ECEN5817 Lecture 16

I will be away on a trip Monday-to-Wednesday, Feb. 27 to Feb.29 (includes lectures 18 and 19). No office hours on Wed. Feb.29.

Lecture 18 will be done after Lecture 17, on Friday, Feb.24, 11-11:50am,

Lecture 19 will be done on Friday, March 2, 10-10:50am, followed by Lecture 20, 11-11:50am
5. Simulation using SPICE

The equivalent circuits of the previous slides suggest that a circuit simulator such as SPICE could be employed to find transfer functions such as $G_{env}(s)$. This can indeed be done; however, since SPICE can’t handle complex-valued voltages and currents, it is first necessary to decompose the phasor-transformed signals into their real and imaginary parts. Let

\[ \hat{v} = \hat{v}_1 + j\hat{v}_2 \]

where

- $\hat{v}$ is a phasor-transformed voltage in the model
- $\hat{v}_1$ is the real part of $\hat{v}$
- $\hat{v}_2$ is the imaginary part of $\hat{v}$

Then simulate two circuits: one containing the real parts, and the other containing the imaginary parts.
SPICE inductor model
(ac terms only shown)

Linearized inductor phasor-transformed equation:

$$\hat{v} = L \frac{d\mathbf{i}}{dt} + j\omega_0 L \mathbf{i} + jL \mathbf{I} \hat{\omega}_s$$

Separate real and imaginary parts:

$$\hat{v}_1 + j\hat{v}_2 = L \frac{d(i_1 + j\hat{i}_2)}{dt} + j\omega_0 L (i_1 + j\hat{i}_2) + jL (I_1 + jI_2) \hat{\omega}_s$$

**Real part**

$$\hat{v}_1 = L \frac{d\hat{i}_1}{dt} - \omega_0 L \hat{i}_2 - L \mathbf{I}_2 \hat{\omega}_s$$

**Imaginary part**

$$\hat{v}_2 = L \frac{d\hat{i}_2}{dt} + \omega_0 L \hat{i}_1 + L \mathbf{I}_1 \hat{\omega}_s$$
**SPICE capacitor model**

**Real part**

\[ + \quad \hat{v}_1 \quad C \quad \omega_0 C \hat{v}_2 \quad CV_2 \hat{\omega}_s \quad \downarrow \quad \hat{i}_1 \quad - \]

**Imaginary part**

\[ + \quad \hat{v}_2 \quad C \quad \omega_0 C \hat{v}_1 \quad CV_1 \hat{\omega}_s \quad \downarrow \quad \hat{i}_2 \quad - \]

**Resistor model:** Resistor $R$ appears in both real and imaginary part.

**Switch model:** The switch output voltage is defined as the zero phase reference of the circuit, and hence it output voltage phasor is purely real. Switch voltage sources appear in real part, and are replaced by short circuits in imaginary part.
Parallel resonant inverter example
SPICE model

**Real part**

\[ \sqrt{2} V_s \cos \left( \frac{\pi D}{2} \right) \hat{d} \]

\[ \frac{2\sqrt{2}}{\pi} \sin \left( \frac{\pi D}{2} \right) \hat{d} \]

**Imaginary part**

\[ \omega_0 L_i L_2 \]

\[ CV C_\omega \hat{d} \]

\[ R \hat{d} \]

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Recovering the output envelope in SPICE

Write the previous expression for the scalar envelope in terms of the real and imaginary components. The result is:

\[ \hat{v}_{env} = \frac{V_1 \hat{v}_1 + V_2 \hat{v}_2}{\sqrt{V_1^2 + V_2^2}} \]
Selected additional reading


Time-Domain Analysis of Resonant and Soft-Switching Converters

• So far:
  • Steady-state and dynamic analyses based on sinusoidal approximation
  • Advantages: it is possible to use frequency-domain techniques
  • Shortcomings
    • Approximate solutions even for traditional resonant converters
    • Sinusoidal approximation does not apply in many important cases, where waveforms are not even close to sinusoidal
      • Various resonant converter modes
      • Various soft-switching converters
• Next: **Time-Domain Analysis**
  • Introduction to state-plane approach
    • Normalization, notation, and simple examples
    • Averaging, charge and volt-second balance
  • Exact solutions for series-resonant and parallel-resonant converters
  • Various important soft-switching converter examples
Introduction to state-plane analysis

2 components in a resonant tank, $L, C$

Initial conditions:
$t = 0, \ v(0) = V_0, i(0) = I_0$

$\omega_0 = \frac{1}{\sqrt{LC}}, \ f_0 = \frac{1}{2\pi \sqrt{LC}}$

$R_0 = \frac{1}{C}$

HW 1 example

HW 1 solution.

$v(t) = V + (V_0 - V) \cos \omega_0 t + R_0 (I_0 - I) \sin \omega_0 t$

$i(t) = I + \frac{V - V_0}{R_0} \sin \omega_0 t + (I_0 - I) \cos \omega_0 t$
Normalization and notation

$v(t) \rightarrow$ normalized voltage.  
$m(t) = \frac{v(t)}{V_{\text{base}}}.$

pick box value (arbitrary) $V_{\text{base}} = \text{const}.$

box current $I_{\text{box}} = \frac{V_{\text{base}}}{R_0}$,  
$R_0 = \sqrt{\frac{L}{C}}$

$i(t) \rightarrow$ normalized current  
$j(t) = \frac{i(t)}{I_{\text{box}}} = \frac{i(t)}{V_{\text{base}}} \cdot \frac{1}{R_0}$

$\omega_0 t = \Theta$  
$\omega_0 = \frac{1}{\sqrt{LC}}$

angle in radians.
\[ \omega_0 t = \theta \Rightarrow \frac{d\theta}{\omega_0} \]
\[ \frac{i}{I_{\text{max}}} = j \rightarrow i = j \cdot I_{\text{max}} = j \cdot \frac{V_{\text{max}}}{R_0} \]

\[ L \frac{di}{dt} = V - v \]
\[ L \frac{V_{\text{max}}}{R_0} \frac{dj}{d\theta} = V - v \]

\[ \frac{d\theta}{\omega_0} = \frac{dj}{dj} = M - m \]

\[ \theta = \frac{V}{V_{\text{max}}} - 1 \]

\[ \frac{d\theta}{d\theta} = 1 - m \]

\[ C \frac{dv}{dt} = i - I \]

\[ \omega_0 C \frac{dm}{d\theta} = i - I \]

\[ \frac{dm}{d\theta} = j - J \]

\[ J = \frac{I}{I_{\text{max}}} = \frac{I}{V} \cdot R_0 \]
\[ \frac{dj}{d\Theta} = 1 - m \] \quad \text{solution} \quad \begin{cases} \frac{dm}{d\Theta} = j - J \\ m(\Theta) = 1 + r \cos(\Theta + \Theta_0) \checkmark \\ j(\Theta) = J - r \sin(\Theta + \Theta_0) \checkmark \end{cases}

Check:
\[ \frac{dj}{d\Theta} = -r \cos(\Theta + \Theta_0) \checkmark \]
\[ \frac{dm}{d\Theta} = -r \sin(\Theta + \Theta_0) \checkmark \]

Equate \( \Theta \):
\[ (m - 1)^2 + (j - J)^2 = r^2 \cos^2(\Theta + \Theta_0) + r^2 \sin^2(\Theta + \Theta_0) \]

\[ (m - 1)^2 + (j - J)^2 = r^2 \]
DC value of $i(t) = I \rightarrow \frac{I}{I_{	ext{max}}} = \frac{I}{V_{	ext{max}}} \cdot R_0 = \frac{I}{V} \cdot R_0 = J$

\[\begin{align*}
\text{State plane} & \quad m > 1 ? \quad \frac{dm}{d\theta} > 0 \\
\text{Direction} & \quad n > 1 \quad \frac{dn}{d\theta} < 0
\end{align*}\]

Remarks to be found:
1) radius
2) with pt.
(3) directon.

\[J = \frac{I}{V} \cdot R_0\]