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.
  - Learning Center EERC 123: W,F 4-5pm, Sat 4-6pm.
  - Office: EERC 614. Phone: 906.487.2857
  - Book exercises from Ch.6,7 solutions posted, part of homework.

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
LAG PF
(VR pos)

UNITY PF
(VR pos)

LEAD PF

VR often neg.
Reactive Compensation

- All a series cap or C.

- Shunt Compensation

- First, review key concepts.
  - Ferranti limits
  - Power factor rise
  - Ferranti rise
Power Flow thru T-Line

...if we neglect the effects of $R, C$

\[ s \begin{array}{c}
\varepsilon \quad V_T \\
\hline
V_T \\
\end{array} \quad \frac{C}{jX_L} \quad \frac{R}{jX} \quad \frac{V_T}{V_T}
\]

Power transferred:

\[ P = \frac{V_s V_T}{X_L} \sin (\angle V_T - \angle V_T) \]

\[ P_{\text{max}} = \frac{V_s V_T}{X_L} \]

Use same equation for Port of a Synch machine:

\[ P_{\text{out}} = \frac{V_s V_T \sin \delta}{X_S} \]

\[ V_s \begin{array}{c}
\varepsilon \quad jX_S + V_T 10^0 \\
\hline
X_S \\
\end{array} \quad \frac{V_T}{V_T}
\]
Series Compensation

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

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

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 \( R, \text{ Shunt C} \))
Ex: 30% compensation
\[ \frac{X_c}{X_L} = 0.3 \]

\[ P_{\text{MAX}_1} = \frac{V_s V_r}{X_L} \]

\[ P_{\text{MAX} \text{(COMP)}} = \frac{V_s V_r}{0.7 X_L} \Rightarrow 1.43 P_{\text{MAX}_1} \]

70% Comp

\[ \Rightarrow P_{\text{MAX} \text{(COMP)}} = \frac{V_s V_r}{0.3} \Rightarrow 3.33 P_{\text{MAX}_1} \]

But....
\[ \phi = \frac{1}{\sqrt{3}} \left( \frac{3}{x_c} \right)^{\frac{1}{3}} \]

\[ f_c = \frac{1}{2\pi\sqrt{LC}} \]

\[ x_c = \frac{2\pi f_c}{\sqrt{L/C}} \]

\[ x_c = \frac{2\pi f}{\sqrt{L/C}} \]

\[ f_c = \frac{1}{2\pi\sqrt{LC}} \]

\[ f = f_{\text{sync}} \sqrt{1.3} = f_{\text{sync}} \frac{\sqrt{1.3}}{x_c} \]

\[ f_r = \frac{f_{\text{sync}}}{3.3} \Omega \]

\[ f_r = \frac{f_{\text{sync}}}{50\Omega} \]

For 30% comp:

\[ f_r = \frac{f_{\text{sync}}}{200\Omega} \]

For 70% comp:

\[ f_r = \frac{f_{\text{sync}}}{700\Omega} \]
Nat. Freq, if mechanically excited
  i.e. if some mech. natural freq.
  matches an electrical nat.'l 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

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

\[ X_c \gg X_L = \text{some value} > 1. \]
Shunt Compensation:

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

Connect Shunt Reactor at receiving end.

Limit to \( < 1.10 \text{ pu} \).

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.
Xc = 1665.52
Xs = 12052 (typ)

Line Chg:
Ycap = jBc
Zcap = -jXc

\[ V_R = V_s \frac{-j1665}{j120 - j1665} \]

\[ = 1.08 V_s \]
Shunt Comp Factor = $\frac{B_L}{B_c} = \frac{Y_{UL}}{Y_{CH}}$

Total Compensation:

Add a reactor $B_L = B_c$

Total Shunt Admittance $= 0$

\[ \begin{align*}
+jB_c & \quad E - jB_L \\
& \Rightarrow \frac{B_L}{B_c} = 1 \\
\text{then} & \quad \frac{Y_{TOTAL}}{Y_{SHUNT}} = 0 \\
(2\text{shunt} = \infty)
\end{align*} \]
\[ P_{1 \to 2} = \frac{V_1 V_2}{X_L} \sin (\alpha - \beta) \]

Power Transfer Capability.

\[ V_1, V_2 : \min: \frac{(95)(95)}{105(105)} = 0.8185 \Rightarrow 22.1\% \text{ increase!} \]
SHUNT CAPS:

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

\[ VR = \frac{|VR_{NL}| - |VR_{FL}|}{|VR_{FL}|} \]

LAG

\[ V_S = V_{RES} + V_L + VR \]
\[ = I_{load} R + I_{load} jX + VR \]
LEAD

UNITY P.F.

Note: VR can be negative for leading P.F. load.

\[ VR = \frac{V_{VL} - V_{FL}}{V_{FL}} = \frac{V_s - VR}{VR} = \text{pos. no. for Lag, Unity.} \]
Recall: \[ V_R = \frac{V_{R, NL} - V_{R, FL}}{V_{R, FL}} \]
In general,\[ R + jX \]

\[ V_s \]

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

Fig. 6.3

Ex. 6.1
$\frac{X}{R}$ ratio determines effectiveness of \( k \)

Shunt C!

$V_s$

$Z_{bus} = \begin{bmatrix} Z_{kk} \end{bmatrix}$

$\bar{I}_c \bar{X}_l$

$\bar{V}_k$

$I_c R$

If $\frac{X}{R} = 0$, then $\bar{I}_c = \bar{V}_s \Rightarrow \bar{I}_c R$