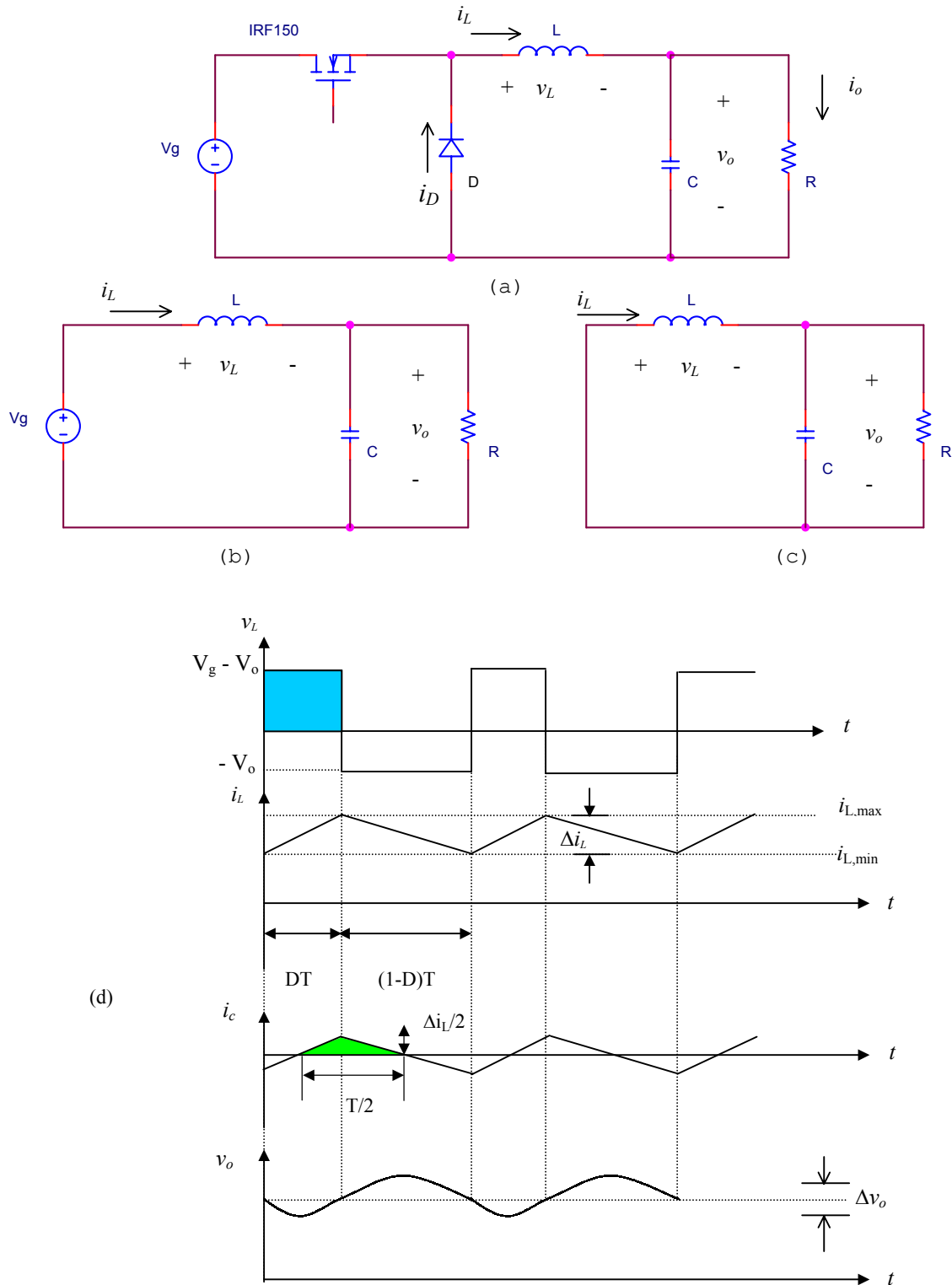


## Buck Converter

### 3-1-1 Circuit diagram and key waveforms



**Figure 3-1** (a) Buck- converter (b) switch on for a time duration  $DT$  (c) switch off for a time duration  $(1-D)T$  (d) key waveforms.

### 3-1-2 Circuit description and operation

**Circuit description.** The three basic dc-dc converters use a pair of switches, usually one controlled (eg. MOSFET) and one uncontrolled (ie. diode), to achieve unidirectional power flow from input to output. The converters also use one capacitor and one inductor to store and transfer energy from input to output. They also filter or smooth voltage and current.

The dc-dc converters can have two distinct modes of operation: Continuous conduction mode (CCM) and discontinuous conduction mode (DCM). In practice, a converter may operate in both modes, which have significantly different characteristics. Therefore, a converter and its control should be designed based on both modes of operation. However, for this course we only consider the dc-dc converters operated in CCM.

**Circuit Operation.** When the switch is on for a time duration  $DT$ , the switch conducts the inductor current and the diode becomes reverse biased. This results in a positive voltage  $v_L = V_g - V_o$  across the inductor. This voltage causes a linear increase in the inductor current  $i_L$ . When the switch is turned off, because of the inductive energy storage,  $i_L$  continues to flow. This current now flows through the diode, and  $v_L = -V_o$  for a time duration  $(1-D)T$  until the switch is turned on again.

### 3-1-3 Analytical expressions for $\frac{V_o}{V_g}$ , $\Delta i_L$ , and $\Delta v_o$

Assumptions made about the operation of the converter are as follows:

- The circuit is operating in the steady state
- The circuit is operating in the CCM
- The capacitor is large enough to assume a constant output voltage
- The components are ideal.

Equating the integral of the inductor voltage over one time period to zero yields

$$\int_0^T v_L dt = \int_0^{t_{on}} v_L dt + \int_0^{t_{off}} v_L dt = 0$$
$$(V_g - V_o) \times DT + (-V_o) \times (1-D)T = 0$$

$$V_o = DV_g$$

or

$$\frac{V_o}{V_g} = D$$

Assuming a lossless circuit,  $P_g = P_o$ ,

Therefore

$$V_g I_g = V_o I_o$$

And

$$\frac{I_o}{I_g} = \frac{V_g}{V_o} = \frac{1}{D}$$

For a buck converter, it is obvious that

$$I_L = I_o$$

$$\begin{aligned} \Delta i_L &= \frac{1}{L} \int_0^{DT} v_L dt \\ &= \frac{1}{L} [\text{Shaded area under waveform } v_L \text{ (Area A)}] \\ &= \frac{1}{L} (V_g - V_o) \times DT \end{aligned}$$

From  $\Delta i_L$  we can obtain  $i_{L,\min}$  and  $i_{L,\max}$

$$\begin{aligned} i_{L,\min} &= I_L - \frac{\Delta i_L}{2} \\ i_{L,\max} &= I_L + \frac{\Delta i_L}{2} \end{aligned}$$

To obtain the average inductor current, we can use the relationship

$$I_L = I_o = \frac{V_o}{R}$$

**The peak-peak output voltage ripple,  $\Delta v_o$ .** From the information of the capacitor current,  $i_c$ , we can obtain  $\Delta v_o$ .

$$\begin{aligned} \Delta v_o = \Delta v_c &= \frac{1}{C} \int i_c dt \\ &= \frac{1}{L} [\text{Shaded area under waveform } i_c] \\ &= \frac{1}{C} \times \frac{1}{2} \times \frac{T}{2} \times \frac{\Delta i_L}{2} \end{aligned}$$

therefore

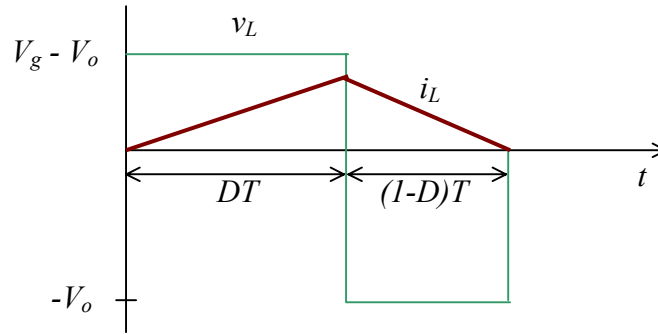
$$\Delta v_o = \frac{\Delta i_L}{8fC}$$

### 3-1-4 CCM/DCM boundary condition

Being at the boundary between the continuous and the discontinuous mode, by definition, the inductor current  $i_L$  goes to zero at the end of the off period. At this boundary, the average inductor current is

$$I_L = \frac{\Delta i_L}{2}$$

the minimum inductor current,  $i_{L, \min} = 0$  and the maximum inductor current  $i_{L, \max} = \Delta i_L$ .



We know that for buck converters  $I_L = I_o = \frac{V_o}{R}$  and  $\Delta i_L = \frac{1}{L}(V_g - V_o)DT = \frac{1}{L}V_o(1-D)T$ .

Equation at the CCM/DCM boundary,  $I_L = \frac{\Delta i_L}{2}$ , can be used to determine the combination of  $L$ ,  $f$  and  $R$  that will result in CCM. The minimum load current required for CCM operation is:

$$I_L = I_o = \frac{\Delta i_L}{2}$$

$$\therefore I_{o, \min} = \frac{1}{2L}V_o(1-D)T$$

If the desired switching frequency  $f$  and load resistance  $R$  are established, the minimum inductor current required for CCM is:

$$I_L = \frac{\Delta i_L}{2}$$

$$\frac{V_o}{R} = \frac{1}{2L}V_o(1-D)T$$

$$\therefore L_{\min} = \frac{(1-D)T \times R}{2}$$

$$= \frac{(1-D)R}{2f}$$

If the desired value of the inductor  $L$  and the load resistance  $R$  are established, the minimum switching frequency required for CCM is

$$f_{\min} = \frac{(1-D)R}{2L}$$

If the desired switching frequency and the value of the inductor  $L$  are established, the minimum load resistance required for CCM is

$$R_{\min} = \frac{2fL}{(1-D)}$$

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