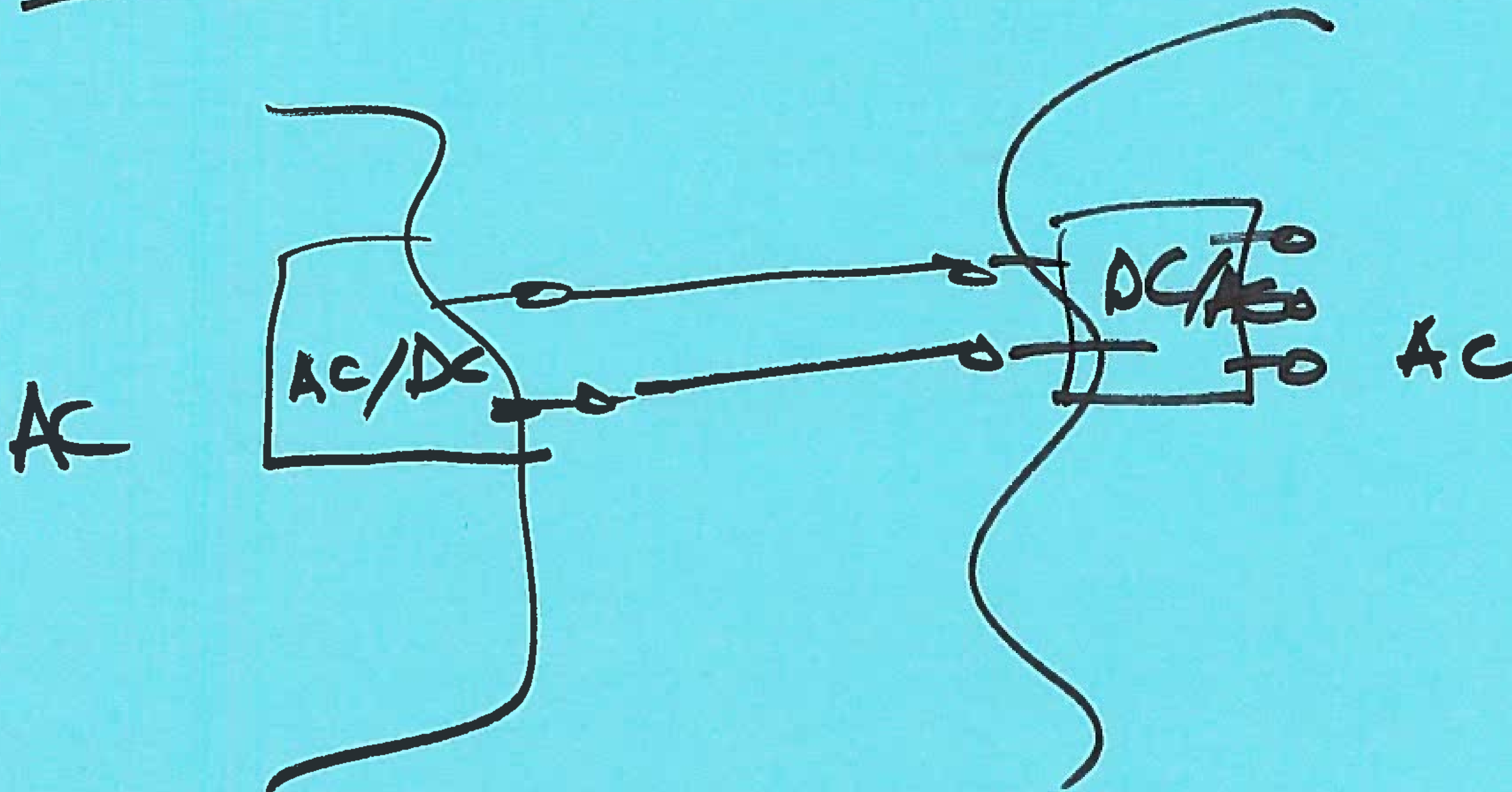
EE 5220 - Lecture 21 Friday Feb 21, 2024

Topics for Today:

- Course Info:
  - Web page: https://pages.mtu.edu/~bamork/ee5220/
  - Software - Matlab. ATP/EMTP [License - www.emtp.org] ATP tutorials posted on our course web page
  - EE5220-L@mtu.edu (participation = min of half a letter grade, 5%)

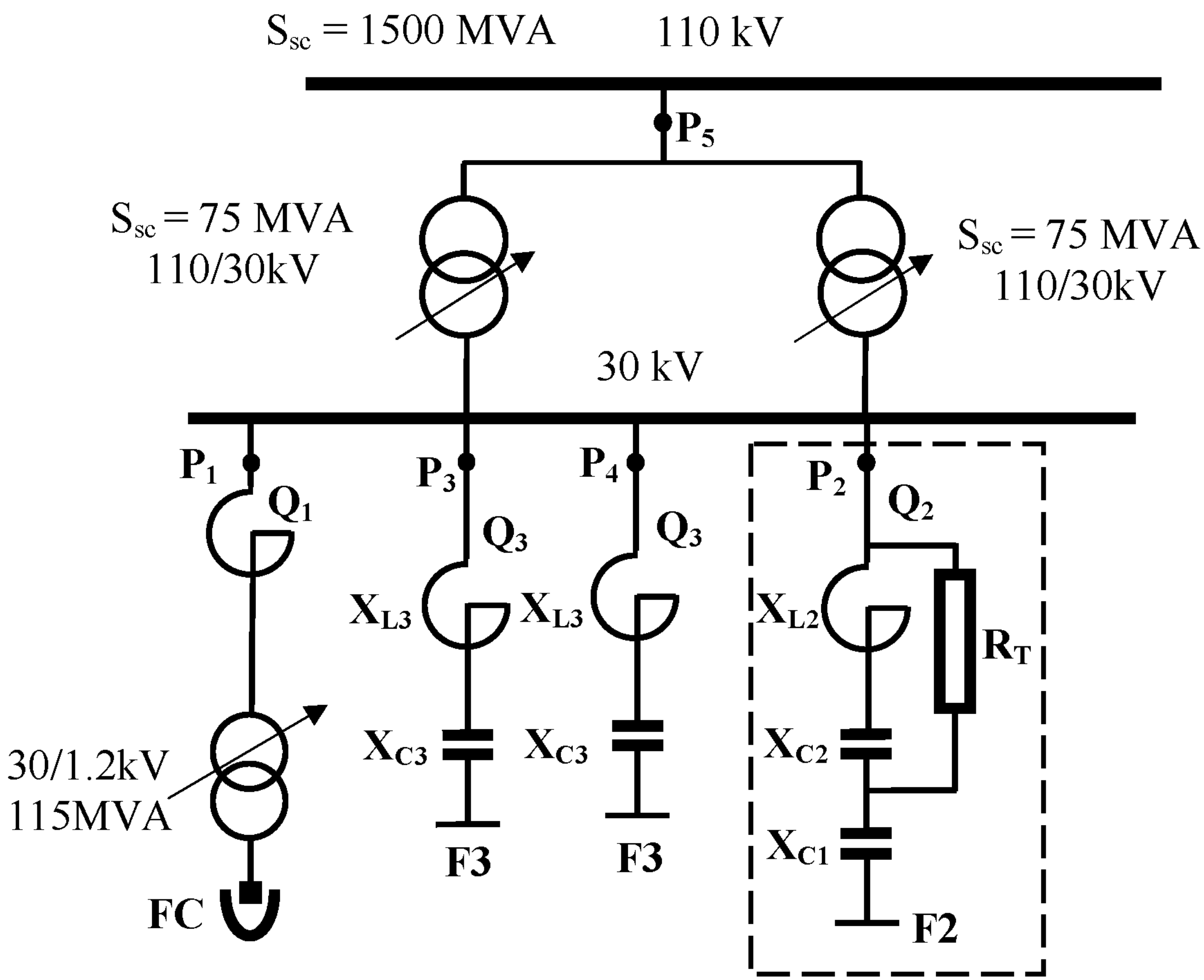
- HW#7 - due Tues March 13th, 9am).
- Term Project - after topic approved - complete reference list and fully-detailed table of contents, submit via e-mail
- Use of Line Constants .lis output file to obtain detailed matrices, line parameters, propagation constants.
  - Interpreting the matrices: Phase matrices; Sequence matrices; B; Z
- Long-Line approximations, performance as fraction of wavelength
- Basics for lines vs. cables; traveling wave model (See video/ATP)
  - HW#7
- Next:
  - Multi-conductor line models for transient and traveling wave behaviors

FREQ SCAN



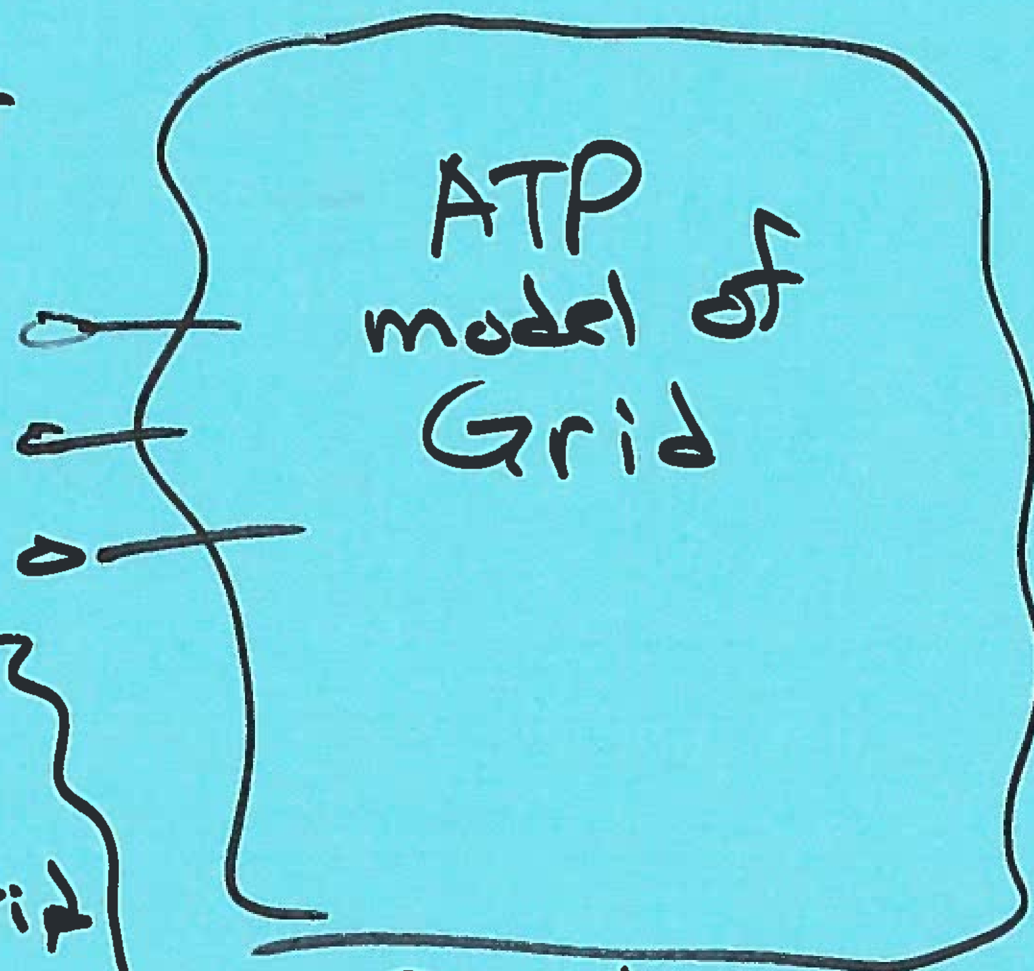
Example of harmonic filter bank at dc terminus or freq convertor.

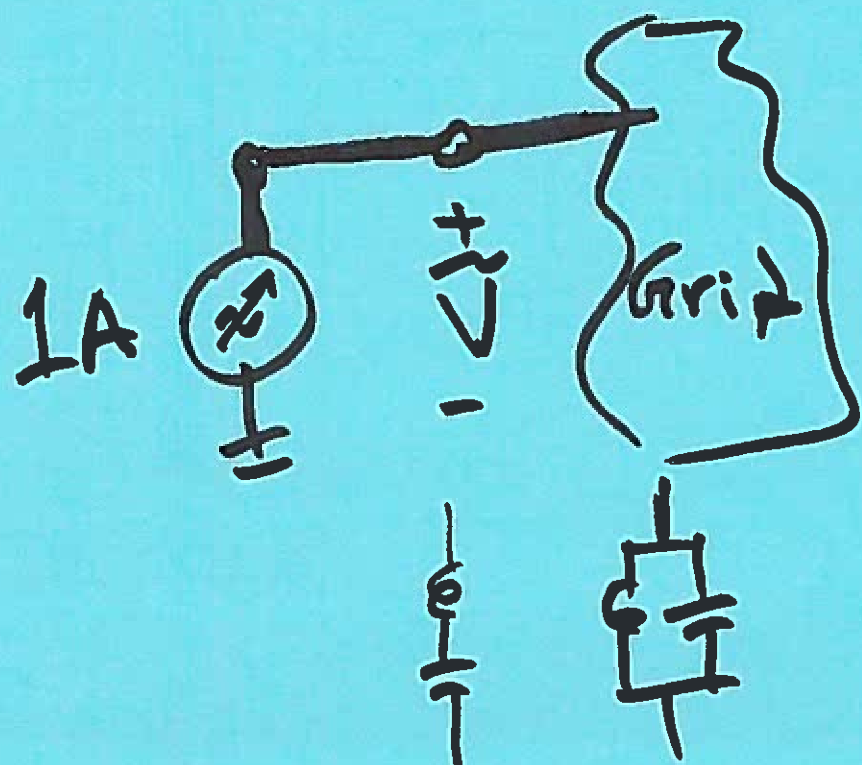
Great overview article is available at:
https://www.intechopen.com/books/power-quality-issues/bank-harmonic-filters-operation-in-power-supply-system-cases-studies

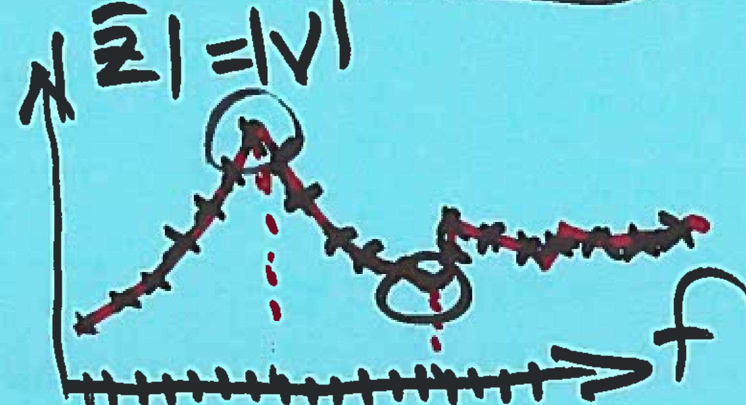


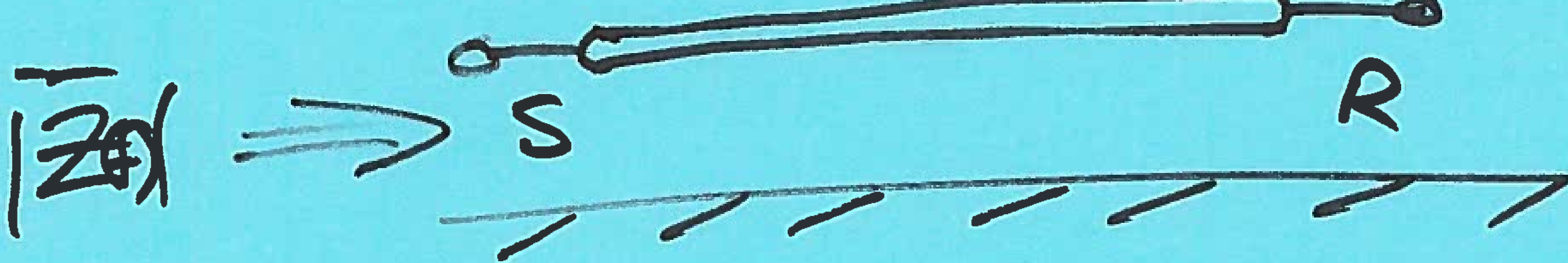
$$\bar{Z} = \frac{\tilde{V}}{\tilde{I}}\Bigg|_{f=\text{const}}$$

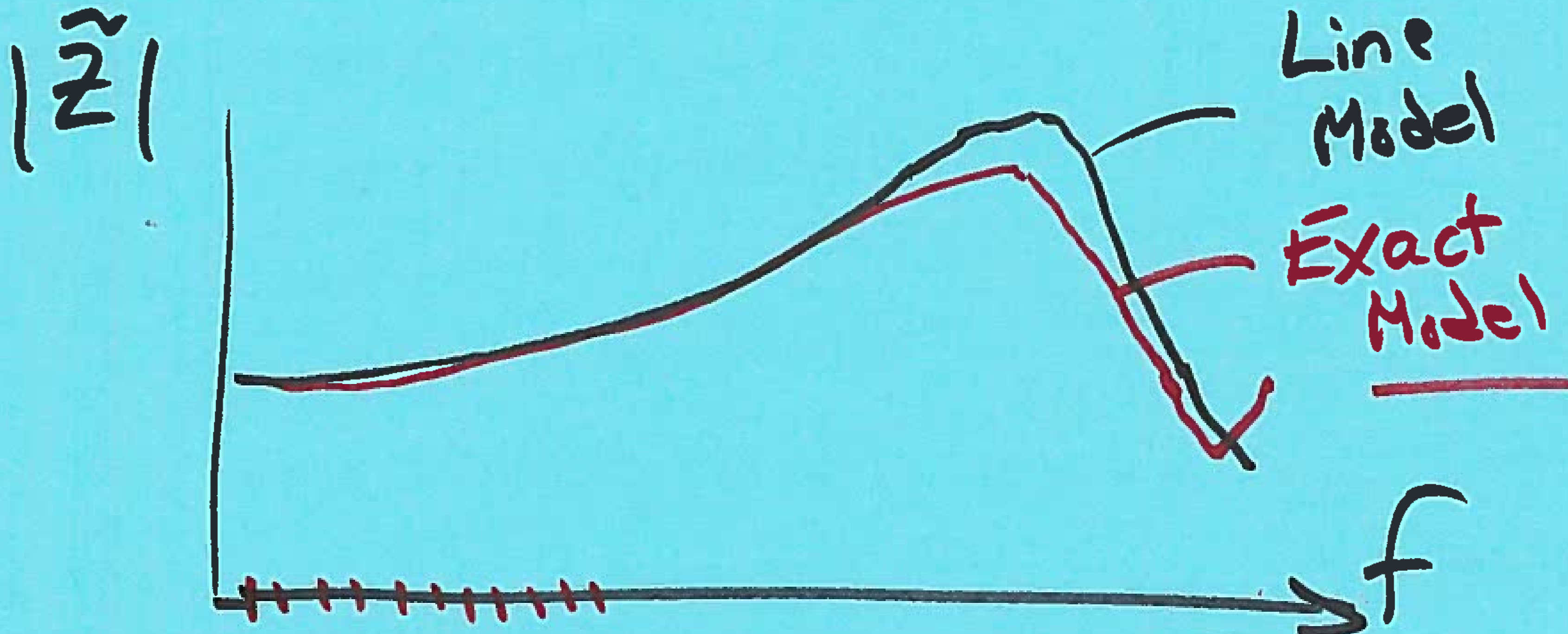
$\bar{Z}(f)$

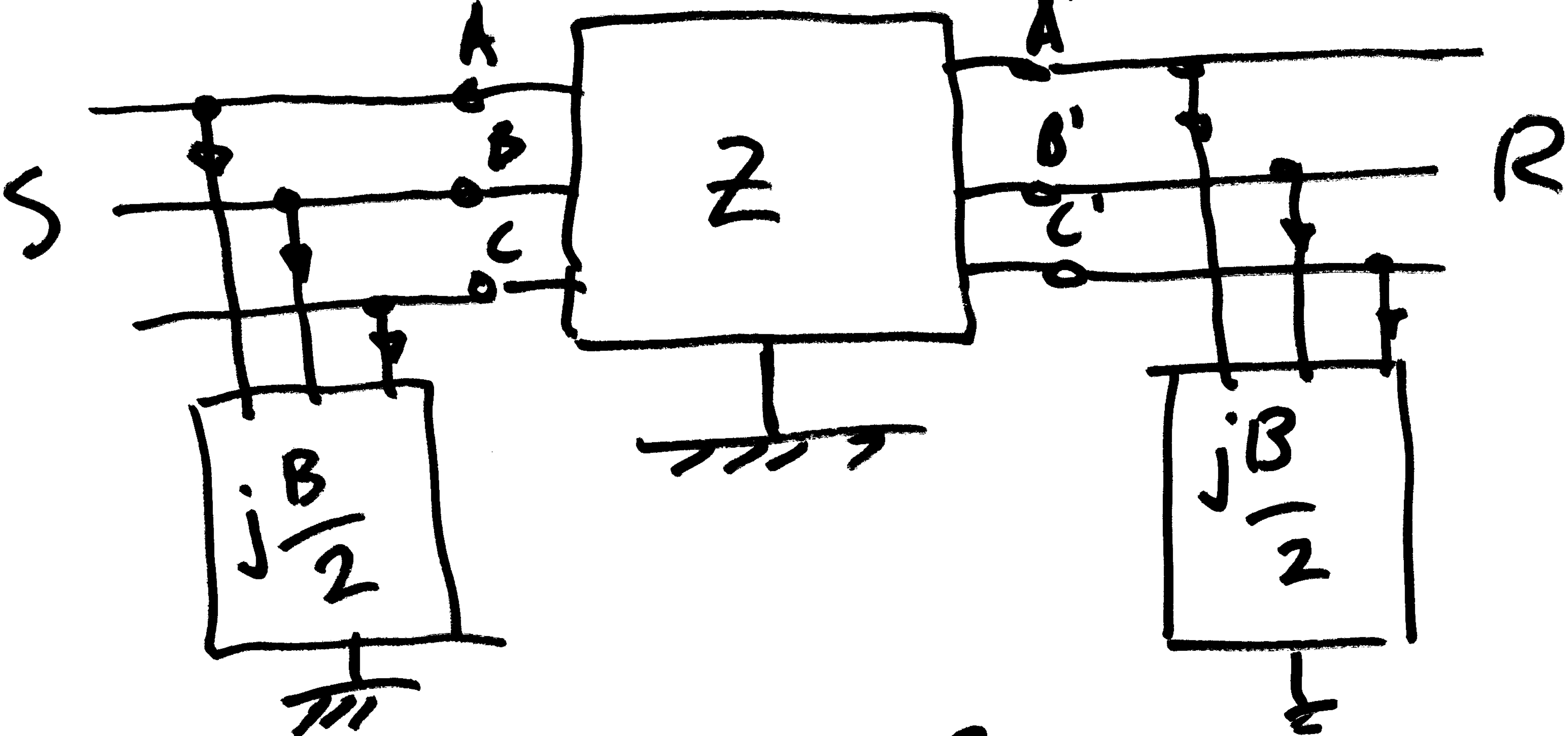




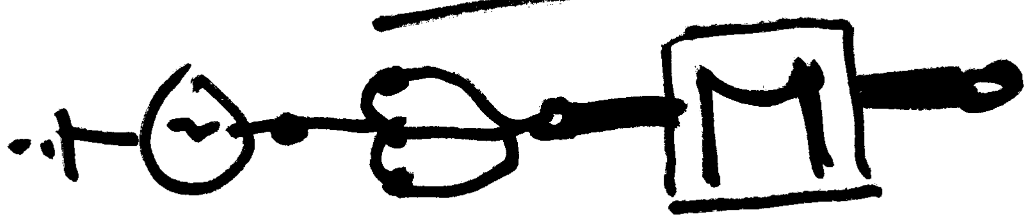



S
R

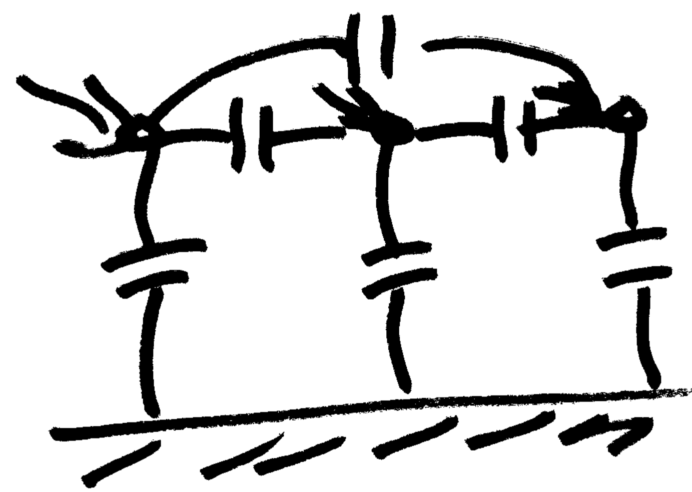

|Z̃|
Line Model
Exact Model
f



Coupled - Pi

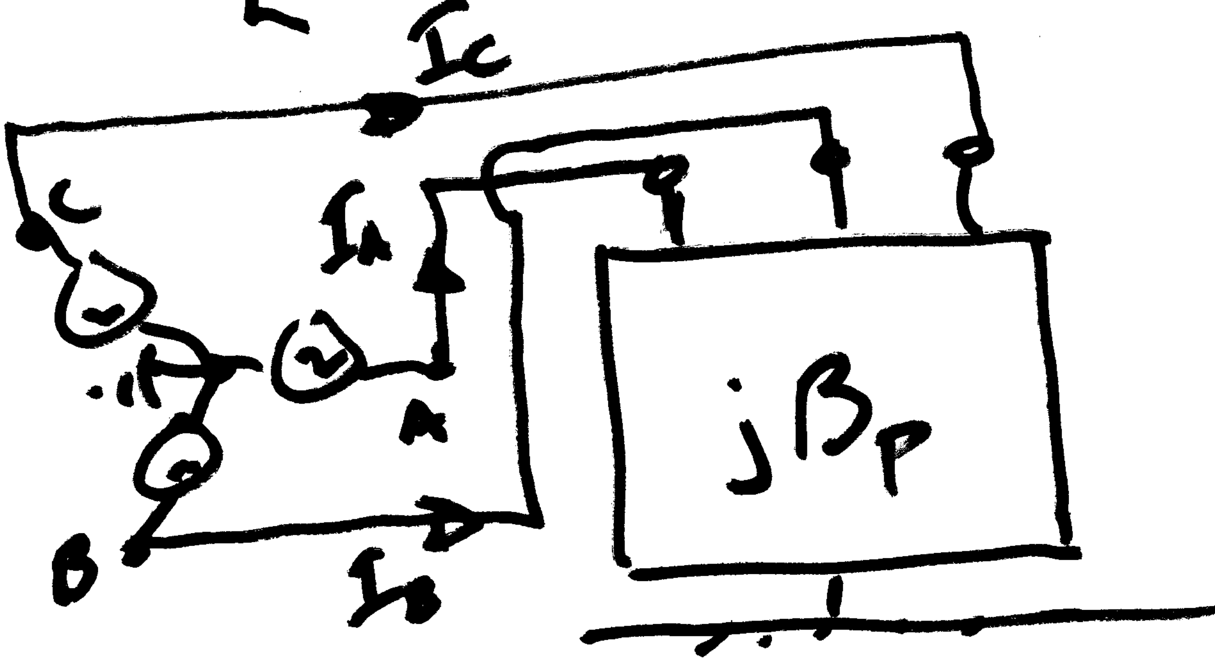


$$[B_p] = \begin{bmatrix} B_{AA} & B_{AB} & B_{AC} \\ B_{BA} & B_{BB} & B_{BC} \\ B_{CA} & B_{CB} & B_{CC} \end{bmatrix}$$



$$\Big[\; jB_p \;\Big] \begin{bmatrix} \tilde{V}_A \\ \tilde{V}_B \\ \tilde{V}_C \end{bmatrix} = \begin{bmatrix} \tilde{I}_A \\ \tilde{I}_B \\ \tilde{I}_C \end{bmatrix}$$

$B = \omega C$



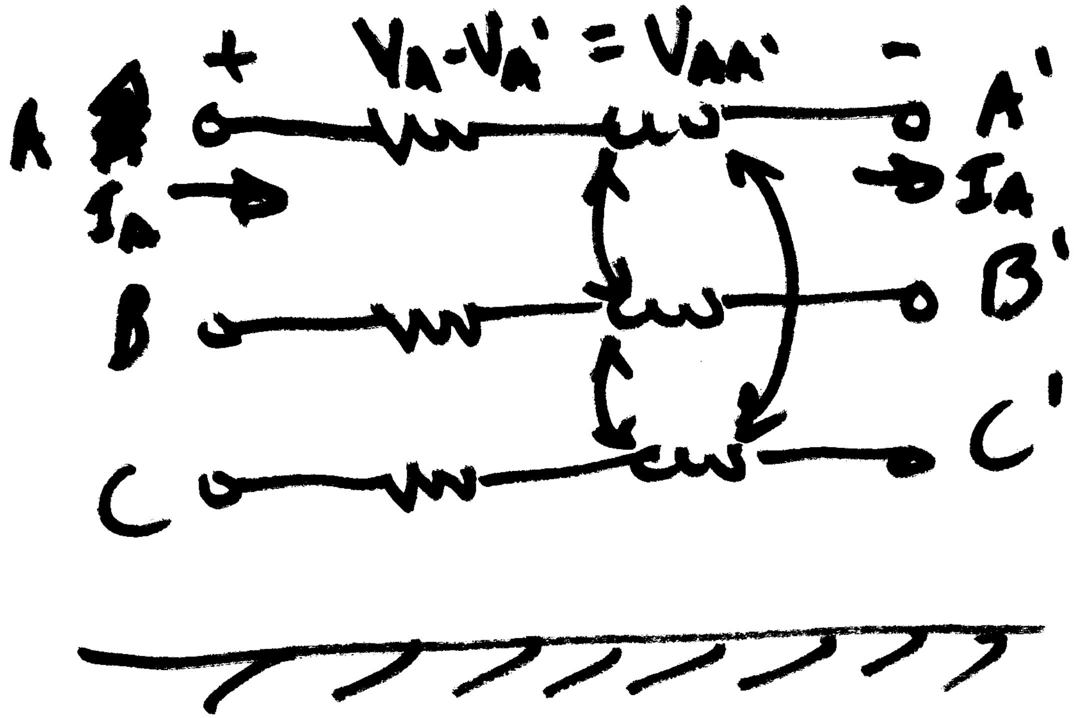
Line Chg MVARS

$$Q_{LINE} = \tilde{V}_A \tilde{I}_A^* + \tilde{V}_B \tilde{I}_B^* + V_C \tilde{I}_C^*$$

$$[Y_p] = j[B_p]$$

$$[Y_s] = [A^{-1}][Y_p][A]$$

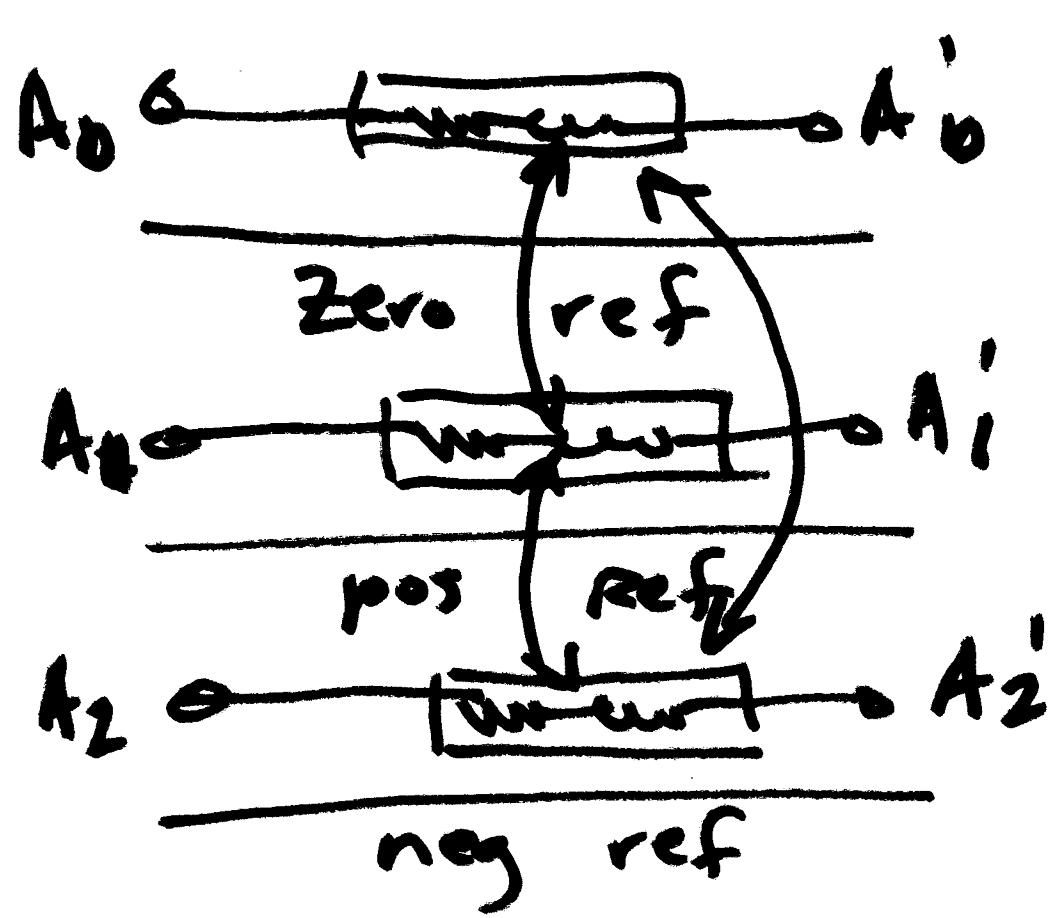
$$[\bar{Z}] = \begin{bmatrix} Z_{AA} & Z_{AB} & Z_{AC} \\ Z_{BA} & Z_{BB} & Z_{BC} \\ Z_{CA} & Z_{CB} & Z_{CC} \end{bmatrix}$$

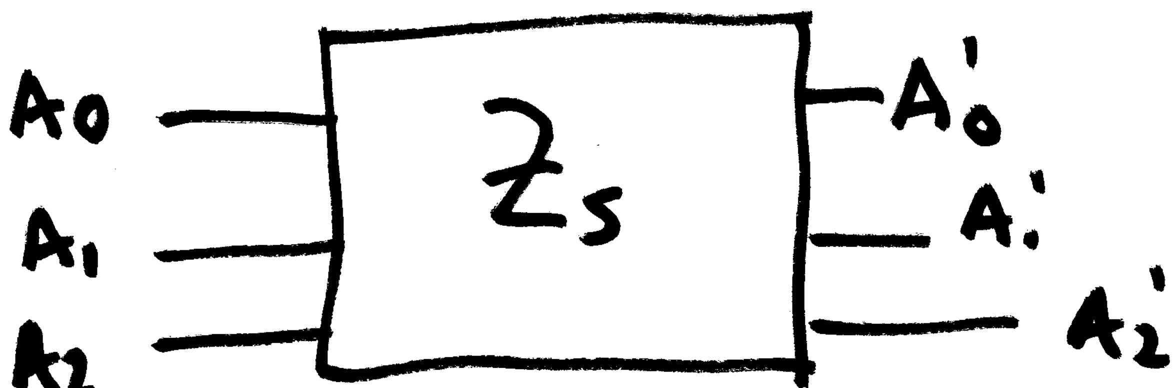


$$\begin{bmatrix} & & \\ & Z_p & \\ & & \end{bmatrix} \begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} = \begin{bmatrix} V_A - V_A' \\ V_B - V_B' \\ V_C - V_C' \end{bmatrix} = \begin{bmatrix} V_{AA'} \\ V_{BB'} \\ V_{CC'} \end{bmatrix}$$

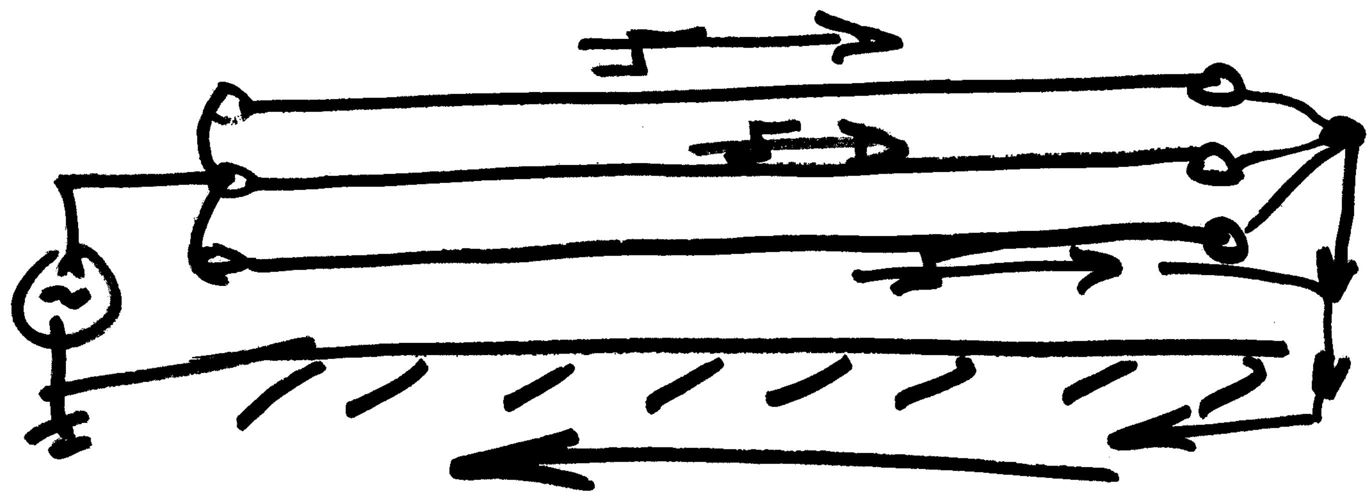
$$Z_s = A^{-1} Z_p A$$

$$= \begin{bmatrix} Z_{00} & Z_{01} & Z_{02} \\ Z_{10} & Z_{11} & Z_{12} \\ Z_{20} & Z_{21} & Z_{22} \end{bmatrix}$$


A_0
A_0'
zero ref
A_1
A_1'
pos ref
A_2
A_2'
neg ref


A_0
A_1
A_2
Z_s
A_0'
A_1'
A_2'

Zero Sequence



Z_C for waves thru gnd is higher.

For oil (mineral oil)

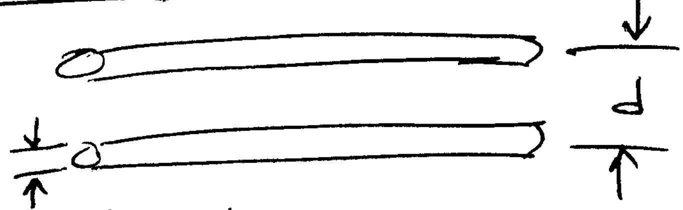
$\varepsilon_R \approx 2.2$

For cellulose:

$\varepsilon_R \approx 5\text{-}7$

§13.7 - Greenwood. Transient T-Line Parameters

Simple Case:



r: diameter

$$L = \frac{\mu_0}{\pi} \ln \frac{d}{r} \quad H/m \quad (\text{approx})$$

OK for transients.

neglects inherent/internal inductance: ($2\pi \times 10^{-7}$ H/m)

$$C = \frac{\pi \epsilon_0}{\ln \frac{d}{r}} \quad F/m$$

For $d = 5m$ & $r = 2.5cm$, $L = 2.119\ \mu H/m$

$C = 5.25\ pF/m$

$$v = \frac{1}{\sqrt{LC}} \approx \frac{1}{\sqrt{\mu_0 \epsilon_0}} = 2.998 \times 10^8\ m/s$$

$$Z_0 = \sqrt{\frac{L}{C}} = 635\ \Omega$$

Actual lines are 3ϕ, sometimes multi-circuit, w/ gnd effects

For 500 KV line: $Z_0 = 275\ \Omega$

$I_{CHG} = 2-2.3$ A/mile @ 60 Hz.

$\frac{X}{R}$ ratios are in range 1-5 (seems low)

if Gnd is involved, R increases more than X.

Cables: $v = 500-600\ ft/\mu s = \left(1.52-1.83 \times 10^{8}\ m/s\right)$

$Z_0 = 30-35\ \Omega$

$v = \dfrac{1}{\sqrt{\mu \varepsilon}}$

$$C_{coax} = \frac{2\pi \varepsilon_0 k}{\ln r_2/r_1}$$

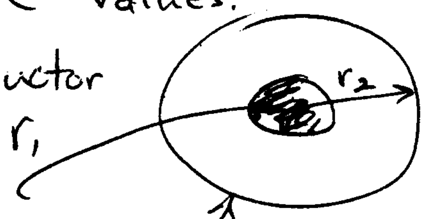
$k = \varepsilon_r$

r_2 = sheath radius

r_1 = cond radius

See Table 13.8 for C values.

inner conductor radius = r_1



Sheath involved in gnd faults, but not normally for load (neu current) if balanced.

$$L = \frac{\mu_0}{2\pi} \ln \frac{r_2}{r_1}\ H/m$$

$$= 7.43 \times 10^{-4} \log \frac{r_2}{r_1}\ H/mile.$$

$$Z_0 = \frac{1}{2\pi}\left(\frac{\mu_0}{\varepsilon_0 \varepsilon_r}\right)^{1/2} \ln \frac{r_2}{r_1}\ \Omega$$

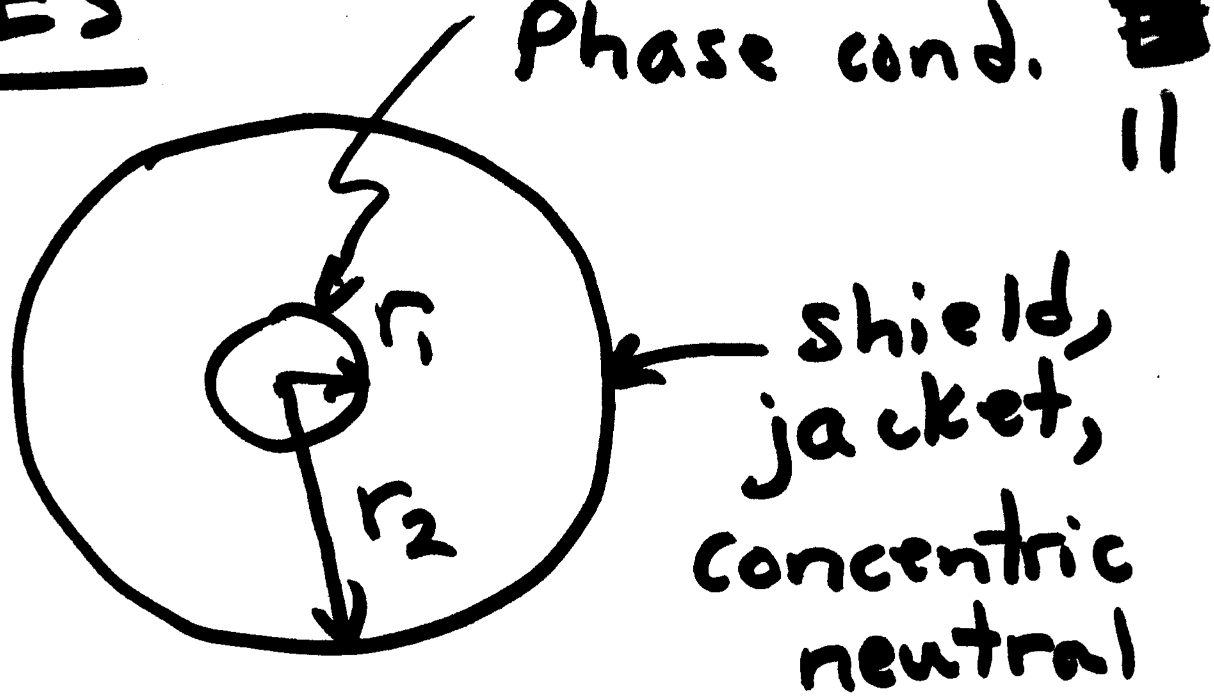
Typical L = 400-700 μH/mile. ?

$\frac{X}{R}$ ratios are lower than for OH T-Lines.

Lots of different types of cables & shields.

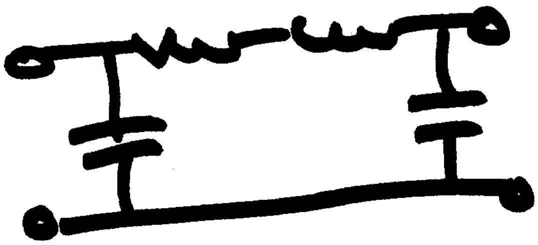
NOTE: CH 13 is bible of parameter estimation, if no other info is available.

CABLES



$$C = \frac{2\pi \epsilon_0 \epsilon_r}{\ln \frac{r_2}{r_1}} \quad H/m$$

As $V \uparrow$, $C \downarrow$



$\downarrow I_{CHG} = \underline{V\omega C}$

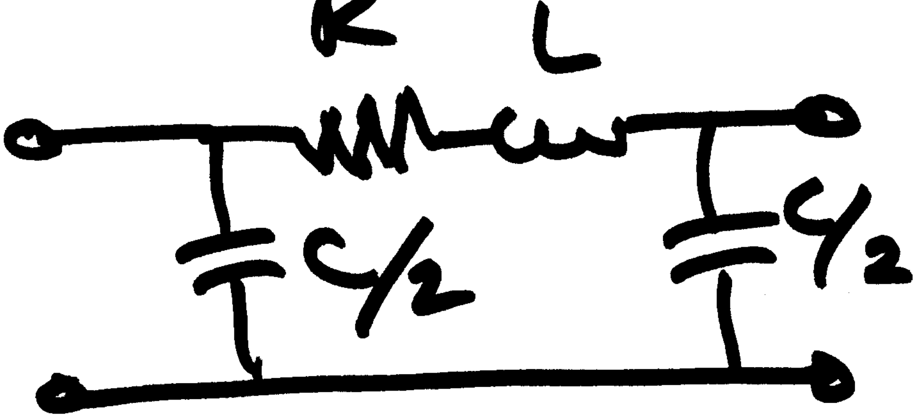
NEXT: Charging MVAR?

$Q = \frac{V^2}{X_c}$ $\therefore$ Q increases rapidly.

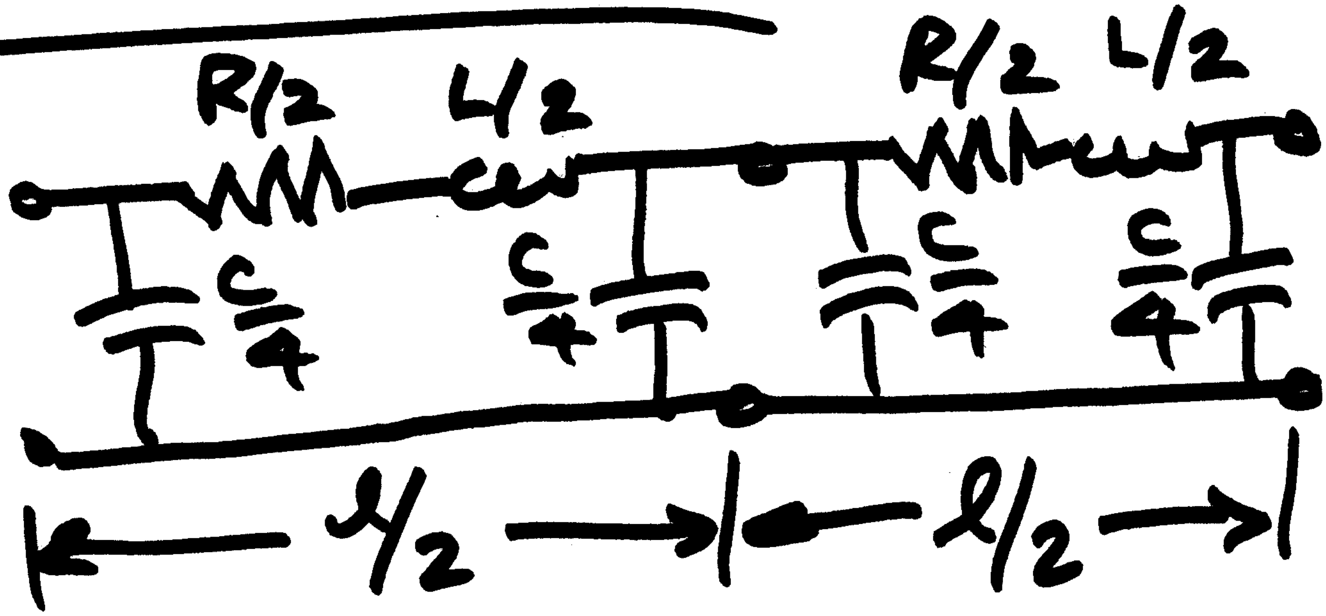
$Z_c = \frac{1}{\omega C} = X_c$

Long Line Approximations

(Like TNA or reduced-order model).



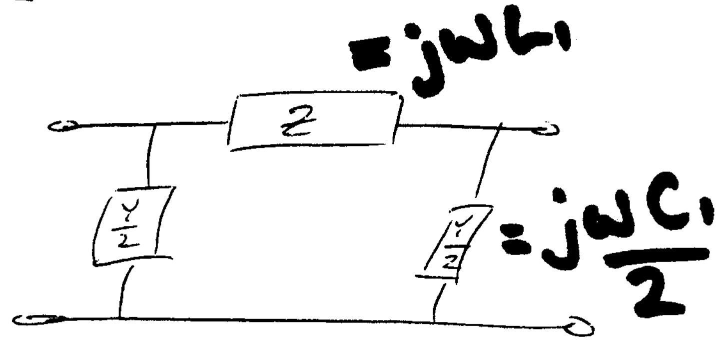
Cascaded models



If you use an ∞ no. of sections then we approach a distrib. param line.

Greenwood

§11.4 – Overhead Transmission Lines



L_1 = Total Series Ind

C_1 = Total Shunt Cap

For Lossless case:

$$\boxed{\begin{aligned} V_s &= V_R \underbrace{\cosh j\omega\sqrt{L_1C_1}} + I_R Z_0 \underbrace{\sinh j\omega\sqrt{L_1C_1}} \\ I_s &= I_R \underbrace{\cosh j\omega\sqrt{L_1C_1}} + \frac{V_R}{Z_0}\underbrace{\sinh j\omega\sqrt{L_1C_1}} \end{aligned}}$$

Open Circuit Input Impedance: Set $I_R = 0 \Rightarrow Z_{oc} = \left.\frac{V_s}{I_s}\right|_{I_R=0}$

$$\underline{Z_{oc}} = \frac{V_R \cosh j\omega\sqrt{L_1C_1}}{\frac{V_R}{Z_0}\sinh j\omega\sqrt{L_1C_1}} = \boxed{Z_0 \coth j\omega\sqrt{L_1C_1}}$$

Short Circuit Impedance:

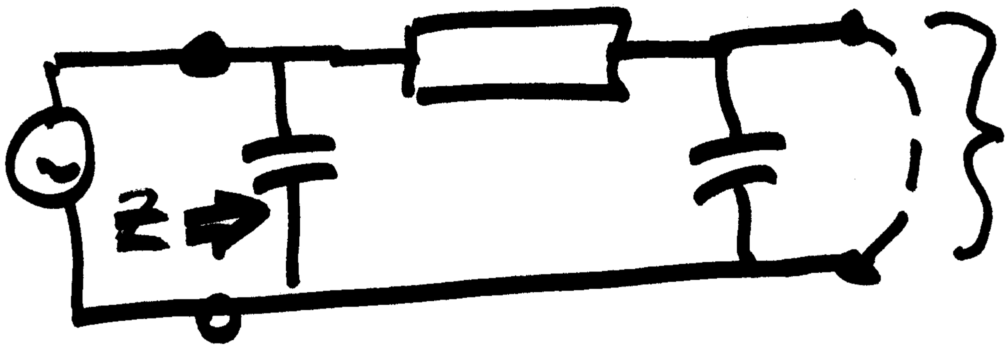
$$\underline{Z_{sc}} = \left.\frac{V_s}{I_s}\right|_{V_R=0} = \frac{I_R Z_0 \sinh j\omega\sqrt{L_1C_1}}{I_R \cosh j\omega\sqrt{L_1C_1}} = \boxed{Z_0 \tanh j\omega\sqrt{L_1C}}$$

For π-ckt,

$$Z_{oc} = \frac{2}{Y}\,\frac{ZY+2}{ZY+4}$$

$$Z_{sc} = \frac{2ZY}{ZY+2}$$

$$Z = \omega L_1\left[\frac{\sinh j\omega\sqrt{L_1C_1}}{j\omega\sqrt{L_1C_1}}\right] \qquad \frac{Y}{2} = \frac{\omega C_1}{2}\left[\frac{\tanh \frac{1}{2}j\omega\sqrt{L_1C_1}}{\frac{1}{2}j\omega\sqrt{L_1C_1}}\right]$$



$$\bar{Z}_{oc} = \left.\frac{\tilde{V}_s}{\tilde{I}_s}\right|_{I_R=0}$$

$$\bar{Z}_{sc} = \left.\frac{\bar{V}_s}{\bar{I}_s}\right|_{V_R=0}$$

Look at freq Response for $Z_{oc}(\omega)$ and $Z_{sc}(\omega)$

Compare models freq resp to actual line.

- Lumped Pi
- Bergeron
- Marti
- Semlyen
- Noda