Lecture 10: Isolated Converters II & DCM Introduction

ECE 481: Power Electronics

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Effect of nonidealities on transformer volt-second balance

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

$$(V_g - (Q_1 \text{ and } Q_4 \text{ forward voltage drops}))(Q_1 \text{ and } Q_4 \text{ conduction time})$$

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

$$-(V_g - (Q_2 \text{ and } Q_3 \text{ forward voltage drops}))(Q_2 \text{ and } Q_3 \text{ conduction time})$$

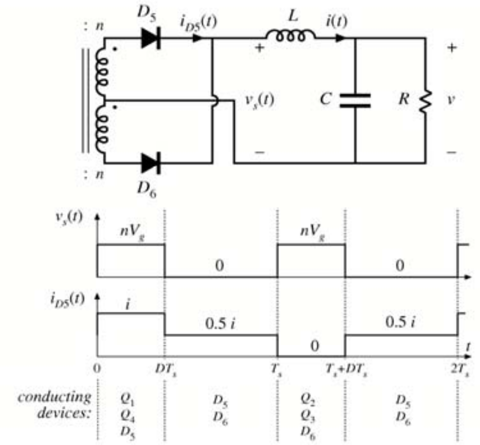
These volt-seconds never add to *exactly* zero.

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

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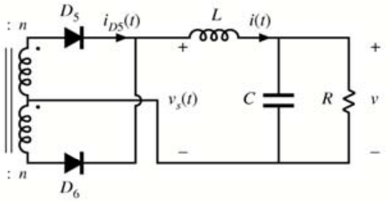
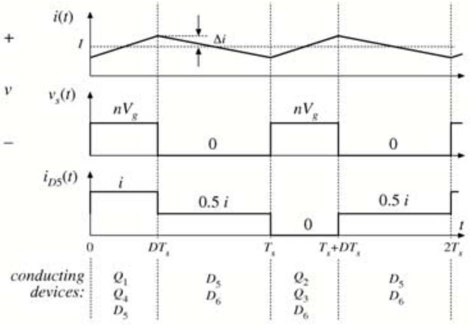
Volt-second balance on output filter inductor



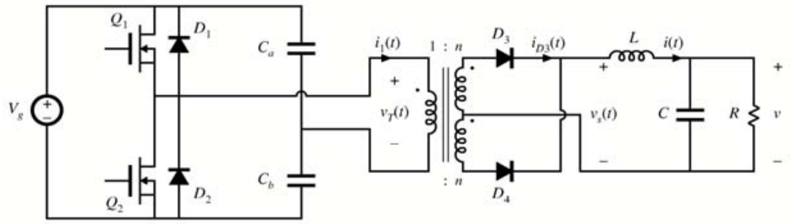


$$V = \langle v_s \rangle$$

$$V = nDV_g$$

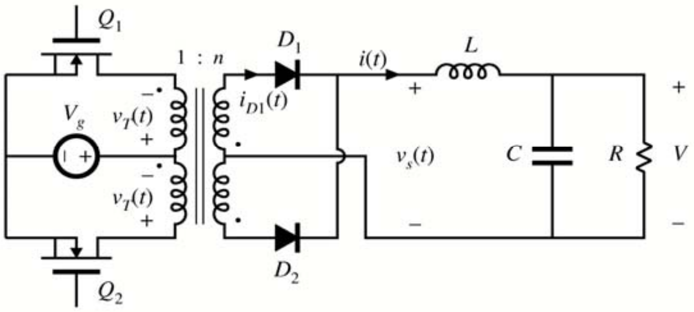
$M(D) = nD$ buck converter with turns ratio

Half-bridge isolated buck converter



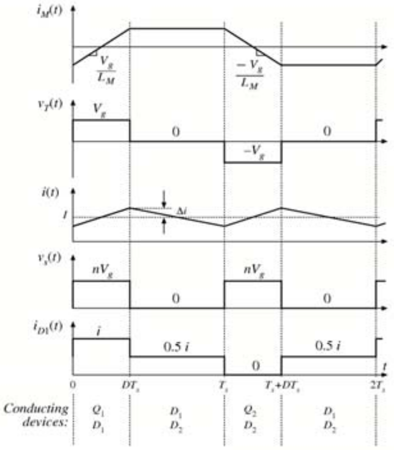
- Replace transistors Q_3 and Q_4 with large capacitors
- Voltage at capacitor centerpoint is $0.5V_g$
- $v_s(t)$ is reduced by a factor of two
- $M = 0.5\, nD$

6.3.3. Push-pull isolated buck converter



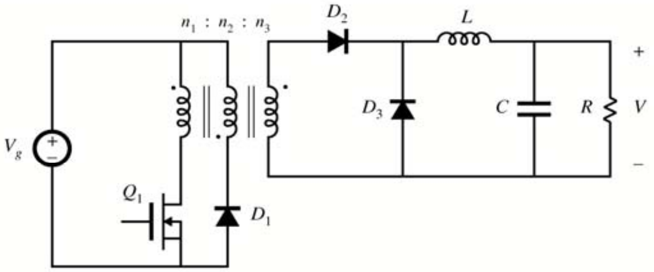
$V = nDV_g \qquad 0 \le D \le 1$

Waveforms: push-pull



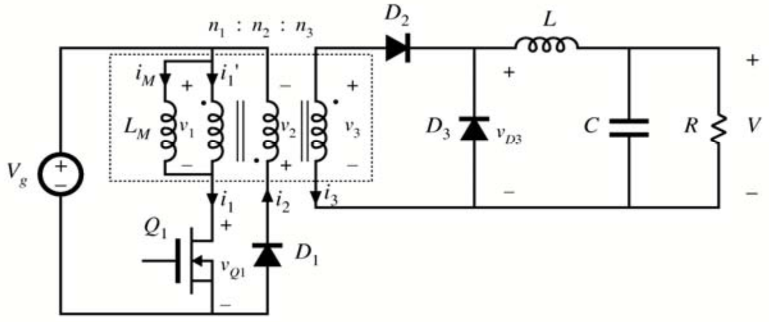
- Used with low-voltage inputs
- Secondary-side circuit identical to full bridge
- As in full bridge, transformer volt-second balance is obtained over two switching periods
- Effect of nonidealities on transformer volt-second balance?
- Current programmed control can be used to mitigate transformer saturation problems. Duty cycle control not recommended.

6.3.2. Forward converter

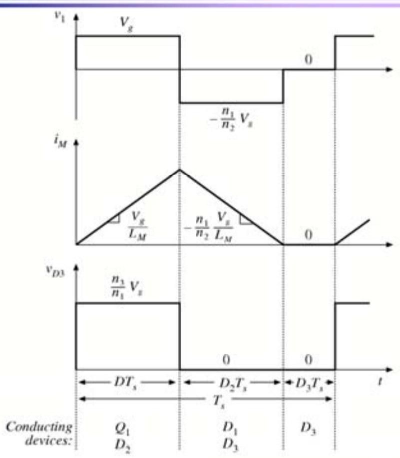


- Buck-derived transformer-isolated converter
- Single-transistor and two-transistor versions
- Maximum duty cycle is limited
- Transformer is reset while transistor is off

Forward converter with transformer equivalent circuit

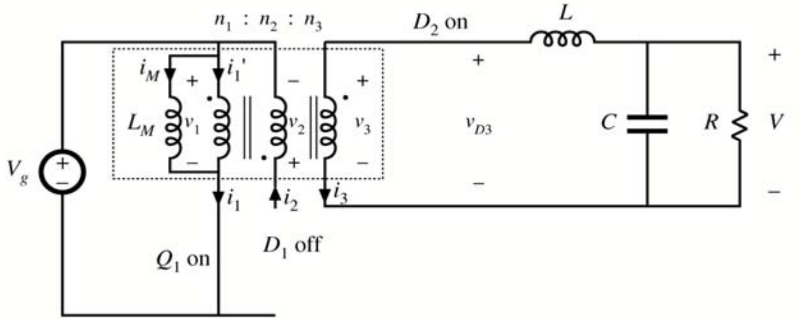


Forward converter: waveforms

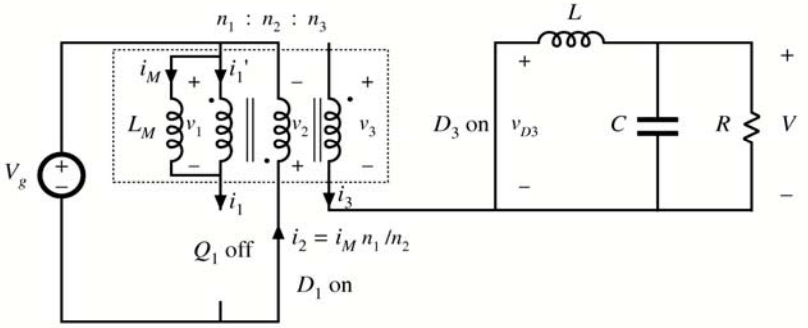


- Magnetizing current, in conjunction with diode D_1, operates in discontinuous conduction mode
- Output filter inductor, in conjunction with diode D_3, may operate in either CCM or DCM

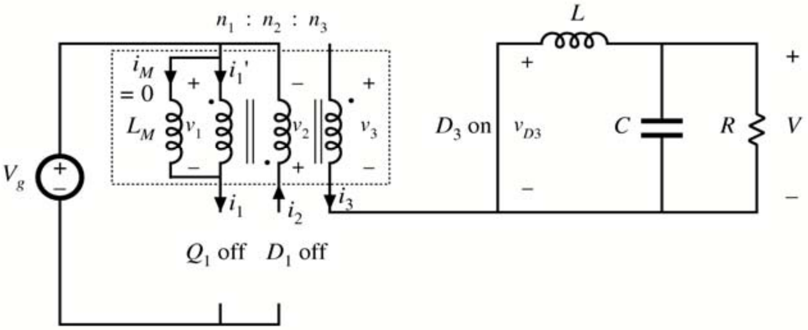
Subinterval 1: transistor conducts



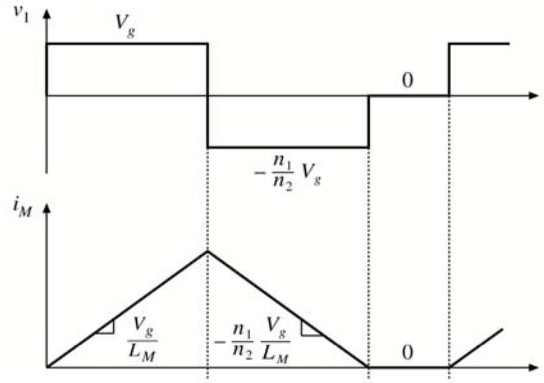
Subinterval 2: transformer reset



Subinterval 3



Magnetizing inductance volt-second balance



$$\langle v_1 \rangle = D\left(V_g\right) + D_2\left(-V_g n_1/n_2\right) + D_3\left(0\right) = 0$$

Transformer reset

From magnetizing current volt-second balance:

$$\langle v_1 \rangle = D\left(V_g\right) + D_2\left(-V_g n_1/n_2\right) + D_3\left(0\right) = 0$$

Solve for D_2:

$$D_2 = \frac{n_2}{n_1} D$$

D_3 cannot be negative. But $D_3 = 1 - D - D_2$. Hence

$$D_3 = 1 - D - D_2 \geq 0$$

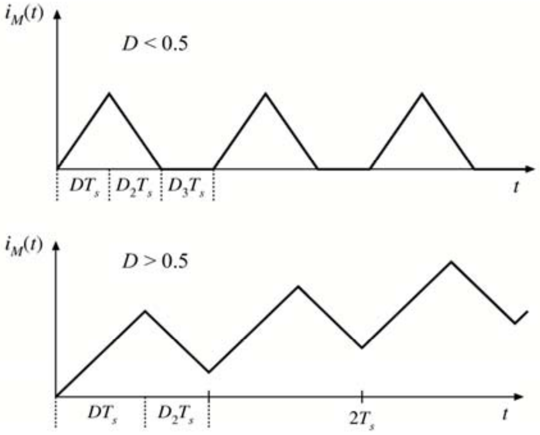
$$D_3 = 1 - D\left(1 + \frac{n_2}{n_1}\right) \geq 0$$

Solve for D

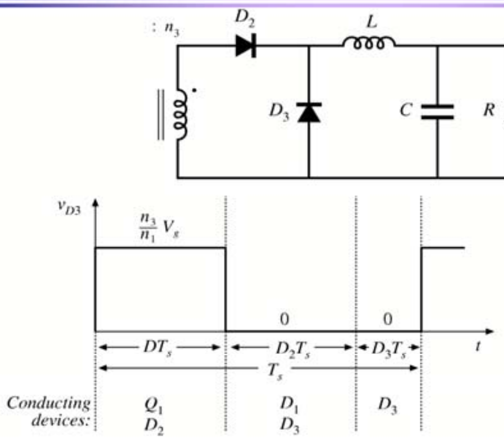
$$D \leq \frac{1}{1 + \frac{n_2}{n_1}} \qquad \text{for } n_1 = n_2\text{:} \quad D \leq \frac{1}{2}$$

What happens when $D > 0.5$

magnetizing current waveforms, for $n_1 = n_2$



Conversion ratio *M(D)*



$$\langle v_{D3} \rangle = V = \frac{n_3}{n_1} D V_g$$

Maximum duty cycle vs. transistor voltage stress

Maximum duty cycle limited to

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

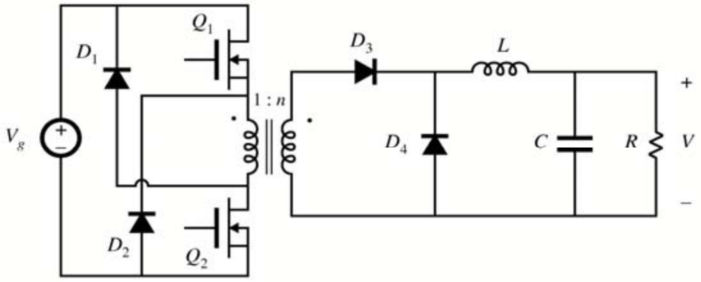
which can be increased by increasing the turns ratio n_2 / n_1. But this increases the peak transistor voltage:

$$\max\left(v_{Q1}\right) = V_g\left(1 + \frac{n_1}{n_2}\right)$$

For $n_1 = n_2$

$$D \leq \frac{1}{2} \quad \text{and} \quad \max(v_{Q1}) = 2V_g$$

The two-transistor forward converter



$V = nDV_g$ $\quad$ $D \le \frac{1}{2}$ $\quad$ $\max(v_{Q1}) = \max(v_{Q2}) = V_g$

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

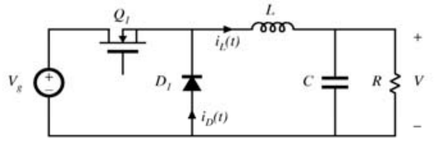
  Output impedance is increased

  Dynamics are altered

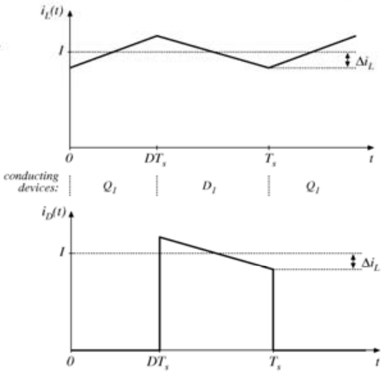
  Control of output voltage may be lost when load is removed

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

Buck converter example, with single-quadrant switches



continuous conduction mode (CCM)



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

Dc component $I = V/R$

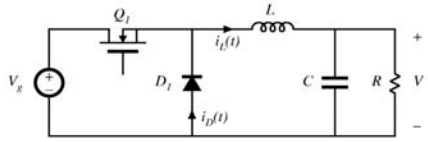
Current ripple is

$$\Delta i_L = \frac{(V_g - V)}{2L} DT_s = \frac{V_g DD'T_s}{2L}$$

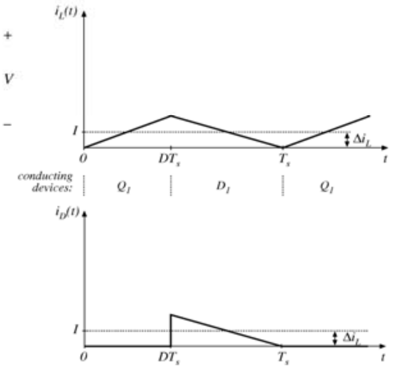
Note that I depends on load, but Δi_L does not.

Reduction of load current

Increase R, until $I = \Delta i_L$



CCM-DCM boundary



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

Dc component $I = V/R$

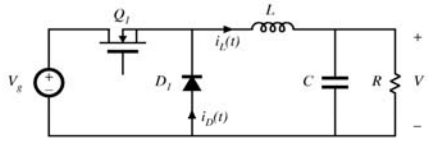
Current ripple is

$$\Delta i_L = \frac{(V_g - V)}{2L} DT_s = \frac{V_g DD'T_s}{2L}$$

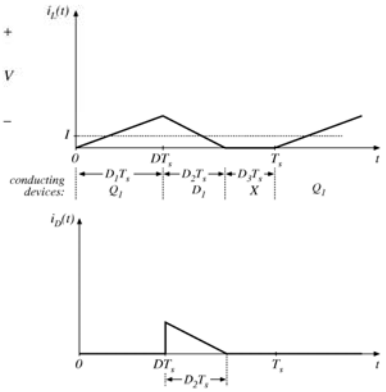
Note that I depends on load, but Δi_L does not.

Further reduce load current

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



Discontinuous conduction mode



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

Dc component $I = V/R$

Current ripple is

$$\Delta i_L = \frac{(V_g - V)}{2L} DT_s = \frac{V_g DD'T_s}{2L}$$

Note that I depends on load, but Δi_L does not.

The load current continues to be positive and non-zero.

Mode boundary

$$I > \Delta i_L \quad for\ CCM$$
$$I < \Delta i_L \quad for\ DCM$$

Insert buck converter expressions for I and Δi_L :

$$\frac{DV_g}{R} < \frac{DD'T_sV_g}{2L}$$

Simplify:

$$\frac{2L}{RT_s} < D'$$

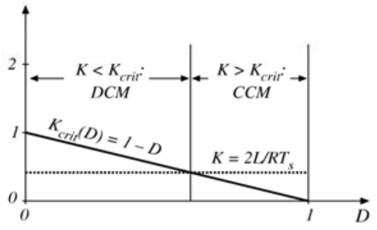
This expression is of the form

$$K < K_{crit}(D) \qquad for\ DCM$$

$$\text{where} \quad K = \frac{2L}{RT_s} \quad and \quad K_{crit}(D) = D'$$

K and K_{crit} vs. D

for $K < 1$:



for $K > 1$: