Lecture 10: Isolated Converters II & DCM Introduction

ECE 481: Power Electronics
Prof. Daniel Costinett
Department of Electrical Engineering and Computer Science
University of Tennessee Knoxville
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Effect of nonidealities on transformer volt-second balance

Volt-seconds applied to primary winding during first switching period:

\[(V_e - (Q_1 \text{ and } Q_4 \text{ forward voltage drops}))(Q_1 \text{ and } Q_4 \text{ conduction time})\]

Volt-seconds applied to primary winding during next switching period:

\[-(V_e - (Q_2 \text{ and } Q_3 \text{ forward voltage drops}))(Q_2 \text{ and } Q_3 \text{ conduction time})\]

These volt-seconds never add to exactly zero.
Net volt-seconds are applied to primary winding
Magnetizing current slowly increases in magnitude
Saturation can be prevented by placing a capacitor in series with primary, or by use of current programmed mode (Chapter 12)
Operation of secondary-side diodes

- During second (D') subinterval, both secondary-side diodes conduct.
- Output filter inductor current divides approximately equally between diodes.
- Secondary amp-turns add to approximately zero.
- Essentially no net magnetization of transformer core by secondary winding currents.

Volt-second balance on output filter inductor

\[ V = \left\{ v_i \right\} \]

\[ V = nDV_g \]

\[ M(D) = nD \quad \text{buck converter with turns ratio} \]
Half-bridge isolated buck converter

- Replace transistors $Q_3$ and $Q_4$ with large capacitors
- Voltage at capacitor centerpoint is $0.5V_e$
- $V_e(t)$ is reduced by a factor of two
- $M = 0.5$ nD

6.3.3. Push-pull isolated buck converter

$V = nDV_e$  
$0 \leq D \leq 1$
### 6.3.2. Forward converter

- Buck-derived transformer-isolated converter
- Single-transistor and two-transistor versions
- Maximum duty cycle is limited
- Transformer is reset while transistor is off
Forward converter
with transformer equivalent circuit

- Magnetizing current, in conjunction with diode $D_1$, operates in discontinuous conduction mode
- Output filter inductor, in conjunction with diode $D_3$, may operate in either CCM or DCM
Subinterval 1: transistor conducts

Subinterval 2: transformer reset
Subinterval 3

Magnetizing inductance volt-second balance

\[ \langle v_1 \rangle = D(V_g) + D_2(-V_gn_1/n_2) + D_3(0) = 0 \]
Transformer reset

From magnetizing current volt-second balance:

\[ \langle v_i \rangle = D(v_i) + D_2(-V_p n_1 / n_2) + D_3[0] = 0 \]

Solve for \( D_2 \):

\[ D_2 = -\frac{n_2}{n_1} D \]

\( D_2 \) cannot be negative. But \( D_1 = 1 - D - D_2 \). Hence

\[ D_2 = 1 - D - D_2 \geq 0 \]

\[ D_2 = 1 - D\left(1 + \frac{n_2}{n_1}\right) \geq 0 \]

Solve for \( D \):

\[ D \leq \frac{1}{1 + \frac{n_2}{n_1}} \quad \text{for } n_1 = n_2; \quad D \leq \frac{1}{2} \]

What happens when \( D > 0.5 \)

magnetizing current waveforms, for \( n_1 = n_2 \)

\[ i_{sd}(t) \]

\[ D < 0.5 \]

\[ D > 0.5 \]

\[ DT_i, D_1T_i, D_2T_i \]

\[ DT_i, D_1T_i, 2T_i \]
Conversion ratio $M(D)$

$$
\langle v_{DS} \rangle = V = \frac{n_3}{n_1} DV_g
$$

Maximum duty cycle vs. transistor voltage stress

Maximum duty cycle limited to

$$
D \leq \frac{1}{1 + \frac{n_2}{n_1}}
$$

which can be increased by increasing the turns ratio $n_2/ n_1$. But this increases the peak transistor voltage:

$$
\max(v_{G}) = V_g \left( 1 + \frac{n_2}{n_1} \right)
$$

For $n_2 = n_1$,

$$
D \leq \frac{1}{2} \quad \text{and} \quad \max(v_{G}) = 2V_g
$$
Chapter 5. The Discontinuous Conduction Mode

5.1. Origin of the discontinuous conduction mode, and mode boundary
5.2. Analysis of the conversion ratio $M(D,K)$
5.3. Boost converter example
5.4. Summary of results and key points
Introduction to Discontinuous Conduction Mode (DCM)

- Occurs because switching ripple in inductor current or capacitor voltage causes polarity of applied switch current or voltage to reverse, such that the current- or voltage-unidirectional assumptions made in realizing the switch are violated.
- Commonly occurs in dc-dc converters and rectifiers, having single-quadrant switches. May also occur in converters having two-quadrant switches.
- Typical example: dc-dc converter operating at light load (small load current). Sometimes, dc-dc converters and rectifiers are purposely designed to operate in DCM at all loads.
- Properties of converters change radically when DCM is entered:
  - $M$ becomes load-dependent
  - Output impedance is increased
  - Dynamics are altered
  - Control of output voltage may be lost when load is removed

5.1. Origin of the discontinuous conduction mode, and mode boundary

Buck converter example, with single-quadrant switches

Minimum diode current is $(I - \Delta I_d)$

DC component $I = \frac{V}{R}$

Current ripple is

$$\Delta I_d = \frac{V - V_0}{2L} DT$$

Note that $I$ depends on load, but $\Delta I_d$ does not.
Reduction of load current

Increase $R$, until $I = \Delta I_L$

Minimum diode current is $(I - \Delta I_L)$
Dc component $I = V/R$
Current ripple is
$$\Delta I = \frac{(V_i - V)}{2L} DT = \frac{V_i DT}{2L}$$
Note that $I$ depends on load, but $\Delta I$ does not.

Further reduce load current

Increase $R$ some more, such that $I < \Delta I_L$

Minimum diode current is $(I - \Delta I_L)$
Dc component $I = V/R$
Current ripple is
$$\Delta I = \frac{(V_i - V)}{2L} DT = \frac{V_i DT}{2L}$$
Note that $I$ depends on load, but $\Delta I$ does not.
The load current continues to be positive and non-zero.
Mode boundary

\[ I > \Delta I_c \quad \text{for CCM} \]
\[ I < \Delta I_c \quad \text{for DCM} \]

Insert buck converter expressions for \( I \) and \( \Delta I_c \):
\[ \frac{D V_v}{R} < \frac{D D T V_v}{2L} \]

Simplify:
\[ \frac{2L}{R T_s} < D' \]

This expression is of the form:
\[ K < K_{\text{crit}}(D) \quad \text{for DCM} \]

where \( K = \frac{2L}{R T_s} \) and \( K_{\text{crit}}(D) = D' \)

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K and \( K_{\text{crit}} \) vs. \( D \)

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for \( K < 1 \):
\[ K < K_{\text{crit}} \quad \text{DCM} \]
\[ K > K_{\text{crit}} \quad \text{CCM} \]
\[ K_{\text{crit}}(D) = 1 - D \]

for \( K > 1 \):
\[ K > K_{\text{crit}} \quad \text{CCM} \]
\[ K_{\text{crit}}(D) = 1 - D \]