Lecture 15 - Isolated DC-DC converters

Often, the output DC voltage from a DC-DC converter must be isolated from the input AC supply. DC power supplies for appliances and equipment are good examples. It is advantageous to have the isolation transformer on the DC side, where the switching frequency is high.

1. **Isolation**

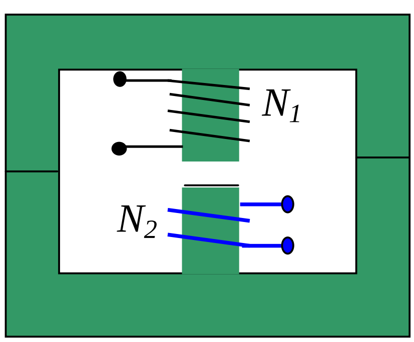
   Transformer isolation at the AC side is bulky.

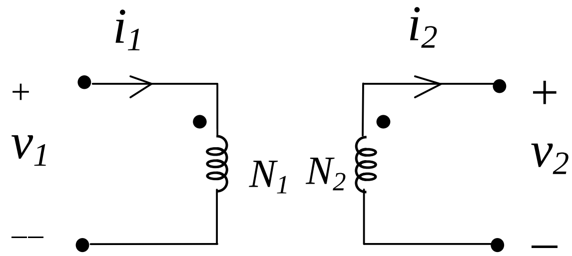
2. **Multiple Outputs**

   Multiple isolated outputs possible, using one high frequency core.

3. **Regulation (PWM duty cycle *D*-control) can take advantage of the transformer ratio.**

   DC side transformer allows design flexibility by making the range of *D* more suitable.





$$V_1/N_1 = V_2/N_2\ ; \qquad I_1N_1 = I_2N_2$$

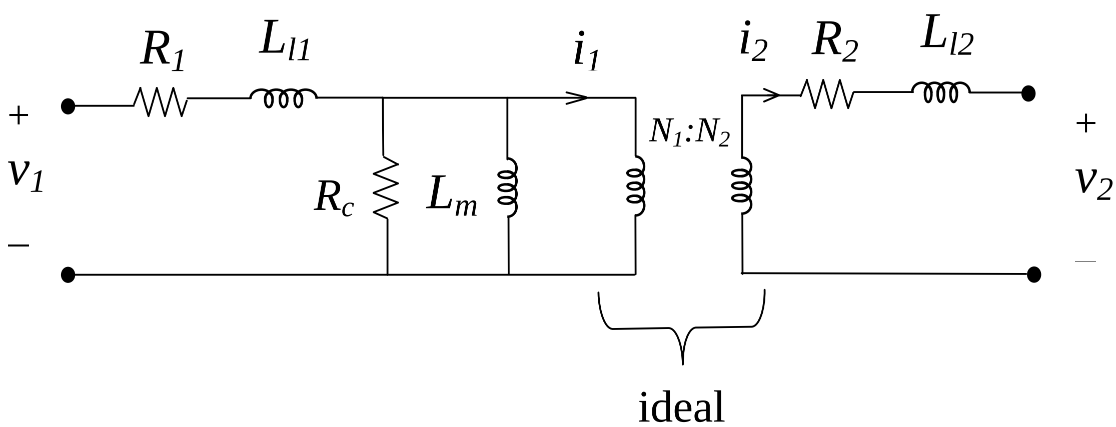


Figure 15.1(a)

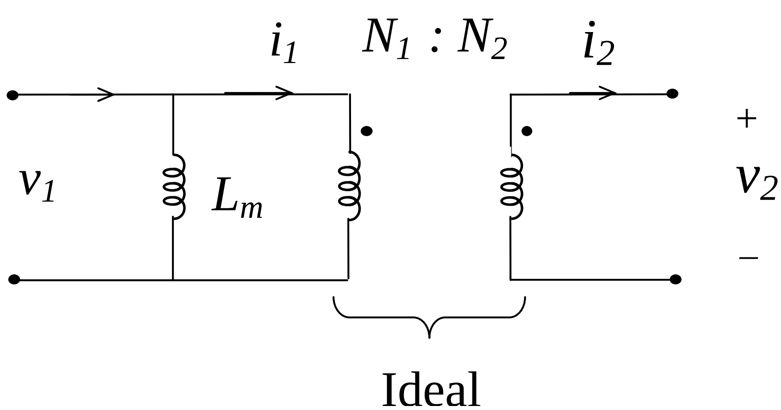


Figure 15.1 (b)

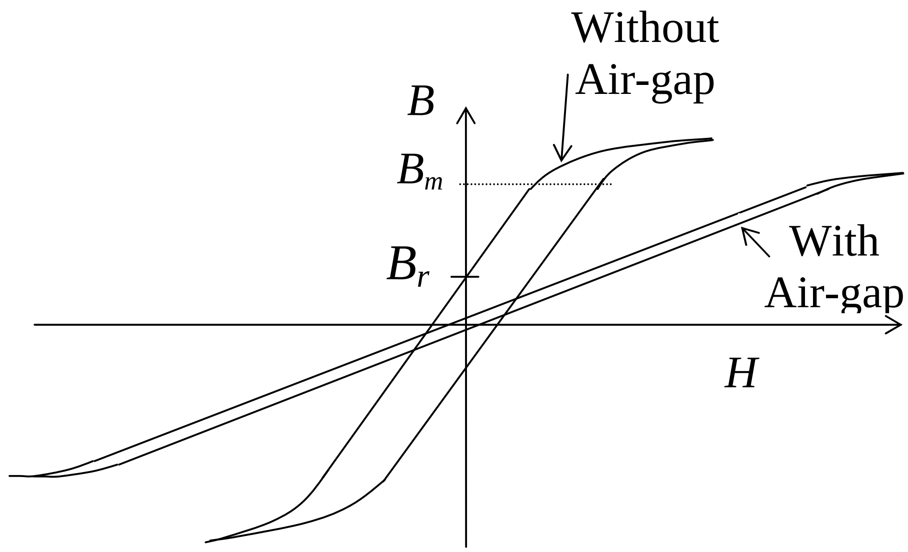


Figure 15.2

The airgap reduces the B_r, which is the B when i_m (or H_c) falls to zero. In a converter, this minimizes the snubber components which would be required to reset the core flux in each switching cycle. Operation with flux reset increases the range of variation of the flux in the core thereby increasing the utilization of the transformer (or reducing its size).

- **Unidirectional core excitation**

  Flyback (buck-boost derived) and Forward (buck derived) converters

- **Bidirectional core excitation**

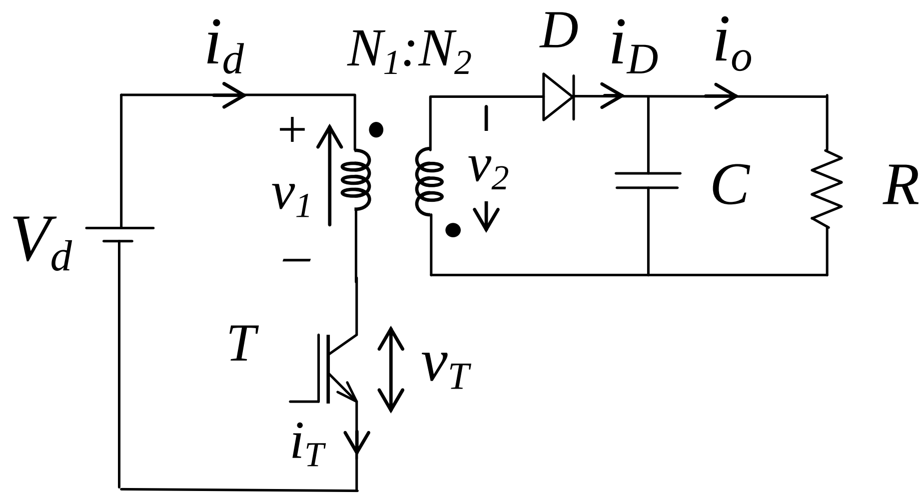
  Push-pull, half-bridge and full-bridge converters

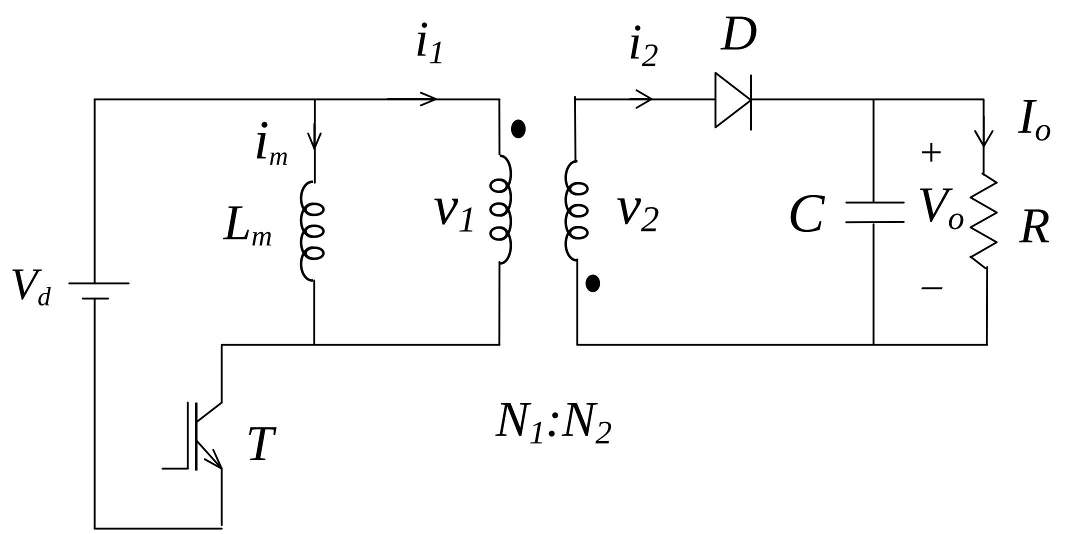
L_1, L_2 must be as small as possible for power loss considerations of the switches.

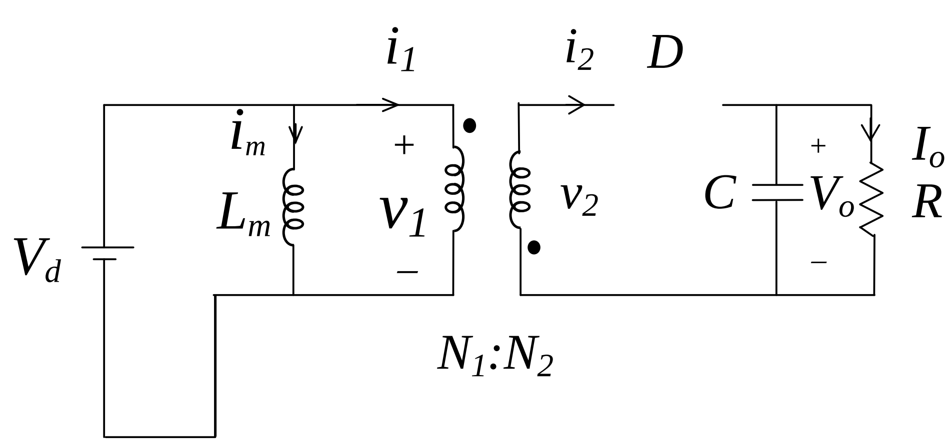
L_m must be as large/small as practicable from energy storage considerations. L_m should be large for forward converters, small for flyback converters.

Space for Figures on magnetic materials

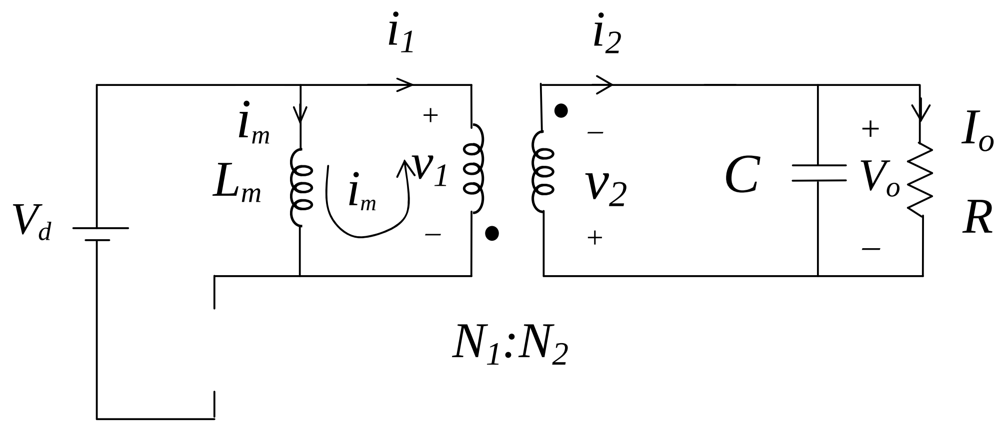
Flyback Converter (Derived from the Buck-Boost Converter)







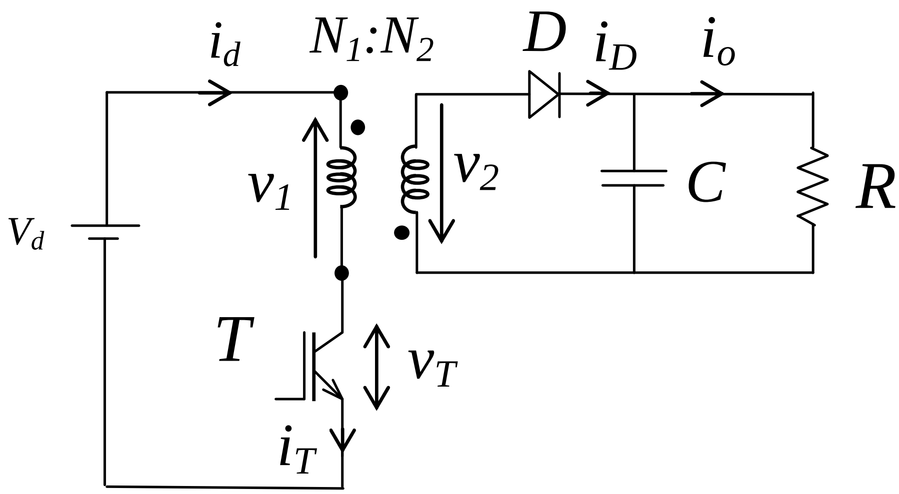
Circuit during t_{on} ; $v_1 = V_d$



Circuit during t_{off} ; $i_2 = i_D$

Figure 15.3

Analysis of the Flyback converter



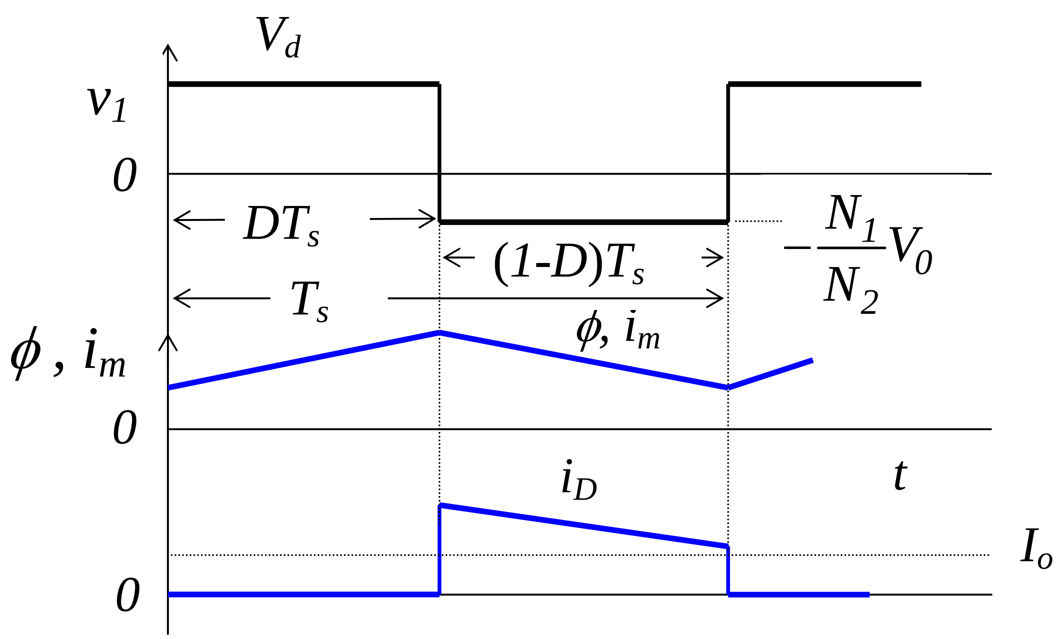


Figure 15.4

$$v = N\frac{d\phi}{dt} \quad \text{or} \quad \frac{v}{N} = \frac{d\phi}{dt} \tag{15.1}$$

During $0 < t < t_{on}$, for the primary side,

$$\phi = \phi_0 + \frac{1}{N_1}\int_0^t V_d\,dt \qquad (15.2)$$

$$\phi(t_{on}) = \phi_0 + \frac{V_d}{N_1}t_{on} = \phi_0 + \frac{V_d}{N_1}DT_s = \phi_{max} \qquad (15.3)$$

During $t_{on} < t < T_s$ for the secondary side,

$$-V_o = N_2\frac{d\phi}{dt} \qquad (15.4)$$

$$\therefore -\frac{1}{N_2}\int_{t_{on}}^{t} V_o\,dt = \phi_{max} - \frac{V_o}{N_2}\left(t - t_{on}\right) \qquad (15.5)$$

$$\phi(T_s) = \phi_{max} - \frac{V_o}{N_2}\left(T_s - t_{on}\right) = \phi_o + \frac{V_d}{N_1}DT_s - \frac{V_o}{N_2}\left(T_s - t_{on}\right)$$
$$(15.6)$$

If $\phi(0) = \phi(T_s)$

$$\therefore \frac{V_o}{V_d} = \frac{N_2}{N_1}\frac{D}{1-D} \qquad (15.7)$$

Note that $\phi(0)$ should be as small as possible in order to have the highest flux variation possible.

From power balance, $\dfrac{I_d}{I_0} = \dfrac{N_2}{N_1}\dfrac{D}{1-D}$ (15.8)

Analysis for continuous conduction

From $v = L\dfrac{di}{dt}$

During $0 < t < t_{on}$, $i_D = 0$, $\therefore$ $V_d = L_m \dfrac{di_m}{dt}$ (15.9)

$$\therefore i_m = i_T = \int_0^{t_{on}} \frac{V_d}{L_m} dt = i_{m\,min} + \frac{V_d}{L_m} t$$

$$i_{m\,max} = i_{m\,min} + \frac{V_d}{L_m} t_{on} \qquad (15.10a)$$

During $t_{on} < t < T_s$, $i_T = 0$ and

$$v_1 = -\frac{N_1}{N_2} V_o$$

$$i_m(t) = i_{m\,max} - \frac{(N_1/N_2)V_o}{L_m}(t - t_{on}) \qquad (15.10b)$$

$$i_D(t) = \frac{N_1}{N_2} i_m = \frac{N_1}{N_2}\left[i_{m\,max} - \frac{(N_1/N_2)V_o}{L_m}(t - t_{on}) \right]$$

(15.11)

Note that i_D or i_m becomes minimum when $t = T_s$. Thus,

$$i_{D\,min} = \frac{N_1}{N_2}\left[i_{m\,max} - \frac{(N_1/N_2)V_o}{L_m}(1-D)T_s \right] \quad (15.11a)$$

Also, $$i_{D\,max} = \frac{N_1}{N_2} i_{m\,max} \quad (15.11b)$$

Now, $$I_D = I_o = \frac{i_{D\,max} + i_{D\,min}}{2} \times \frac{(1-D)T_s}{T_s} \quad (15.11c)$$

From (15.11a-c)

$$\therefore \quad i_{m\,max} = i_{T\,max} = \frac{N_2}{N_1}\frac{1}{1-D} I_o + \frac{N_1}{N_2}\frac{(1-D)T_s V_o}{2L_m}$$

(15.12)

Equation 15.12 specifies i_{Tmax} for a given maximum load (I_{omax}).

Operation on continuous-discontinuous boundary

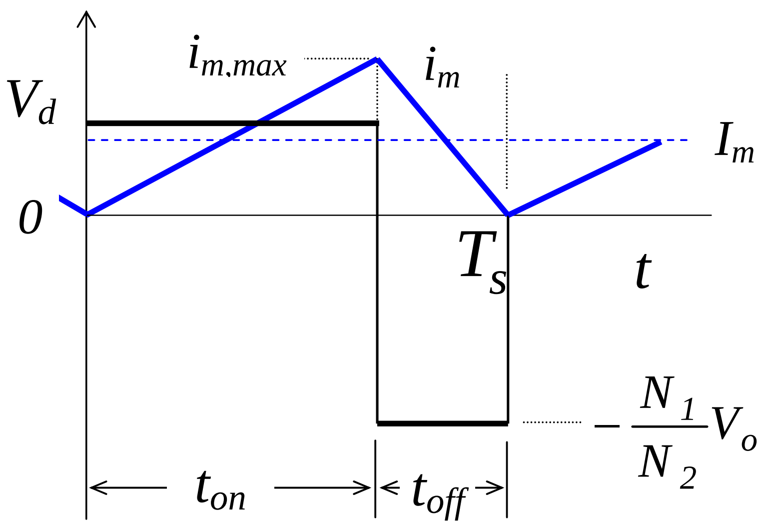


Figure 15.5

$$P_d = P_o \qquad \therefore V_d I_d = \frac{V_o^2}{R} \tag{15.13}$$

$$I_d = \frac{I_m D T_s}{T_s} = I_m D \tag{15.14}$$

where I_m is the average magnetizing current.

$$\therefore V_d I_m D = \frac{V_o^2}{R} \text{ so that } I_m = \frac{V_o^2}{V_d R D} \tag{15.15}$$

And

$$I_m = \frac{V_0^2}{V_d R D} = \frac{V_d D}{(1-D)^2 R}\left(\frac{N_2}{N_1}\right)^2 = \frac{V_0}{(1-D)R}\left(\frac{N_2}{N_1}\right)$$

(15.16)

$$\therefore i_{m,max} = I_m + \frac{\Delta i_m}{2} = \frac{V_d D}{(1-D)^2 R}\left(\frac{N_2}{N_1}\right)^2 + \frac{V_d D T_s}{2L_m} \tag{15.17}$$

$$i_{m,min} = \frac{V_d D}{(1-D)^2 R}\left(\frac{N_2}{N_1}\right)^2 - \frac{V_d D T_s}{2L_m} \tag{15.18}$$

$$\therefore L_m f_s\Big|_{min} \leq \frac{(1-D)^2 R}{2}\left(\frac{N_1}{N_2}\right)^2 \tag{15.19}$$

to ensure discontinuous conduction. Note that discontinuous conduction of i_m ensures the largest flux variation in the core of the transformer.

Flyback converter under discontinuous conduction

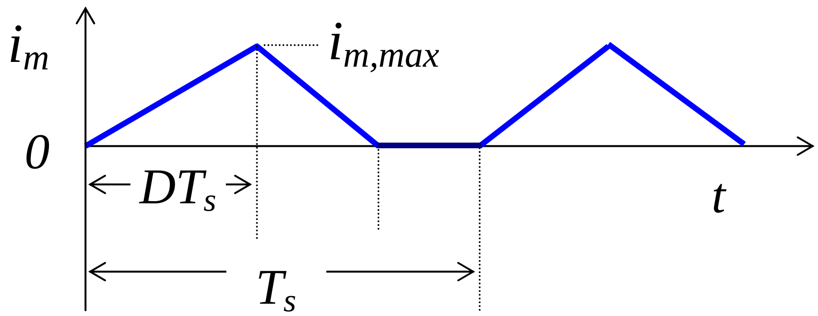


Figure 15.6

$$i_{m\,max} = \frac{V_d D T_s}{L_m}$$

$$V_d I_d = \frac{V_0^2}{R} \tag{15.20}$$

$$I_d = \frac{1}{2}\frac{V_d DT_s}{L_m} DT_s / T_s \tag{15.21}$$

$$= \frac{V_d D^2 T_s}{2L_m} \tag{15.22}$$

$$\therefore V_d I_d = \frac{V_d^2 D^2 T_s}{2L_m} = \frac{V_0^2}{R} \tag{15.23}$$

$$\therefore \frac{V_o}{V_d} = D\sqrt{\frac{T_s R}{2L_m}}$$

$$= D \times \sqrt{\frac{R}{2 f_s L_m}} \tag{15.24}$$

$$\therefore \; D = \frac{V_o}{V_d} \sqrt{\frac{2 f_s L_m}{R}} \tag{15.25}$$

Switch voltage, v_T, during $t_{on} < t < T_s$

$$v_T = V_d + \frac{N_1}{N_2} V_o$$

$$= V_d + \frac{N_1}{N_2} \frac{N_2}{N_1} \frac{D}{1 - D} V_d = \frac{V_d}{1 - D} \tag{15.26}$$

Note: Operation in discontinuous mode utilizes the transformer better. Snubber requirement is also the lowest.

Output voltage ripple

$$\frac{\Delta V_0}{V_0} = \frac{D}{RCf_s} \tag{15.26}$$

as for a buck-boost converter, assuming continuous conduction. For discontinuous conduction, ΔV_o will be worse than this because the output capacitor will lose charge for longer than t_{on}.

Two-switch Flyback converter

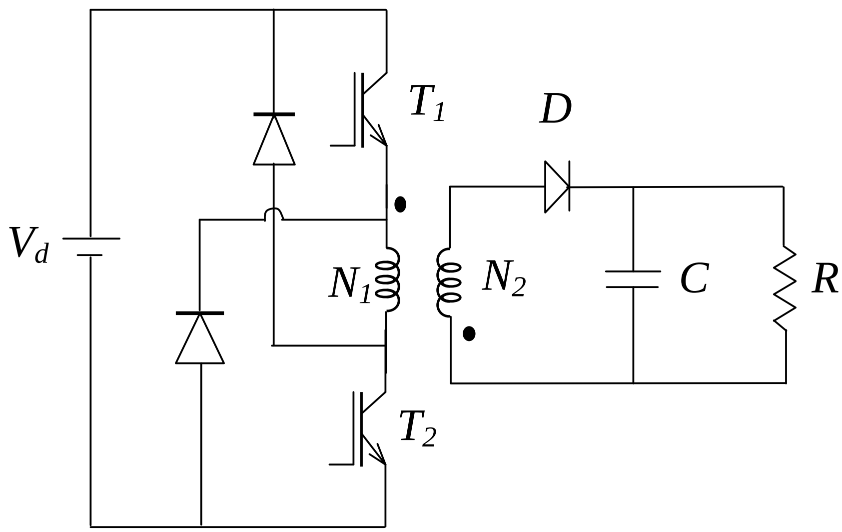


Figure 15.7

- Transistors T1 and T2 are turned on and off simultaneously.
- Energy trapped in the leakage inductances now has a regenerative path to flow through. Trapped energies in these inductances return to the DC source.
- Snubber requirement is thus even smaller.
- The two transistors may have half the voltage rating of the single-transistor Flyback converter.