Topics for Today:

- Announcements
  - Software: online students - apply for ATP/ATPDraw license, verify licensing when you receive it by e-mail, and we will mail you the install CD.
  - Office hrs: 2-3pm M,W,F
  - Office: EERC 614. Phone: 906.487.2857
  - Book exercises from Ch.6,7 solutions posted

Chapter 6 - Shunt Capacitance Transmission Lines

- Using the T-Line models
  - Short Transmission Lines - up to 50 miles (80 km)
  - Voltage Regulation, phasor diagrams, Per-phase impedance diagrams (positive seq only)
  - Medium-Length Lines (50 - 150 miles)
  - ABCD parameters for Medium-lines, power flow
  - Long Lines - more than 150 miles (240 km)
  - Compensation - shunt and series
  - Derivation of long-line equations, meaning of equations
  - Characteristic Impedance $Z_c$
  - Propagation Constant $\gamma = \alpha + j\beta$
  - Surge-Impedance Loading (SIL)
  - Wavelength, velocity, Traveling waves, reflections
\[ V_R = V_s - I_R (R + jX) \]

- **LAG PF**
  - \((V_R \text{ pos})\)
- **UNIT PF**
  - \((V_R \text{ pos})\)
- **LEAD PF**
  - \(V_R \text{ often neg.}\)
Reactive Compensation
- All a series cap or C

Shunt Compensation
- Shunt for Ferranti Rise

First, review key concepts
- Power Flows Limits
- Ferranti Rise
Power Flow thru T-Line

Power transferred:

$$P = \frac{V_s I_l \sin \phi}{X_L}$$

$$P_{\text{max}} = \frac{V_s V_L}{X_L}$$

Use same segregation of a synch machine

$$P_{\text{out}} = \frac{V_L V_s \sin \phi}{X_S}$$
Series Compensation

\[ \frac{1}{j\omega C} = -jX_C \]

\[ P_{\text{MAX}} = \frac{V_s \cdot V_r}{(X_L - X_C)} \]

Compensation Factor:

\[ \frac{X_C}{X_L} \]

typically 0.2 → 0.7

Problem: Subsynchronous Resonance

\[ X_C = X_L \]

then 100% comp.

\[ P_{\text{MAX}} = \infty \]

(neglecting \( R \), Shunt \( C \))
Ex: 30% compensation

i.e. \( \frac{X_C}{X_L} = 0.3 \)

\[
P_{\text{Max}} = \frac{V_s V_r}{X_L} \Rightarrow P_{\text{Max (comp)}} = \frac{V_s V_r}{0.7 X_L}
\]

\[
\Rightarrow 1.43 P_{\text{Max}}
\]

70% comp

\[
P_{\text{Max (comp)}} = \frac{V_s V_r}{0.3}
\]

\[
\Rightarrow 3.33 P_{\text{Max}}
\]

But....
\[ f_r = \frac{1}{2\pi \sqrt{L C}} = \frac{1}{2\pi \sqrt{\frac{X_L}{X_C}}} \]

\[ X_L = 2\pi f L \]
\[ X_C = \frac{1}{2\pi f C} \]

For 30% comp: \[ f_r = f_{synch} \sqrt{1.3} = f_0 \sqrt{\frac{X_C}{X_L}} = 53 \text{ Hz} \]

For 70% comp: \[ f_r = 50 \text{ Hz} \]
Nat. Freq. if mechanically excited
i.e. if some mech. natural freq.
matches an electrical nat. freq.
then we will "excite" this
resonance.

First well-documented case:
- Salt River Project

- Careful:
  - Long HV compensated line
  - Lots of local gen
  - Lots of remote load
Ferranti Rise

Closed

\[ V_{\text{out}} = V_0 \frac{-jX_c}{j(X_c - X_L)} \]

\[ X_c \gg X_L = \text{Some Value} \geq 1 \]
Shunt Compensation:

\[ I_{\text{shunt}} = I_{\text{line}} \]

Connect Shunt Reactor at receiving end.

Limit to \( \leq 1.10 \text{ pu} \)
Compensates for Ferranti rise.

- Can also use Shunt Reactor (inductor) to hold \( V_p \) down during lightly-loaded cases.
- Too heavily loaded, low voltage
  - add cap in shunt.
Shunt Compensation

100 mi Bluebird
Deg = 20 ft.
$X_c = 1665 \frac{S}{Z}$
$X_s = 12052$ (typ)

Line Chg:
$Y_{cp} = jB_c$
$Z_{cp} = -jX_c$

$V_R = V_s \frac{-j1665}{j120 - j1665}$
$= 1.08 V_s$
Shunt Comp Factor: \( \frac{B_L}{B_c} = \frac{\sqrt{Q_L}}{w C_{CH4}} \)

Total Compensation:
Add a reactor \( B_L = B_c \)

Total Shunt Admittance: \( 0 \)

\[ +jB_c \quad E - jB_L \quad \Rightarrow \quad \frac{B_L}{B_c} = 1 \]

then

\[ Y_{\text{TOTAL}} = jB_c - jB_L = 0 \]

\( (Z_{\text{SHUNT}} = \infty) \)
Power Transfer Capability:

\[ P_{1\rightarrow 2} = \frac{V_1 V_2}{X_L} \sin (\alpha - \beta) \]

\[ V_{1,2} \]

\[ (95)(1.95) \]

\[ (1.05)(1.05) \approx 0.8185 \Rightarrow 22.1\% \text{ increase!} \]
Shunt Caps:

- P.F. Correction (on consumer side of meter)
- Voltage Support
- Max Power Transfer (see next slide)
Voltage Regulation:

\[ VR = \left| V_{R,\text{NL}} \right| - \left| V_{R,\text{FL}} \right| \]

\[ \left| V_{R,\text{FL}} \right| \]

LAG

\[ V_s = V_{R,\text{NL}} + V_{R,\text{FL}} + V_L \]

\[ V_s = V_{\text{RES}} + V_L + V_R = I_{\text{Load}} R + I_{\text{Load}} jX + V_R \]
LEAD

\[ I_{\text{load}} \quad \text{Vs} \quad V_L \quad \text{VR} \quad V_{\text{RES}} \]

\[ VR = \frac{V_{\text{HL}} - V_{\text{FL}}}{V_{\text{FL}}} = \frac{V_S - V_R}{V_R} = \text{pos. no. for Lag, Unity} \]

Note: VR can be negative for leading P.F. load.
$v_R$ in terms of $A-B-C-O$. 

Recall:

\[ v_R = \frac{v_R, NL - v_R, FL}{v_R, FL} \]

\[ \frac{v_R}{v_R, FL} = \frac{v_s/A + v_R, FL}{v_R, FL} \]
IN General,

\[ R + jX \]

\[ A \quad V_{IN} \quad \text{Sent.} \quad V_1/2 \quad \text{Rec.} \quad A' \]

Neutral

\[ x \quad l \]

\[ \frac{\text{Short Line}}{\leq 50 \text{mi} \, (80 \text{km})} \]

\[ \overbrace{\text{Ex. 6.1}}^{\text{Fig. 6.3}} \]
\[ \frac{x}{R} \text{ ratio determines effectiveness of } k \]

\[ \tilde{V}_s \]

\[ Z_{bus} = \begin{bmatrix} \cdots \end{bmatrix} \]

\[ \tilde{I}_c \]

\[ \tilde{V}_s \]

\[ \tilde{I}_c^R \]

If \( \frac{x}{R} = 0 \), \( \tilde{I}_c \rightarrow \tilde{V}_s \rightarrow \tilde{I}_c^R \)