Topics for Today:

- Announcements
  - Expanded Term Project outline (i.e. Table of Contents + List of references (suggest about half a dozen to start with) by end of week.
  - Software: online students - apply for ATP/ATPDraw license, verify licensing when you receive it by e-mail, and we will mail you the install CD.
  - Office: EERC 623. Phone: 906.487.2857
  - Recommended problems & all solutions: Ch.6 solns posted.

- Chapter 6 - Using the T-Line models
  - Pi-Equivalent circuit for long-line
  - Characteristic Impedance $Z_C$
  - Propagation Constant $\gamma = \alpha + j\beta$
  - Surge-Impedance Loading (SIL)
  - Wavelength, velocity
  - Traveling waves, reflections
\[ Z_c = \sqrt{\frac{z}{y}} \]
\[ Z = \sqrt{Z' y} = \alpha + j\beta \]

Phase angle rotation and how a wave travels down line.

Attenuation

Open Receiving End

\[ \text{Return} = Z_c \quad (S I) \]

- Full Load
- Short Circuit
Another Point:

- SIL = Surge Impedance Loading
- \( R_{\text{Load}} = |Z_c| \)
- Total Reactive Power Consumed in Line = 0.
- "Flat" Line or flat voltage profile:

\[ \text{SIL} = \frac{V^2}{Z_c} = \frac{V_s^2}{Z_c} = \frac{V_R^2}{Z_c} \]
Propagation Wavelength $\lambda$

$\lambda$ = distance req'd to change $\psi$ by $360^\circ$.

$\gamma = \sqrt{2g} = \alpha + j\beta$ (Assume Lossless)

$e^{j\beta x}$: term provides phase rotation in each term of $I(x), V(x)$.

$\lambda = x \frac{2\pi}{\beta} \Rightarrow \lambda = \frac{2\pi}{\omega \sqrt{LC}} = \frac{2\pi}{2\pi f \sqrt{LC}}$

$\lambda = \frac{1}{f \sqrt{LC}}$

$V = f \lambda = \frac{1}{\sqrt{LC}} = 3 \times 10^8 \text{ m/s} = \frac{1}{\sqrt{E_0 M_0}}$
@ 60 Hz, \( \lambda = \frac{v}{f} = \frac{3 \times 10^8 \text{ m/s}}{60} \approx 5000 \text{ Km} \approx 3100 \text{ miles} \)

@ 2 MHz, \( \lambda = \frac{3 \times 10^8}{2 \times 10^6} = 150 \text{ m} \)

- Side Comments (later) on
  - T-Line loading limits
  - Thermal
  - Voltage Limits, \( V_S \& V_R \Rightarrow V_R^{.95 < V < 1.05} \)
  - Stability Limits
\[ V(x) = \left( \frac{v_R + \frac{z_c}{2} i_R}{2} \right) e^{z_c x} + \left( \frac{v_R - \frac{z_c}{2} i_R}{2} \right) e^{-z_c x} \]

\[ I(x) = \left( \frac{v_R + \frac{z_c}{2} i_R}{2} \right) e^{z_c x} - \left( \frac{v_R - \frac{z_c}{2} i_R}{2} \right) e^{-z_c x} \]

Best for Trav. Waves.

\[
Z_c = \sqrt{\frac{z_c}{y}} = \text{Characteristic Impedance.}
\]

\[
Y = \sqrt{\frac{z_c}{y}} = \alpha + j\beta = \text{Propagation Coefficient}
\]

\[ \alpha = \text{attenuation constant} \]

\[ \beta = \text{angular propagation constant} \]
Travelling Waves

Impedance at receiving end:

\[ Z_R = \frac{V_R}{I_R} = \frac{V_R^+ + V_R^-}{I_R^+ + I_R^-} = \frac{V_R^+ + V_R^-}{\frac{V_R^+}{Z_R} - \frac{V_R^-}{Z_c}} = Z_R \]

\[ \frac{V_R^-}{V_R^+} = \frac{Z_R - Z_c}{Z_R + Z_c} = R_R \]

Reflection Coefficient
If receiving end is...

- Open-ckt (i.e. $Z_R = \infty$)
  
  $$P_R = \frac{R - Z_C}{R + Z_C} = +1$$
  
  $$ \therefore V_R^- = V_R^+ P_R = V_R^+$$

- Short-ckt (i.e. $Z_R = 0$)
  
  $$P_R = \frac{0 - Z_C}{\infty + Z_C} = -1$$
Traveling Wave Example (ATPDraw) 7

See page 14, Lecture 13

\[ Z_c = 294.3 \angle -9.22^\circ \Omega \]

\[ Y = 0.00215 \angle 80.8^\circ = \frac{0.00034}{\alpha} + j \frac{0.00212}{\beta} \]

250-miles long

\[ Z = 0.2 + j 0.6 \Omega / \text{mi} \]
\[ Y = j 7.3 \mu \text{s/mi} \]

\[ L = 0.398 \text{ H} \]
\[ C = 484 \mu \text{F} \]
\[ R = 50 \Omega \]

If losses are ignored,

\[ \lambda = \frac{2 \pi}{\beta} = \frac{2 \pi \text{ rad}}{0.00209 \text{ rad/mi}} \]

\[ = 3006 \text{ mi} \]
Before creating ATP example, let's predict behavior:

**Lossless:** \( \lambda = \frac{2\pi}{\beta} = \frac{2\pi}{0.00209} = 3006 \text{ mi} \)

\[ f\lambda = \nu = 2.9 \times 10^8 \text{ m/s} \quad (f=60 \text{ Hz}) \]

(Should be \( 3 \times 10^8 \).... rounding.)

Propagation Time: Approx:

\[ t = \frac{x}{\nu} = \frac{(250 \text{ mi})(1.6 \text{ km/mi})}{2.9 \times 10^6 \text{ km/s}} = 138 \mu s \]
250-mile transmission line example - traveling wave model in ATP

Select Distributed 1-phase Clarke Line Model.

Input (click Help button):
- ILINE option: 0
- \(R/\ell = 0.2 \text{ Ohms/mi}\)
- \(A = j0.6 \text{ Ohms/mi}\)
- \(B = 7.3 \mu\text{S/mi}\)
- \(\ell \text{ (length)} = 250 \text{ mi}\)

\[
\begin{align*}
z &= 0.2 + j0.6 \text{ Ohms/mi} \\
y &= j7.3 \mu\text{S/mi} \\
Z_C &= 294.3 \angle -9.22^\circ \text{ Ohms} \\
\gamma &= 0.00215 \angle 80.8^\circ \text{ /mi}
\end{align*}
\]

Ref: EE5200 notes, Lectures 13 and 14.
First Case: Lossless. \( Z_s = 0 \); Receiving end open-circuited.

Predicted propagation time (rough calculation): 138 \( \mu s \).

Actual propagation time: 139 \( \mu s \).

\[ \mathcal{E}_s = -1, \quad \mathcal{E}_R = +1 \]
Second Case: $R=0.2 \text{ Ohm/mi}; \ Z_s = 0; \ Receiving \ end \ open-circuited.$

* 10-kV wave is attenuated 8.5%, arrives as 9.15 kV, reflected double, to 18.3 kV.

250-mi line. $Z_s=0; \ R=0.2 \text{ ohm/mi}; \ S1 \ closes \ at \ t=0; \ S2 \ open; \ S3 \ open.$

* 18.3 kV

$V_R$

$V_S$

\[ P_R = +1 \]
\[ P_S = -1 \]

*Note: Attenuation of voltage wave is $a = l$

\[ = (0.00034/\text{mi})(250\text{mi}) = 0.085 \text{ or } 8.5\% \]

i.e. Mag at end of line is only 91.5%.
Third Case: Lossless line; $Z_s=0$; $Z_R = Z_C$

Note: no reflection or voltage overshoot at receiving end!