Topics for Today:

- Announcements
  - Detailed project outline, TLIN2 due end of this week.
  - Office hrs: 1:30-2:30pm Tues; 2:30-3:30pm Thurs
  - Office: EERC 623. Phone: 906.487.2857
  - Recommended problems from Ch.6 solutions posted
  - Next: Long Lines, Transient operation of T-lines.

Chapter 6 - Operation & Performance Calcs - transmission lines

- ABCD parameters- wrapup. Table A.6 (page 753)
- P & Q flow thru Medium Line (i.e. Pi-equivalent)
- Series compensation, Subsynchronous Resonance (SSR)
- Shunt compensation, Ferranti Rise
- Long Lines
**TABLE A.6**

**ABCD** constants for various networks

### Series impedance

\[
\begin{align*}
A &= 1 \\
B &= Z \\
C &= 0 \\
D &= 1
\end{align*}
\]

### Shunt admittance

\[
\begin{align*}
A &= 1 + YZ_1 \\
B &= Z_1 + Z_1 + YZ_1Z_2 \\
C &= Y \\
D &= 1 + YZ_2
\end{align*}
\]

### Unsymmetrical T

\[
\begin{align*}
A &= 1 + Y_2Z \\
B &= Z \\
C &= Y_1 + Y_1 + ZY_1Y_2 \\
D &= 1 + Y_2Z
\end{align*}
\]

### Unsymmetrical π

\[
\begin{align*}
A &= A_1A_2 + B_1C_2 \\
B &= A_2B_3 + B_3D_2 \\
C &= A_4C_1 + C_2D_1 \\
D &= B_4C_1 + D_1D_2
\end{align*}
\]

### Networks in cascade

\[
\begin{align*}
A &= (A_1B_2 + A_2B_1)/(B_1 + B_3) \\
B &= B_3B_4/(B_1 + B_3) \\
C &= C_1 + C_2 + (A_1 - A_2)(D_1 - D_1)/(B_1 + B_3) \\
D &= (B_2D_1 + B_1D_2)/(B_1 + B_2)
\end{align*}
\]

### Networks in parallel
1) [20pts] A medium-length transmission line connects Bus 2 to Bus 3 in a power system. The system base used for calculations is 100 MVA. It is modelled as a π-section. \( R = 0.08 \text{ p.u.} \) and \( X = 0.105 \text{ p.u.} \). The total shunt susceptance is given as 8.0 MVAR at rated voltage. \( V_2 \) is known to be 1.0/0° p.u. The magnitude of \( V_3 \) is known to be 0.95 p.u. It is known that the complex power leaving Bus 2 (toward Bus 3) is 0.4 + j0.3 p.u. The current flowing through the series impedance of the equivalent circuit is 0.4 - j0.34 p.u. When calculating P & Q, give the correct signs based on the reference directions shown on the figure below.

\[
\begin{align*}
\bar{S}_{23} &= 0.4 + j0.3 \text{ p.u} \\
\bar{V}_2 &= 1.0 \angle 0^\circ \text{ p.u} \\
\bar{V}_3 &= 0.95 \text{ p.u} \\
\end{align*}
\]

a) Calculate the correct value of susceptance to use for each capacitance in the π equivalent. Calculate the actual value of \( Q_{N2} \) and \( Q_{N3} \) in per unit.

\[
Q_{N2} = \frac{V_2^2}{X_c} = V_2^2 B_c = V_2^2 (\omega C_{N2}) \\
Q_{N3} = \frac{V_3^2}{X_c} = V_3^2 B_c (N_3)
\]

b) Find \( P_2 \) and \( Q_2 \) in per unit.

c) Find \( P_3 \) and \( Q_3 \) in per unit.

d) Find \( P_{32} \) and \( Q_{32} \) in per unit.

e) What is the efficiency of this section of transmission line?
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 $R, C$

\[ V_s \quad \frac{jX_L}{10} \quad R \quad \frac{jX_L}{10} \quad 0 \]

\[ V_s^+ \quad V_e^+ \quad V_e^- \quad V_e^- \]

Power transferred:

\[ P = \frac{|V_s||V_e|}{X_L} \sin \left( \frac{V_s - V_e}{X_L} \right) \]

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

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

\[ P_{\text{out}} = \frac{V_g V_T}{X_s} \sin \delta \]

\[ V_g \frac{180}{\pi} \quad \frac{jX_s}{10} + V_T \quad 180^\circ \]
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 $\rightarrow$ 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. \( x_c = 0.3 \)

\[
\frac{y_s V_N}{x_L} = \frac{y_s V_N}{x_L} = \frac{y_s V_N}{x_L}
\]

\[
P_{\text{MAX}} = \frac{y_s V_N}{0.7 x_L}
\]

\( P_{\text{MAX}} \) (Comp) = 1.43 \( P_{\text{MAX}} \)

\[
\frac{y_s V_N}{x_L} = 3.33 \ P_{\text{MAX}}
\]

70% Comp

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

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

For 30% comp: \[ f_r = f_{synch} \sqrt{3} = f_0 \sqrt{\frac{X_C}{X_L}} \approx 33 \text{ Hz} \]
For 70% comp: \[ f_r = 50 \text{ Hz} \]
Nat Freq, if mechanically excited
i.e. if some mech natural freq matches an electrical nat’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

Hydro is
Less Suscept.
Ferranti Rise

Closed

\[ I_{cap} \]

\[ V_{drop} \]

\[ V_{S} \]

\[ jX_L \]

\[ jX_L \]

\[ V_{in} \]

\[ V_{out} \]

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

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

\[ I_{\text{shunt}} = I_{\text{line}} \text{ (chg)} \]

Connect Shunt Reactor at receiving end.

Limit to 
\[ < 1.10 \text{ p.u.} \]
Compensates for Ferranti rise.

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

Line Chg:

\[ jX_c = \frac{1}{jBCe} \]

\[ Y_{cap} = jBCe \]

\[ Z_{cap} = -jX_c \]

Bluebird

\[ Dg = 20 \text{ ft.} \]
\[ X_c = 1665.5\Omega \]
\[ X_s = 12052 \text{ (typ)} \]

\[ V_r = V_s \frac{-j1665}{j120 - j1665/2} = 1.08V_s \]
Shunt Comp Factor = \( \frac{B_L}{B_c} \)

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

Total Shunt Admittance = 0

\[
\begin{align*}
\begin{array}{c}
\text{\text{+j}B_c} \\
\text{\text{\text{E-j}B_L}} \\
\end{array}
\end{align*}
\Rightarrow \frac{B_L}{B_c} = 1
\]

then

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

\[Z_{\text{SHUNT}} = \infty\]