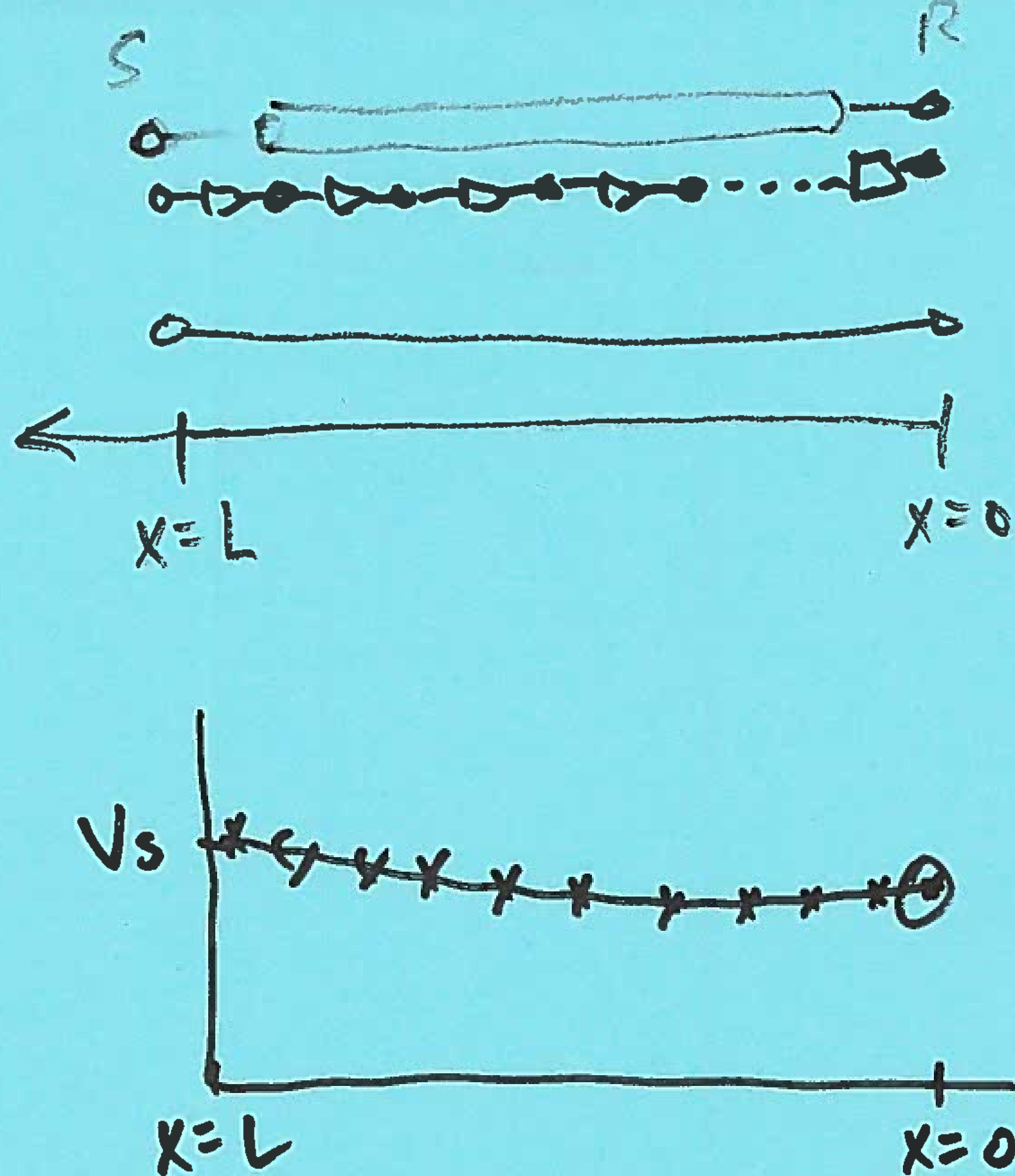
EE 5200 - Lecture 26 **Wednesday Oct 30, 2019**

Topics for Today:

- Announcements
  - Detailed term project outlines (i.e. Table of Contents + List of references
  - ASPEN software - remote.mtu.edu
  - Office hrs: EERC 123, WF 4-6pm. Instructor’s office: EERC 614
  - Recommended problems & all solutions: Ch.7 solns posted.

- Chapter 7 - Network Equations, Admittance Approaches
  - How’s your linear algebra? Time to make use of it...
  - Basic strategy for building up [Y] for whole network
  - Quick recap of xfmrs and lines.
  - Generators
  - Example of building [Y] for 4-bus system.
  - Network Reduction (Kron Reduction)
  - Solution of matrix equations (system of linear equations)
  - Upcoming homework - intro to Matlab, matrices, equations.

- Spreadsheet
- ASPEN
  - LF — phasor
  - SC
    - Arc Flash
  - Relay Coordination
- CYME — Optimal LF
- ATP
  - Line Constants
  - Time-domain
  - Feedback control
  - Relay Prot
- Matlab
  - Simulink
  - SimPower



S
R
x=L
x=0
Vs
x=L
x=0

Close look at $\gamma = \alpha + j\beta$

$$\gamma = \sqrt{zy} = \sqrt{(.2+j.6)\,\Omega/mi * j7.3\,\mu S/mi}$$

Very high X/R ⇒ may assume lossless?

$$= .00034/mi \;+ j0.00212\text{ rad}/mi$$

$$= \underbrace{.00034\,\frac{neper}{mi}} + j.00212\text{ rad}/mi$$

Tells us how much attenuation/mi the wave will experience.

For 250 mi : $\text{Atten} = \left(.00034\,\frac{neper}{mi}\right)(250\,mi)$

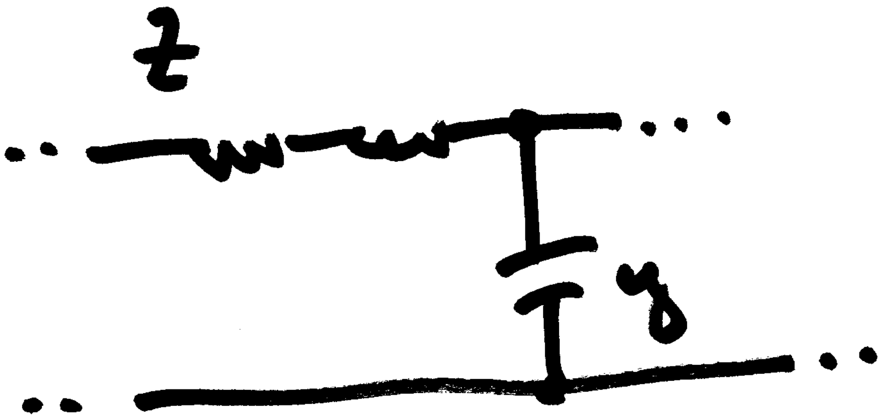
$= 0.085$ or 8.5%.

$$Z_c = \sqrt{\frac{z}{y}} \Rightarrow \text{Real for lossless.}$$

$\sim \underline{300}\ \Omega$ (OHD)

$(250 - 400\ \Omega)$

$\sim 70 - 80\ \Omega$ (cables)



$$\bar{Z}_c = \sqrt{\frac{R + jX_L}{jB_c}}$$

Reflections

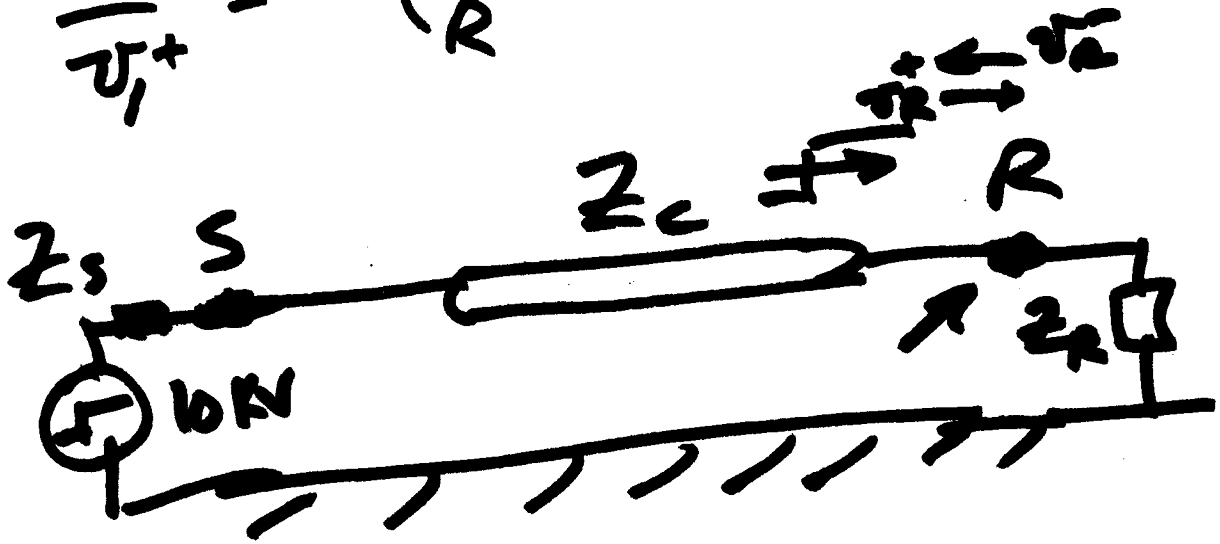
Voltage Reflection Coefficient:

$$\frac{v_R^-}{v_R^+} = \frac{Z_R - Z_C}{Z_R + Z_C} = \rho_R \qquad \frac{Z_S - Z_C}{Z_S + Z_C} = \rho_S$$

Current Reflection Coefficient

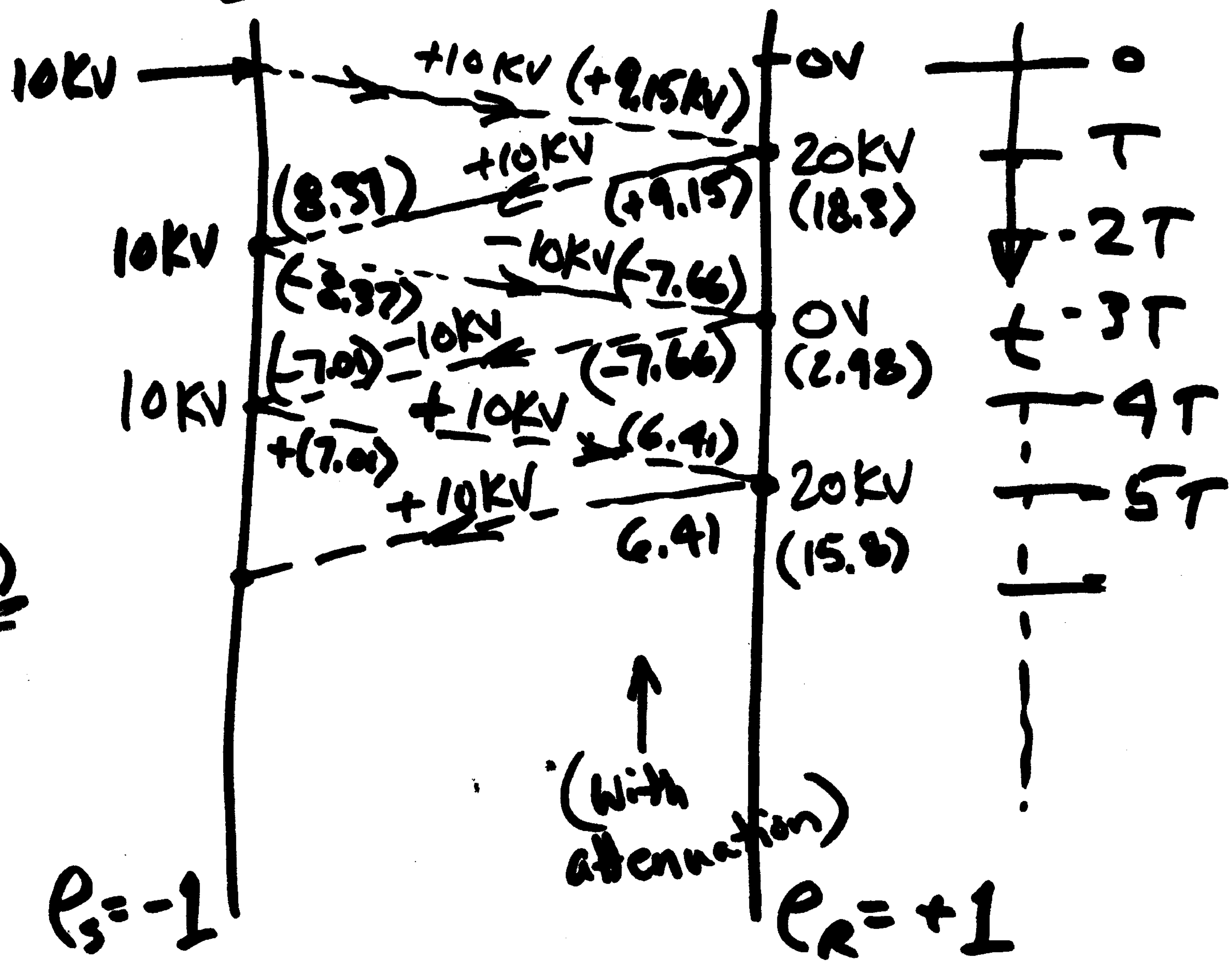
$$\frac{i_R^-}{i_R^+} = -\frac{v_R^-}{v_1^+} = -\rho_R$$

$$\left.\begin{aligned} i_R^+ &= \frac{v_R^+}{Z_C} \\ i_R^- &= -\frac{v_R^-}{Z_C} \end{aligned}\right\}$$

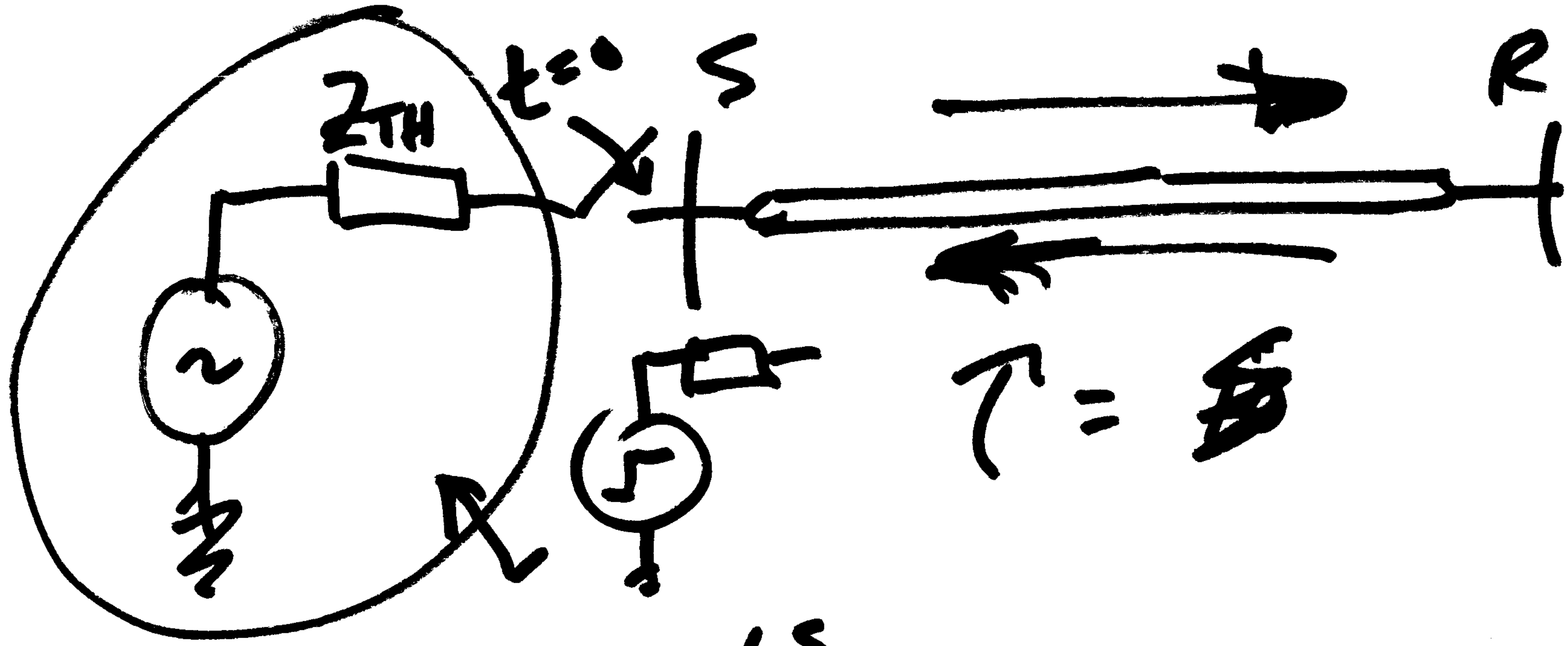


"Bounce Diagrams"

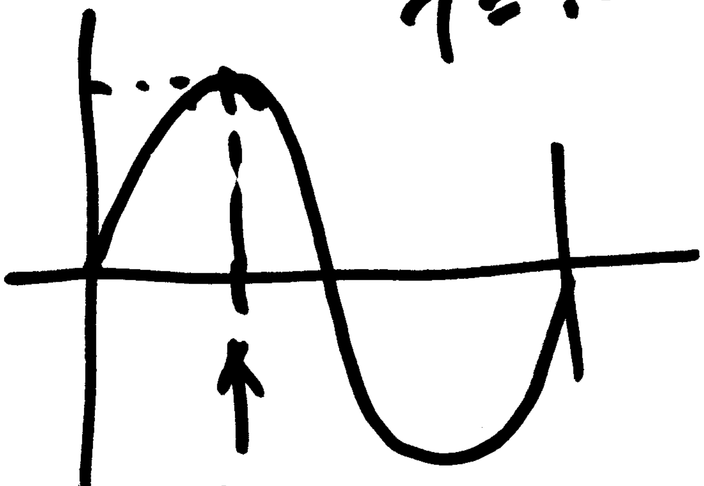
Refer to end of Lecture 20 notes...



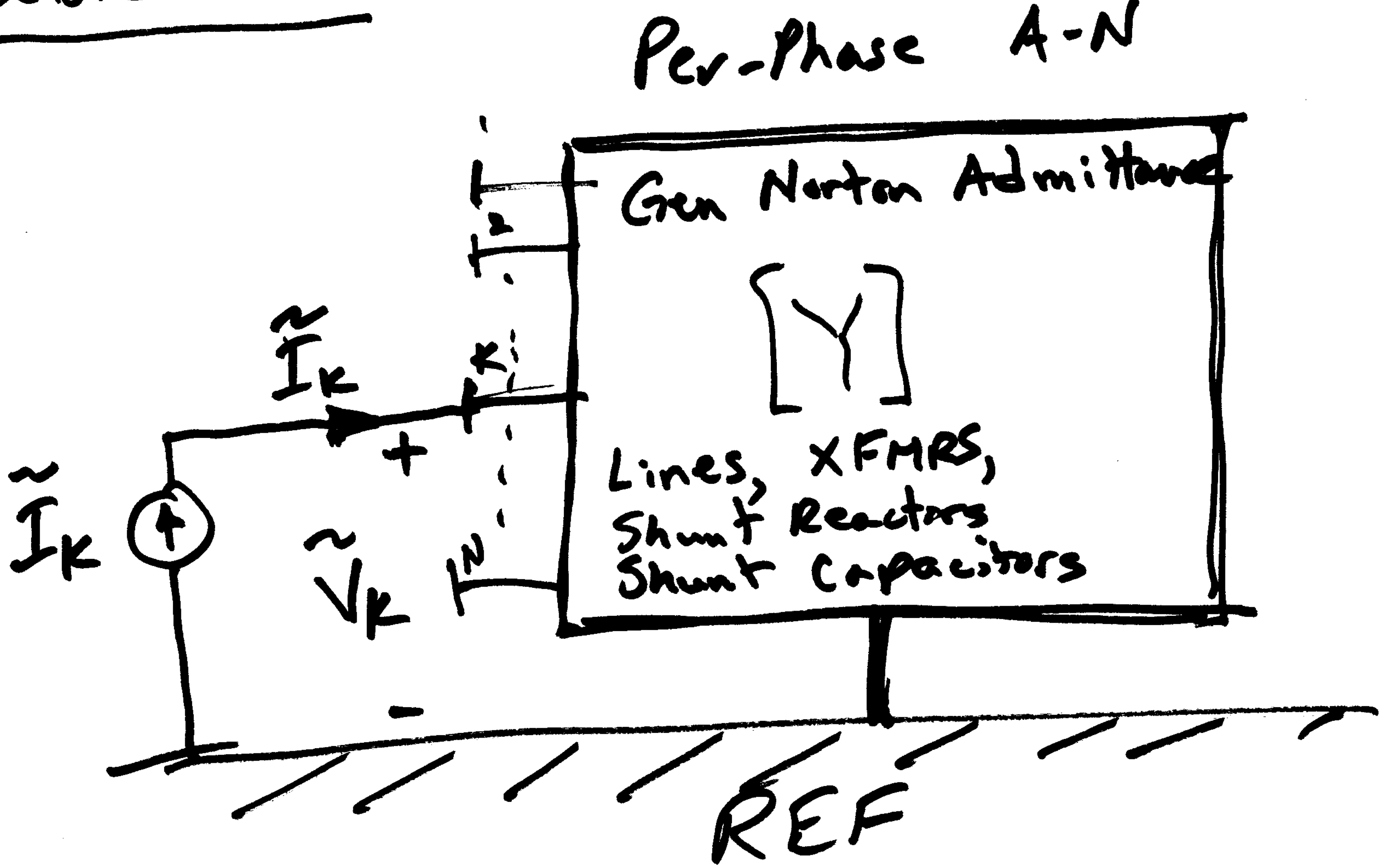
Bewely



$T = .016\,s$

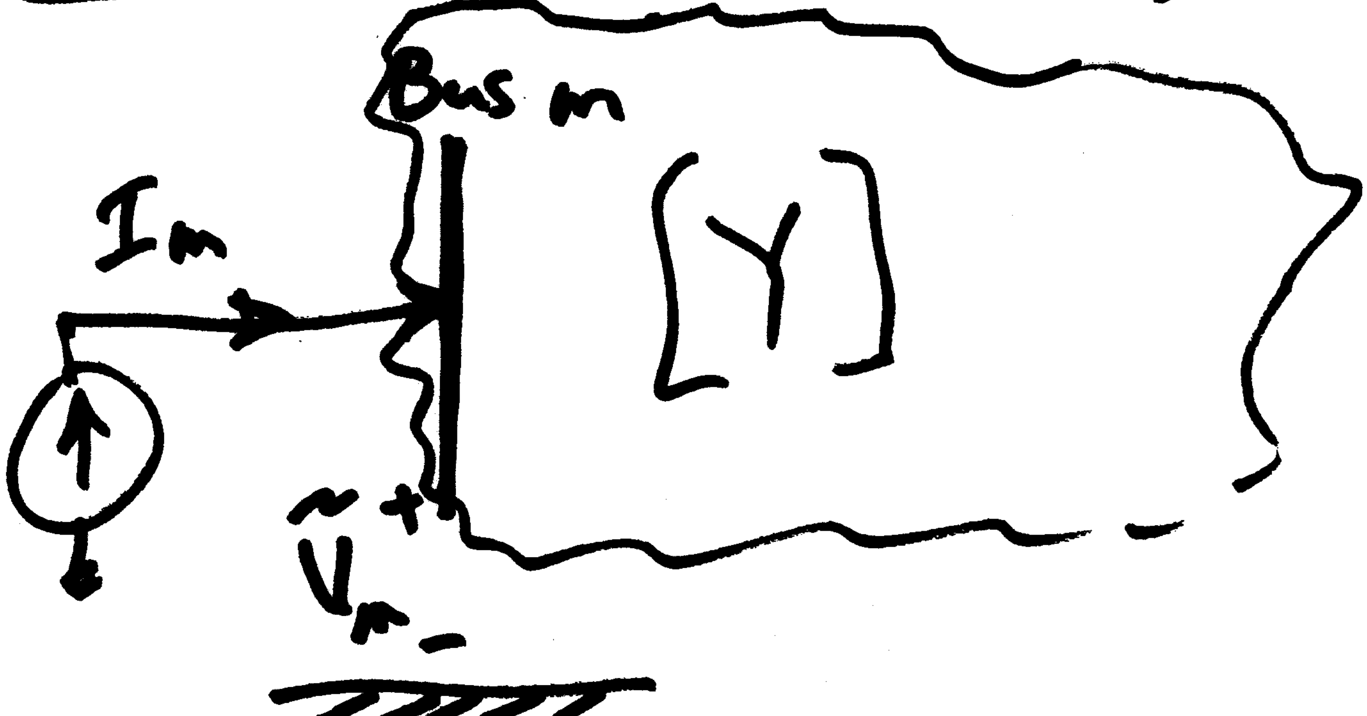


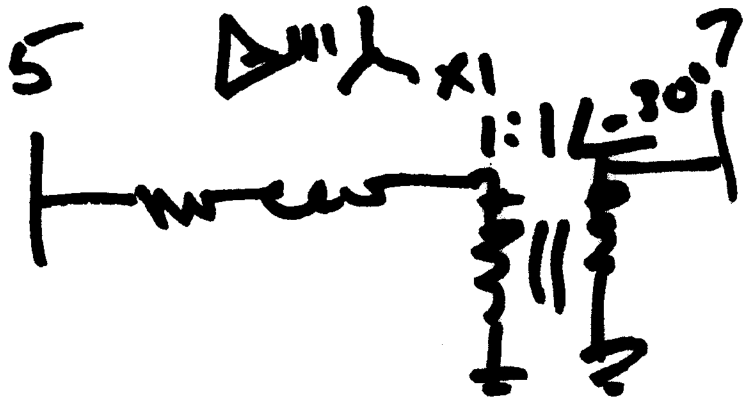
Basic Idea:



$$[Y][V] = [I_{inj}]$$

$$\begin{array}{c} \\ m \\ \\ \end{array} \begin{array}{c} 1 \cdots\cdots m \cdots N \\ \left[\quad Y \quad \right] \end{array} \left[\begin{array}{c} V \\ V_m \\ \\ \end{array} \right] = \left[\begin{array}{c} I_{inj} \\ I_m \\ \\ \end{array} \right] \begin{array}{c} \\ m \\ \\ \end{array}$$

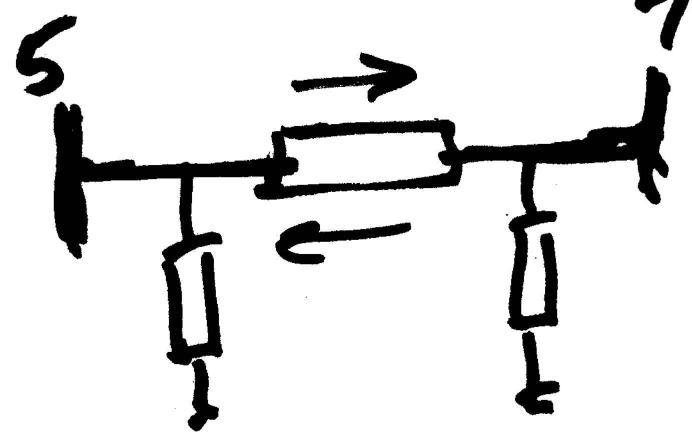




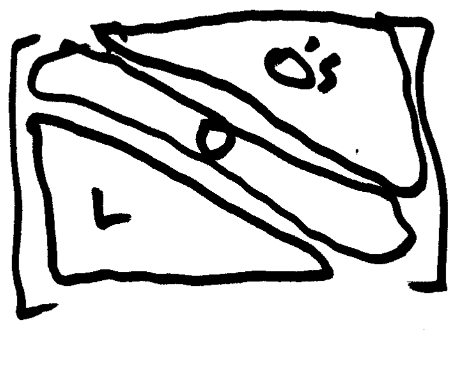
treat as
off-nominal
turns ratio.

$$[Z_B] = [Y_B]^{-1}$$

$\Longrightarrow$



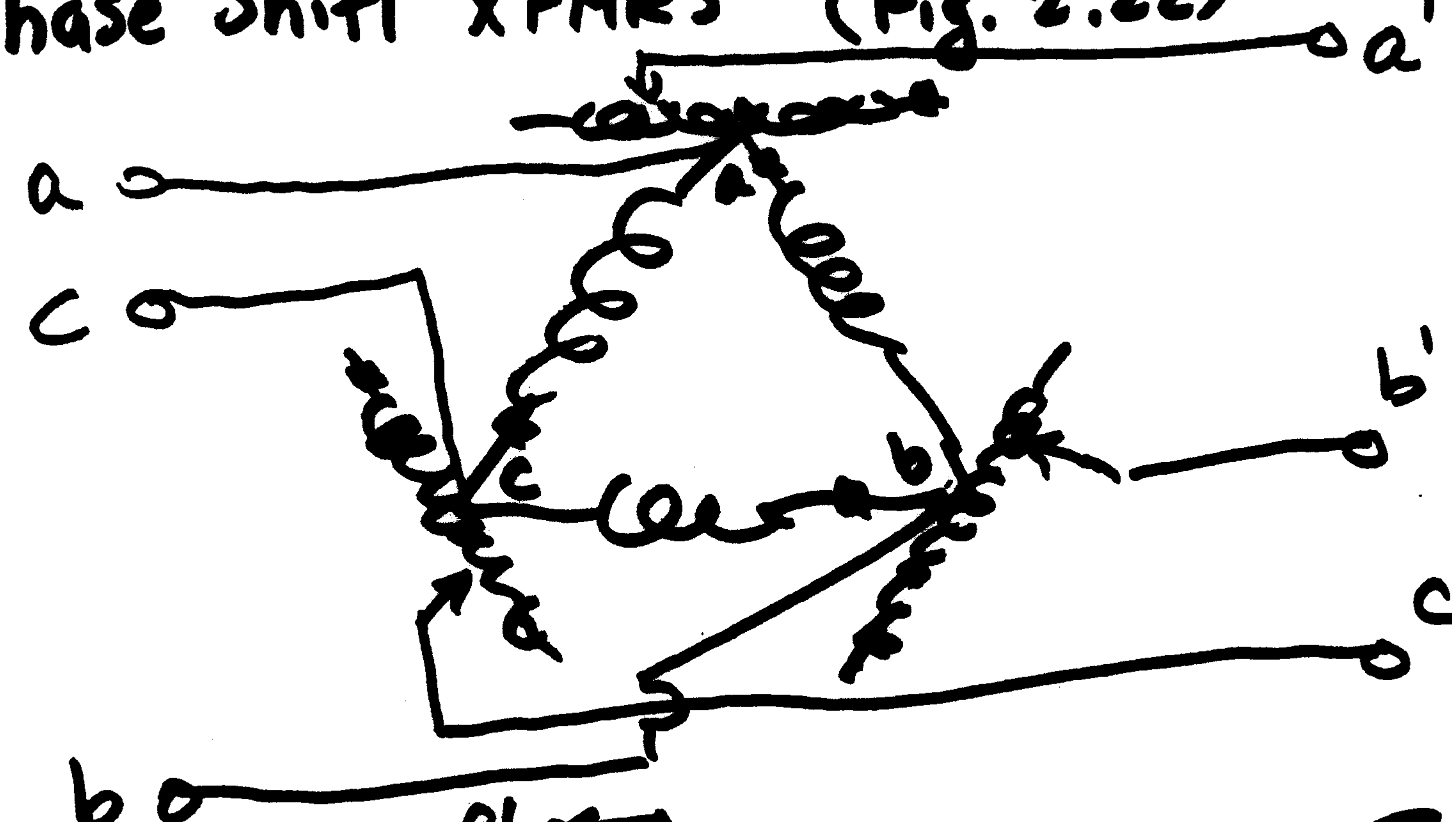
...still only need modify

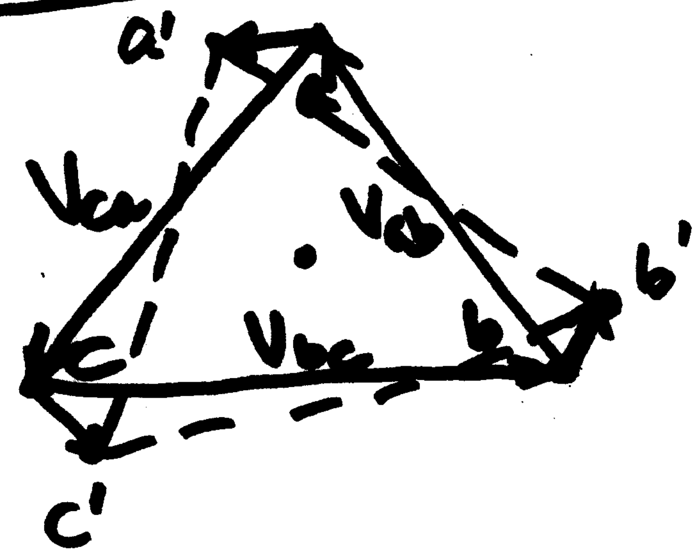


y_{55} y_{57}

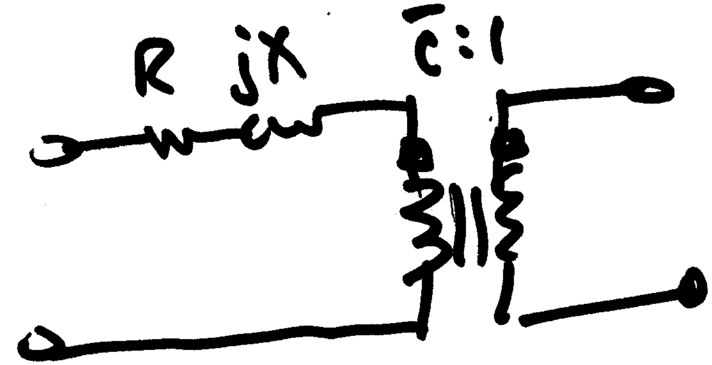
y_{75} y_{77}

Phase Shift XFMRS (Fig. 2.22)

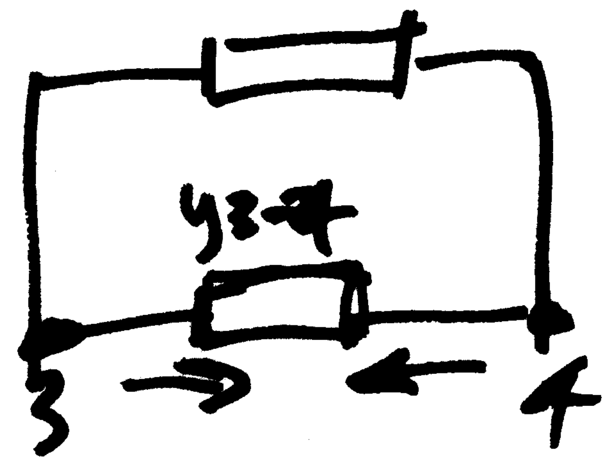




Read § 2.9!



$\rightarrow [Y_{Bus}]$



Building by inspection:

$$
\begin{array}{c|cccc}
 & 1 & 2 & 3 & 4 \\
\hline
1 & & & & \\
2 & & & & \\
3 & & & y_{33} & y_{34} \\
4 & & & y_{43} & y_{44}
\end{array}
$$

$-y_{3-4}$

$-y_{4-3}$

From KCL

$\Sigma I\text{s in} = 0$

$y_{33} = y_{33} + y_{3-4}$

$y_{44} = y_{44} + y_{4-3}$

$y_{34} = y_{34} - y_{3-4}$

$y_{43} = y_{43} - y_{4-3}$

$y_{3-4} = y_{4-3}$
if <u>bilateral</u>.

<u>FACTS</u> -

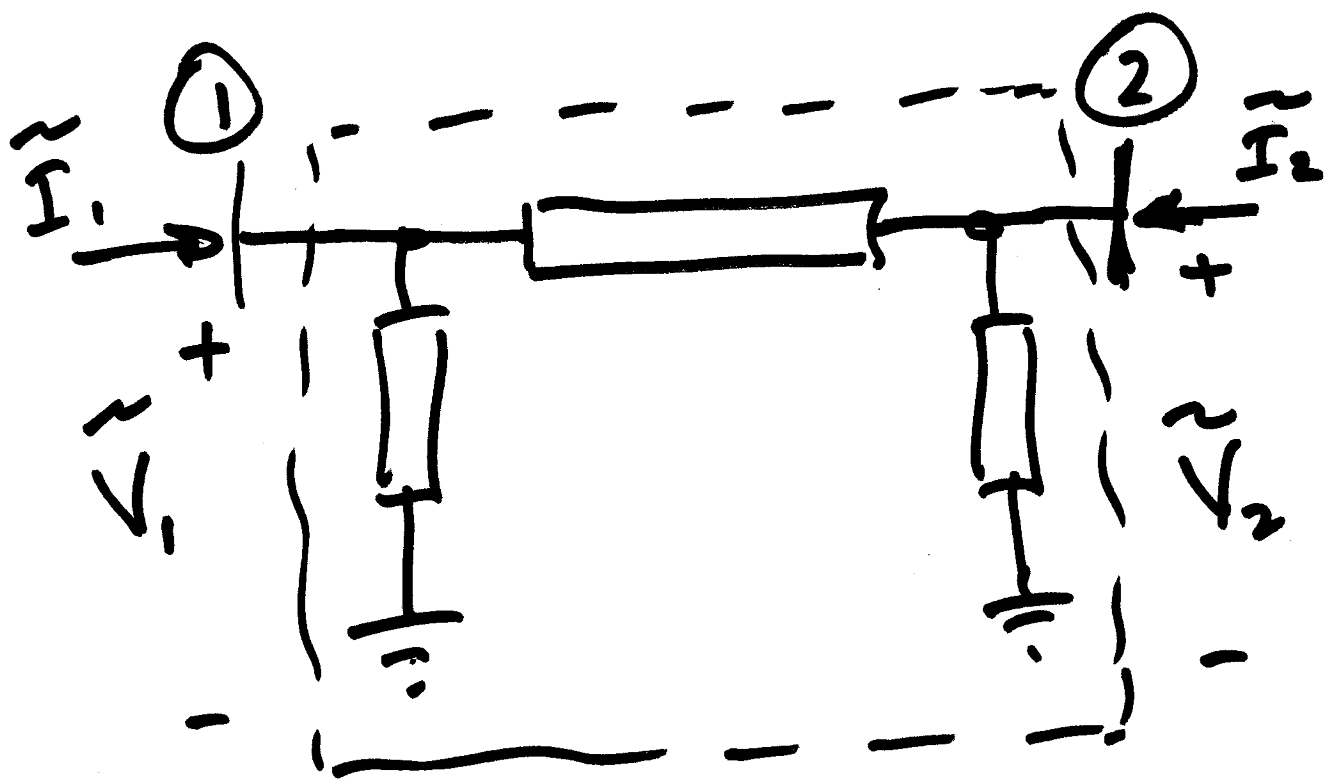
<u>non-bilateral</u>

$y_{m-n} \neq y_{n-m}$

<u>ex:</u>

$\left\{ \begin{array}{l} \underline{\text{UPFC}} - P \,\&\, Q \\ \text{SVC} - \text{Shunt } Q \\ \text{P.S. Transformer} \end{array} \right.$

$$\begin{bmatrix} \bar{y}_{11} & \bar{y}_{12} \\ \bar{y}_{21} & \bar{y}_{22} \end{bmatrix} \begin{bmatrix} \tilde{V}_1 \\ \tilde{V}_2 \end{bmatrix} = \begin{bmatrix} \tilde{I}_1 \\ \tilde{I}_2 \end{bmatrix}$$

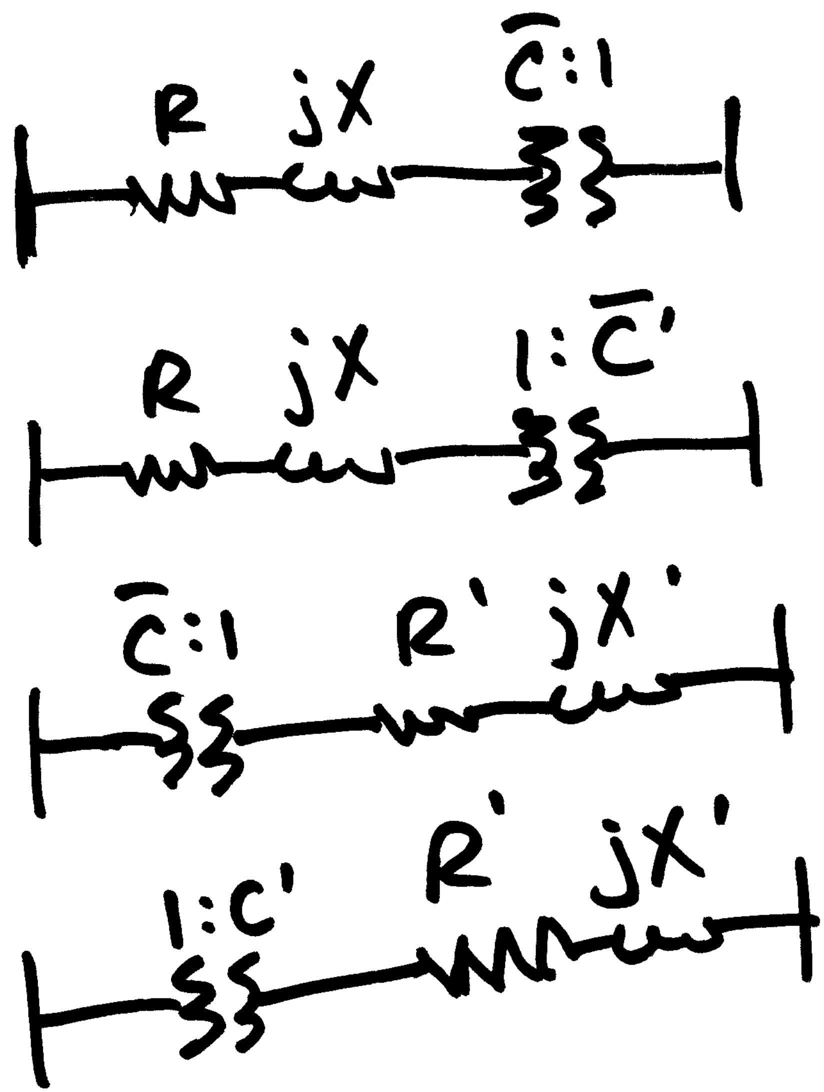


$$\bar{y}_{11} = \left.\frac{\tilde{I}_1}{\tilde{V}_1}\right|_{\tilde{V}_2=0} \qquad \bar{y}_{12} = \left.\frac{\tilde{I}_1}{\tilde{V}_2}\right|_{\tilde{V}_1=0}$$

$$\bar{y}_{21} = \left.\frac{\tilde{I}_2}{\tilde{V}_1}\right|_{\tilde{V}_2=0} \qquad \bar{y}_{22} = \left.\frac{\tilde{I}_2}{\tilde{V}_2}\right|_{\tilde{V}_1=0}$$

OPEN- and SHORT-CIRCUIT TESTS

Four Cases

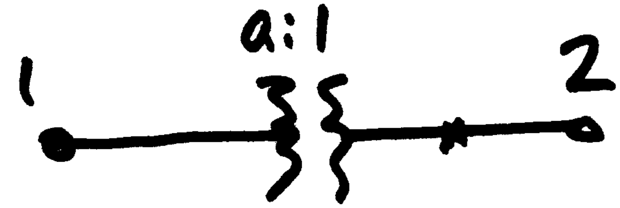


Next:

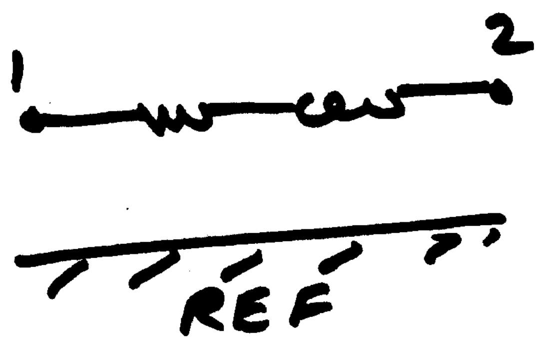
XFMRS $\begin{bmatrix} y_{11} & y_{12} \\ y_{21} & y_{22} \end{bmatrix}$

Basic Approach: Develop π-Equiv and handle just like T-Line.

One-Line:

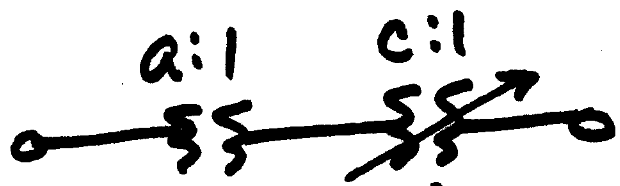


per-unit per-phase



Tap-Changers

- LTC's
- Phase-Shift



NOMINAL TURNS RATIO

± Adjustment in phase angle (PS) or volt mag (LTC)

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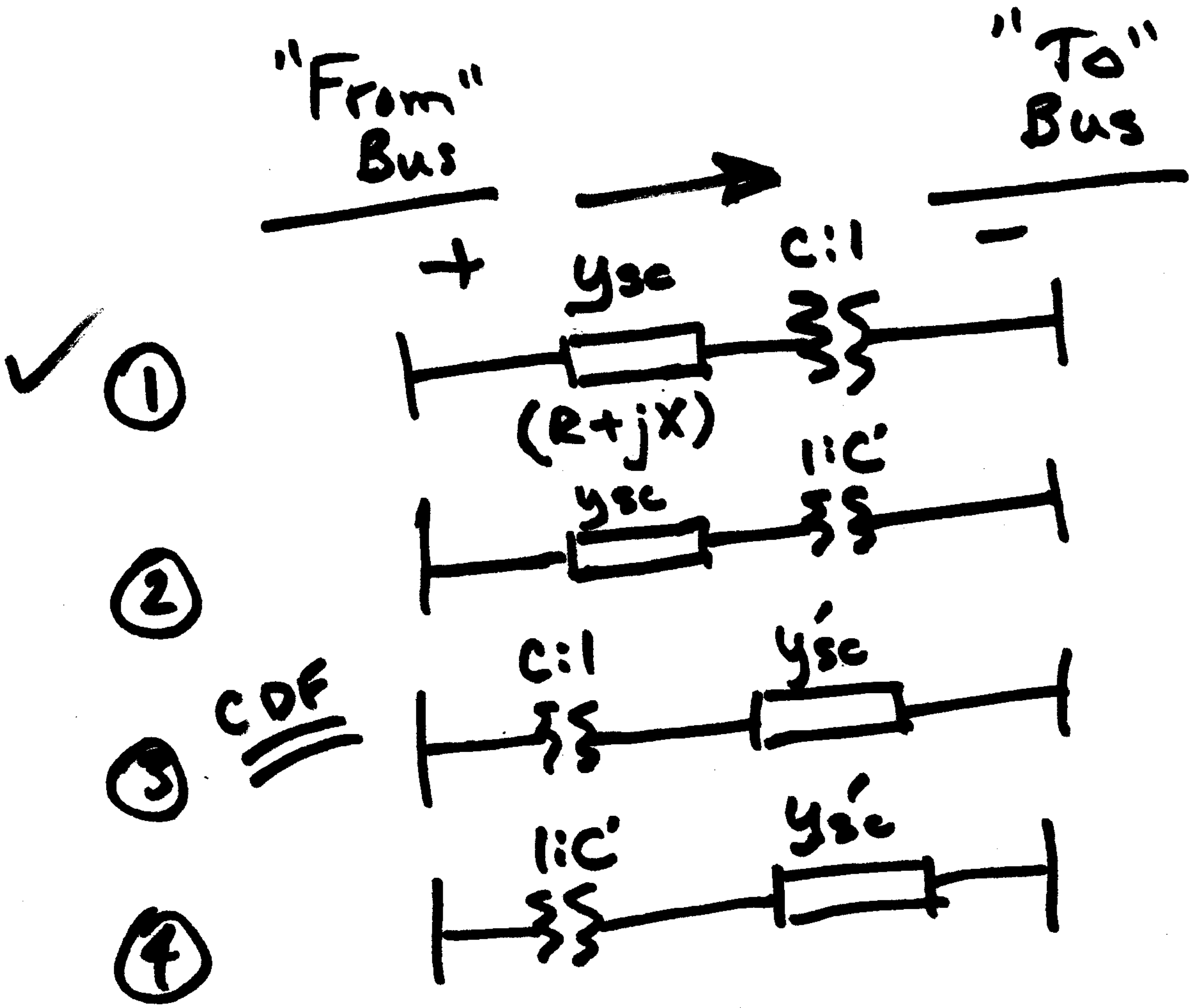
Tap Changing XFMRS – Variations (p.u. representations)



$$y_{sc} = \frac{1}{R + jX}$$

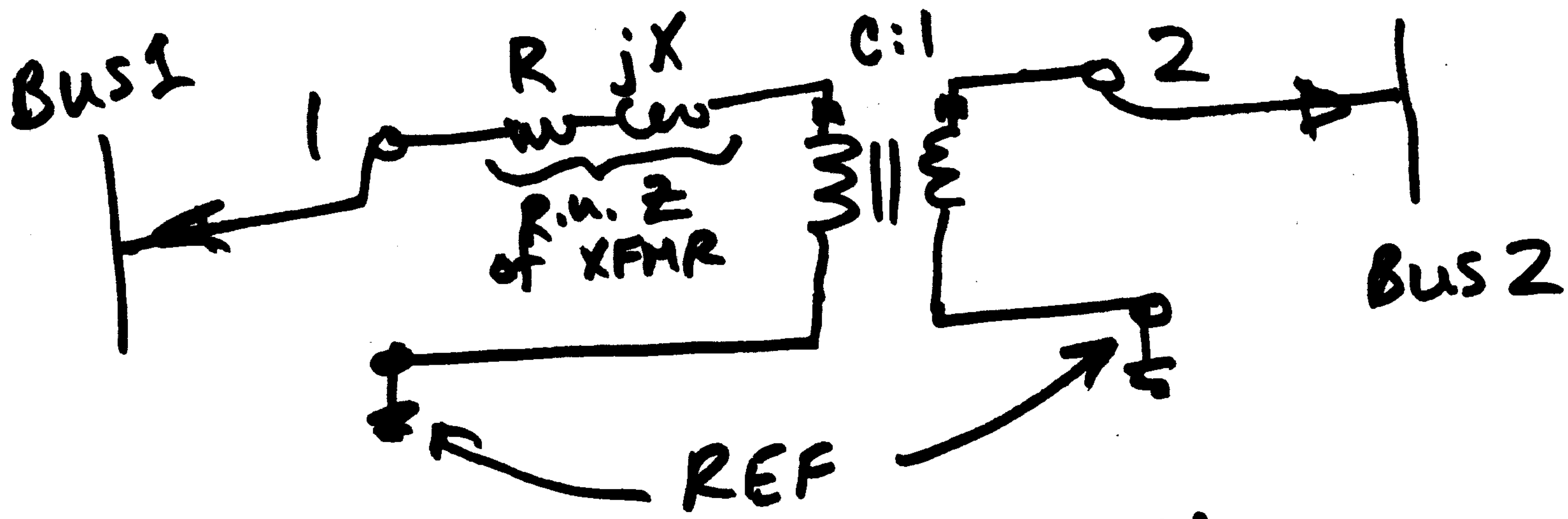
"C" is off-nominal turns ratio. In general C is complex.

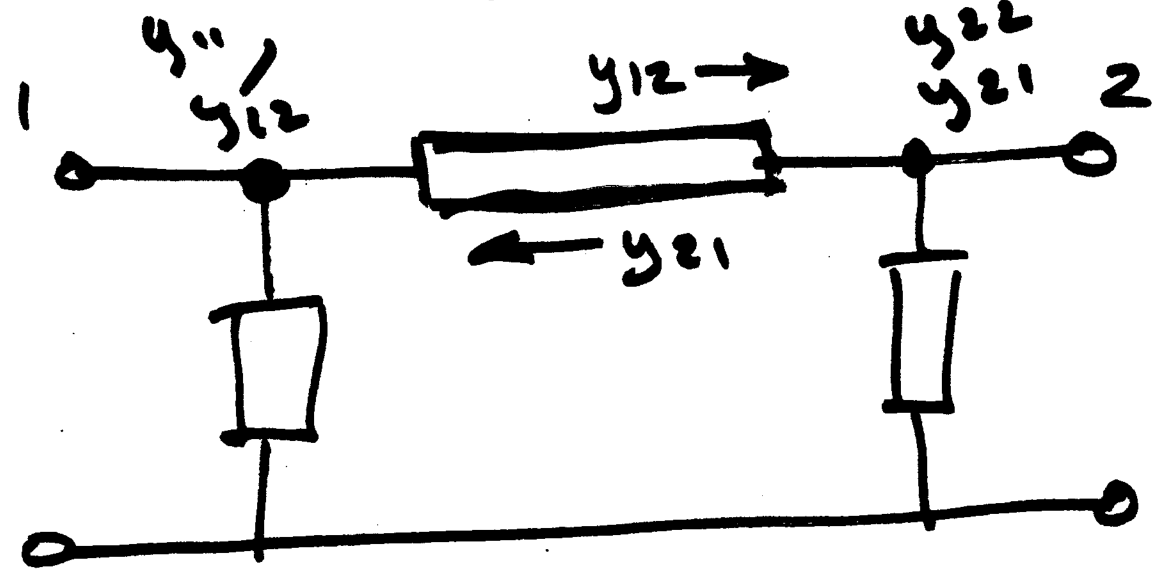
C is real for LTC.

C is complex for PS.

If $|C| \neq 1$ then magnitude change.

If C is complex, Phase Shift.





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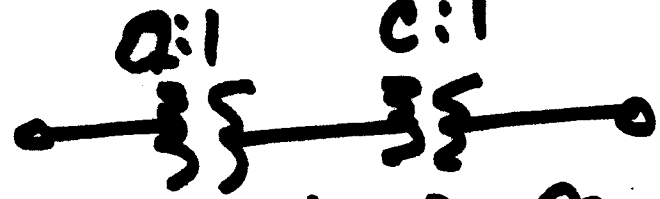
TAP-CHANGERS

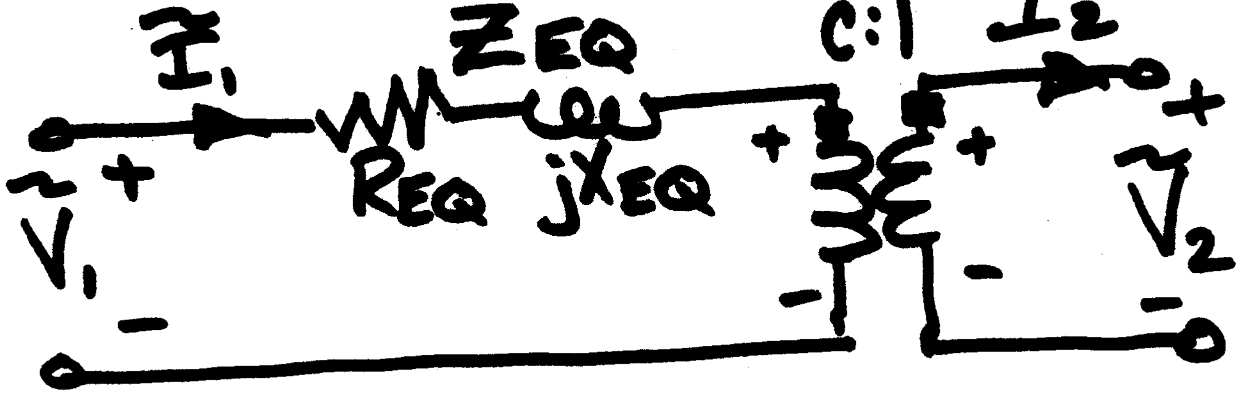
a

On One-Line Diags:

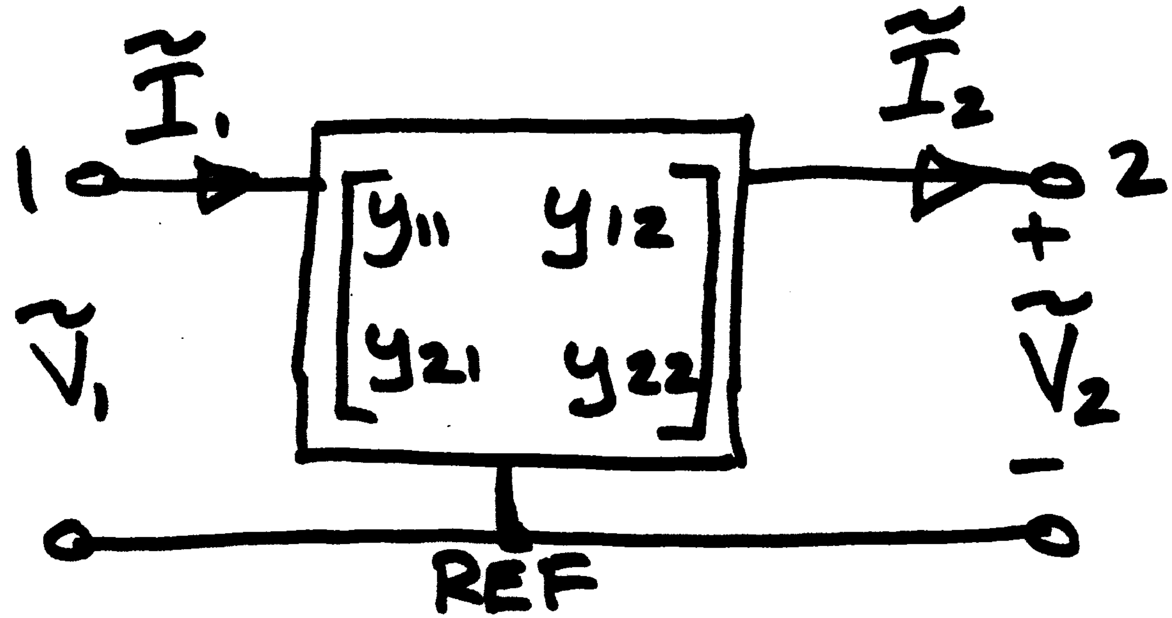
Conceptually:



In per unit, nominal transformation "disappears"



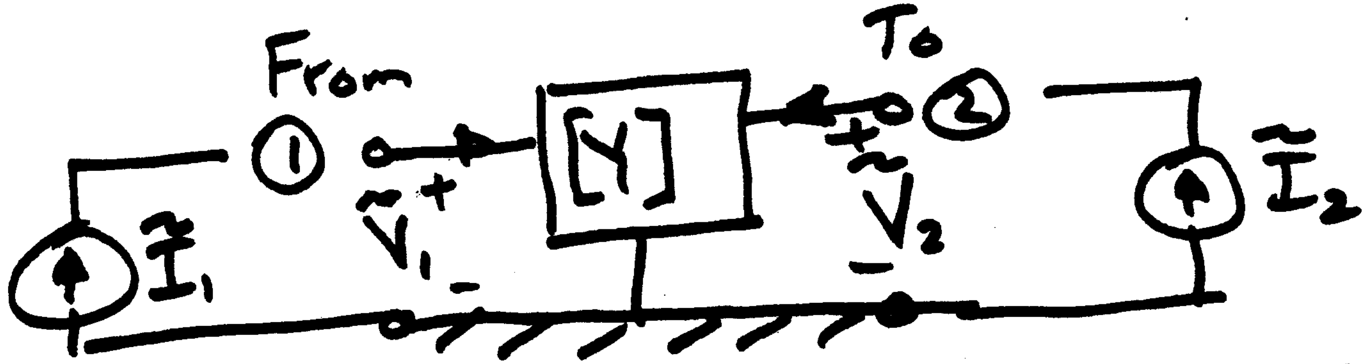
Generically, we can describe this b as a 2-node $[Y]$



where

$$\begin{bmatrix} y_{11} & y_{12} \\ y_{21} & y_{22} \end{bmatrix} \begin{bmatrix} \tilde{V}_1 \\ \tilde{V}_2 \end{bmatrix} = \begin{bmatrix} \tilde{I}_1 \\ -\tilde{I}_2 \end{bmatrix}$$

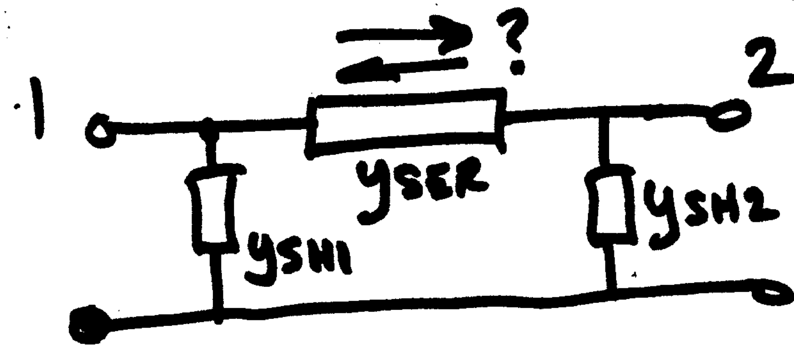
Standard Approach:



$$\begin{bmatrix} y_{11} & y_{12} \\ y_{21} & y_{22} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} I_1 \\ I_2 \end{bmatrix}$$

injected currents!

Goal:



$y_{11} = \overrightarrow{y_{SER}} + y_{SH1}$

$y_{12} = -\overrightarrow{y_{SER}}$

$y_{21} = -\overleftarrow{y_{SER}}$

$y_{22} = \overleftarrow{y_{SER}} + y_{SH2}$

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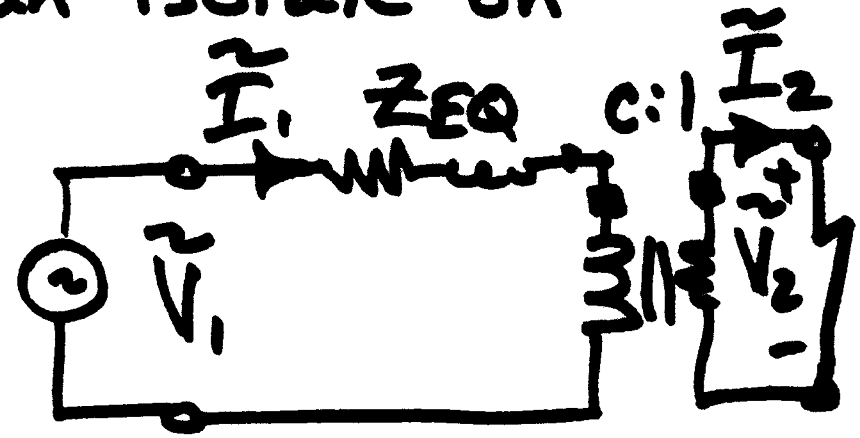
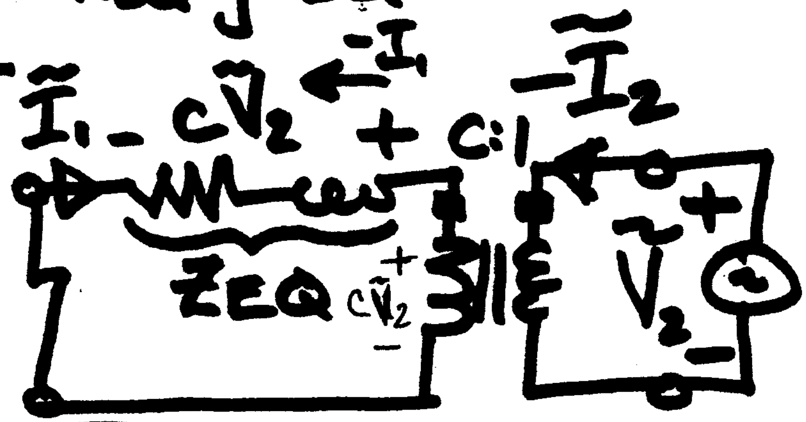
Strategically using shorts [redacted]

[redacted], we can isolate on the values of [Y].



$$y_{11} = \left.\frac{\tilde{I}_1}{\tilde{V}_1}\right|_{\tilde{V}_2=0} = \frac{1}{Z_{EQ}} = Y_{EQ} = \frac{1}{R_{EQ}+jX_{EQ}}$$



$$y_{22} = \left.\frac{-\tilde{I}_2}{\tilde{V}_2}\right|_{\tilde{V}_1=0} = \frac{1}{Z_{EQ}/|c|^2} = |c|^2 Y_{EQ}$$

c

$$\tilde{I}_1 = -\frac{c\tilde{V}_2}{Z_{EQ}}; \quad -\tilde{I}_2 = -\tilde{I}_1 * c^* = -\left[-\frac{c\,\tilde{V}_2}{Z_{EQ}}\right]c^*$$

$$= \frac{|c|^2\,\tilde{V}_2}{Z_{EQ}}$$

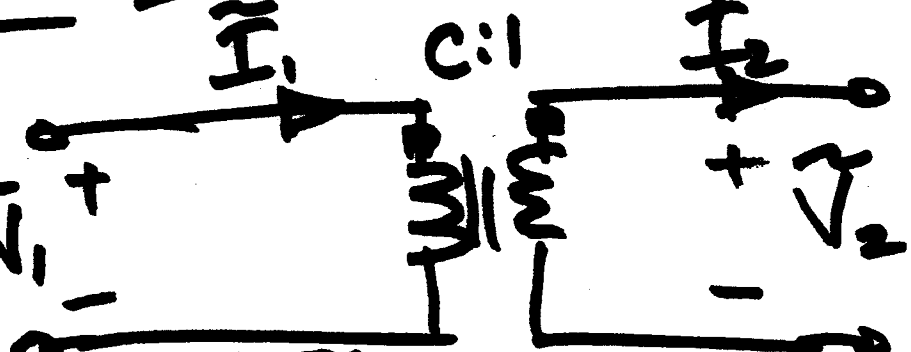
Note: $\frac{I_2}{I_1} = c^*$

$$y_{12} = \left.\frac{\tilde{I}_1}{\tilde{V}_2}\right|_{\tilde{V}_1=0} = \frac{-c\tilde{V}_2/Z_{EQ}}{\tilde{V}_2} = -cY_{EQ}$$

d

$$y_{21} = \left.\frac{-\tilde{I}_2}{\tilde{V}_1}\right|_{\tilde{V}_2=0} = \frac{-c^*\tilde{I}_1}{\tilde{V}_1} = -c^*Y_{EQ}$$

Note: Ideal XFMR, by definition, has "c" is voltage ratio.



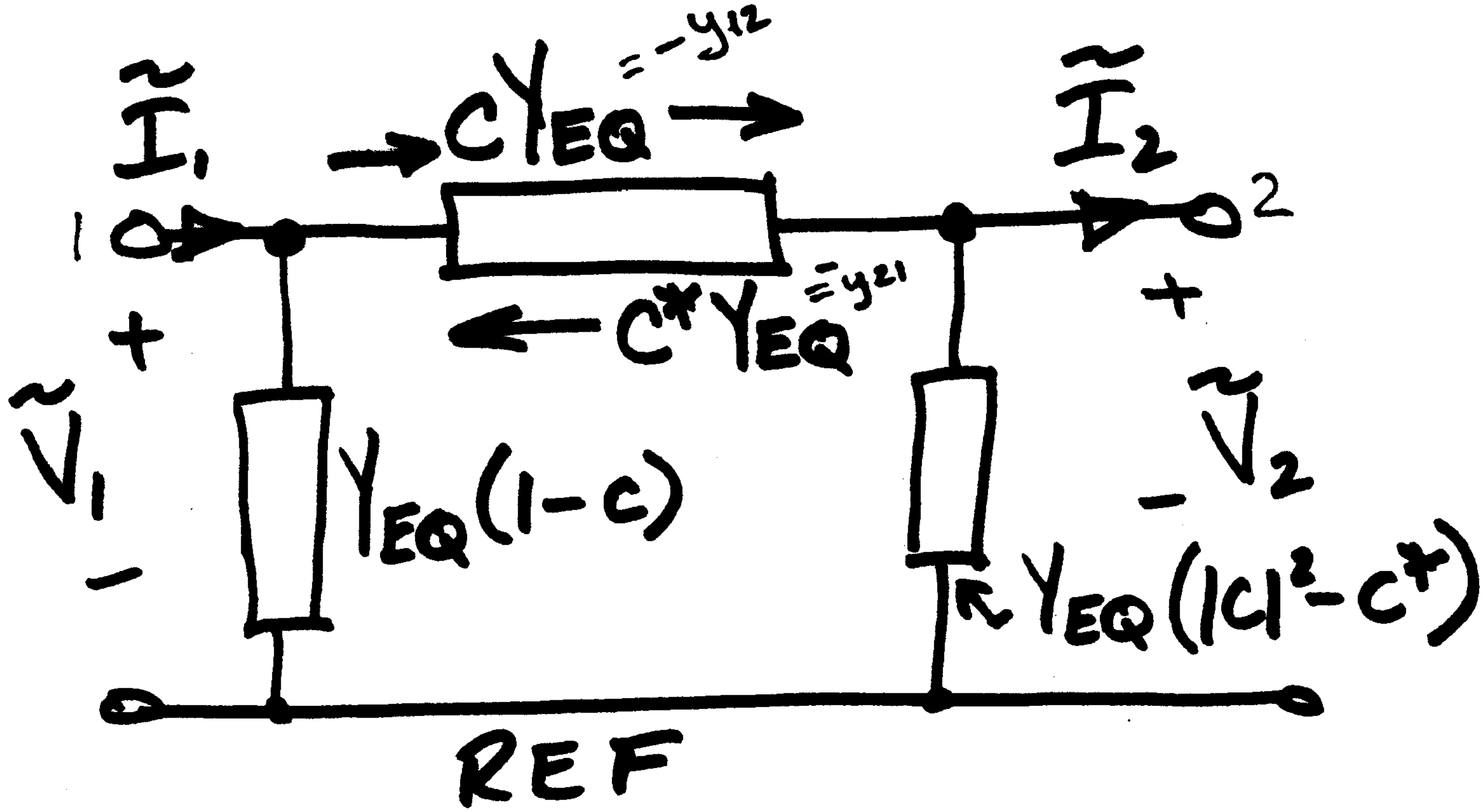
$$S_{IN} = \tilde{V}_1\tilde{I}_1^* = \tilde{V}_2\tilde{I}_2^* = S_{OUT}$$

$$c = \frac{\tilde{V}_1}{\tilde{V}_2} \Rightarrow$$

$$c = \frac{\tilde{I}_2^*}{\tilde{I}_1^*} \Rightarrow \frac{\tilde{I}_2}{\tilde{I}_1} = c^*$$

e)

If we "reverse engineer" our $[Y]$ into an equivalent 2-bus network, then



Observations:

- LTC (TCUL) has a c that is Real.

  $\therefore$ Transfer Admittances

  $$c Y_{EQ} = c^* Y_{EQ}$$

  $\Rightarrow$ Bilateral. $(y_{12} = y_{21})$

- Phase-Shifter (PS) has complex c.

  $\therefore$ Transfer admittances

  $$c Y_{EQ} \neq c^* Y_{EQ}$$

  $$y_{12} \neq y_{21}$$

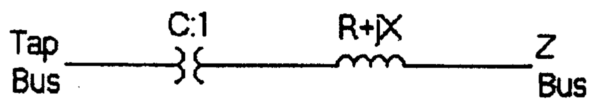
  Not Bilateral. ($[Y]$ not symm. about main diag.)

Transformer LTC's in the CDF File Format

Tap and impedance location specified in first two entries in branch data section.

- **entry 1 is bus non-unity tap is connected to**
- **entry 2 is bus device impedance is connected to**

"From"



Complex turns ratio due to phase shifting transformer split to two entries

- **entry 15 is transformer final turns ratio**
- **entry 16 is transformer (phase shifter) final angle**

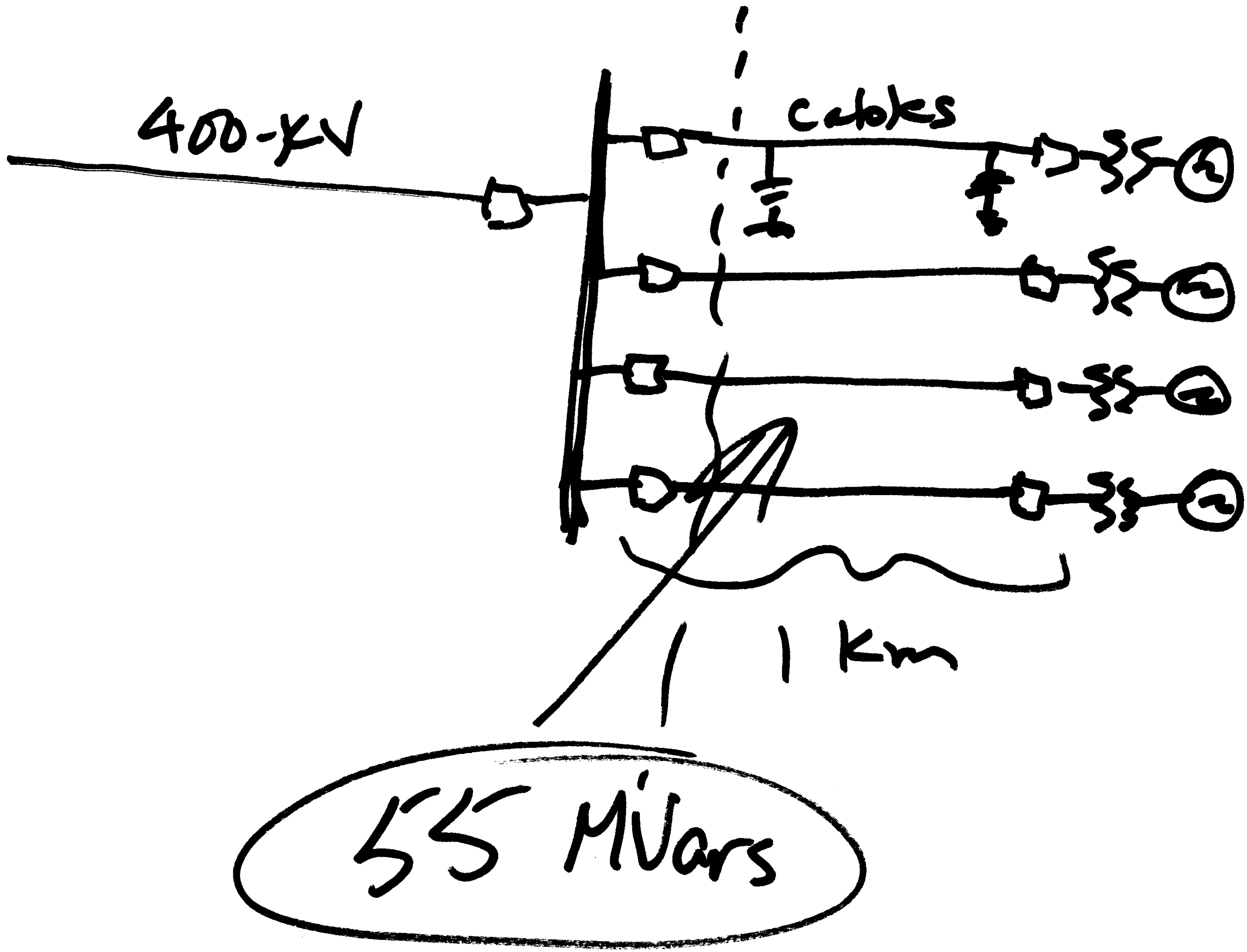
Examples:

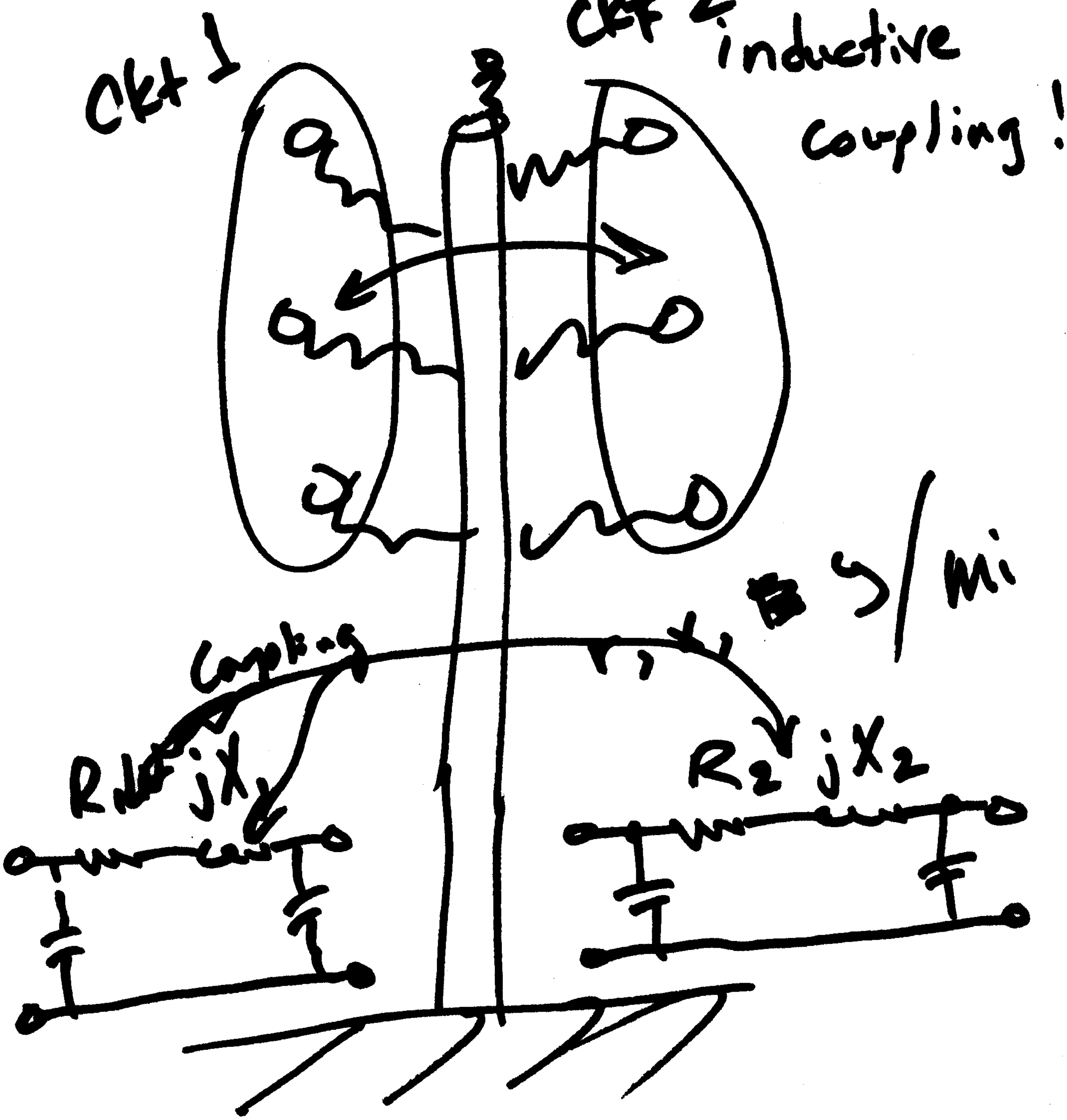
|C|

Entry:	1	2	15	16
	4	7	.975	0

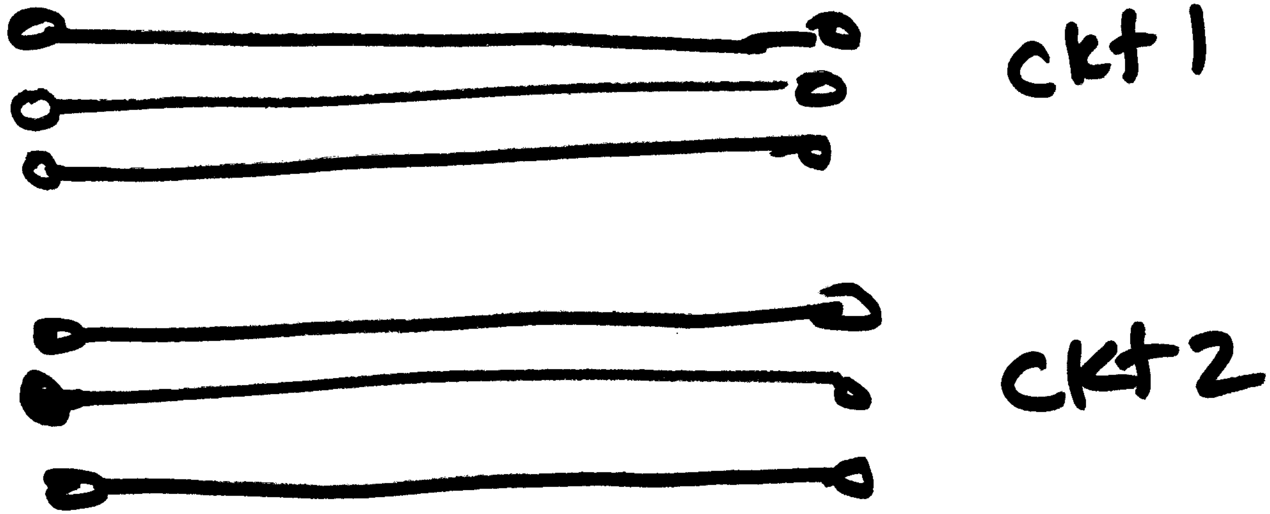
Field no.

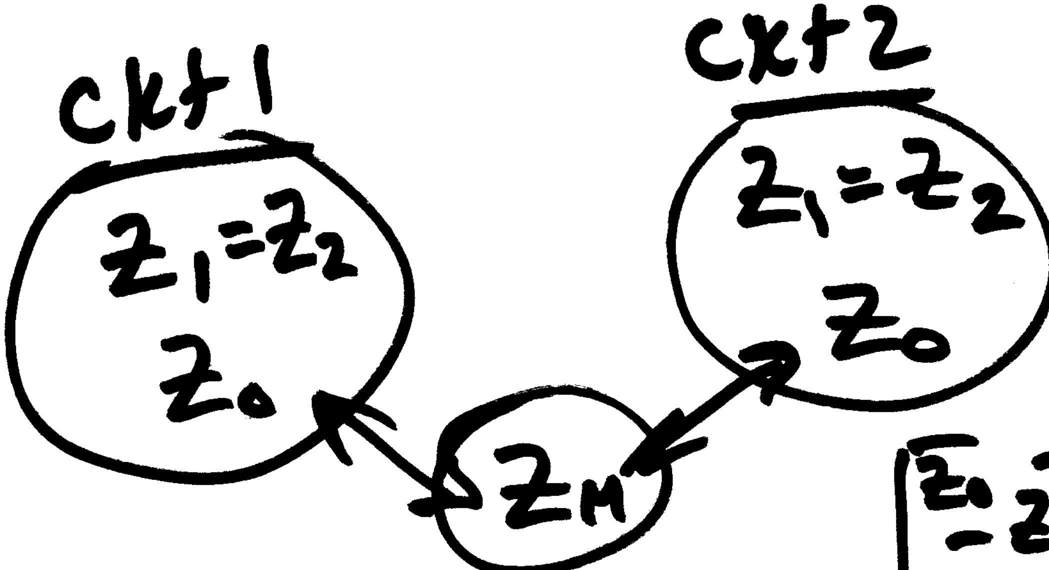
Entry:	1	2	15	16
	9	3	1	30


400-kV
cables
1 km
55 MVars



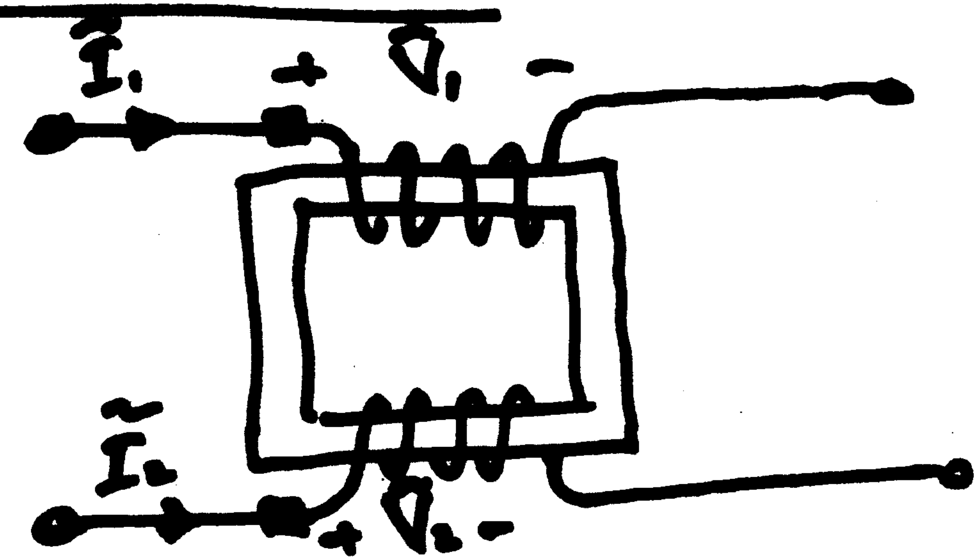
Ckt 1
Ckt 2
inductive coupling!
coupling
r, x, y/mi
R_1 jX_1
R_2 jX_2

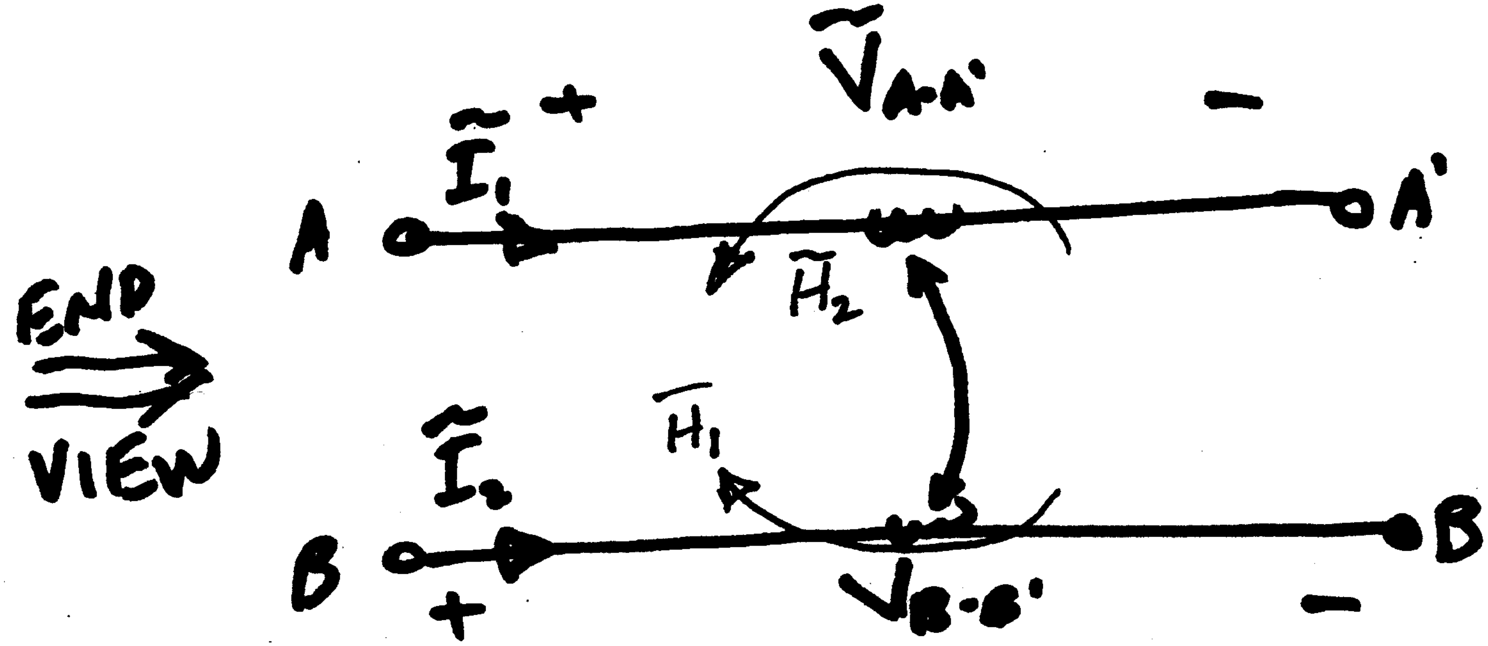




$$Z_S = \left[\begin{array}{ccc|ccc} Z_0 & - & - & Z_M & - & - \\ - & Z_1 & - & - & - & - \\ - & - & Z_2 & - & - & - \\ \hline Z_M & - & - & Z_0 & - & - \\ - & - & - & - & Z_1 & - \\ - & - & - & - & - & Z_2 \end{array}\right]$$

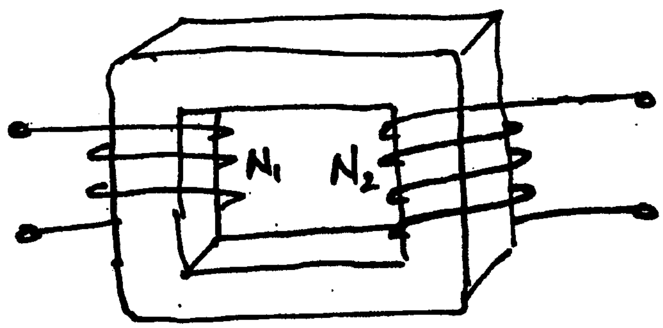
Mutual Inductance



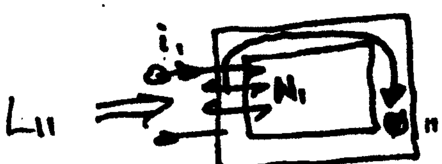


MUTUAL INDUCTANCE

– see also handout on Basic Magnetic Circuits

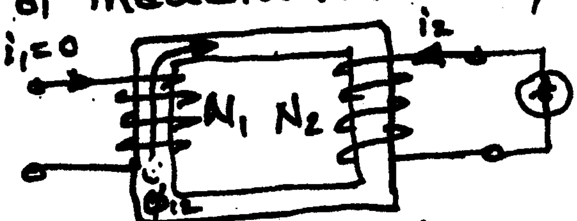


– Fundametal definition of inductance: $L = \frac{\lambda}{i} = \frac{N\phi}{i}$



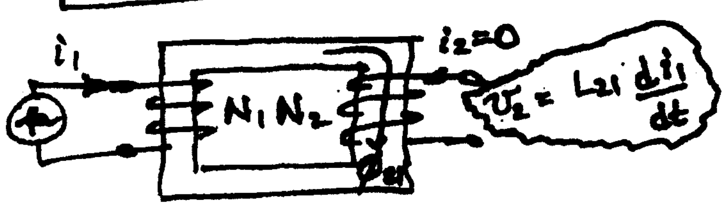
Self-Inductance

$$\boxed{L_{11} = \frac{N_1 \phi_{11}}{i_1} = \frac{\lambda_{11}}{i_1}} = \frac{N_1^2}{\mathcal{R}}$$



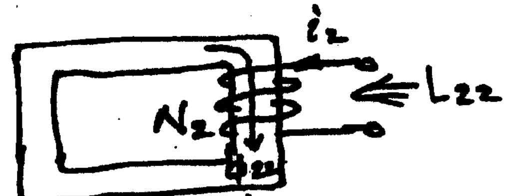
Mutual Inductance

$$\boxed{L_{12} = \frac{N_1 \phi_{12}}{i_2} = \frac{\lambda_{12}}{i_2} = \frac{N_1 N_2}{\mathcal{R}}}$$



$$\boxed{L_{21} = \frac{N_2 \phi_{21}}{i_1} = \frac{\lambda_{21}}{i_1} = \frac{N_2 N_1}{\mathcal{R}}}$$

Mutual Inductance

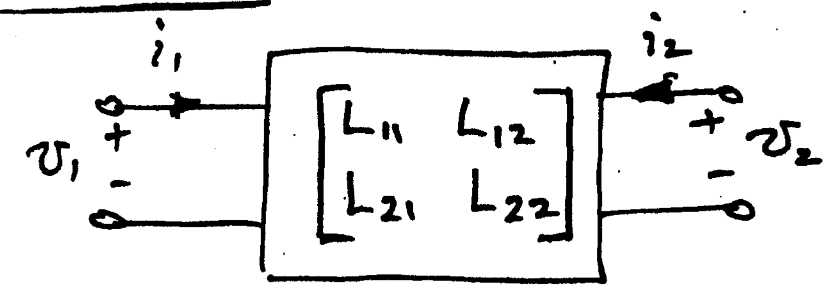


Self Inductance

$$\boxed{L_{22} = \frac{N_2 \phi_{22}}{i_2} = \frac{\lambda_{22}}{i_2} = \frac{N_2^2}{\mathcal{R}}}$$

How to Use the Concept of Mutual Inductance

Two-Port Device:



Note: Reference direction of currents is into terminals at (+) side of voltage.

In time domain:

$$\begin{bmatrix} v_1 \\ v_2 \end{bmatrix} = \begin{bmatrix} L_{11} & L_{12} \\ L_{21} & L_{22} \end{bmatrix} \begin{bmatrix} \frac{di_1}{dt} \\ \frac{di_2}{dt} \end{bmatrix}$$

In phasor domain:

$$\left.\begin{bmatrix} \tilde{V}_1 \\ \tilde{V}_2 \end{bmatrix} = \underbrace{\begin{bmatrix} j\omega L_{11} & j\omega L_{12} \\ j\omega L_{21} & j\omega L_{22} \end{bmatrix}}_{[Z]} \begin{bmatrix} \tilde{I}_1 \\ \tilde{I}_2 \end{bmatrix} \right\}$$

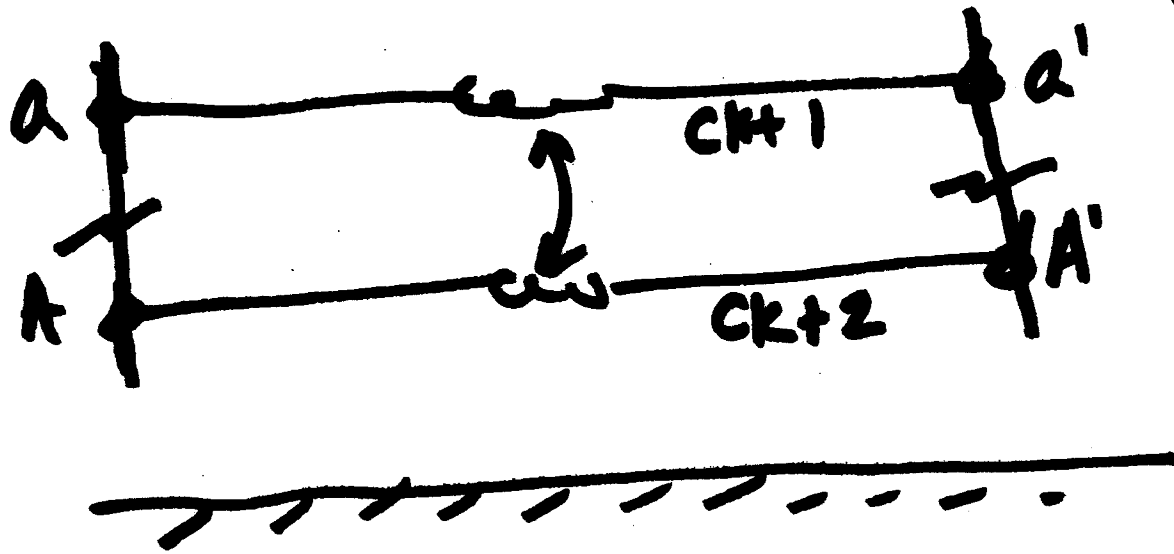
Also of note:

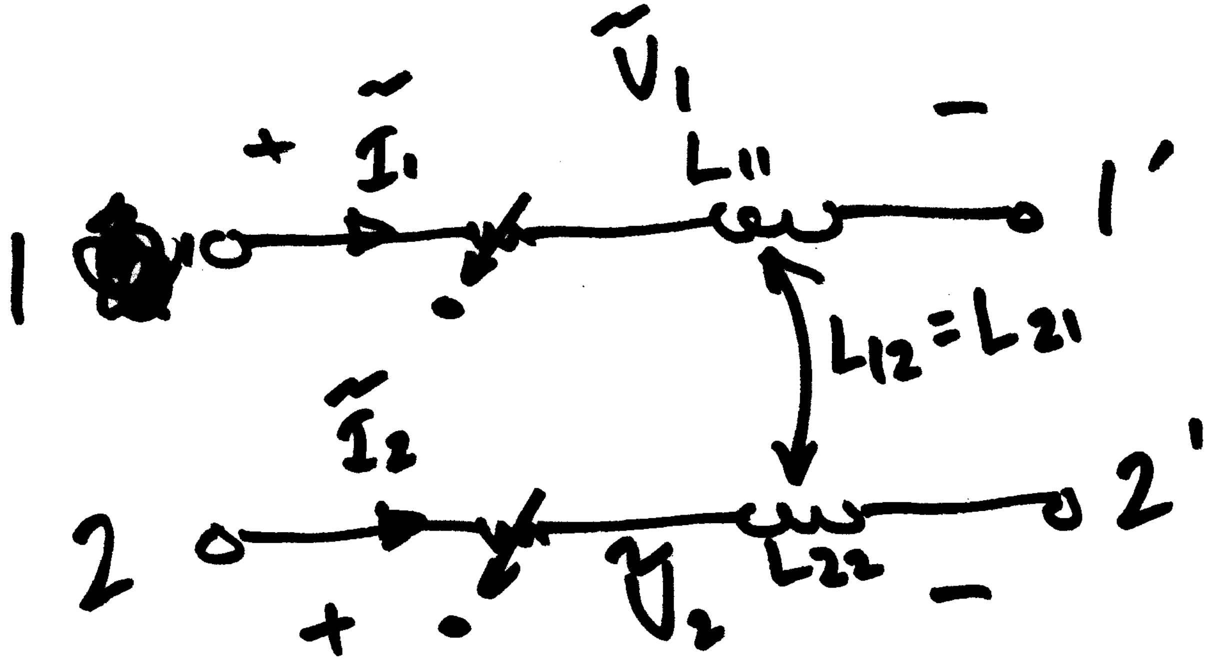
In some texts, since L_{12} and L_{21} are mutal inductances, they are called M_{12} and M_{21}. Same thing.

$$[Z]^{-1} = [Y]$$

$$\begin{bmatrix} y_{11} & y_{12} \\ y_{21} & y_{22} \end{bmatrix} \begin{bmatrix} \tilde{V}_1 \\ \tilde{V}_2 \end{bmatrix} = \begin{bmatrix} \tilde{I}_1 \\ \tilde{I}_2 \end{bmatrix}$$

§ 7.2 of text.





§7.2 Text

Assume high X/R $(R \to 0)$

$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} Z \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} \Rightarrow \begin{bmatrix} Y \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} I_1 \\ I_2 \end{bmatrix}$$

pre-multiply both sides by $[Z]^{-1}$