Topics for Today:

- Startup
  - Web page: [http://www.ee.mtu.edu/faculty/bamork/ee5220/](http://www.ee.mtu.edu/faculty/bamork/ee5220/)
  - Book, references, syllabus, more are on web page.
  - Software - Matlab. ATP/EMTP [ License - [www.emtp.org](http://www.emtp.org) ]
  - **ATP tutorials posted on course web page. DO THEM!**
  - Circuit analysis tutorials posted, “Pre-Req Material”
  - [EE5220-L@mtu.edu](mailto:EE5220-L@mtu.edu) (participation = min half letter grade)

- HW#3 probs 3.2, 3.3, 3.4, 3.6, 3.12 due Mon Feb 1\textsuperscript{st}.
- ATP Simulation pointers
- Cap Bank Switching (continued)
  - First (single) bank energization
  - Back-to-back switching
  - Outrush
  - TRV
  - Voltage Magnification
Shunt Cap Banks

- Voltage Support
- Var
- Power Flow

\[ P_{\text{in}} = V_{\text{in}} \times I \]

\( A - B - C \)
Short Circuit Calcs/Sims

\[ Z_{33} = Z_{TH} \]

\[ V_F \]

They Eqn:

\[ V(t) = V_p \cos(\omega t + \theta) \]
Euler's Identity

\[ V_p \sin \theta = V \]

\[ R = V_p \cos \theta \]

\[ \cos(Wt+90^\circ) = -\sin(Wt) \]
$300 \text{ - } 600 \text{ Hz}$

$u(t)$

$t$

$\cos \omega t$
Forced RLC Responses

Note: Very similar to

Since $L$ is very small and $C$ is sizeable

Then $\omega_0 \gg 377$

Then we can assume that

$V_p \cos 377t \leftrightarrow V_p \delta(t)$
Parallel RLC - Series RLC

Resonant freq:

\[ \omega_0 = \frac{1}{\sqrt{LC}} \]

Exponential Damping Coefficient (or Neper freq)

\[ \alpha = \frac{1}{2RC} \]

Damped or "Natural" Resonant freq

\[ \omega_d = \sqrt{\omega_0^2 - \alpha^2} \]
Damping:

Critical Damping: $\alpha = \omega_0$

$\omega_d = \sqrt{\omega_0^2 - \alpha^2} = 0$

Overdamped: $\alpha > \omega_0$

Underdamped: $\omega_0 > \alpha$

Undamped: $\alpha = 0$

$\omega_d = \omega_0$
Look at series RLC

\[
\begin{align*}
\mathbf{V}_o^- &+ \frac{1}{C} \mathbf{C} \mathbf{V}_o^+ \\
R & \downarrow \mathbf{I}_o = 0 \downarrow \\
\mathbf{L} & \\
\end{align*}
\]

\[z_0 = \sqrt{\frac{L}{C}} = \sqrt{\frac{1}{10^{-6}}} = 100 \Omega\]

\[I_p = \frac{\Delta V}{z_0} = 100 \Omega\]

UNDAMPED \quad R = 0

\[\text{Initial} \quad \text{Final}\]

\[+100 \, \text{V} \quad -100 \, \text{V}\]

\[\text{DAMPED} \quad \text{UNDAMPED} \quad \text{DAMPED}\]

\[\text{Example:} \quad L = 10 \, \text{mH} \quad C = 1 \, \text{mF} \quad R = 0\]

1. \[\omega_0 = \sqrt{\frac{L}{C}} = \sqrt{\frac{0.01}{10^{-6}}}\]

2. \[\omega_0 = 10,000 \, \text{s}^{-1} \quad f = 3 \, 1591 \, \text{Hz} \quad T = 0.63 \, \text{ms} \quad \Delta t = 20 \, \mu\text{s} \quad T_{\text{end}} = \]
Read Ch. 4 - §4.3 - Damping

Make transition from

\[ \alpha, \omega_0, \omega_d \]

to

\[ s = \sigma + j\omega \]

in terms of \( \xi_0, R, L, \eta \)

More on simulation:

Critically damped:

\[ \alpha = \omega_0 = \frac{R}{2L} \]

Check: decrease \( R \)

\[ \alpha = 10,000 = \frac{R}{(2)(.01)} \]

\[ \Rightarrow R = 200 \Omega \]
\[ R = 190 \text{A} \Rightarrow \omega = \frac{R}{2L} \]
\[ = \frac{190}{(2)(.01)} \]
\[ = 9500 \]

\[ \omega_d = \sqrt{\omega_0^2 - \alpha^2} \]
\[ = \sqrt{10,000^2 - 9500^2} = 3122 \text{ s}^{-1} \]
\[ = 497 \text{ Hz} \]
\[ T = 2 \text{ ms} \]

\[ R = 10,000 \rightarrow \text{overdamped} \]
If \( \frac{X}{R} \) ratio is 10, then

\[ R = \frac{X}{10} = \frac{377}{10} = 37.7 \Omega \]
CAP BANK SWITCHING

1 - Energization Inrush - Bus 0V
2 - Back-to-Back Energization
3 - Outrush - HF thru CBS
4 - Voltage Magnification
5 - TRV - Transient Recovery Voltage
Sample 34.5-kV system, developed from Fig. 3.4 in Greenwood.

**System Equivalent**

- \( R_1 = 0.5 \, \text{Ohms} \)
- \( L_1 = 3 \, \text{mH} \)
- \( R_2 = 0.001 \, \text{Ohms} \)
- \( L_2 = 12 \, \text{mH} \)
- \( C_1 = 40.1 \, \mu\text{F (18 MVAR)} \)
- \( C_2 = 22.3 \, \mu\text{F (10 MVAR)} \)
- \( C_{LV} = 601 \, \mu\text{F} \)
- Dist. Transformer: 4:1 ratio
- \( L_B = 19 \, \mu\text{H} \)
- \( C_{BUSH} = 300 \, \text{pF} \) (see p.437)

**Inrush**
- CB1 - Closed
- CB4 - Closed
- SW1 - Closing

\[ V_s \]

Typical: \( 0.2 - 0.4 \, \text{mH/}\sqrt{A} \)

Tube Bus

Strain Bus

\[ V_{\text{bus}} = 0 \, \text{V} \]

\[ @ \, t = 0^+ \]
Series resonance:  $Z_{tot} = jX_L - jX_C$

$X_L = X_C$  

$2\pi f, L = \frac{1}{2\pi f, C}$

$I \to \infty$  

$V_L \to \infty$  

$V_C \to \infty$

Per Unit Voltage at $C_{LV}$ is higher than at $C_1$, thus the name "Voltage magnification."