{\text{max}} := 30^\circ \\
\text{P}_{12\text{max}} := \frac{3 \cdot V_{1p} \cdot V_{2p} \sin \left( (\theta_1 - \theta_2) + \alpha_{\text{max}} \right)}{X_{\text{line}}} \\
&= 1337.49 \text{ MW}
\end{align*}$$

Advantages
1) Effective control of power flow in a given line
2) Can locate at substation at the end of a line
3) Unlikely to create resonance problems

Disadvantages
1) Potential stability problems at large angles
2) Somewhat sensitive to location
3) Stepwise variation in compensation only
4) Slow response if need to change $\alpha$ (can't damp slow oscillations)
C. We next look at adding midpoint compensation. Let's just call it an ideal compensator right now. What midpoint voltage is needed? How much reactive power does the compensator provide? Do you consider this a feasible solution?

![Diagram](image)

\[ |V_1| = 132 \text{ kV (line to line)} \text{ at an angle of 0 degrees} \]

\[ |V_2| = 132 \text{ kV (line to line)} \text{ at an angle of -20.1} \]

\[ X_{\text{half}} := \frac{X_{\text{line}}}{2} \quad X_{\text{half}} = 5 \cdot \text{ohm} \]

Lossless line, so the following relationships hold:

\[ P_{12\text{req}} := 700\text{MW} \]
\[ P_{1m} := P_{12\text{req}} \quad P_{m2} := P_{12\text{req}} \]
\[ \theta_m := \frac{\theta_2 - \theta_1}{2} \]

\[ V_{mp} := \frac{P_{1m} \cdot X_{\text{half}}}{3 \cdot V_{1p} \cdot \sin(\theta_1 - \theta_m)} \]

\[ V_{mp} = 87.55 \cdot \text{kV} \]

\[ V_{mL} := \sqrt{3} \cdot V_{mp} \quad V_{mL} = 151.64 \cdot \text{kV} \]

\[ \text{OverVolt} := \frac{V_{mL}}{V_{1L}} \quad \text{OverVolt} = 114.88\% \]
\[ Q_{m1} := \frac{(V_{mL})^2}{X_{half}} - \frac{V_{mL} \cdot V_{1L} \cdot \cos(\theta_m - \theta_1)}{X_{half}} \quad Q_{m1} = 657.45 \text{MVAr} \]

\[ Q_{m2} := \frac{(V_{mL})^2}{X_{half}} - \frac{V_{mL} \cdot V_{2L} \cdot \cos(\theta_m - \theta_2)}{X_{half}} \quad Q_{m2} = 657.45 \text{MVAr} \]

\[ Q_{\text{compensator}} := Q_{m1} + Q_{m2} \]

\[ Q_{\text{compensator}} = 1314.91 \text{MVAr} \]

This is almost double P12, so this is not a reasonable solution in this case.

**Advantages**
1) Local reactive support
2) Will not create resonance problems unless use fixed capacitors
3) Continuously variable is use synchronous condensor

**Disadvantages**
1) Sensitive to location
2) Relatively slow response if rotating machine
3) Not as effective as series cacacitor or phase shifting transformer
4) High cost
Power Flow Models

\[ |V_1| = 132 \text{kV (line to line)} \text{ \ at an angle of 0 degrees} \]
\[ |V_2| = 132 \text{kV (line to line)} \text{ \ at an angle of -20.} \]

Define Constants

\[
\begin{align*}
\text{MVA} & := \text{MW} \quad \text{pu} := 1 \\
V_B & := 132\text{kV} \\
S_B & := 100\text{MVA} \\
Z_B & := \frac{V_B^2}{S_B} \\
\end{align*}
\]

\[ Z_B = 174.24 \Omega \]

Line Reactance

\[
X_{\text{line}} := 10\text{ohm} \\
X_{\text{line\_pu}} := \frac{X_{\text{line}}}{Z_B} \\
X_{\text{line\_pu}} = 0.0574\cdot\text{pu} \\
\frac{X_{\text{line\_pu}}}{2} = 0.0287\cdot\text{pu} \\
\]

\[
X_{\text{cap\_case1}} := 1.43\text{ohm} \\
\frac{X_{\text{cap\_case1}}}{Z_B} = 0.00821\cdot\text{pu} \\
\]

\[
X_{\text{cap\_max}} := 0.6\cdot X_{\text{line}} \\
\frac{X_{\text{cap\_max}}}{Z_B} = 0.0344\cdot\text{pu} \\
\]