19.4.4 Design Example

Select resonant tank elements to design an **LCC** resonant inverter that meets the following requirements:

- Switching frequency $f_s = 100$ kHz
- Input voltage $V_g = 160$ V
- Inverter is capable of producing a peak open circuit output voltage of 400 V
- Inverter can produce a nominal output of 150 Vrms at 25 W

\[ v_{s1}(t) \propto V_{s1} \sin \omega_s t, \quad V_{s1} = \frac{4}{\pi} V_g \]
Design summary

Found from the required output characteristic (ellipse), based on $V_{oc}$, $V$, $P$

\[
|H_\infty(j\omega_s)| = \frac{V_{oc}}{V_{s1}} = \frac{400 \text{ V}}{\left(\frac{4}{\pi}\right) 160 \text{ V}} = 1.96
\]

\[
|Z_{o0}(j\omega_s)| = \frac{V_{oc}}{I_{sc}} = 1439 \Omega
\]

- $H_\infty$ and $Z_{o0}$ have the same magnitude and phase.

**Nominal load**

\[
R = 900 \Omega
\]

- 3 nF
- $-j498 \Omega$
- 1 nF
- $-j1493 \Omega$

**Active components**

- 1.96 mH
- $j1230 \text{ k}\Omega$

**Impedance calculations**

\[
Z_{i0} = jX_s = j(1230 - 498)\Omega = j732\Omega
\]

\[
Z_{i\infty} = j(X_s + X_p) = j(732 - 1493)\Omega = -j761\Omega
\]

\[
R_{crit} = \| Z_{o0} \| \sqrt{\frac{1}{H_\infty - 1}} = 1466\Omega
\]

- $R < R_{crit}$: ZVS
- $R > R_{crit}$: ZCS
LCC inverter $Z_i$ impedances and corner frequencies

$LCC$ example

$$f_0 = \frac{1}{2\pi \sqrt{LC_s}}$$

$$f_m = \frac{1}{2\pi \sqrt{L/C_s}}$$

$$f_\infty = \frac{1}{2\pi \sqrt{L/C_s||C_p}}$$

$Z_{i0}$

$Z_{i\infty}$

$\omega L$

$\frac{1}{\omega C_s}$

$\frac{1}{\omega C_p}$

$\frac{1}{2\omega \sqrt{LC_s}}$

$R < R_{\text{in}}$ at $f_0$

$Z_{\infty}$, but increased cond. loss at light load.
Extending ZVS range?

\[
\bar{Z}_{i\infty} = -j760 \Omega
\]

Pick \( X_x = 732 \Omega \) (somewhat arbitrary)

\[
\bar{Z}_{i\infty} = \frac{jX_x \cdot (-j760 \Omega)}{jX_x - j760 \Omega} = -j \frac{760 \Omega X_x}{X_x - 760 \Omega}
\]

Pick \( X_x < 760 \Omega \)

\[\omega_s L_x < 760 \Omega \Rightarrow L_x\]

\[\bar{Z}_{i\infty} \text{ for any } R\]

\[
\bar{Z}_{i\infty}^\text{new} = jX_x \frac{j732}{2} \Omega = j361 \Omega \quad \|\bar{Z}_{i\infty}^\text{new}\| = 361 \Omega \\
\text{larger current at low } R
\]

\[
\bar{Z}_{i\infty}^\text{new} = -j \frac{760 \cdot 732}{732 - 760} \Omega = j19 \Omega \\
\|\bar{Z}_{i\infty}^\text{new}\| = 19 \Omega \quad \text{good}
\]

\[R \uparrow \Rightarrow \text{switch current} \downarrow\]
Dynamic Modeling of Resonant Converters

So far:

• Steady-state analysis of resonant converters using sinusoidal approximation

• Resonant-tank design
  • Meet the operating point requirements
  • Favorable ZVS and load-dependent conduction losses

Next:

• Feedback control around resonant converters?
  • Frequency (FM) control, or
  • Amplitude (AM) control via pulse-width modulation

• Need small-signal dynamic models

Extensive notes by Prof. Erickson are available on the course website
Control via frequency modulation (FM) and amplitude modulation (AM)

**Frequency Modulation**
- Vary switching period $T_s$
- Changes frequency of $v_{s1}$ but not amplitude

**Amplitude Modulation**
- Vary duty cycle $D$ with constant switching period $T_s$
- Changes amplitude of fundamental component of $v_{s1}$ but not frequency
Introduction to resonant inverter control

Control-to-output transfer function:

\[ G_{\text{env}}(s) = \frac{\hat{V}_i}{V_i} \]

Envelope transfer function:

Small-signal

\[ \text{VCO} \]

Voltage-controlled oscillator

(FM control)

Compensator

\[ G_c(s) \]

Negative feedback loop

Switch network

\[ V_s \approx V_s \]

Resonant tank

\[ v \]

Peak detector

\[ R \]

\[ R_s \]

\[ R_{\text{ref}} \]

Fixed or variable (for drawing)
Dynamic Modeling and Analysis of Resonant Inverters

Closed-loop control system to regulate amplitude of ac output

(Lamp ballast example shown, but other applications have similar needs) (frequency modulation control shown)

Issues for design of closed-loop resonant converter system:

- Need to model loop gain, closed-loop transfer functions
- How does control-to-output transfer function depend on the tank transfer function $H(s)$?
Introduction to small-signal modeling of resonant converters

\[ G_{env}(s) = \frac{\hat{V}_s}{\hat{f}_s} \]

\[ G_{env}(s) \]?