EE 5220 - Lecture 16 Monday Feb 12, 2024

Topics for Today:

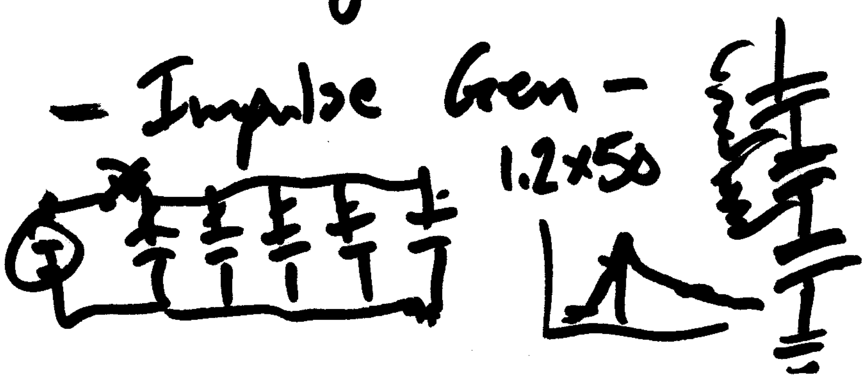
- Course Info:
  - Web page: https://pages.mtu.edu/~bamork/ee5220/index.htm
  - Software - Matlab. ATP/EMTP [License - www.emtp.org]
  - ATP tutorials posted on our course web page
  - EE5220-L@mtu.edu (participation = min of half letter grade)

- HW#5 will be posted. Partnered exercise. Due latest Tues Feb 20th 9am.
  - Section 12.4 - detailed derivation for capacitor
  - Prob 5.3 - first do ATP simulation, then Hand Calculations
  - Prob 5.6
- HW#6 - due ~Tues Feb 20th 9am.
- Term Project - proposed topic(s) by end of this week, via short e-mail.
- Transmission Lines
  - Recap of T-Line equations
  - Meaning and application of T-Line equations
    - Steady-state phasor calculations, ABCD parameters.
    - Traveling wave calculations
    - Propagation constant, Zc, etc.
- Use of ATPDraw's Line Constants to obtain parameters, build line models.

- Partners names (2).
- Topic 1
  - Brief overview: Problem, <u>Do</u>, Results
- Topic 2

T.O.C. – EE5220

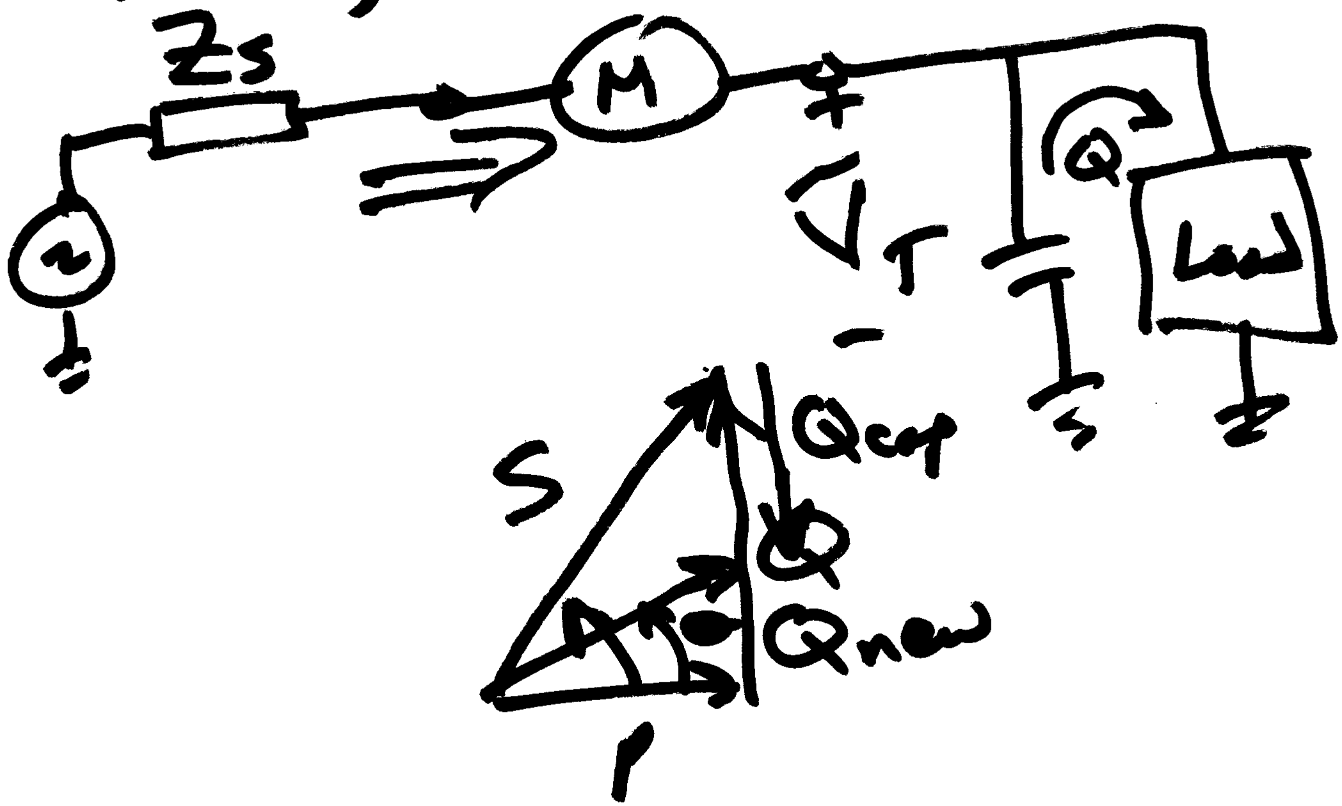
-
- Gens
  - Synch.
- Impulse Gen –



- <u>Time domain</u>
- Transients
- Harmonics – P.Q.
- Protection
- Insulation Coord.
- Stat. Switching.

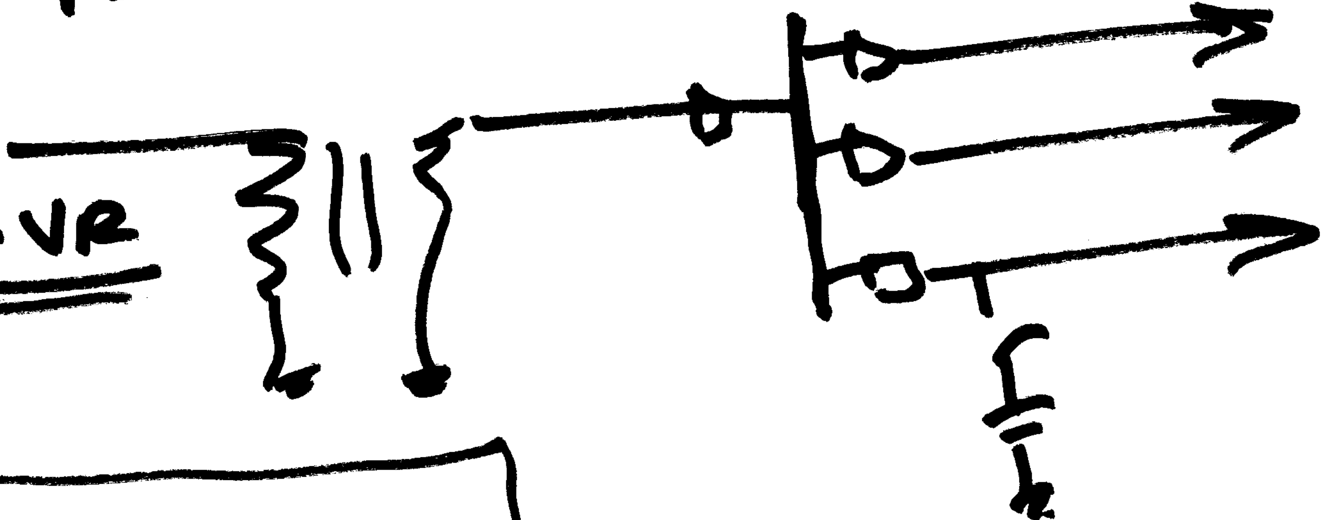
Cap Application

- LV, on customer side of meter
  $\Rightarrow$ Penalty for Low P.F. $\Rightarrow$ P.F. Correction



Compensation, VR.

Dist: VR

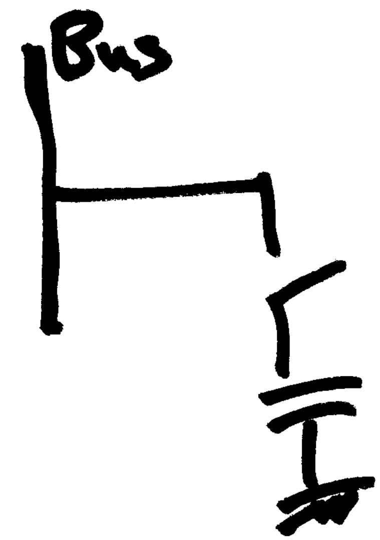


Trans. Tie

XFMR

L.V. Caps are cheaper to mfr.

Compensation



Shunt

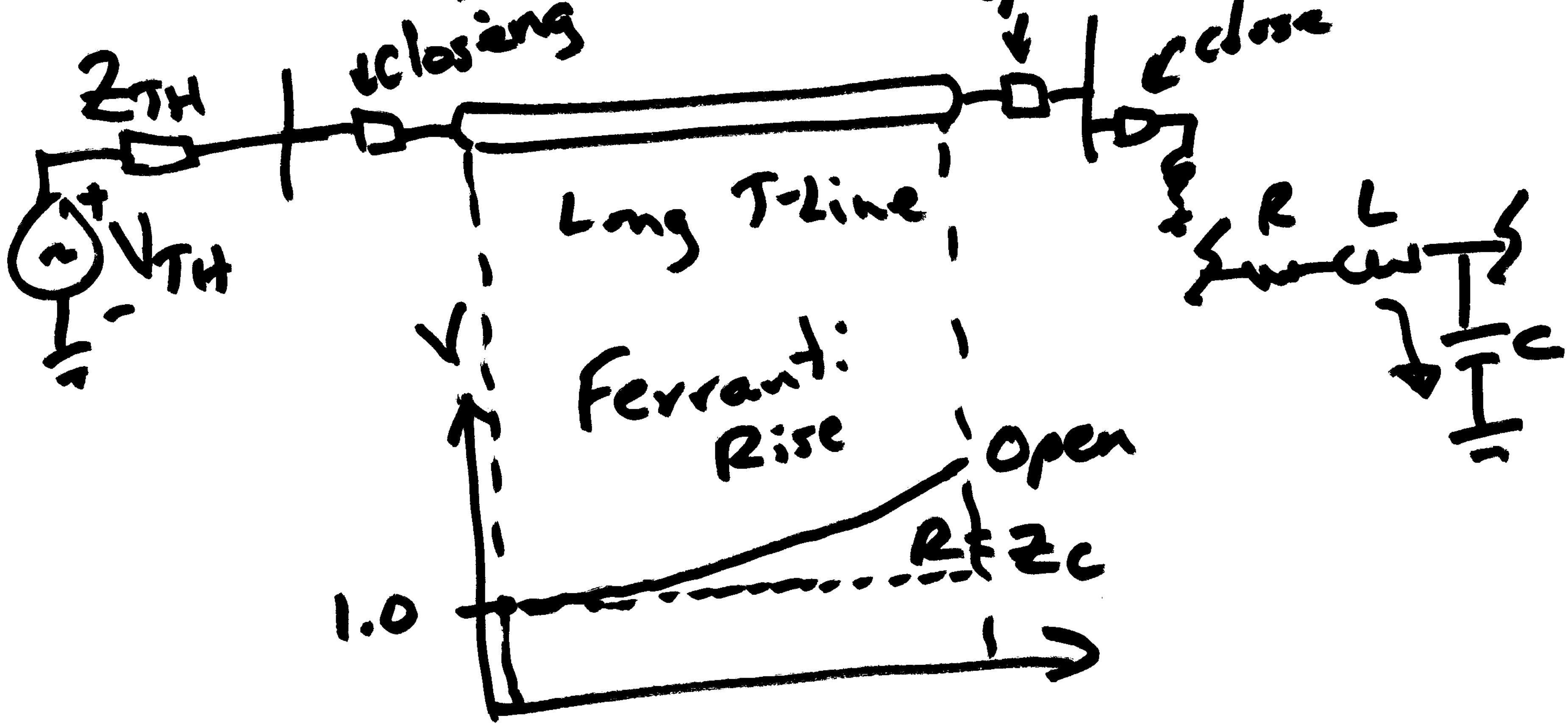
- Voltage Support
- Power Transfer

$$P_{1-2} = \frac{V_1 V_2}{X_{12}} \sin(\delta_1 - \delta_2)$$

21% increase
(.95 → 1.05 p.u. V)

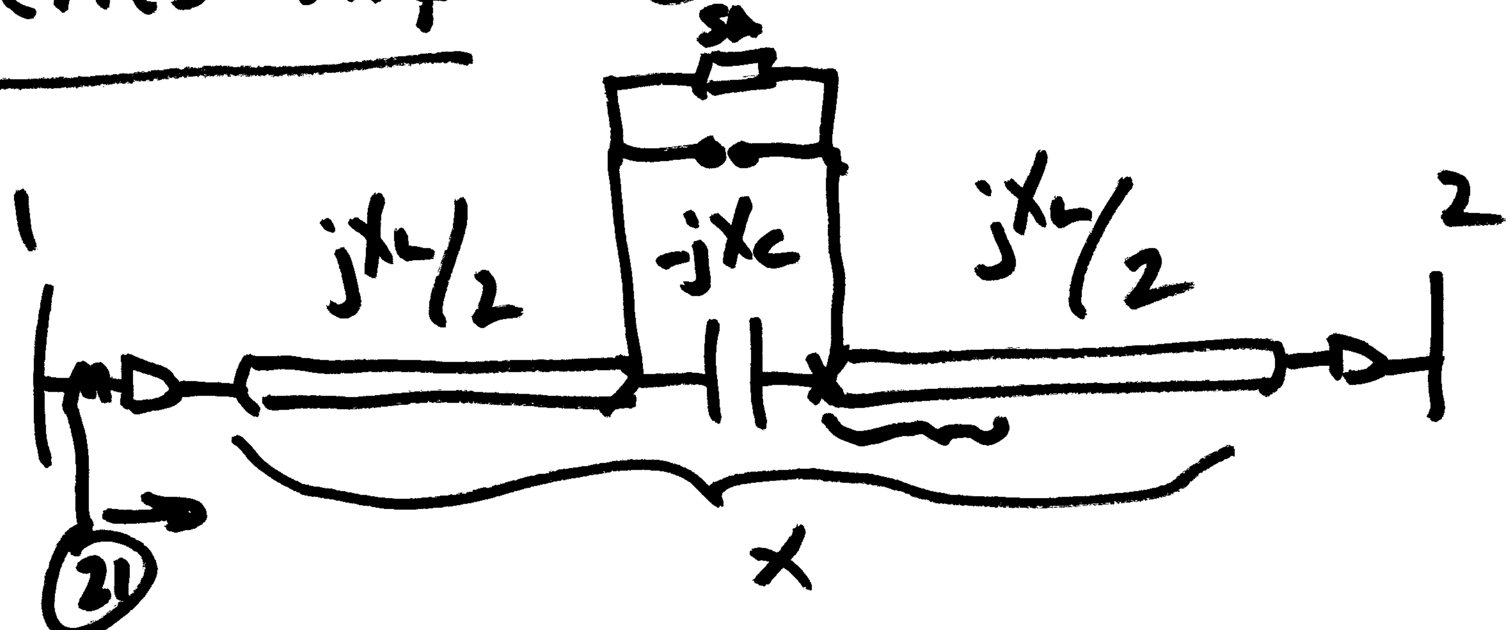
- Stability

Shunt Comp: Reactors



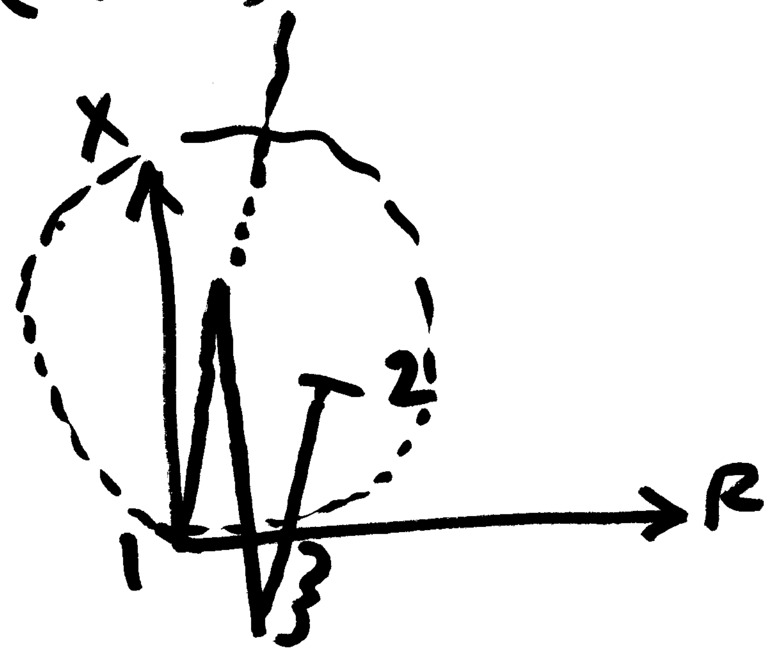
Ref: EE5200

Series Comp: C_{sa}

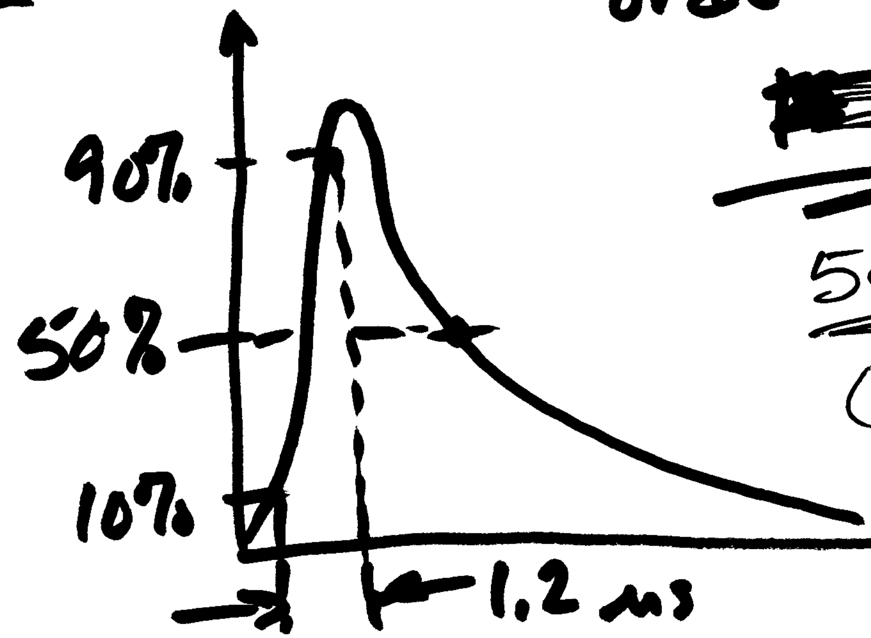


$$P_{1-2} = \frac{V_1 V_2}{X} \sin(\delta_1 - \delta_2)$$

$X_L - X_c$



Lightning -



order of ~~[illegible] MHz.~~

500 KHZ!

(half period ≅ 1 μs)

Switching -

R's, L's & C's in EMTP

Notes

EMTP – BPA, 1970 → '85

1985 EPRI DCG

EPRI EMTP
or DCG EMTP
– TACS

EMTP/RV

F.O.I.

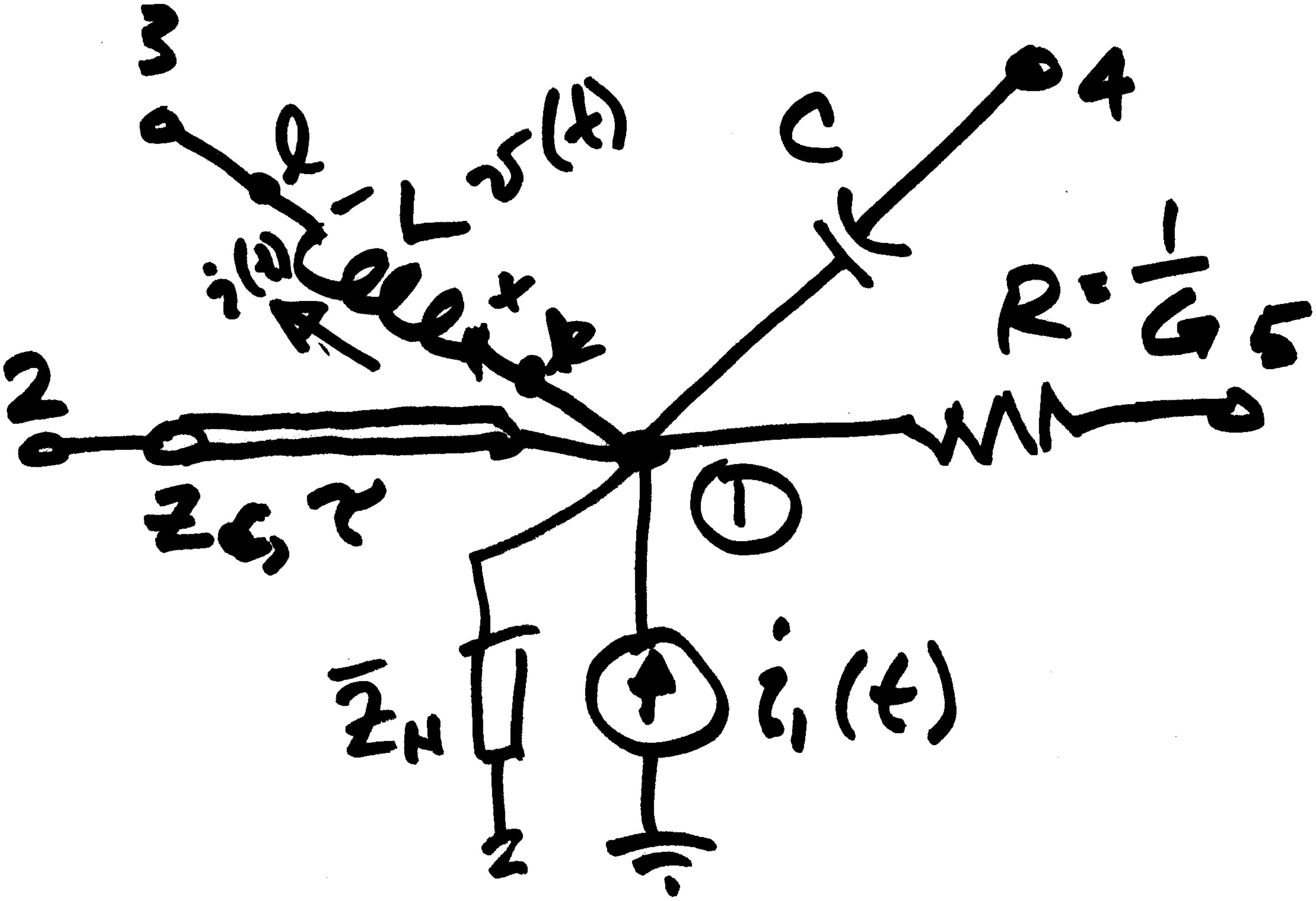
1987

ATP

Different:
- TACS
- MODELS

Controls

OTHERS:
- EMTDC/Pscad
- Micro-Tran
- ABB/Siemens
- EDF – MORGAT



Side Note:

Mathematical Structure is

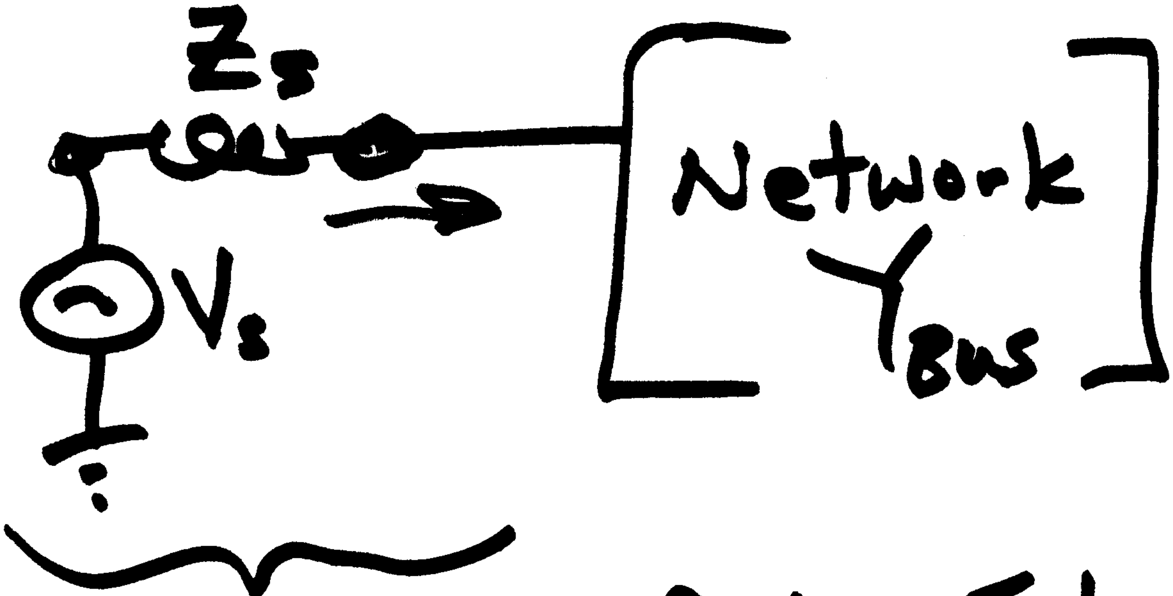
$$[Y][V] = [I]$$

sparse

node V's

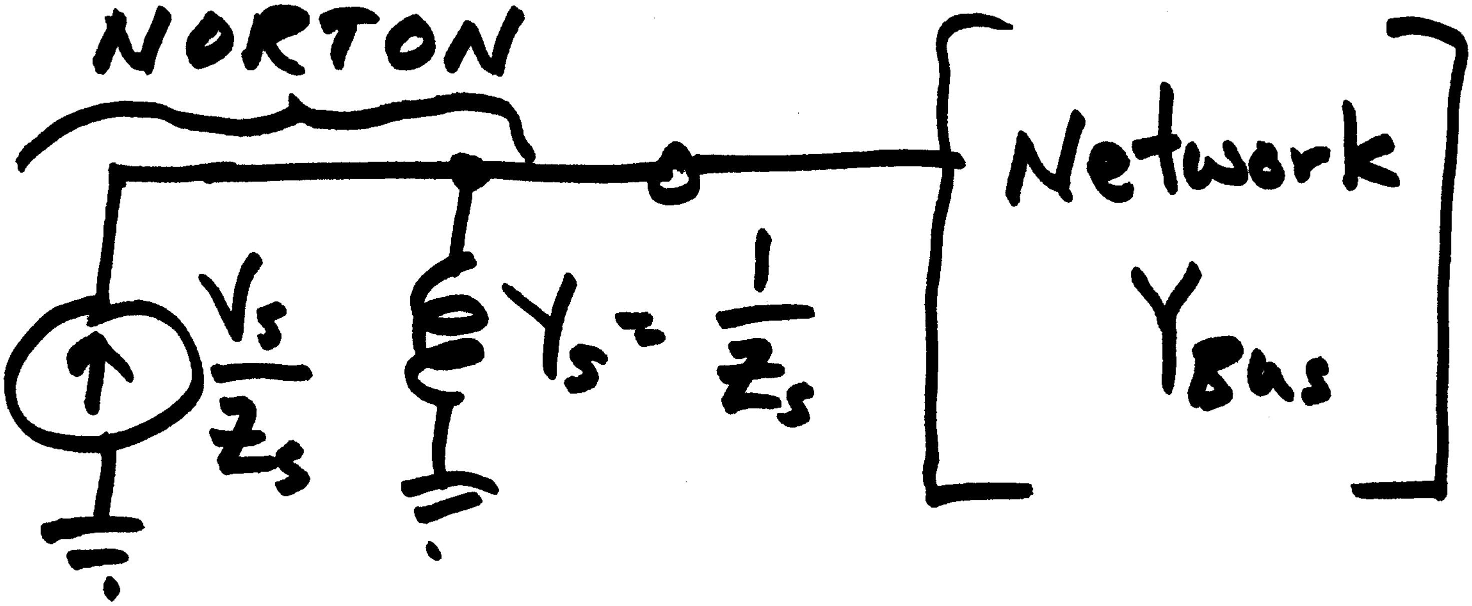
injected currents

Injected Currents!

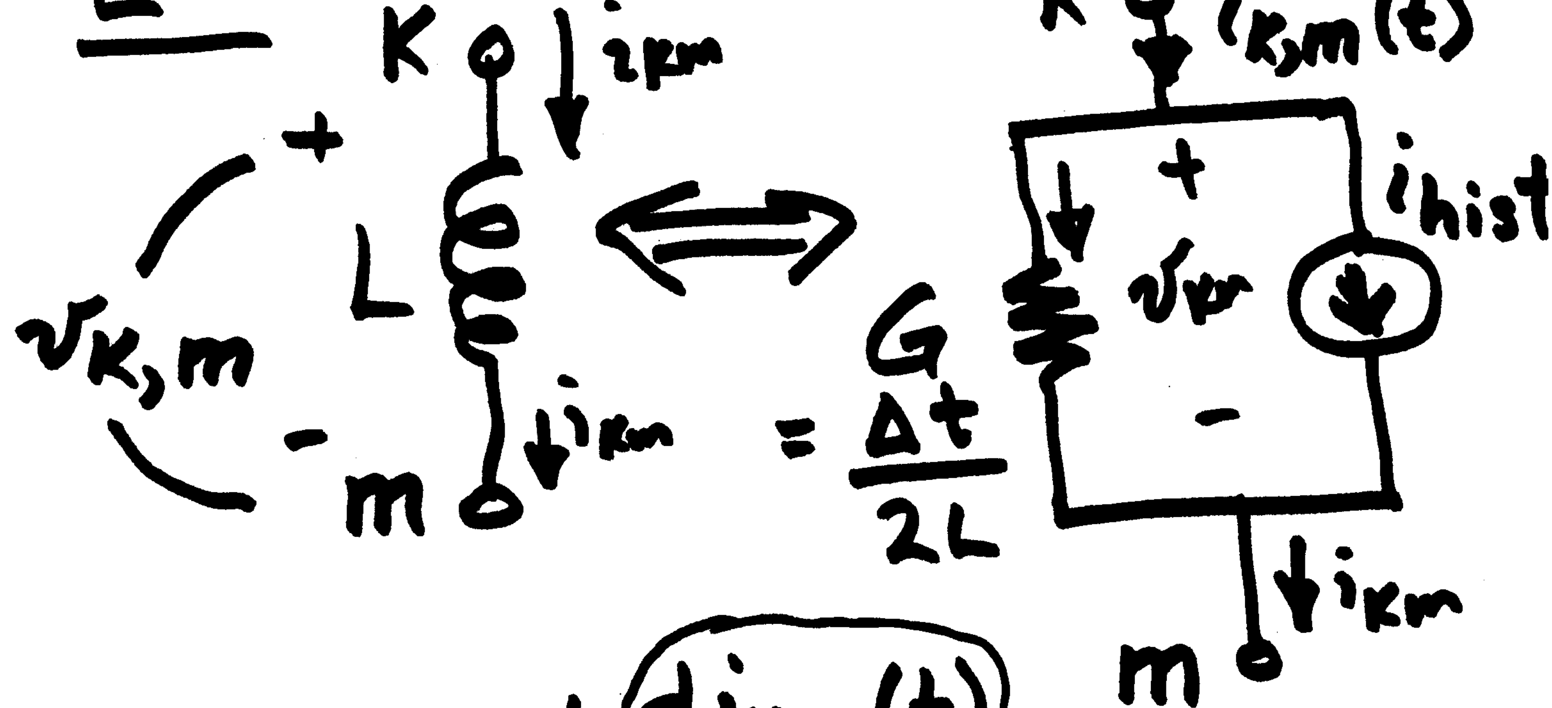


Thevenin = Bad : Extra Node
V = Fixed

Instead, convert to Norton:



L

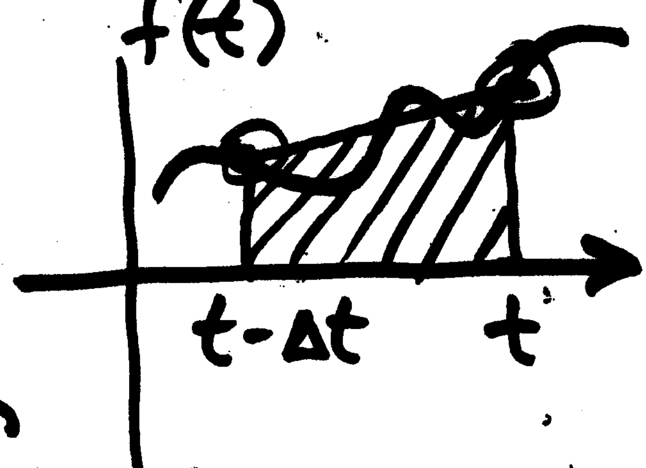


$$v_k - v_m = L\,\frac{d\,i_{k,m}(t)}{dt}$$

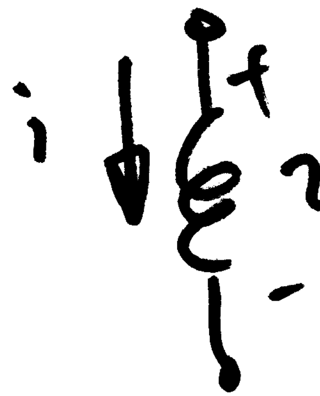
$$d\,i_{k,m}(t) \cong \overbrace{\left\{ i_{k,m}(t) - i_{k,m}(t-\Delta t) \right\}}^{\Delta i}$$

$$dt \cong \Delta t$$

Trapezoidal Integration



$$\int_{t-\Delta t}^{t} f(t)\,dt$$



$$v = L\frac{di}{dt}$$

$$v\,dt = L\,di$$

$$di = \frac{1}{L}v\,dt$$

$$\boxed{i = \frac{1}{L}\int_0^t v\,dt}$$

$i = ?$

Δt in EMTP cannot be as small as dt, Δt is finite.

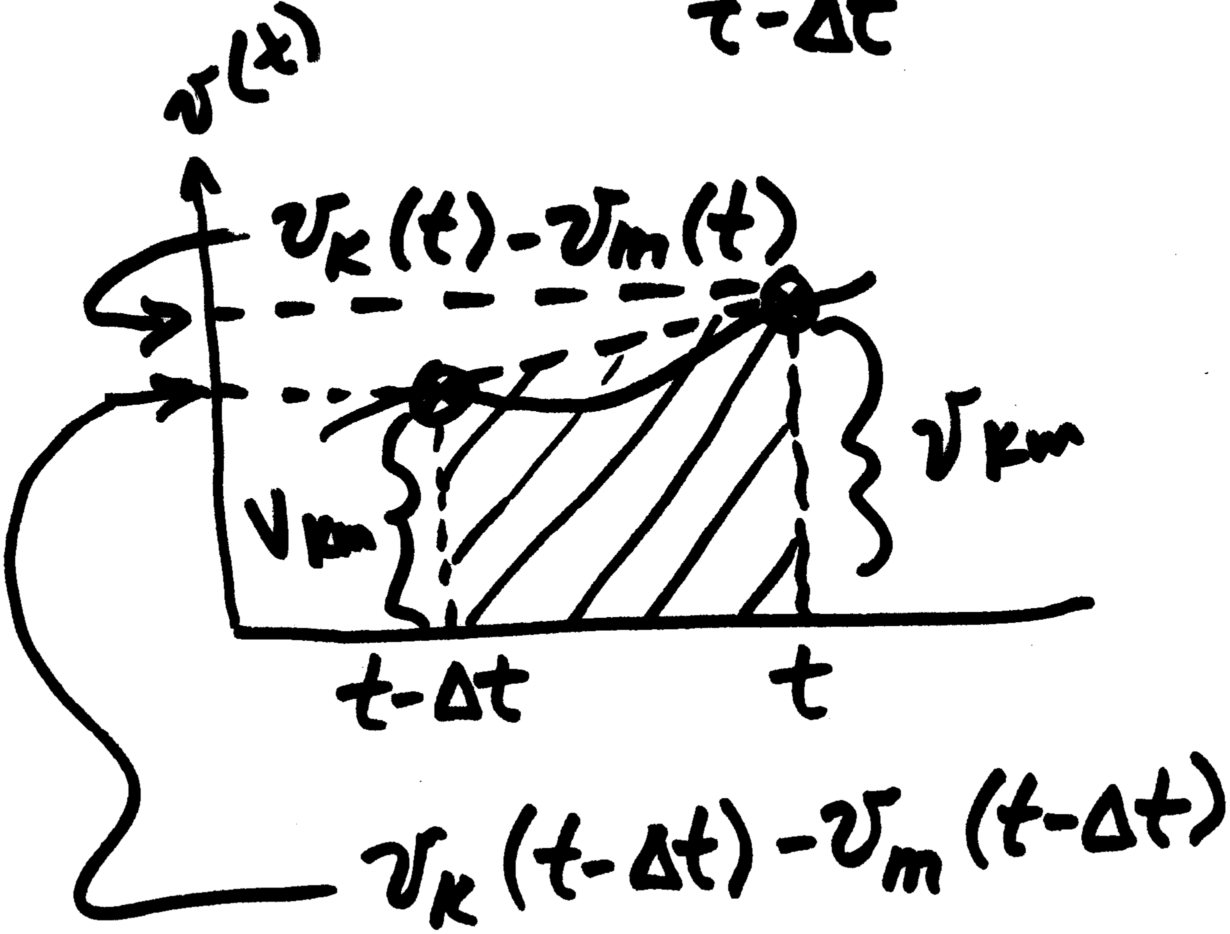
6A

Look at Trapezoidal implementation of eqn:

~~[illegible]~~ 6B

$$v_k(t) - v_m(t) = L \frac{d\, i_{k,m}(t)}{dt}$$

$$d\, i_{k,m}(t) = \frac{1}{L} \int_{t-\Delta t}^{t} \left[v_k(t) - v_m(t) \right] dt$$



The integral can then be approximated as the area of the trapezoid:

$$\frac{1}{L}\int_{t-\Delta t}^{t}\left[v_K(t)-v_m(t)\right]dt$$

$$\cong \frac{\Delta t}{L}\left[\frac{v_K(t)-v_m(t)+v_K(t-\Delta t)-v_m(t-\Delta t)}{2}\right]$$

(i.e. area of trapezoid = $\Delta t \times$ average height of sides)

$$\underbrace{d\,i_{km}(t)}_{\downarrow} = \underbrace{\frac{1}{L}\int_{t-\Delta t}^{t}\left[v_k(t) - v_m(t)\right] dt}$$

$$\underline{\underline{i_{km}(t) - i_{km}(t-\Delta t)}}$$

Integral is:

$$\frac{1}{L}\left[v_k(t) - v_m(t) + v_k(t-\Delta t) - v_m(t-\Delta t)\right]\frac{\Delta t}{2}$$

---

putting pieces together,

OK

$$i_{k,m}(t) \cong i_{k,m}(t-\Delta t) + \frac{\Delta t}{2L}\left[v_k(t) - v_m(t) + v_k(t-\Delta t) - v_m(t-\Delta t)\right]$$

Separating (t) & $(t-\Delta t)$ terms,

$$i_{m,k}(t) \cong \underbrace{\overset{G}{\frac{\Delta t}{2L}} \Big[v_k(t) - v_m(t) \Big]}_{}$$

Current at time = t for present voltage drop

$$+ \underbrace{i_{k,m}(t-\Delta t) + \frac{\Delta t}{2L} \Big[v_k(t-\Delta t) - v_m(t-\Delta t) \Big]}_{}$$

$I_{hist} = I_{k,m}$ = Summation of all currents at past time steps, i.e. $t-\Delta t$, $t-2\Delta t$, $t-3\Delta t$, ...

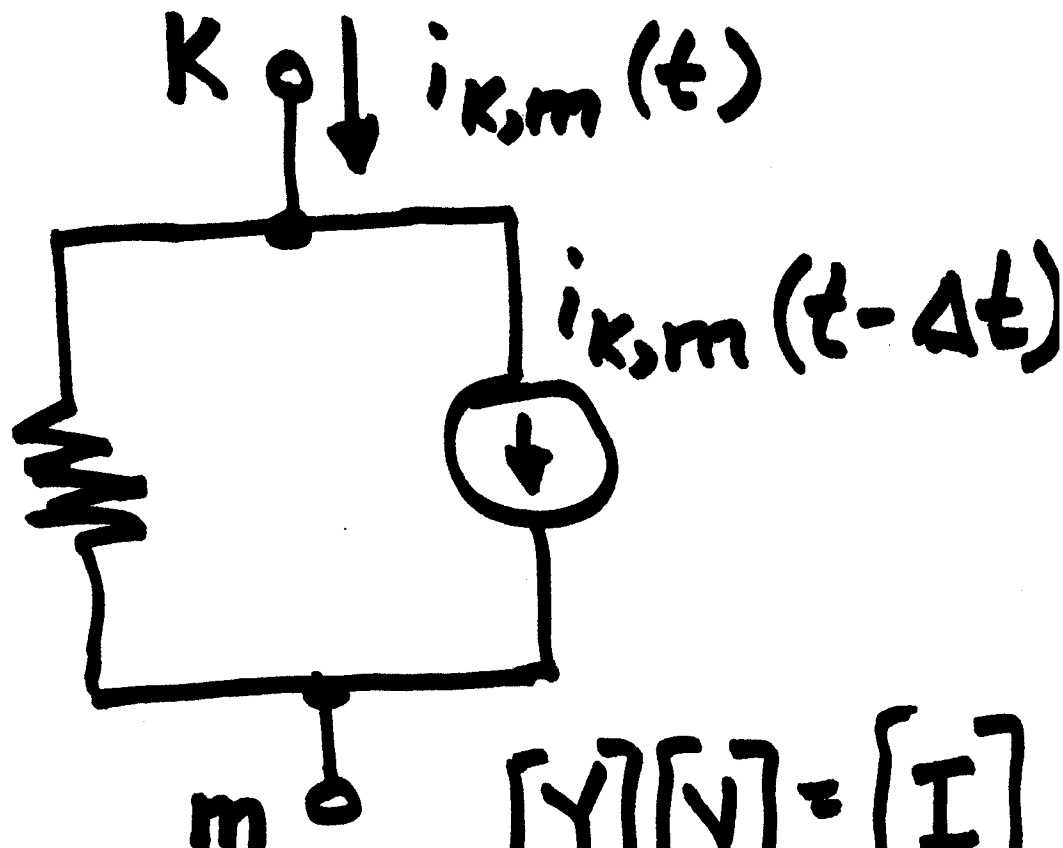
Initialization: $\boxed{I_{hist}(0) = i(0).}$

$[Y_{BUS}]$ is augmented according to system elements needed.

R:

$R = \frac{1}{G}$ → into $[Y_{BUS}]$

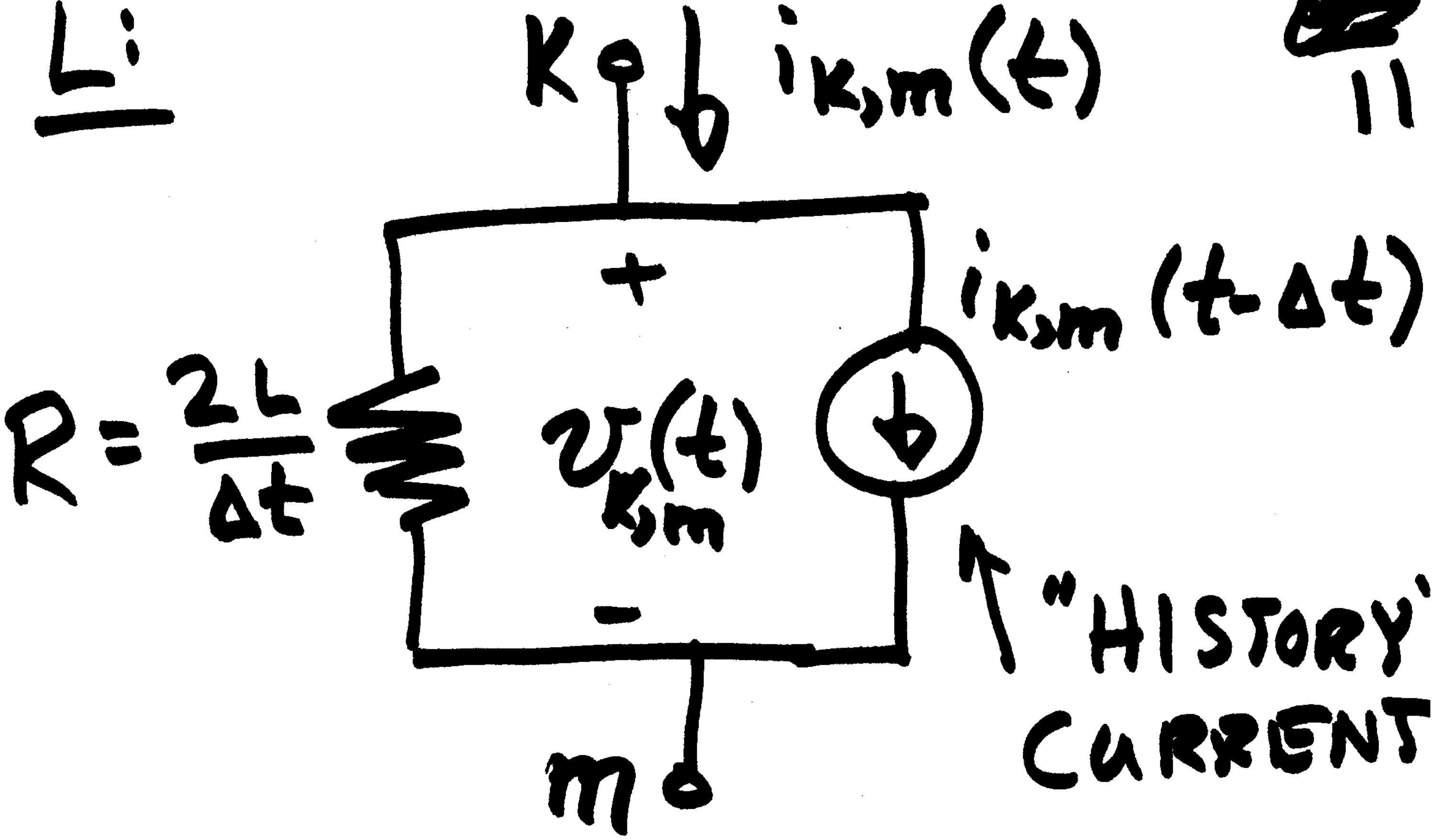
C:



$R = \frac{\Delta t}{2C}$

$[Y][V] = [I]$

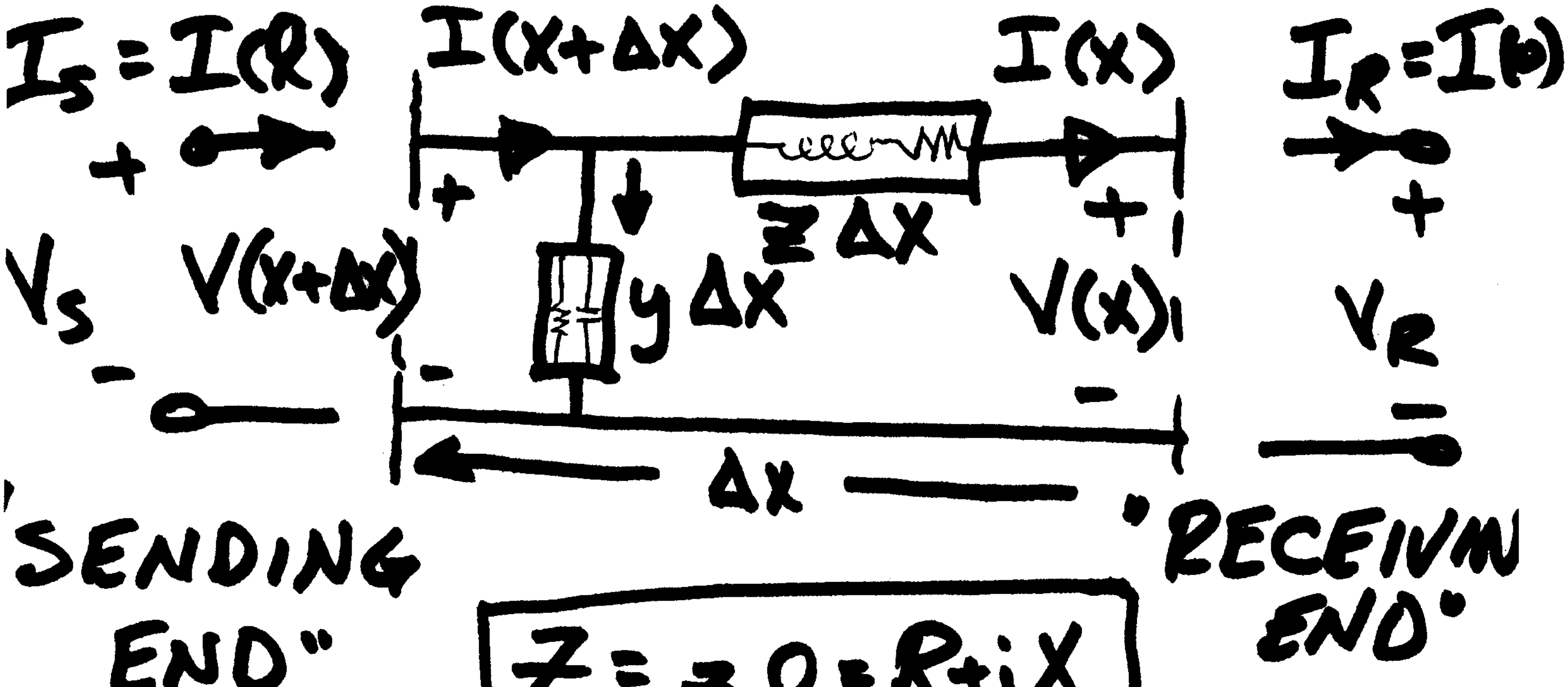
L:



DISTRIBUTED - PARAMER T-LINES

- "LONG LINES" (>250km @ 60Hz)
- FOR LIGHTNING, EVEN VERY SHORT LINES ARE MODELED AS DIST-PARAM.

FOR INCREMENTAL LENGTH:



$$\boxed{\begin{aligned} Z &= z\ell = R + jX \\ Y &= y\ell = G + jB \end{aligned}}$$

Making ΔX very small,

(small Z)

$$\begin{cases} dV = IZ\,dx \\ dI = Vy\,dx \end{cases}$$

Rearranging,

$$\begin{cases} \dfrac{dV}{dx} = IZ & (1) \\ \dfrac{dI}{dx} = Vy & (2) \end{cases}$$

d/dx

Taking derivative of (1),

$$\frac{d^2V}{dx^2} = \frac{dI}{dx} Z$$

Substituting into (2)

$$\boxed{\frac{d^2 V}{dx^2} = V \underline{yz}}$$

This implies gen'l sol'n:

$$\underline{V} = A_1 e^{\sqrt{yz}x} + A_2 e^{-\sqrt{yz}x}$$

Since $I = \dfrac{dV}{dx} \Big/ Z$

$$I = A_1 \sqrt{\frac{y}{z}} e^{\sqrt{yz}x} - A_2 \sqrt{\frac{y}{z}} e^{-\sqrt{yz}x}$$

at $x = 0$, $V = V_R$, $I = I_R$

$$V(0) = V_R = A_1 + A_2$$

$$I(0) = I_R = \sqrt{\frac{y}{z}} A_1 - \sqrt{\frac{y}{z}} A_2$$

Defining $Z_c = \sqrt{\frac{z}{y}}$ = Char Imp.

$\gamma = \sqrt{yz}$ = Propagation Const.

$$\boxed{\begin{aligned} V_R &= A_1 + A_2 \\ I_R &= \frac{A_1 - A_2}{Z_c} \end{aligned}}$$

$$\Longrightarrow \quad A_1 = (V_R + Z_c I_R)/2$$

$$A_2 = \frac{V_R - Z_c I_R}{2}$$

∞

$$V(x) = \frac{(V_R + Z_c I_R)}{2} e^{\gamma x} + \frac{(V_R - Z_c I_R)}{2} e^{-\gamma x}$$

$$I(x) = \left(\frac{V_R + Z_c I_R}{2 Z_c}\right) e^{\gamma x} - \left(\frac{V_R - Z_c I_R}{2 Z_c}\right) e^{-\gamma x}$$

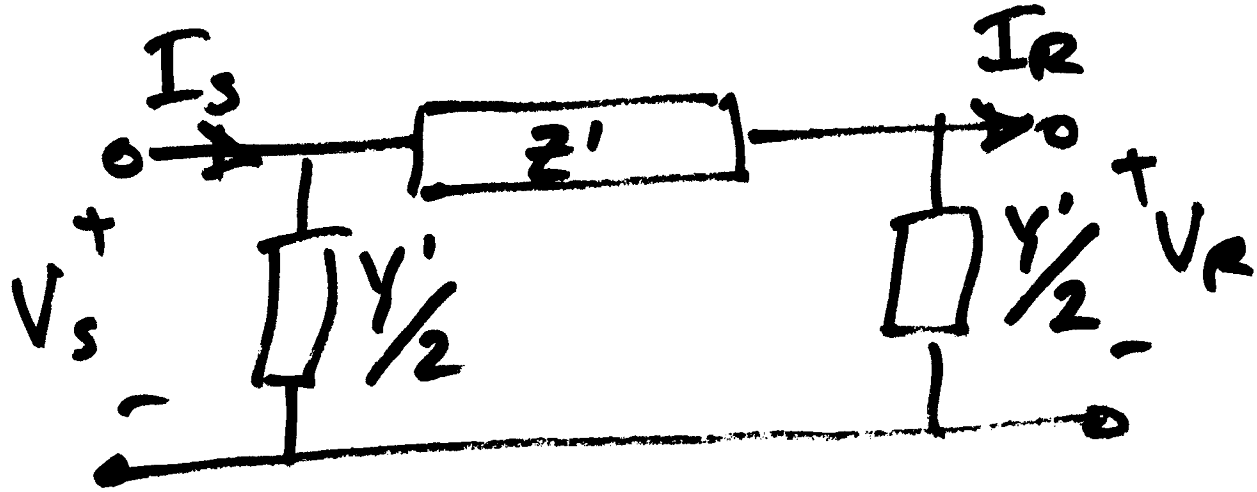
$$V_s = V(\ell) \longleftarrow \underline{\underline{x = \ell}}$$

$$I_s = I(\ell)$$

$$V(x) = V_R \underbrace{\cosh(\gamma x)}_{A} + Z_c I_R \underbrace{\sinh(\gamma x)}_{B}$$

$$I(x) = \underbrace{\frac{V_R}{Z_c} \sinh(\gamma x)}_{C} + I_R \underbrace{\cosh(\gamma x)}_{D}$$

In hyperbolic form,



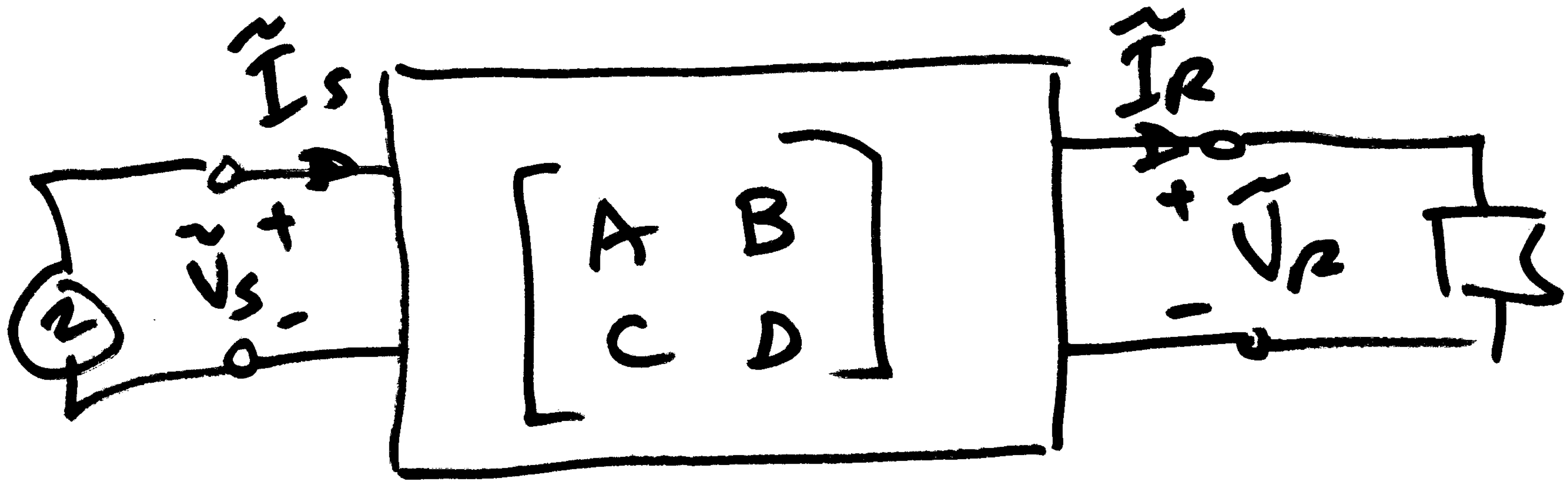
From EQNs:

$$\begin{bmatrix} V_S \\ I_S \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_R \\ I_R \end{bmatrix}$$

If we match $\begin{bmatrix} A & B \\ C & D \end{bmatrix}$ with π-Equiv

$$Z' = Z\left[\frac{\sinh(\gamma l)}{\gamma l}\right]$$

$$\frac{Y'}{2} = \frac{Y'}{2}\left[\frac{\tanh(\gamma l/2)}{\gamma l/2}\right]$$



per-phase T-Line

Propagation Constant

$$\gamma = \sqrt{yz} = \alpha + j\beta$$

α = attenuation constant (nepers/m)

β = phase constant (radians/m)

Referring to p. 8, exponential form of $V(x)$ & $I(x)$.

$$V(x) = V^{+}(x) + V'(x)$$

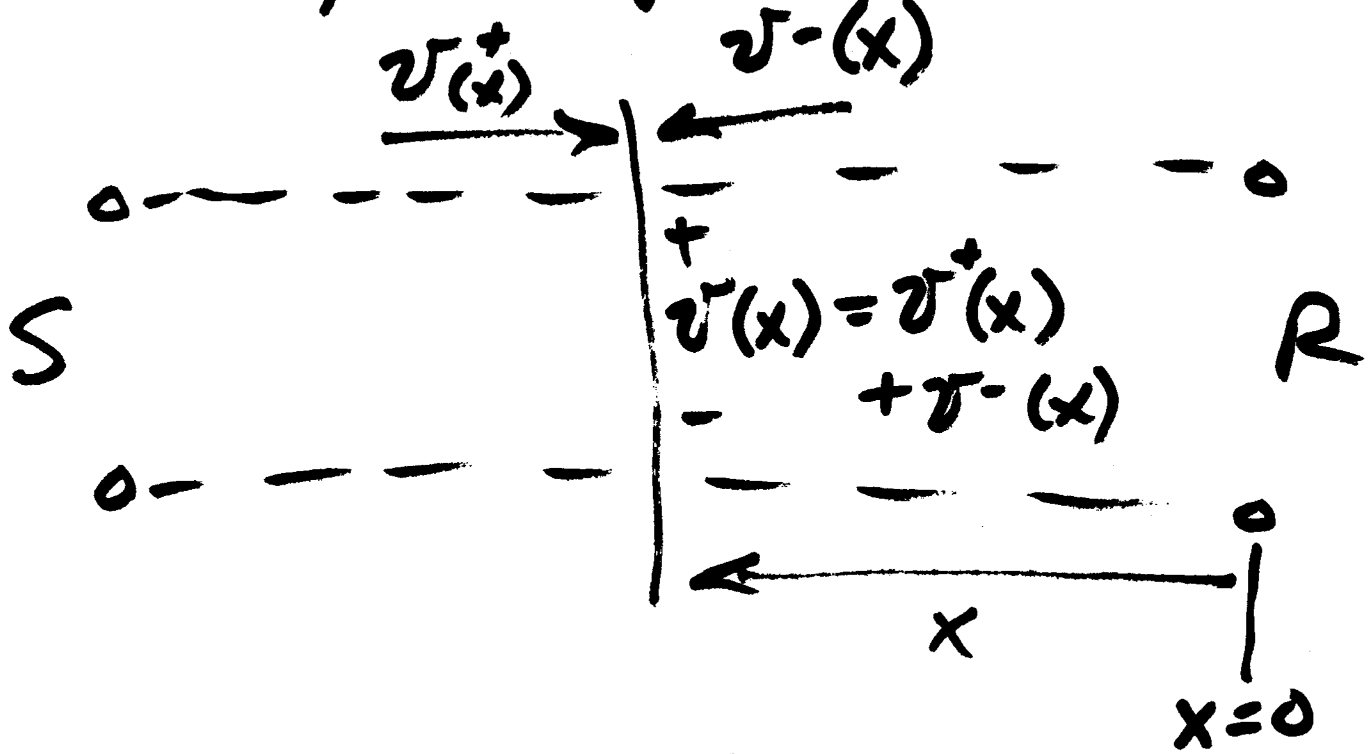
INCIDENT:

$$V^{+}(x) = \frac{V_R + I_R Z_c}{2} e^{+\alpha x} e^{+j\beta x}$$

REFLECTED:

$$V^{-}(x) = \frac{V_R - I_R Z_c}{2} e^{-\alpha x} e^{-j\beta x}$$

Conceptually



Same thing w/ I's

$$I^+(x) = \left(\frac{V_R + Z_c I_R}{2 Z_c}\right) e^{\alpha x} e^{j\beta x}$$

$$I^-(x) = -\left(\frac{V_R - Z_c I_R}{2 Z_c}\right) e^{-\alpha x} e^{-j\beta x}$$

$(Z_R = Z_c)$

- SIL: Surge Imp Loading
- $\lambda = \frac{2\pi}{\beta}$ $e^{-j\beta x}$
- ~~B~~ $v = f\lambda$

@ 60 Hz: $\lambda = 3038$ mi

$v = 182{,}300$ mi/s

see following pages for add'l notes and a numerical ~~ex~~ example for a 3-phase line.

Look at γ

$$\gamma = \alpha + j\beta$$

α = attenuation constant
β = phase constant

$$V = \frac{V_R + I_R Z_C}{2} e^{\alpha x} e^{j\beta x} + \frac{V_R - I_R Z_C}{2} e^{-\alpha x} e^{-j\beta x}$$

$$I = \frac{\frac{V_R}{Z_C} + I_R}{2} e^{\alpha x} e^{j\beta x} - \frac{\frac{V_R}{Z_C} - I_R}{2} e^{-\alpha x} e^{-j\beta x}$$

Magnitude of
$e^{\alpha x}$ & $e^{-\alpha x}$ change with distance x which makes magnitude of V & I vary.

$e^{j\beta x}$ & $e^{-j\beta x}$ change only in angle as x changes. $|e^{j\beta x}| = |e^{-j\beta x}| = 1$

$$V_s^+ = \frac{V_R + I_R Z_c}{2} e^{\alpha x} e^{j\beta x}$$ = <u>incident voltage</u> that strikes receiving end

$$V_s^- = \frac{V_R - I_R Z_c}{2} e^{-\alpha x} e^{-j\beta x}$$ = <u>reflected voltage</u> reflected back from receiving end

If Load on line = Z_c, then reflected voltage = 0 ($\frac{V_R}{I_R} = Z_c$). This is called a flat line or infinite line. Normally this never occurs and it is impractical to attempt to do this.

For power systems, $Z_c = \sqrt{\frac{z}{y}}$ = Surge impedance

if $R_{LINE} = 0$ $\quad Z_c = \sqrt{\frac{L}{C}}$

~~[illegible]~~ if $R_{LOAD} = |Z_c|$ then the reactive power supplied/consumed by line $= 0$

$$\frac{V^2}{X_c} = I^2 X_L \qquad \frac{V}{I} = \sqrt{X_L X_c} = \sqrt{\frac{L}{C}}$$

This is called <u>surge impedance loading</u>

Load is purely resistive $\quad R_L = \sqrt{\frac{L}{C}}$

$$|I_L| = \frac{V_L}{\sqrt{3}}\left(\frac{1}{\sqrt{\frac{L}{C}}}\right) \text{ Amps}$$

$$SIL = \sqrt{3}|V_L||I_L|$$

$$= \sqrt{3}|V_L|\left(\frac{|V_L|}{\sqrt{3}} \frac{1}{\sqrt{\frac{L}{C}}}\right) = \boxed{\frac{|V_L|^2}{\sqrt{\frac{L}{C}}} \text{ MW}}$$

where V is in k[illegible]

Sometimes SIL is given in p.u.

wavelength

$$\lambda = \frac{2\pi}{\beta} \cong 3000 \text{ miles @ } 60 \text{ Hz}$$

$$v = f\lambda \cong \text{speed of light}$$

$$v = \frac{\omega}{\beta} = \frac{1}{\sqrt{\mu\varepsilon}}$$

EX: GROSSBEAK $D_{EQ} = 15$ ft. $l = 300$ mi

100 MW 200 KV_{L-L} PF = 1

$X_L = .412 + .3286 = .7406\ \Omega/mi$

$L = 1.965\ mH/mi$

$X_C = .0946 + .0803\ M\Omega\text{-}mi = .1747\ M\Omega\text{-}mi$

$C = .01518\ \mu F/mi$

$R = .1454\ \Omega/mi$

$z = .1454 + j.7406 = .7547\ \angle 78.9^\circ\ \Omega/mi$

$y = 5.724 \times 10^{-6}\ \angle 90^\circ\ \mho/mi = \frac{1}{X_c}$

$\gamma l = \sqrt{yz}\, l = .6235\ \angle 84.45^\circ = \underbrace{\boxed{.0603}}_{\alpha l} + \underbrace{\boxed{j.6205}}_{j\beta l}$

$Z_c = \sqrt{\frac{z}{y}} = 363\ \angle -5.5^\circ\ \Omega$

$V_R = 200/\sqrt{3} = 115.2\ \angle 0^\circ\ KV$

$I_R = 100 \times 10^6 / \sqrt{3}\,(200K) = 288.6\ \angle 0^\circ\ A$

INCID. $V_R^+ = \frac{V_R + I_R Z_c}{2} = 109.85\ \angle -2.62^\circ\ KV$

REFL. $V_R^- = \frac{V_R - I_R Z_c}{2} = 7.42\ \angle 42.57^\circ\ KV$

INCID $V_s^+ = \frac{V_R + I_R Z_c}{2} e^{\alpha l} e^{j\beta l} = 116.68\ \angle 32.93^\circ\ KV$

REFL. $V_s^- = \frac{V_R - I_R Z_c}{2} e^{-\alpha l} e^{-j\beta l} = 6.986\ \angle 7.018^\circ\ KV$

$V_{LOAD} = V_R^+ + V_R^- = 115.2\ \angle 0^\circ\ KV$ ∴ Checks ok

$V_s = V_s^+ + V_s^- = 123.04\ \angle 31.5^\circ\ KV$

$\beta = \overset{\text{Phase}}{\text{Constant}} = .002068 \text{ Rad/mi}$

$\lambda = \frac{2\pi}{\beta} = 3038 \text{ miles}$

$V = F\lambda = 182{,}300 \text{ mi/sec}$

$I_s^+ = \frac{V_s^+}{Z_c} = 321.43 \angle 38.43° \text{ A}$

$I_s^- = \frac{V_s^-}{Z_c} = -19.24 \angle 112.518° \text{ A}$

$I_s = I_s^+ + I_s^- = 304.2 \angle 40.01°$

$MVA = \sqrt{3} V_{LS} I_{LS} = \sqrt{3} (213.04)(304.2) = 112.25 \text{ MVA}$

$P_s = 112.25 \cos(40.01 - 31.5) = \underline{111.26 \text{ MW}}$

$Q_s = \underline{-16.61 \text{ MVAR}}$

x.lis file:

in c:/atp/atpdraw/lcc/....*.lis

Use "line check" also....

Click on
ATP → Linecheck