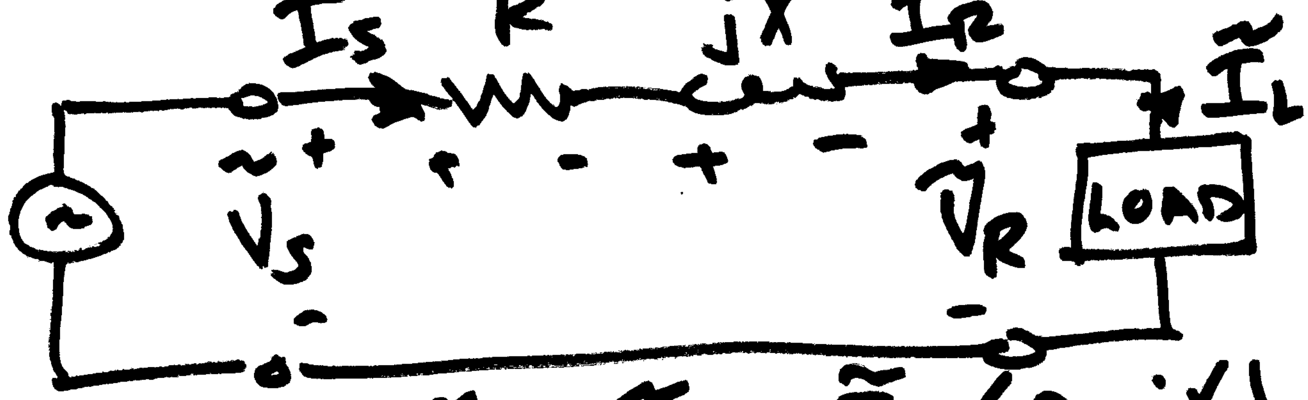
EE 5200 - Lecture 22 Mon Oct 21, 2019

Topics for Today:

- Announcements
  - ATP is on remote.mtu.edu. You may apply for ATP/ATPDraw license, verify licensing when you receive it by e-mail, and we will mail you an install CD.
  - Office: EERC 614. Phone: 906.487.2857
  - Book exercises from Ch.6,7 solutions posted, part of homework.
  - Next homework: Transmission Lines as 2-port networks. Matlab.

Chapter 6 - Shunt Capacitance Transmission Lines

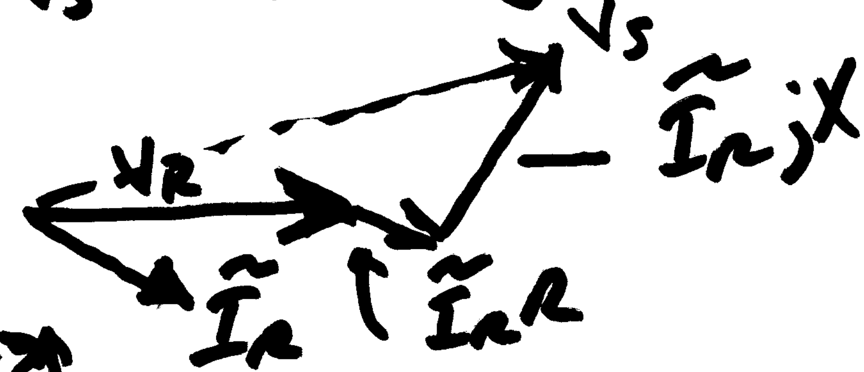
- Using the T-Line models
  - Short Transmission Lines - up to 50 miles (80 km)
  - Voltage Regulation, phasor diagrams, Per-phase impedance diagrams (positive seq only)
  - Medium-Length Lines (50 - 150 miles)
  - ABCD parameters for Medium-lines, power flow
  - Long Lines - more than 150 miles (240 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



$$\tilde{V}_R = \tilde{V}_S - \tilde{I}_R(R + jX)$$

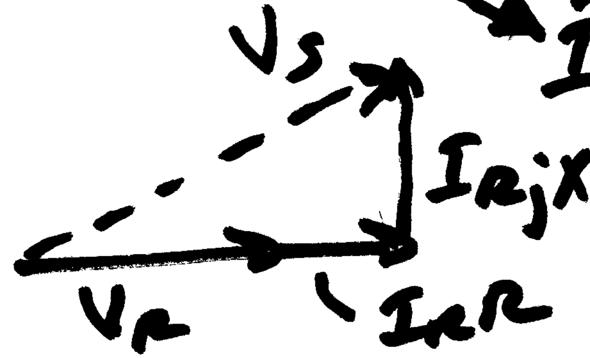
LAG PF

(VR pos)



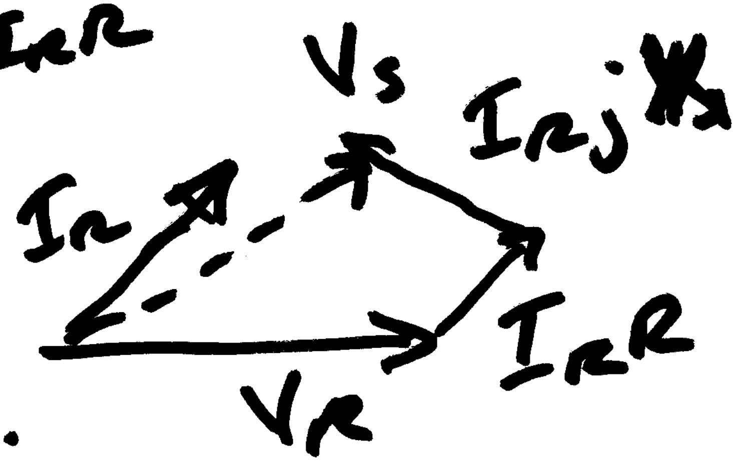
UNITY PF

(VR pos)



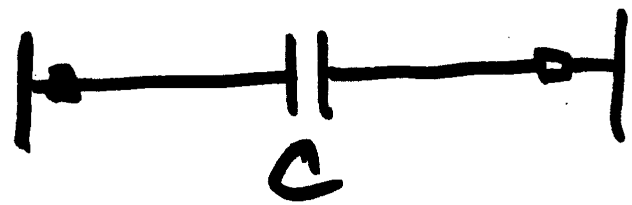
LEAD PF

VR often neg.



Reactive Compensation

- Add a series cap



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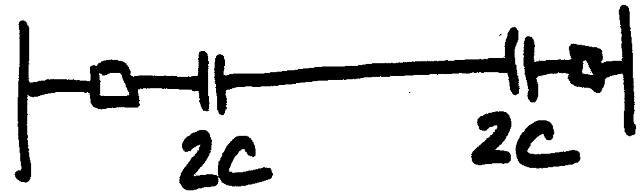
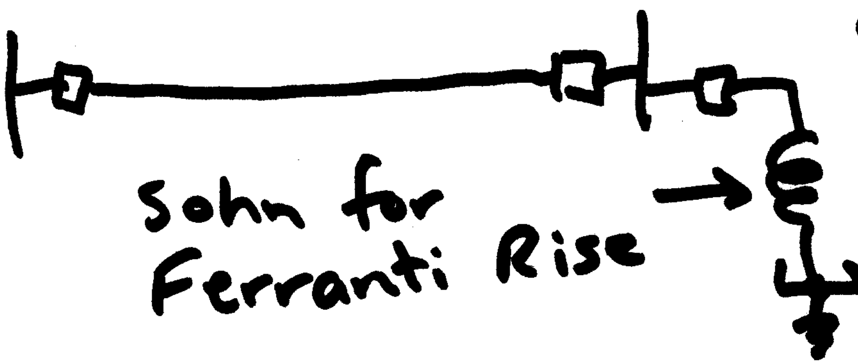


- Shunt Compensation



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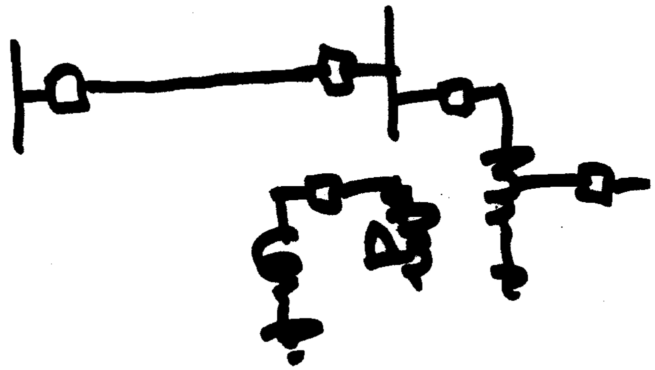
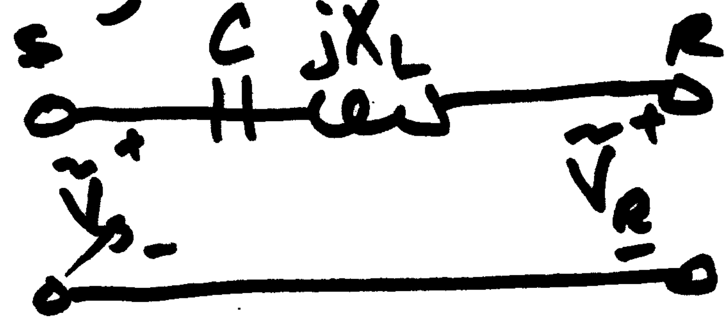


- First, review key concepts
  - Power Flow Limits
  - Ferranti Rise ←

Power Flow thru T-Line

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



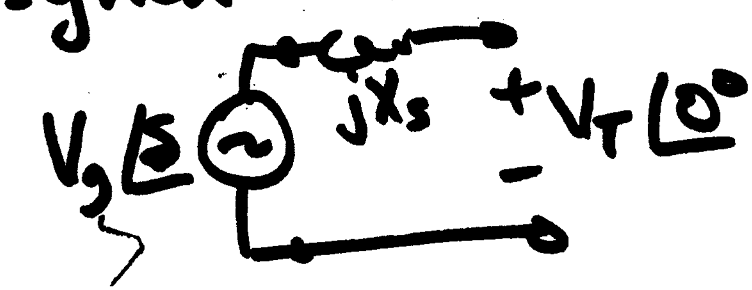
Power transferred:

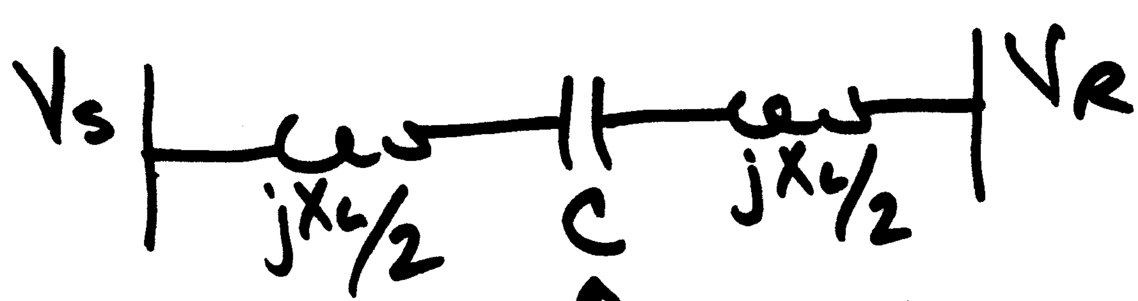
$$P = \frac{|\tilde{V}_S||\tilde{V}_R|}{X_L} \sin\left(\underbrace{\angle\tilde{V}_S - \angle\tilde{V}_R}_{\delta}\right)$$

$$P_{MAX} = \frac{V_S V_R}{X_L}$$

use same equation for P_{out} of a synch machine:

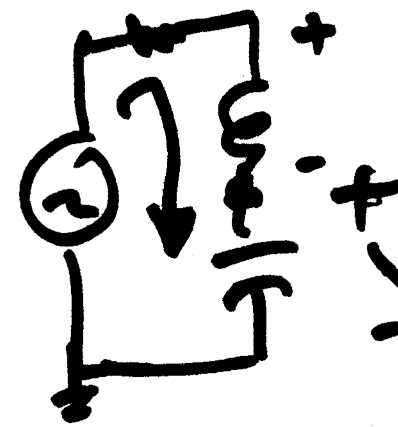
$$P_{OUT} = \frac{V_g V_T}{X_S} \sin\delta$$





$C \leftarrow \frac{1}{j\omega C} = -jX_C$

Series Compensation



$$P_{MAX} = \frac{V_S V_R}{(X_L - X_C)}$$

$X_C = X_L$
then 100% comp.
$P_{MAX} = \infty$ (neglecting R, Shunt C)

Compensation Factor:

$$\boxed{\frac{X_C}{X_L}}$$ typically $0.2 \rightarrow 0.7$

Problem: Subsynchronous Resonance

<u>Ex:</u> 30% compensation

i.e. $\frac{X_C}{X_L} = 0.3$

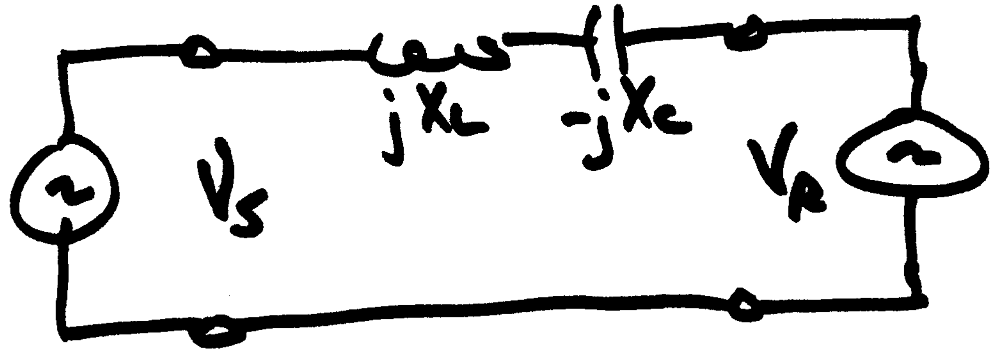
$$P_{MAX_I} = \frac{V_S V_R}{X_L} \qquad P_{MAX\,(COMP)} = \frac{V_S V_R}{0.7 X_L}$$

$$\Longrightarrow \quad = 1.43\, P_{MAX_I}$$

70% comp $\Longrightarrow$ $P_{MAX\,(comp)} = \frac{V_S V_R}{0.3}$

$$\Longrightarrow 3.33\, P_{MAX_I}$$

But....



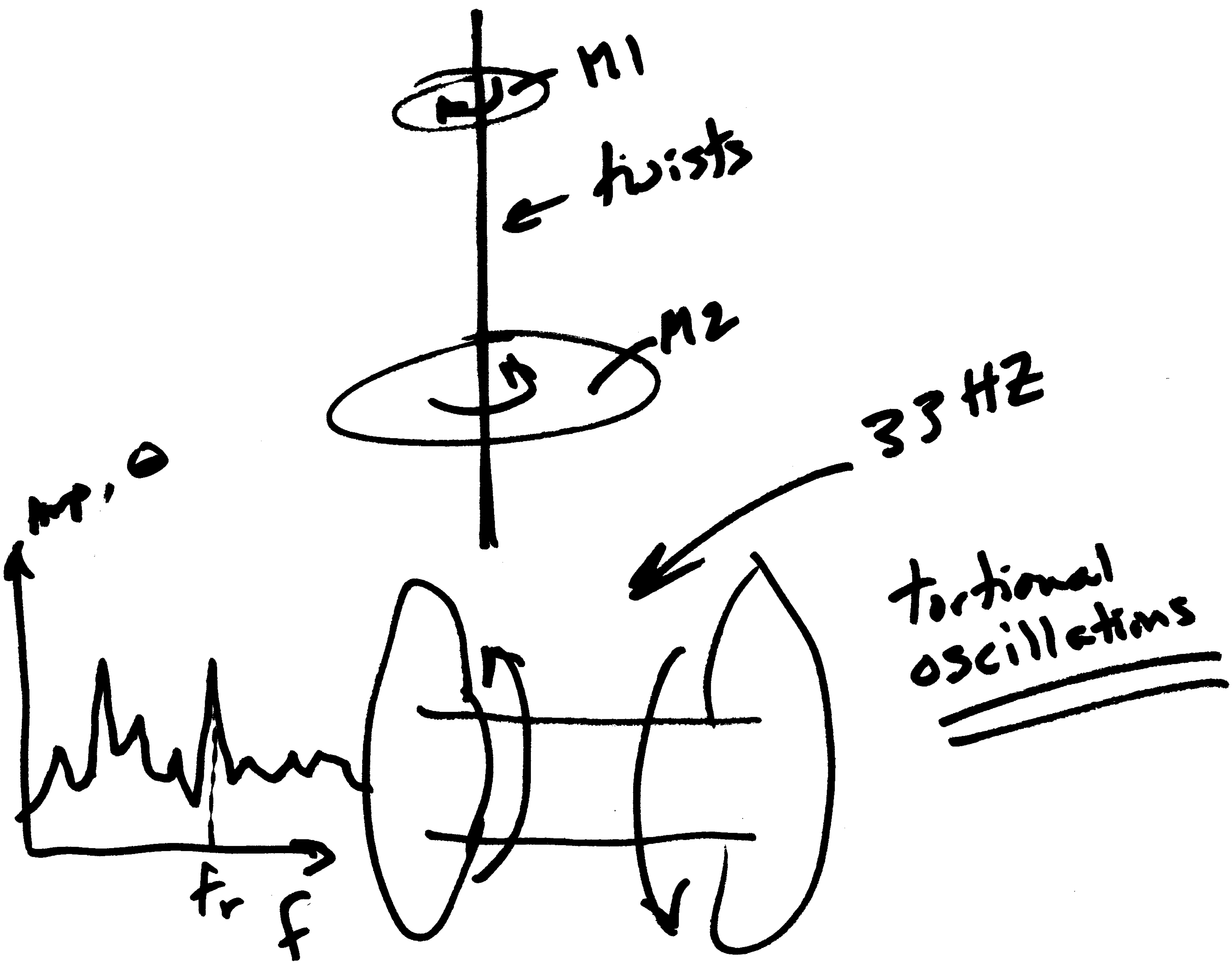
$$f_r = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{\frac{X_L}{\omega}\frac{\omega}{X_C}}}$$

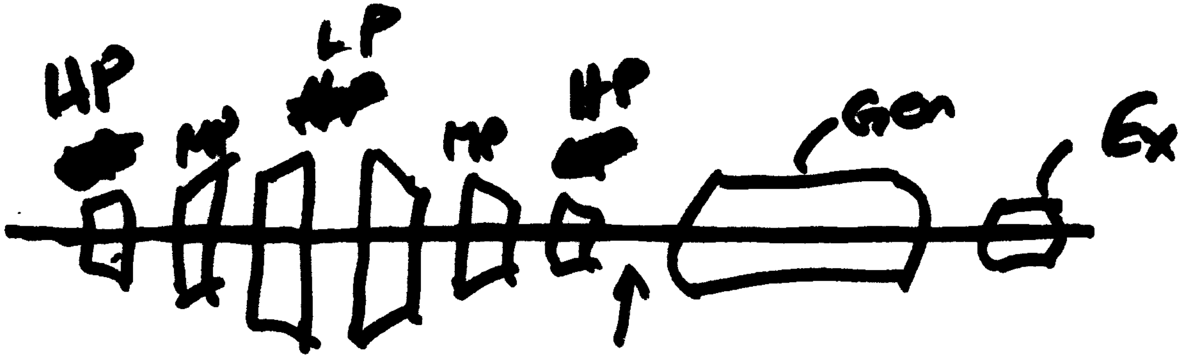
$$X_L = 2\pi f L$$

$$X_C = \frac{1}{2\pi f C}$$

for 30% comp $\quad f_r = f_{synch}\sqrt{.3} = f_0\sqrt{\frac{X_C}{X_L}}$ $= 33\,Hz$

70% comp $\quad f_r = 50\,Hz$


M1
twists
M2
33 HZ
Amp, θ
fr
f
tortional
oscillations



Hydro is Less Suscept.

Nat Freq, if mechanically excited

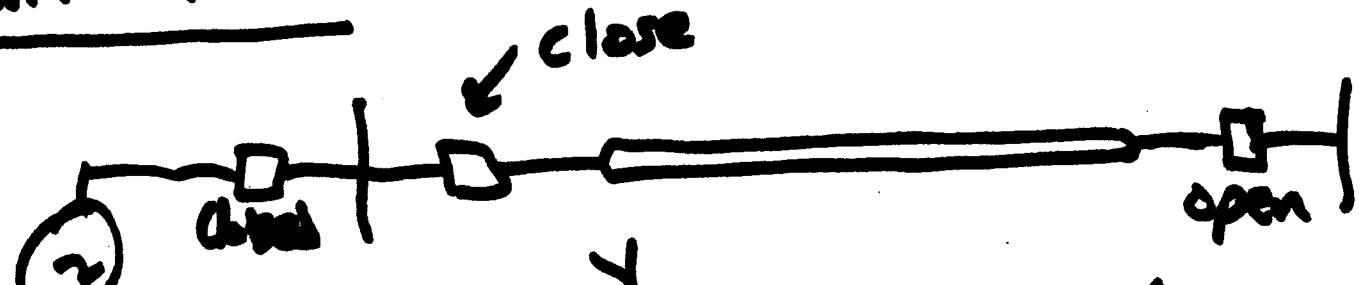
i.e. if some mech natural freq matches an electrical nat'l freq then we will "excite" this resonance.

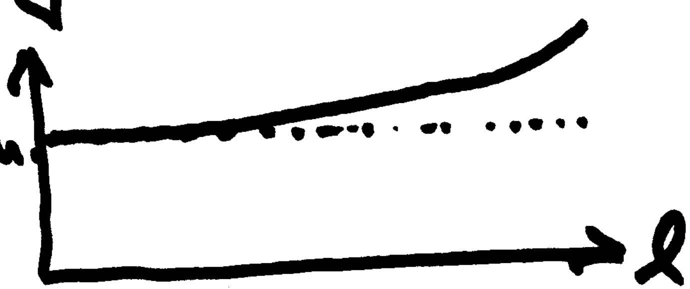
First Well-documented case:

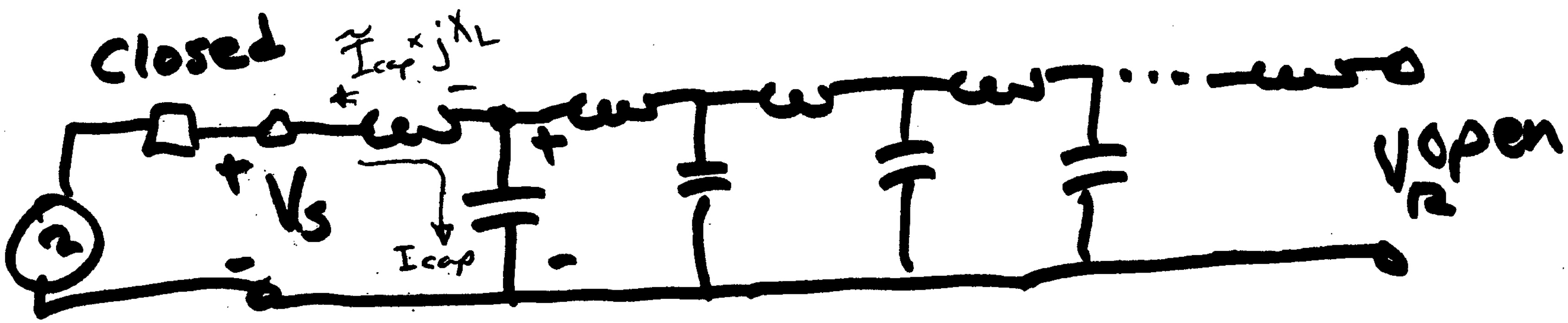
- Salt River Project

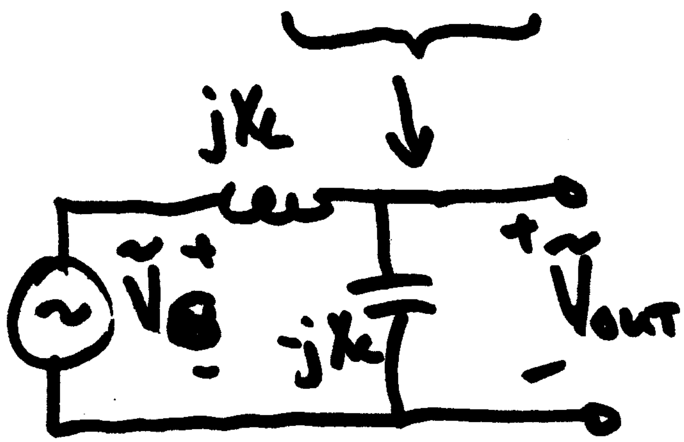
- Careful:
  - Long HV compensated Line
  - Lots of Local Gen
  - Lots of Remote Load

Ferranti Rise







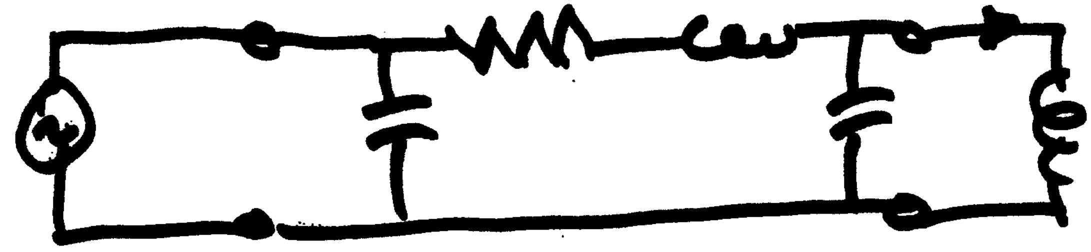


$$\tilde{V}_{OUT} = V \frac{-jX_c}{j(X_L - X_c)} = \text{some value} > 1.$$

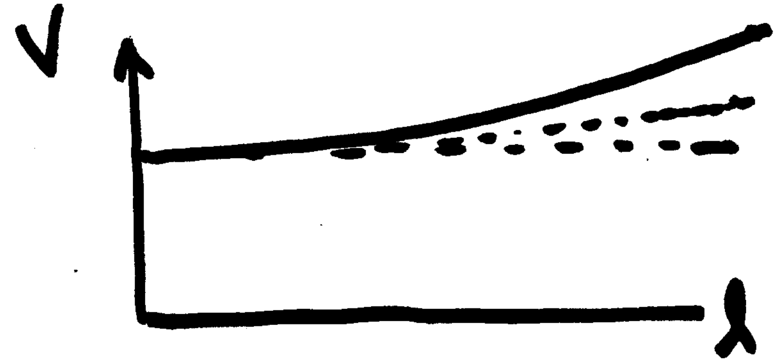
$$X_c >> X_L$$

Shunt Compensation:

$I_{SHUNT} = I_{LINE\ CHG}$



Connect Shunt Reactor at receiving end.

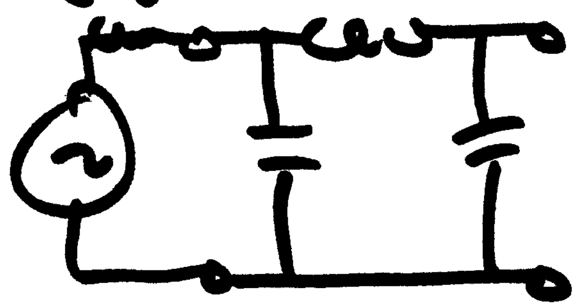


Limit to < 1.10 p.u.

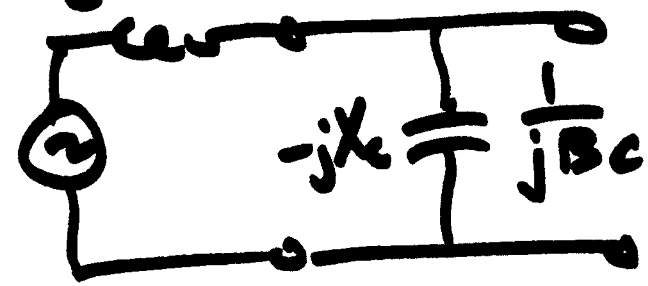
Compensates for Ferranti rise.

- 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:



100 mi Bluebird

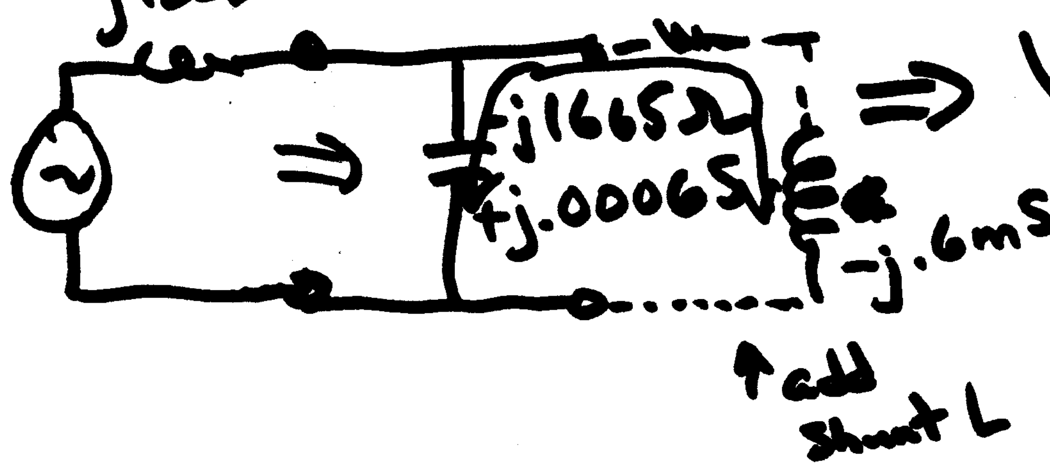
$D_{eq} = 20$ ft.

$X_c = 1665\Omega$

$X_s = 120\Omega$ (typ)

$Y_{cap} = jB_c$

$Z_{cap} = -jX_c$



$$\Rightarrow V_R = V_s \frac{-j1665}{j120 - j1665}$$

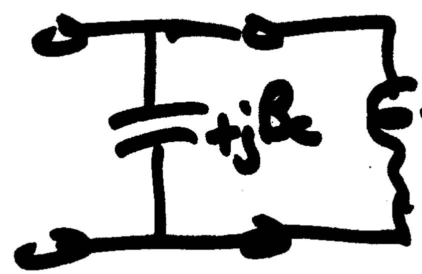
$$= \underline{1.08\, V_s}$$

Shunt Comp Factor = $\frac{B_L}{B_C} = \frac{1/\omega L}{\omega C_{CHG}}$ ||

Total Compensation:

Add a reactor $B_L = B_C$

Total Shunt Admittance = 0



$\Rightarrow \frac{B_L}{B_C} = 1$

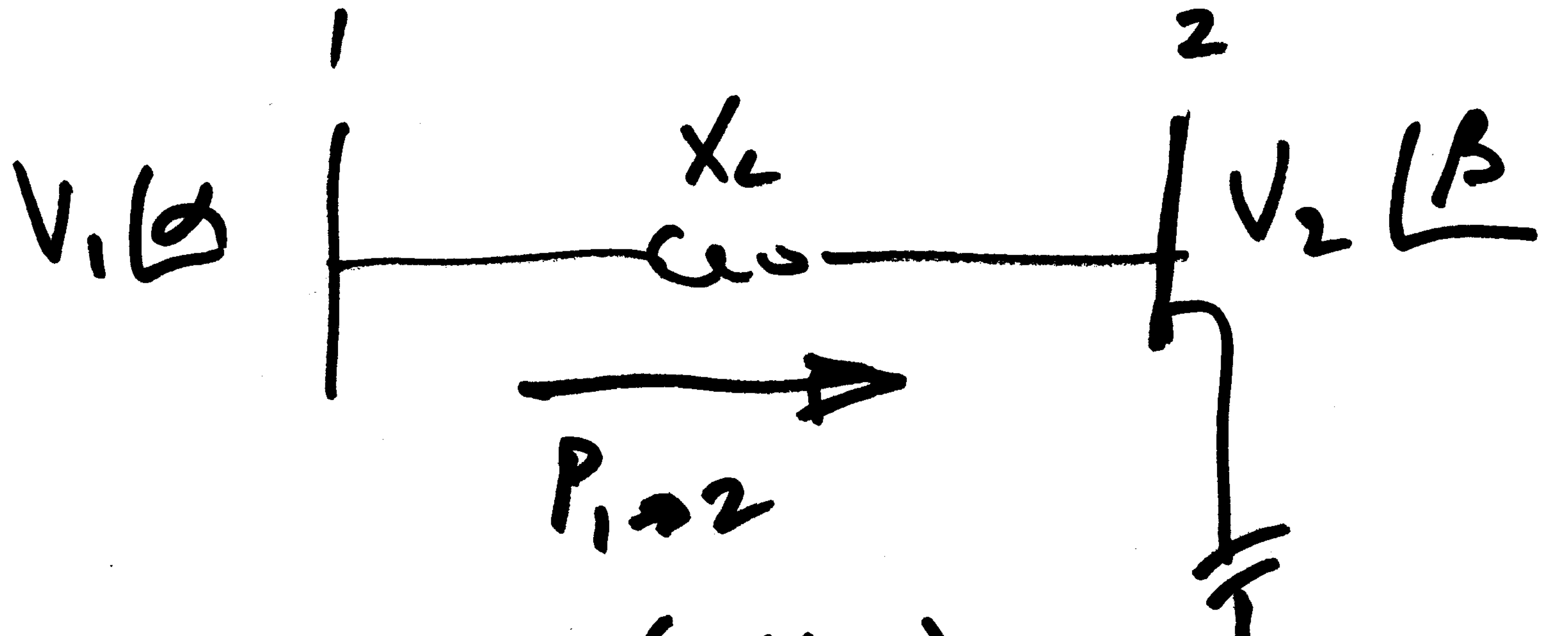
then

$Y_{TOTAL} = jB_C - jB_L = 0$

$(Z_{SHUNT} = \infty)$

$$P_{1\to 2} = \frac{V_1 V_2}{X_L} \sin(\alpha - \beta)$$

Power Transfer Capability.

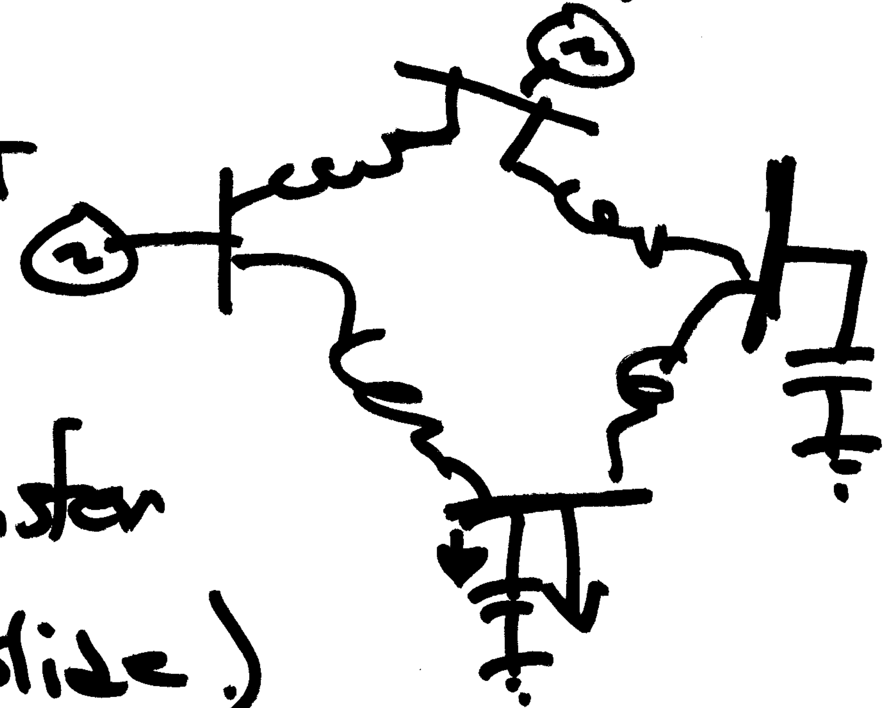


V_1V_2 : min : $\frac{(.95)(.95)}{(1.05)(1.05)} \approx .8185 \Rightarrow$ 22.1% increase!

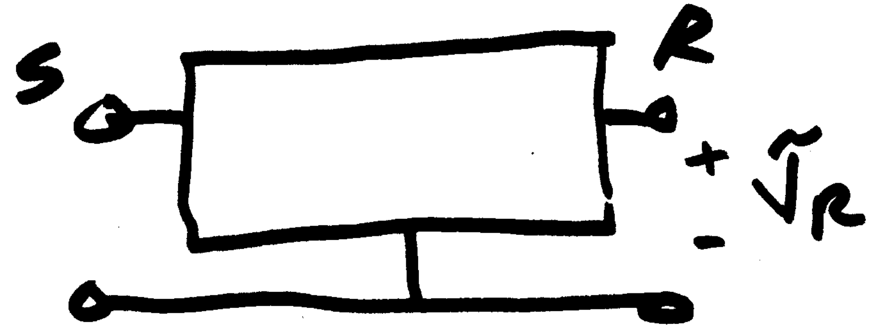
: max :

SHUNT CAPS:

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

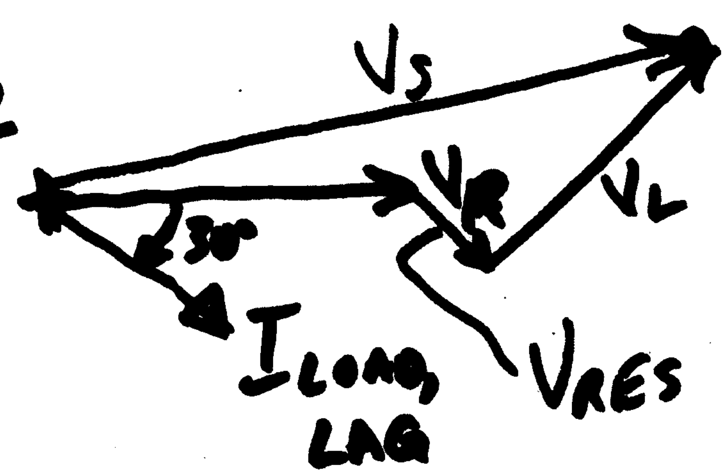


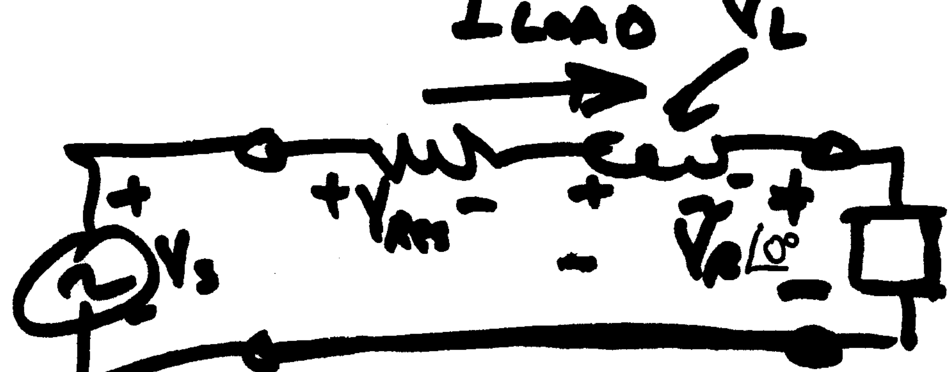
Voltage Regulation:



$$VR = \frac{|\tilde{V}_{R,NL}| - |\tilde{V}_{R,FL}|}{|\tilde{V}_{R,FL}|}$$

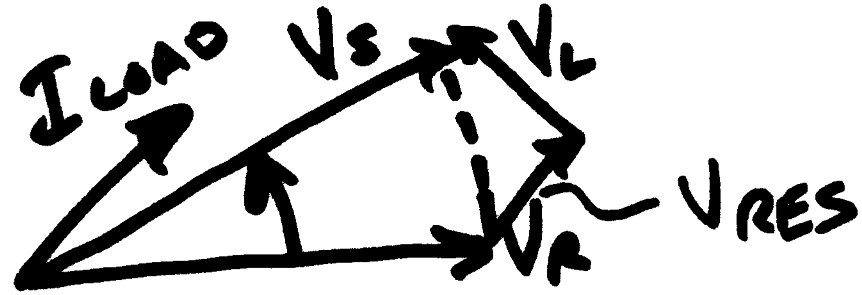
LAG





$$\tilde{V}_S = \tilde{V}_{RES} + \tilde{V}_L + \tilde{V}_R$$
$$= \tilde{I}_{LOAD} R + \tilde{I}_{LOAD} \cdot jX + \tilde{V}_R$$

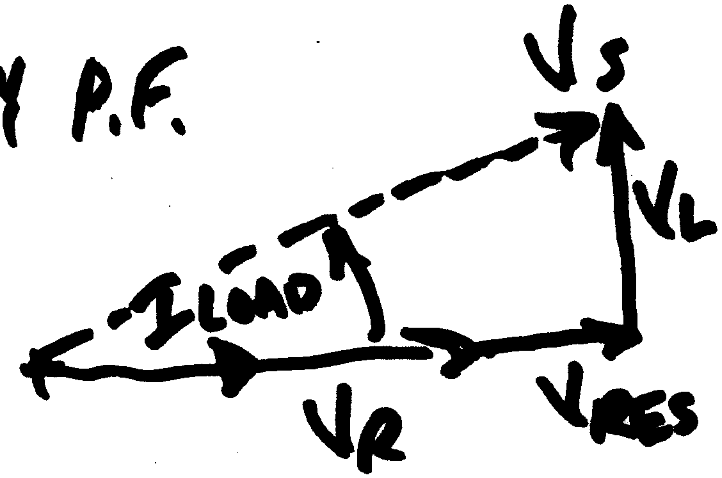
LEAD



Note: VR can be <u>negative</u> for Leading P.F. load.

UNITY P.F.

[redacted]



$$VR = \frac{V_{NL} - V_{FL}}{V_{FL}} = \frac{V_S - V_R}{V_R} = \_\_\_\_ \text{ pos. no. for Lag, Unity.}$$

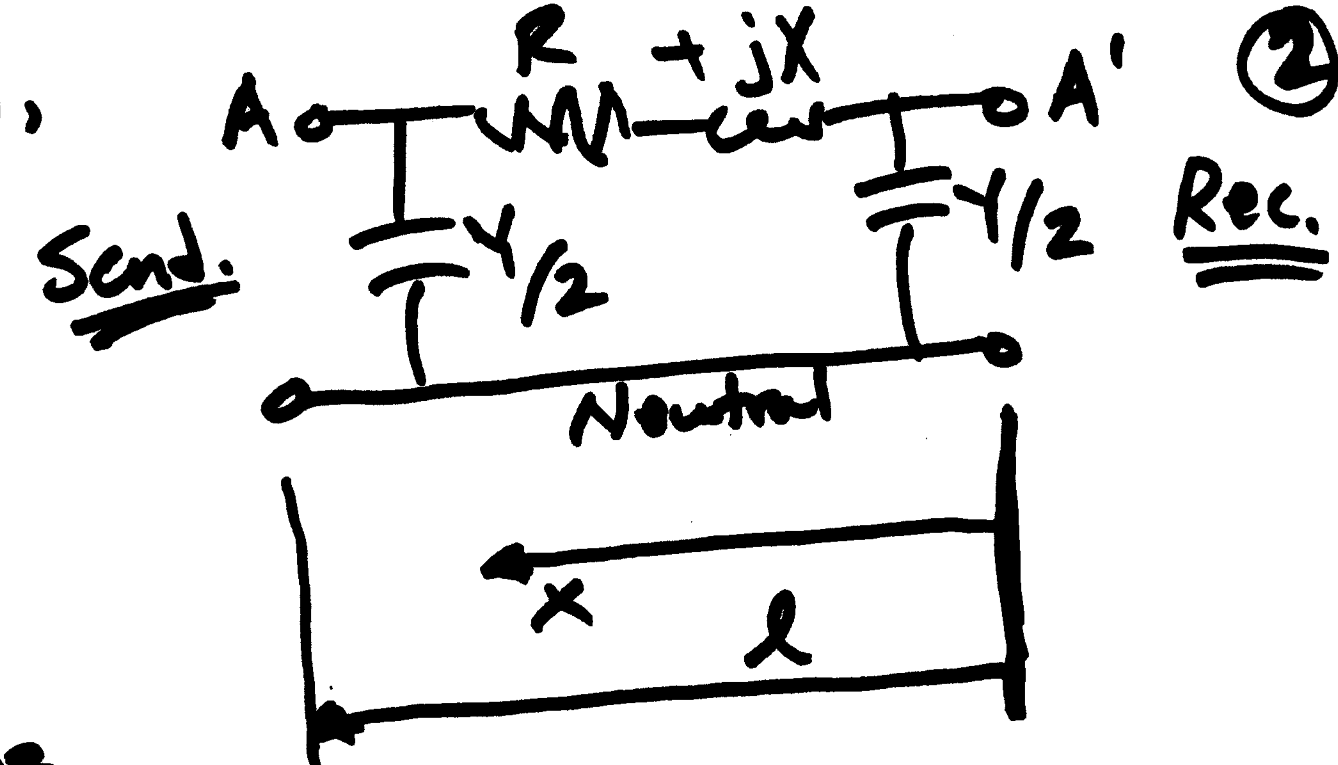
VR in terms of A-B-C-D.

Recall:

$$V_R = \frac{V_{R,NL} - V_{R,FL}}{V_{R,FL}}$$

$$= \frac{V_S/A - V_{R,FL}}{V_{R,FL}}$$

IN General,



Short Line

≤ 50 mi (80 km)

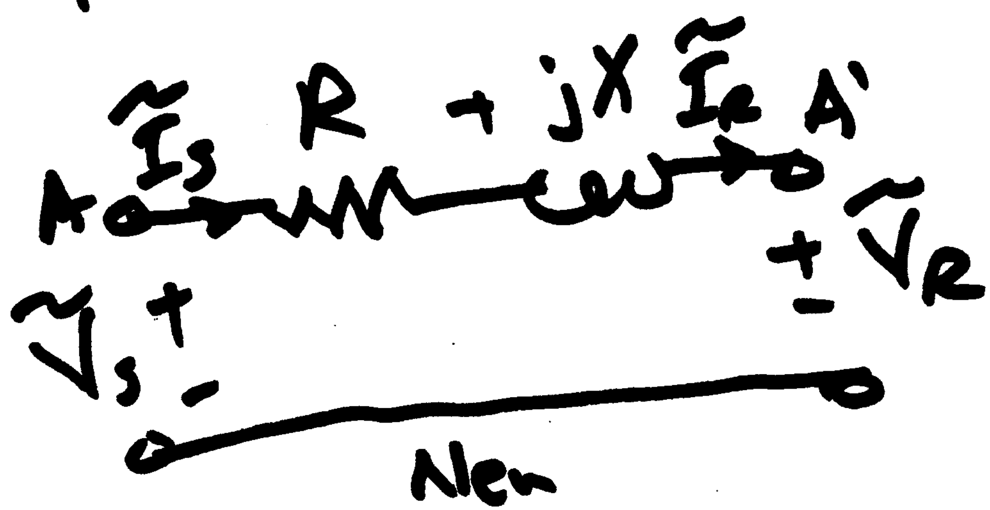
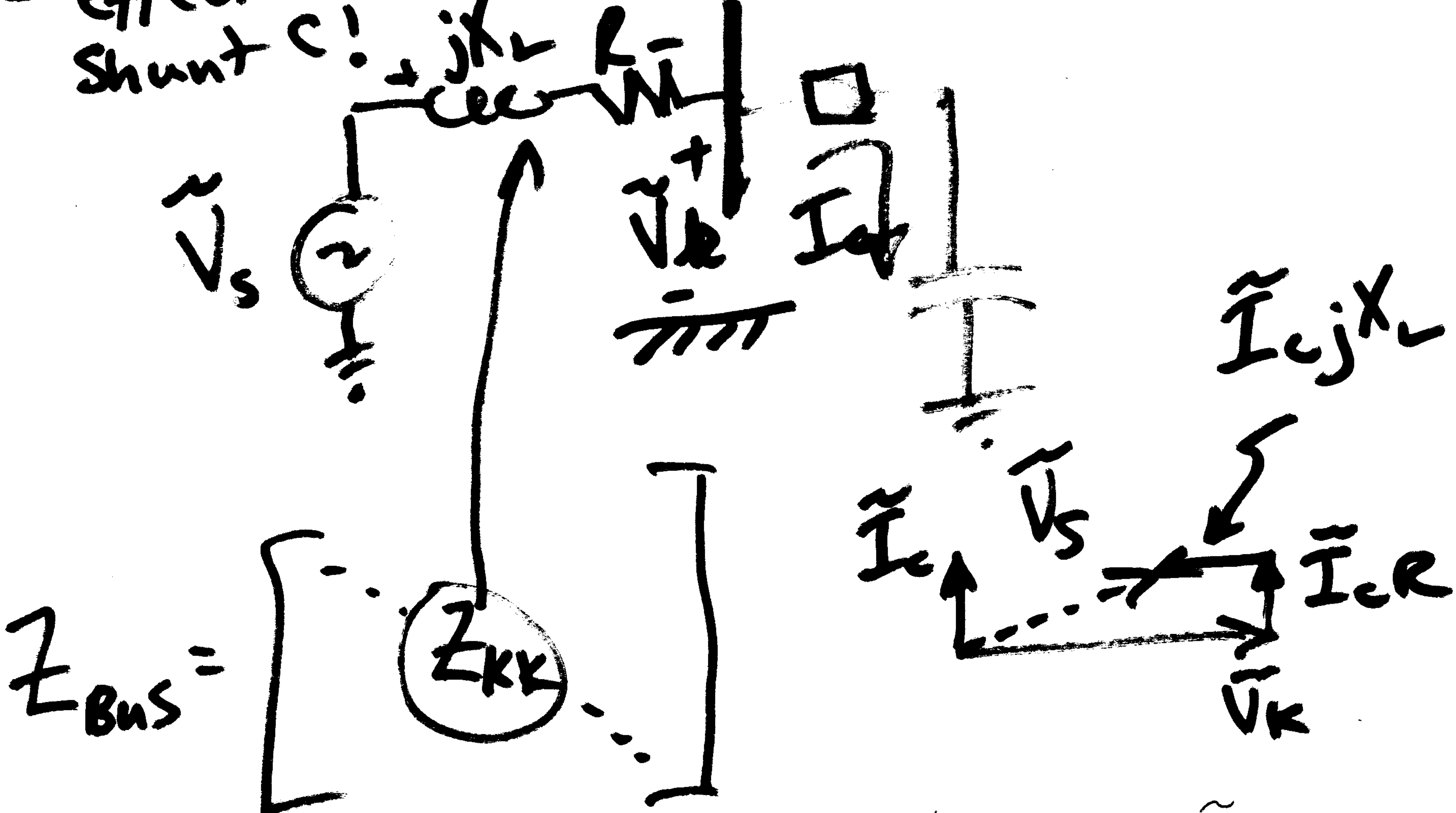


Fig. 6.3

Ex. 6.1

$\frac{X}{R}$ ratio determines effectiveness of shunt C!



If $\frac{X}{R} = 0$,