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
LAG PF  \[
(VR \text{ pos})
\]
UNITY PF  \[
(VR \text{ pos})
\]
LEAD PF  \[
VR \text{ often neg.}
\]

\[
\vec{V}_R = \vec{V}_S - \vec{I}_R (R + jX)
\]

\[
\begin{align*}
\vec{V}_R &\quad \vec{V}_S \\
\vec{I}_R &\quad \vec{I}_{jX}
\end{align*}
\]

\[
\begin{align*}
\vec{V}_R &\quad \vec{V}_S \\
\vec{I}_R &\quad \vec{I}_{jX}
\end{align*}
\]

\[
\begin{align*}
\vec{V}_R &\quad \vec{V}_S \\
\vec{I}_R &\quad \vec{I}_{jX}
\end{align*}
\]
Reactive Compensation
- Add a series cap

- Shunt Compensation

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

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

\[ V_s \quad jX_L \quad R \quad V_t \]

Power transferred:

\[ P = \frac{\vert V_s \vert \vert V_t \vert}{X_L} \sin \left( \frac{(\vec{V}_s - \vec{V}_t)}{S} \right) \]

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

Use same equation for $P_{\text{out}}$ of a synch machine:

\[ P_{\text{out}} = \frac{V_s V_t}{X_s} \sin \delta \]

\[ V_s/\angle 0 \quad jX_s + V_t/\angle 10^\circ \]
Problem: Synchronous Resonance

Compensation Factor: \(0.2 \to 0.7\)

Series Compensation

\[ P_{\text{MAX}} = \frac{V_s V_a}{(X_L - X_c)} \]

\[ X_c = \frac{X_L}{X_c} \]

\[ X_{L\text{=XL}} \]

\[ X_{L\text{=Xc}} \]

\[ P_{\text{MAX}} = 100\% \text{ comp.} \]

\[ p = (\text{neglecting } R, \text{ Shunt}) \]
Ex: 30% compensation

\[
\frac{X_c}{X_L} = 0.3
\]

\[
P_{MAX_I} = \frac{V_s V_r}{X_L}
\]

\[
P_{MAX_{(COMP)}} = \frac{V_s V_r}{0.7 X_L}
\]

\[
\Rightarrow P_{MAX_{(COMP)}} = 1.43 P_{MAX_I}
\]

70% comp

\[
P_{MAX_{(COMP)}} = \frac{V_s V_r}{0.3}
\]

\[
\Rightarrow 3.33 P_{MAX_I}
\]

But....
\[ - \frac{3L}{X_c} \]

\[ 2\pi \sqrt{L \cdot C} = \frac{3L}{X_c} \]

\[ f_c = \frac{1}{2\pi \sqrt{L \cdot C}} \]

\[ X_C = \frac{1}{2\pi fC} \]

\[ f = f_{\text{sync}} \cdot \sqrt{1.3} = f_0 \sqrt{1.3} \]

\[ f_r = \frac{33 \text{ Hz}}{50 \text{ Hz}} \]

for 30% comp

\[ f_r = \frac{2 \pi fL}{\frac{C}{X_c}} \]

for 70% comp

\[ f_r = \frac{2 \pi fC}{\frac{L}{X_c}} \]
Nat. Freq, if mechanically excited
i.e. if some mech natural freq.
matches an electrical nat'1 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

Hydro is less swept.
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 \(< 1.10 \text{ pm} - \text{Compensates for Ferranti rise.}\)

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

jXs

100 mi Bluebird

Dgy = 20 ft.
Xc = 166.5 ohms
Xs = 12052 (HP)

Ycap = jBc
Zcap = -jXc

VR = Vs - jXs

\[ V_R = \frac{\sqrt{3} \cdot V_S}{j180 - j1665} \]

\[ S = \frac{j1665}{j180} \]

Vs
Shunt Comp Factor = \( \frac{B_L}{B_c} = \frac{\sqrt{V_L}}{\omega C_{CH6}} \)

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

Total Shunt Admittance = 0

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

(\( \conformal{Z_{shunt}} = \infty \))
\[ P_{1 \Rightarrow 2} = \frac{V_1 V_2}{X_L} \sin(\alpha - \beta) \]

Power Transfer Capability.

\[ V_{1,2} \]

\[ V_1, V_2 : \min : \frac{(95)(95)}{} \]

\[ : \max : (1.05)(1.05) \]

\[ \Rightarrow 22.1\% \quad \text{increase!} \]
SHUNT CAPS:

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

\[ V_R = \frac{|V_{R,NL}| - |V_{R,FL}|}{|V_{R,FL}|} \]

\[ V_S = V_{RES} + V_L + V_R = I_{load}R + I_{load}jX + V_R \]
VR = \frac{V_{NL} - V_{FL}}{V_{FL}} = \frac{V_S - V_R}{V_R} = \text{pos. no. for Lag, Unity}

Note: VR can be negative for leading P.F. load.
$VR$ in terms of $A$, $B$, $C$, $D$. 

Recall: $VR = \frac{VR_{NL} - VR_{FL}}{VR_{FL}}$

$VR = \frac{V_{S/A} + VR_{FL}}{VR_{FL}}$
IN General,

\[ A_0 + jX \quad \text{Send.} \quad Y/2 \quad \text{Rec.} \quad Y/2 \quad A' \]

Short Line

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

\[ \text{Fig. 6.3} \quad \text{Ex. 6.1} \]

\[ V_s^+ \quad \text{Neutral} \quad \sqrt{V_R} \]
\[
\frac{X}{R} \text{ ratio determines effectiveness of } \frac{1}{k} \\
\text{Shunt C!} \quad jX - \frac{1}{k} \\
\begin{array}{c}
\tilde{V}_s \quad \tilde{V}_k \quad \tilde{I}_c \\
\mathbf{z}_\text{Bus} = \\
\begin{bmatrix}
\mathbf{z}_k \\
\end{bmatrix}
\end{array} \\
\tilde{I}_c jX - \frac{1}{k} \\
\tilde{I}_c \tilde{V}_s \\
\tilde{I}_c R \\
\tilde{V}_k
\]