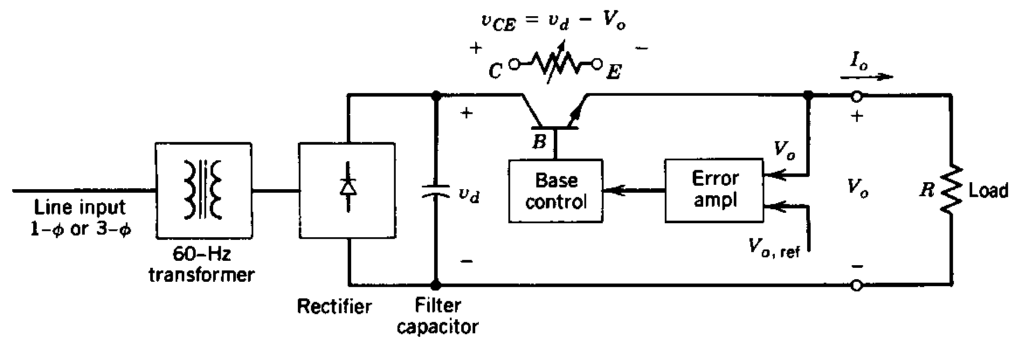
Electronic Power Conversion

Switch Mode DC-DC Converters with Isolation

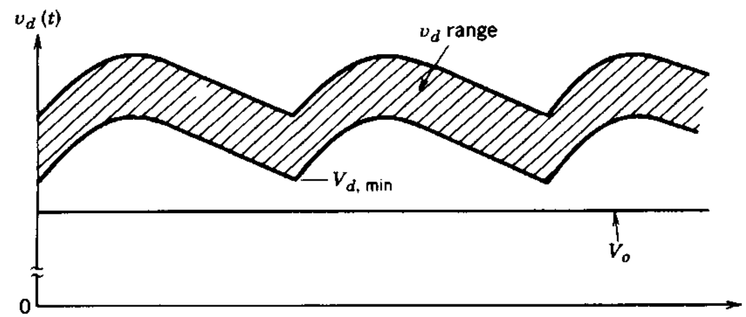
Switch mode dc-dc converters

Frequent requirements:
- regulated output
- isolation (safety)
- multiple outputs



(a)

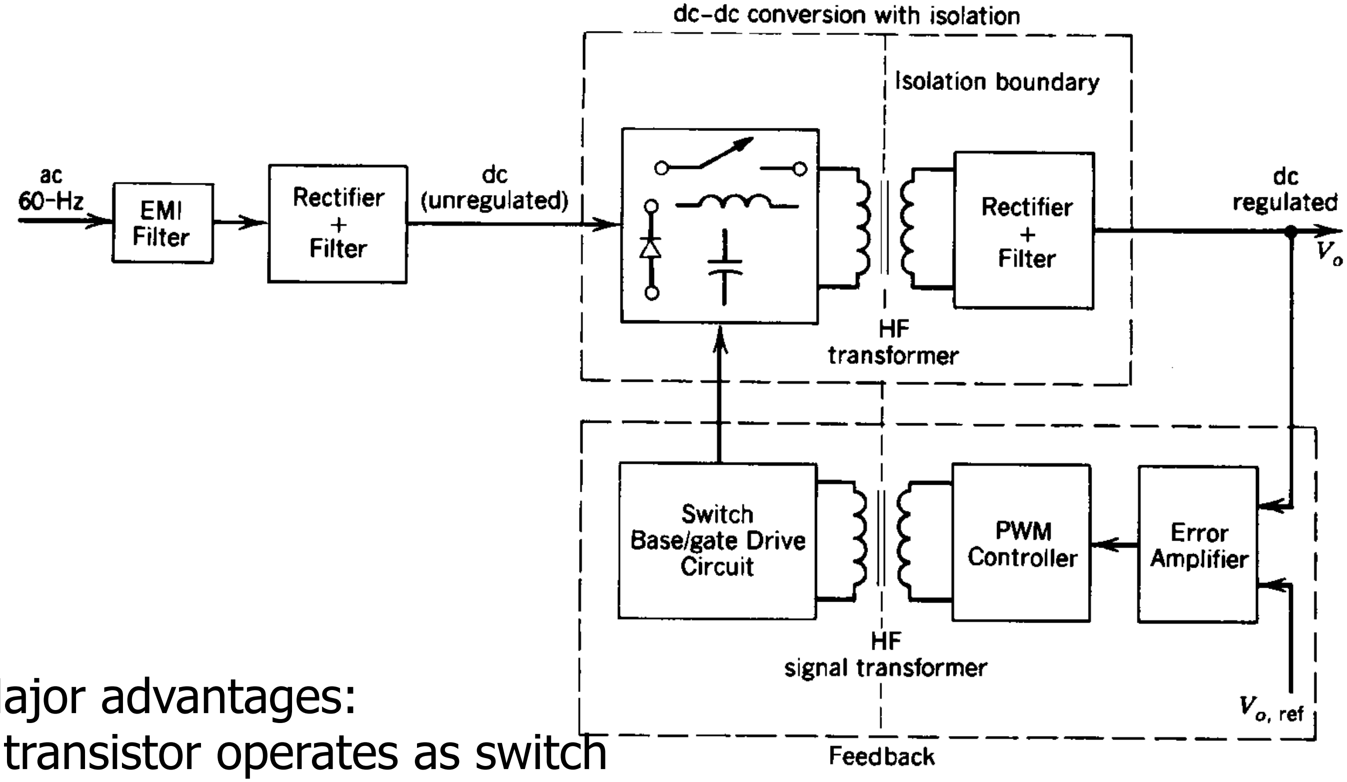
Solutions:
- Linear power supplies
- Switch mode power supplies



(b)

Drawbacks of linear power supplies
- 50Hz transformer required
- transistor absorbs voltage ➔ loss, heat

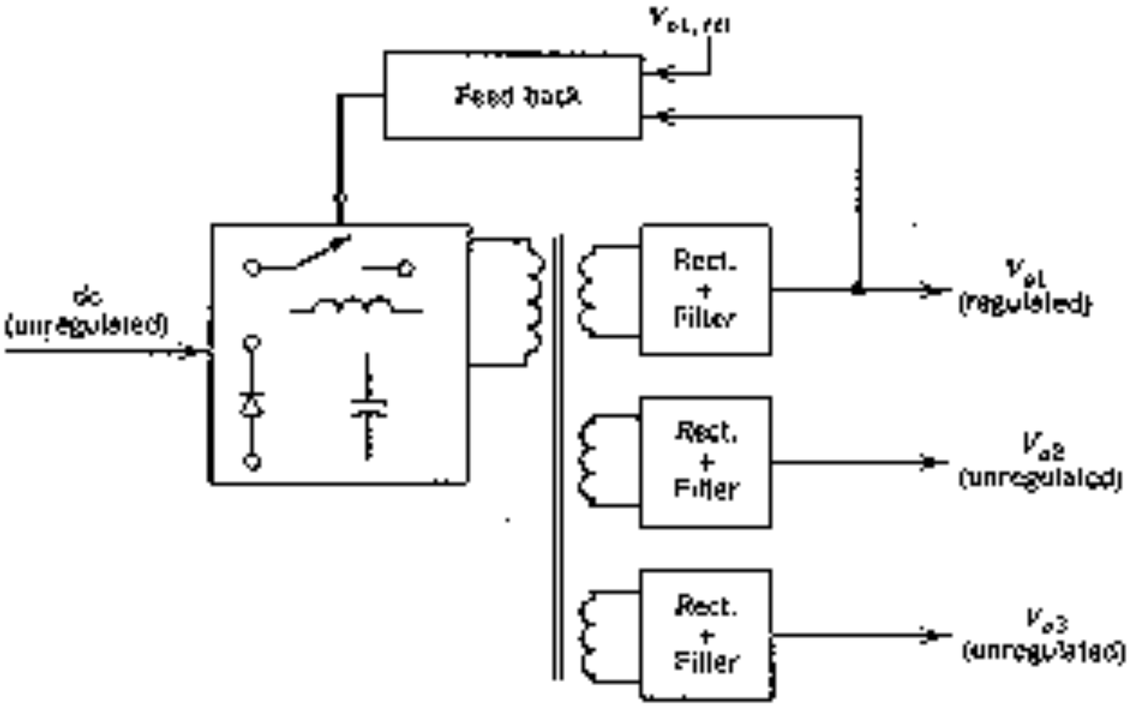
Switch-mode power supplies



Major advantages:
- transistor operates as switch
- no 50Hz transformer needed ➔ reduced weight and costs

however:
- more complex
- measures to prevent (conducted) EMI needed
- resonant type dc power supplies are not considered here (Ch9)

Multiple outputs



- one output is regulated by PWM
- if needed other output can be post-regulated by linear regulators

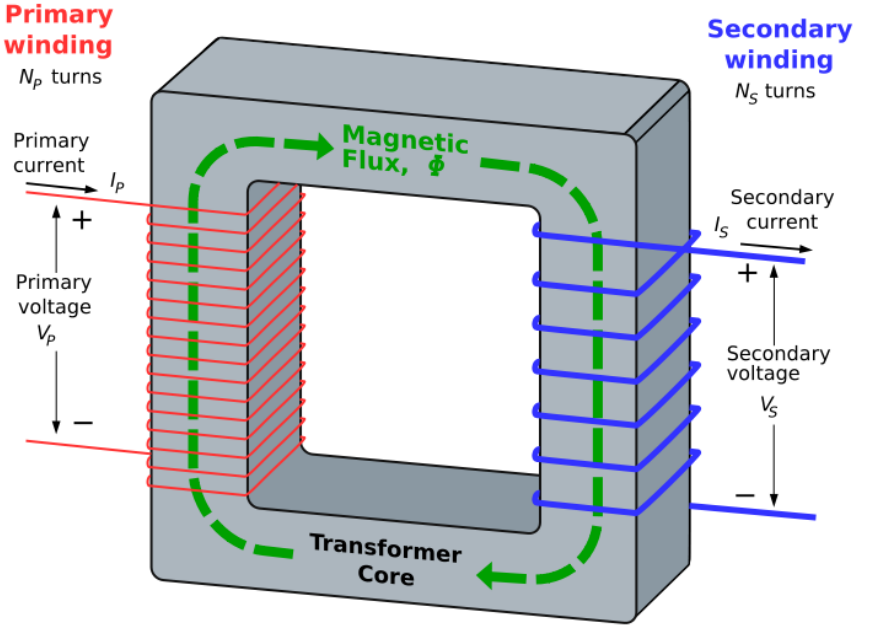
Transformer

- Ideal transformer

Faraday's law

$$v_1 = N_1 \cdot \frac{d\phi}{dt} \qquad v_2 = N_2 \cdot \frac{d\phi}{dt}$$

$$\frac{v_1}{N_1} = \frac{v_2}{N_2}$$

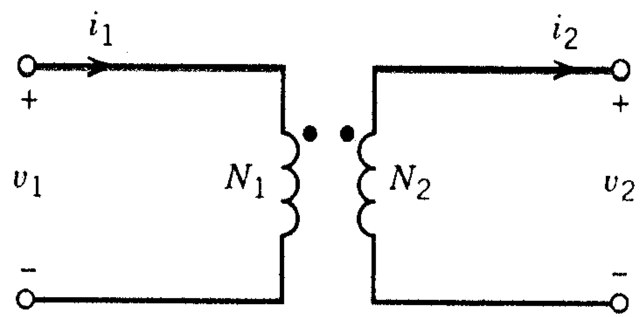


Ampere's law

$$\sum_{i=1,2} N_i i_i = \phi \cdot \Re \qquad N_1 i_1 - N_2 i_2 = \phi \cdot \Re$$

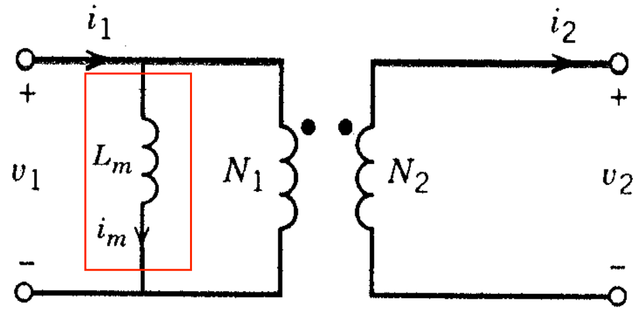
$$i_1 N_1 = i_2 N_2$$

Core reluctance $\Re = \dfrac{l}{\mu A} \approx 0$



Transformer

- Magnetising inductance



$$\Re = \frac{l}{\mu A} \neq 0$$

Non-zero
core reluctance

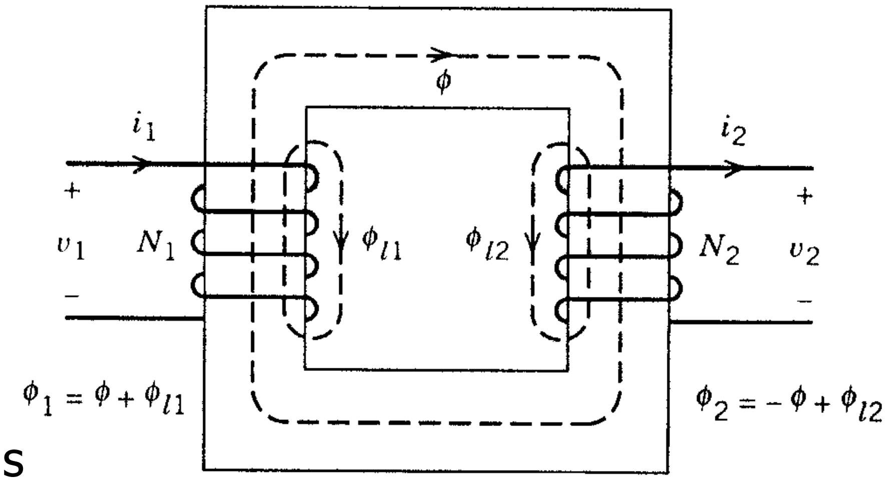
$$\left.\begin{aligned} N_1 i_1 - N_2 i_2 &= \phi \cdot \Re \\ v_1 &= N_1 \cdot \frac{d\phi}{dt} \end{aligned}\right\} \quad v_1 = \frac{N_1}{\Re} \cdot \frac{d}{dt}\left(i_1 - \frac{N_2}{N_1} i_2\right) = L_m \cdot \frac{d}{dt} i_m$$

$$L_m = \frac{N_1^2}{\Re}$$

$$i_m = i_1 - \frac{N_2}{N_1} i_2$$

Transformer

- Leakage flux



$\phi_{l1,2}$ – leakage flux

$$\phi_1 = \phi + \phi_{l1}$$

$$\phi_2 = -\phi + \phi_{l2}$$

$R_{1,2}$ – ohmic resistances of the windings

$$v_1 = R_1 i_1 + N_1 \frac{d\phi_1}{dt} = R_1 i_1 + N_1 \left(\frac{d\phi_{l1}}{dt} + \frac{d\phi}{dt} \right)$$

$$v_2 = -R_2 i_2 - N_2 \frac{d\phi_2}{dt} = -R_2 i_2 - N_2 \left(\frac{d\phi_{l2}}{dt} - \frac{d\phi}{dt} \right)$$

Equivalent Transformer Circuit

$$v_1 = R_1 i_1 + N_1 \frac{d\phi_1}{dt} = R_1 i_1 + N_1 \left(\frac{d\phi_{l1}}{dt} + \frac{d\phi}{dt} \right)$$

$$L = N \cdot \phi / i$$

$$v_1 = R_1 i_1 + L_{l1} \frac{di_1}{dt} + L_m \frac{di_m}{dt}$$

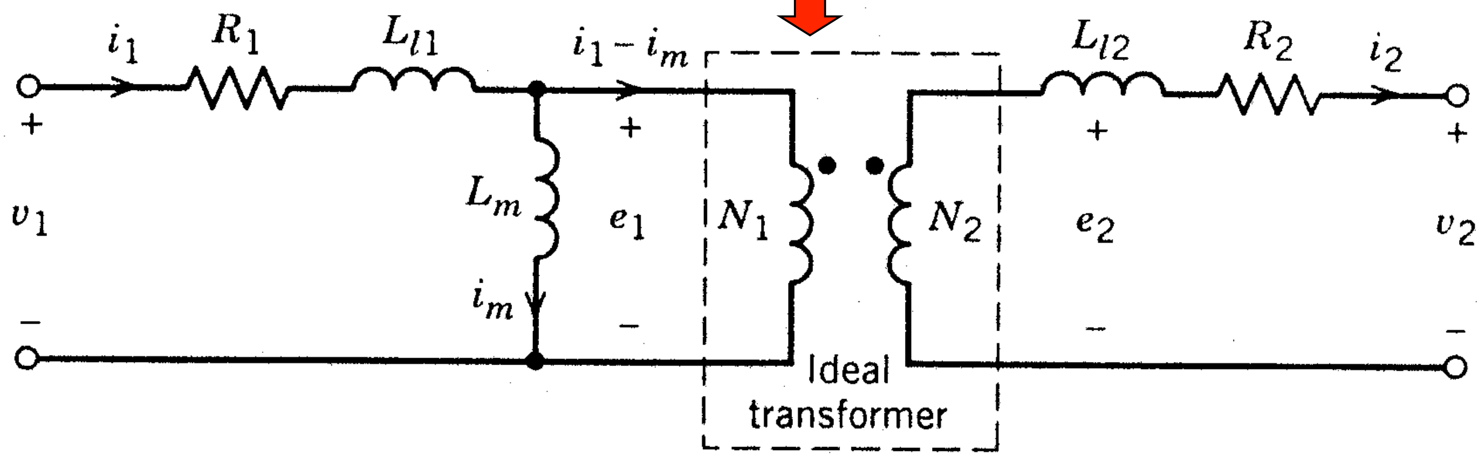
$$v_2 = -R_2 i_2 - N_2 \frac{d\phi_2}{dt} = -R_2 i_2 - N_2 \left(\frac{d\phi_{l2}}{dt} - \frac{d\phi}{dt} \right)$$

$$v_2 = -R_2 i_2 - L_{l2} \frac{di_2}{dt} + \frac{N_2}{N_1} L_m \frac{di_m}{dt}$$

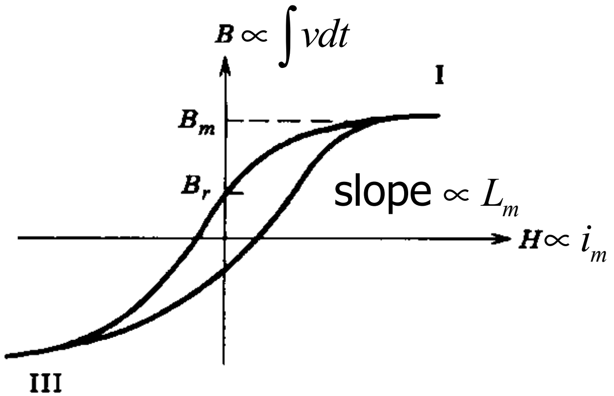
$$v_1 = R_1 i_1 + L_{l1} \frac{di_1}{dt} + e_1$$

$$i_1 = i_m + \frac{N_2}{N_1} i_2$$

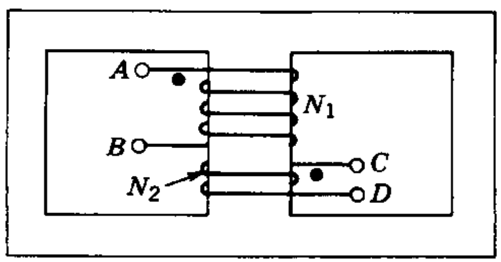
$$v_2 = -R_2 i_2 - L_{l2} \frac{di_2}{dt} + e_2$$



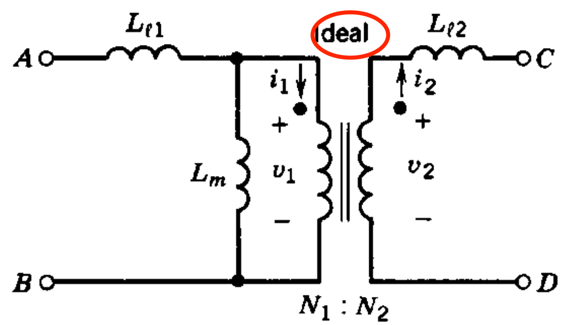
Transformer representation



(a)



(b)



(c)

$$V_1 / N_1 = V_2 / N_2$$

and

$$N_1 i_1 = N_2 i_2$$

- L_{l1} and L_{l2} are often neglected because they are intentionally small and have a minor effect on the voltage transfer function (they are important for switch selection and snubber design)
- L_m is taken into account because it affects circuit operation

- To understand operation of transformer-isolated converters:
  - replace transformer by equivalent circuit model containing magnetizing inductance
  - analyze converter as usual, treating magnetizing inductance as any other inductor
  - apply volt-second balance to all converter inductors, including magnetizing inductance

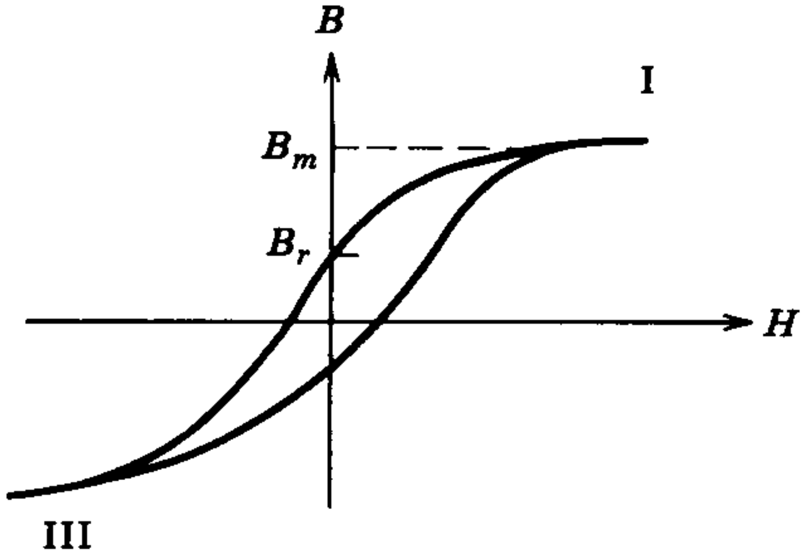
DC-DC converters with electrical isolation

Unidirectional core excitation

- flyback converter
- forward converter

Bidirectional core excitation

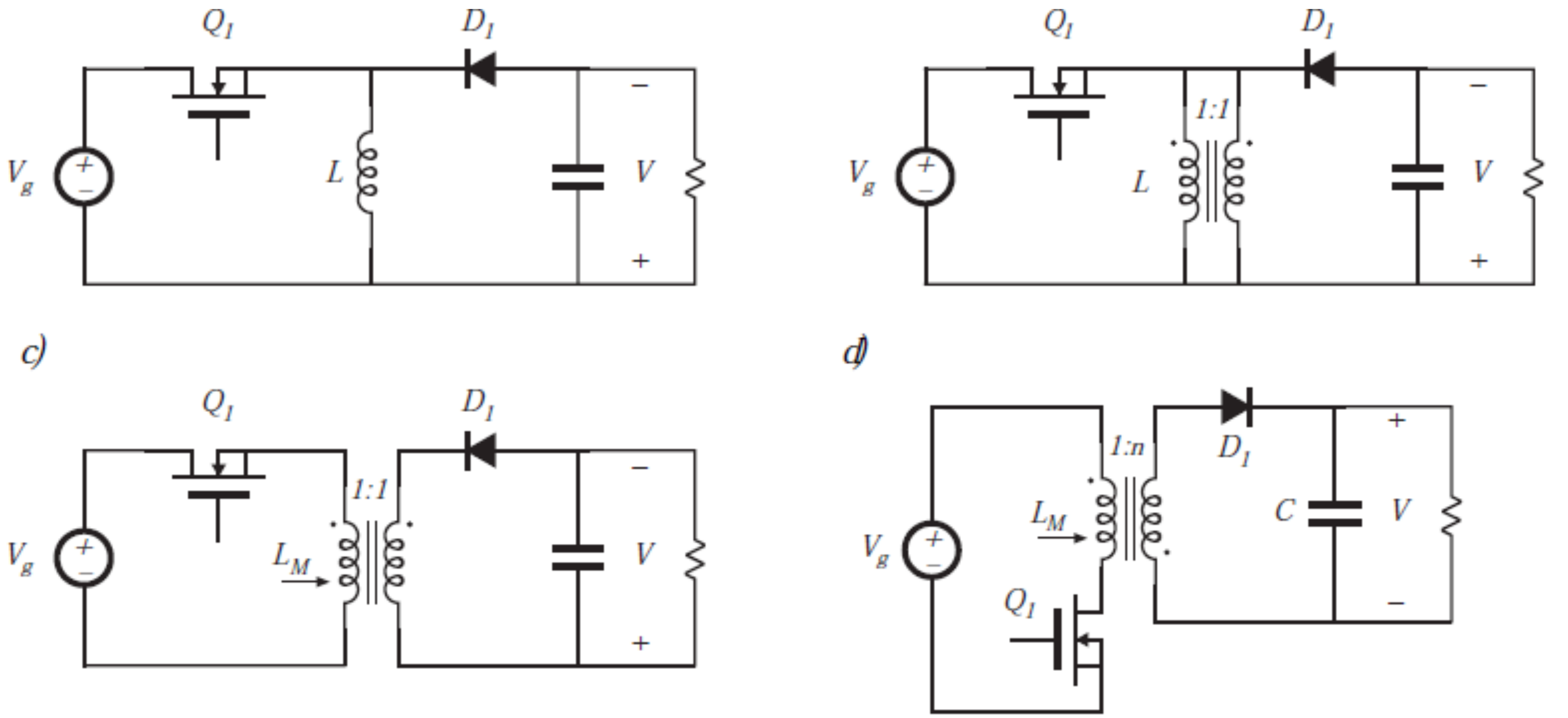
- full-bridge converter
- half-bridge converter
- push-pull converter



(a)

Flyback converter

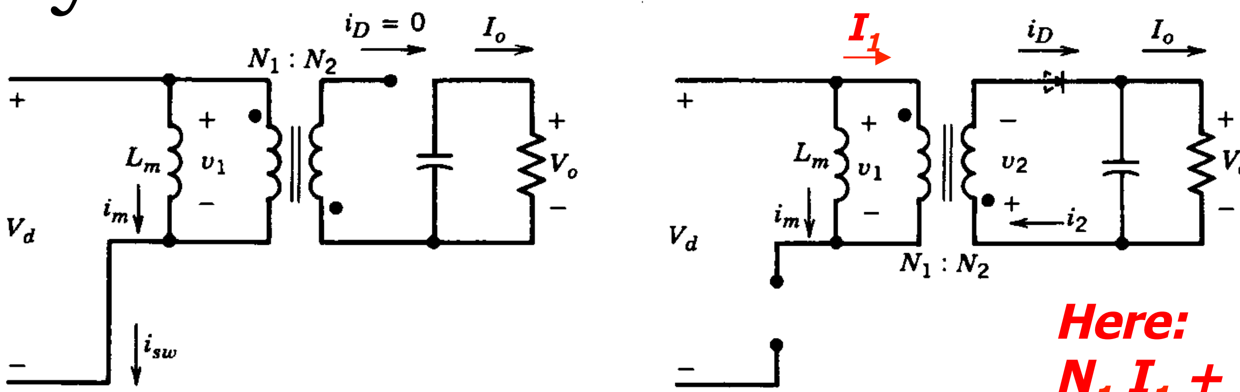
Derived from buck-boost



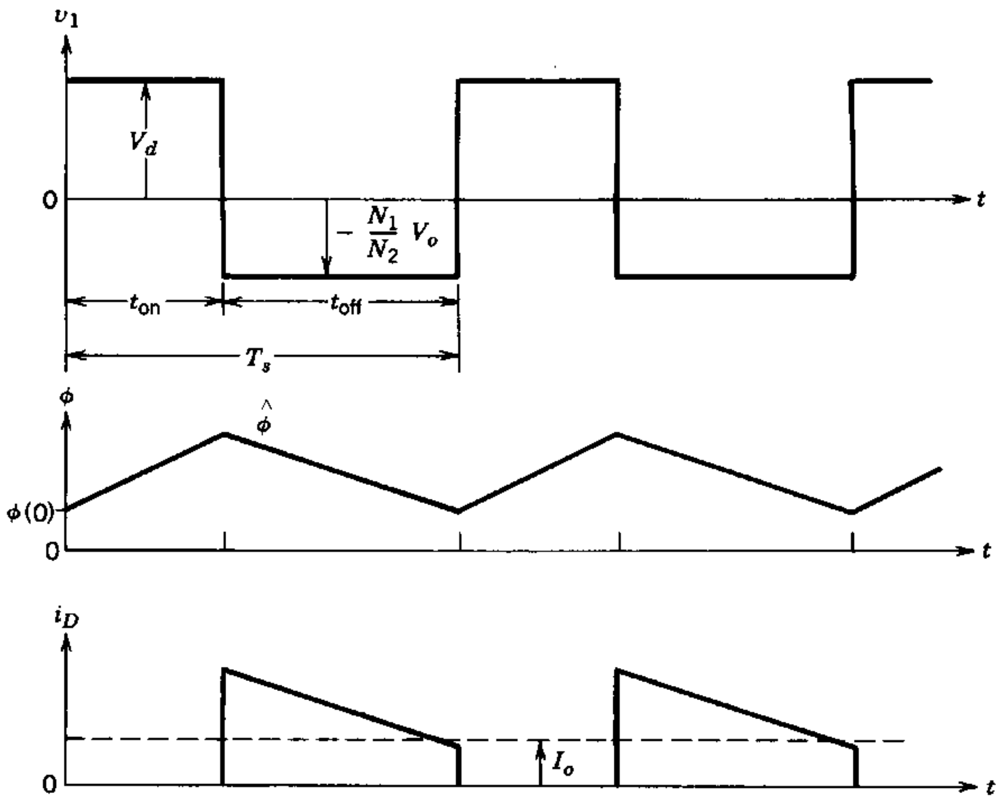
Magnetic component:

- energy storage (coupled inductor)
- transformation
- isolation

Flyback converter



(b)



Here:

$$N_1 I_1 + N_2 I_2 = 0$$

Steady state:

$$V_{L,av} = 0$$

$$V_d\, t_{on} - V_0 \frac{N_1}{N_2} (T_s - t_{on}) = 0$$

so:

$$\frac{V_0}{V_d} = \frac{N_2}{N_1} \frac{D}{1 - D}$$

Approach in book: " up-flux - down flux"

$$\hat{\phi}(t) = \phi(0) + \frac{V_d}{N_1} t_{on} \quad \Rightarrow \quad \phi(T_s) = \hat{\phi} - \frac{V_0}{N_2}(T_s - t_{on})$$

gives same result.

$$= \phi(0) + \frac{V_d}{N_1} t_{on} - \frac{V_0}{N_2}(T_s - t_{on})$$

'Inductor' current

$$i_m(t) = i_m(0) + \frac{V_d}{L_m} t$$

$$i_m(t) = \hat{i}_m - \frac{V_0 (N_1 / N_2)}{L_m}(t - t_{on})$$

Switch utilisation

$$\hat{V}_T = V_d + \frac{N_1}{N_2} V_o = \frac{V_d}{1-D}$$

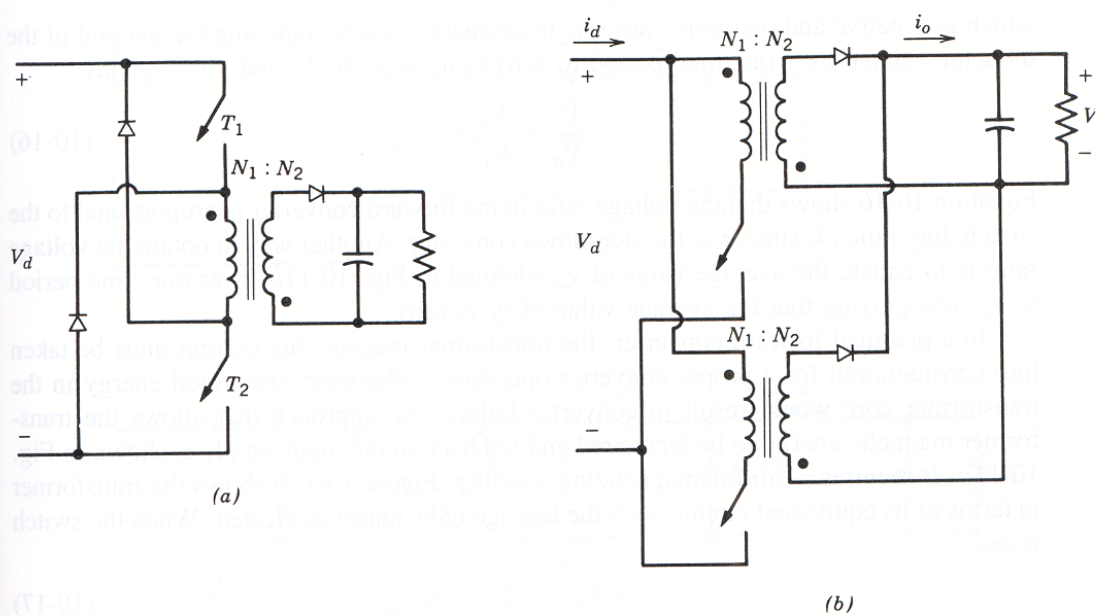
$$\hat{I}_T = i_m(0) + \frac{V_d}{L_m} t_{on}$$

Example:

V_d=350; D=0.5 ➔ $V_{T,max}$=700V

- CCM
  - Larger transformer
  - Smaller peak currents
- DCM
  - Smaller transformer
  - Larger peak currents
- BCM (boundary condition mode)
  - "Design of low power power supplies" course – Q3 (control, EMI, magnetics design, loss calculation)
- Flyback converter
  - Low part count (cheap)
  - High transistor voltage stress

Other flyback converter topologies



Two-switch flyback converter

- T1 and T2 switch simultaneously
- switch voltage halved

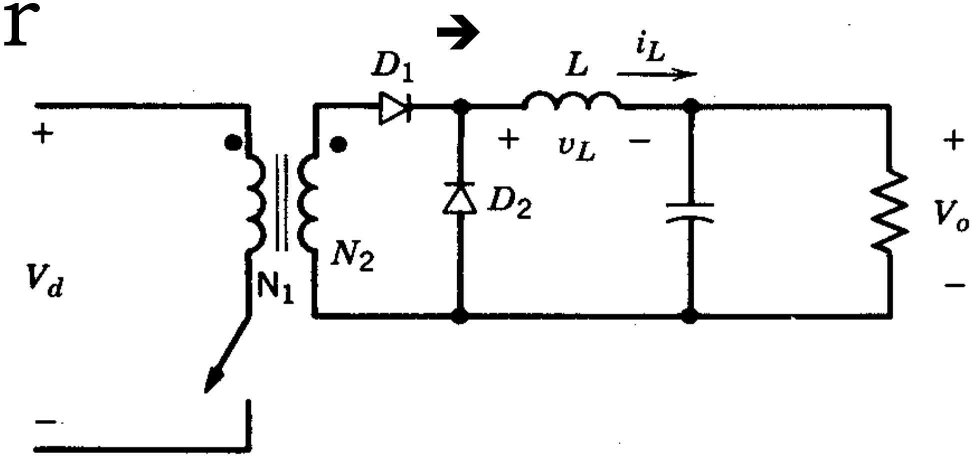
$$2\hat{V}_T = V_d + V_{x1}$$

Paralleling flyback converters

- phase shifted operation
- common output cap C filter
- double ripple current frequency at input cap and output cap ➔ smaller passives

Forward converter

$\frac{V_0}{V_d}$? $v_{L,av} = 0$



switch on, D_1 on

$$v_L = \frac{N_2}{N_1} V_d - V_0 \qquad (0 < t < t_{on})$$

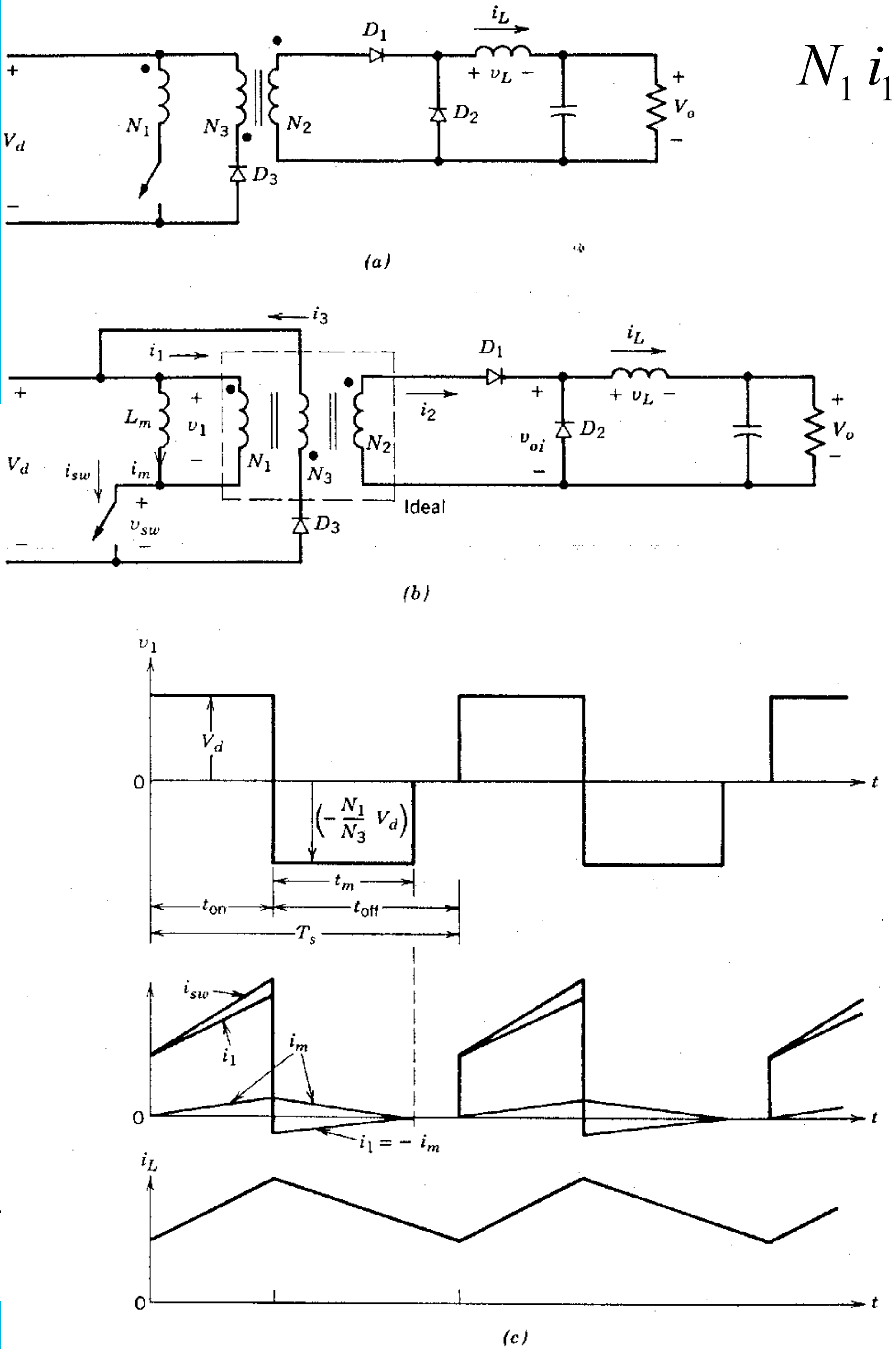
switch off, D_2 on

$$v_L = -V_0 \qquad (t_{on} < t < T_s)$$

$$v_{L,av} = 0 \;\rightarrow\; \left(\frac{N_2}{N_1} V_d - V_0\right) t_{on} - V_0 (T_s - t_{on}) = 0 \;\rightarrow\; \frac{V_0}{V_d} = \frac{N_2}{N_1} D$$

Demagnetisation winding

function: remove energy stored in L_m



$$N_1 i_1 + N_3 i_3 = N_2 i_2$$

switch off: $V_1 = -\frac{N_1}{N_3} V_3$

$v_{Lm,av} = 0 \rightarrow t_{on} V_d = t_m \frac{N_1}{N_3} V_d$

or: $\frac{t_m}{T_s} = \frac{N_3}{N_1} D \qquad (1)$

with $t_m < T_s(1-D) \qquad (2)$

From (1)&(2): $D < \frac{1}{1+N_3/N_1}$

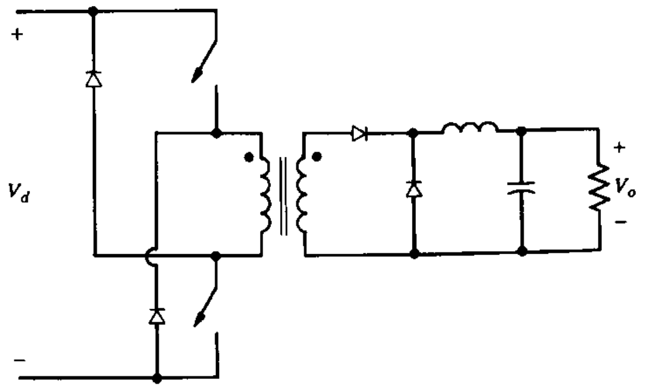
Mostly $N_1 = N_3$ so D<0.5

Switch voltage: $\hat{V}_T = V_d + \frac{N_1}{N_3} V_d$

or $\hat{V}_T = 2V_d$

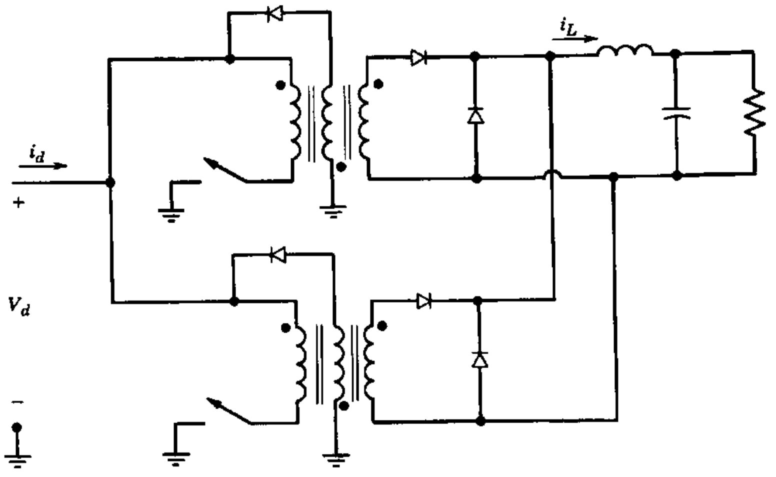
Other forward converter topologies

Two-switch forward converter
- T1 and T2 switch simultaneously
- switch voltage halved
- no demagnetisation winding needed

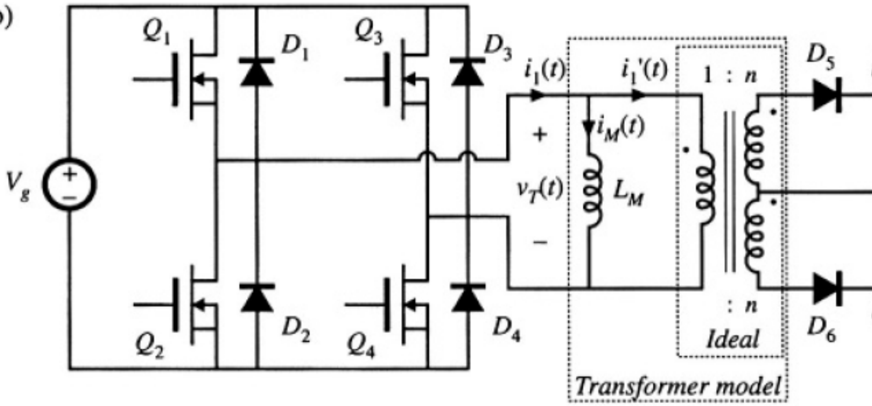


(a)

Paralleling forward converters
- phase shifted operation
- single LC filter
- double ripple current frequency at input cap and LC filter ➔ smaller passives



(b)



$$\frac{V_0}{V_d}?$$

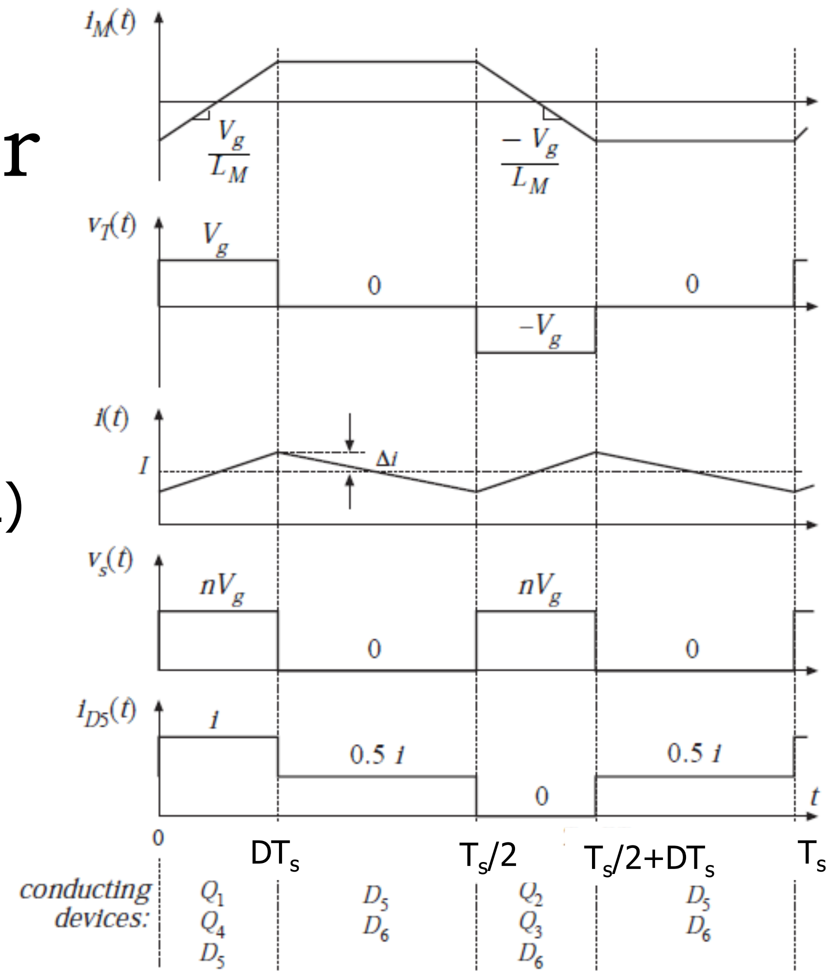
Full-bridge converter

$$v_L = \frac{N_2}{N_1} V_d - V_0 \qquad (0 < t < DT_s)$$

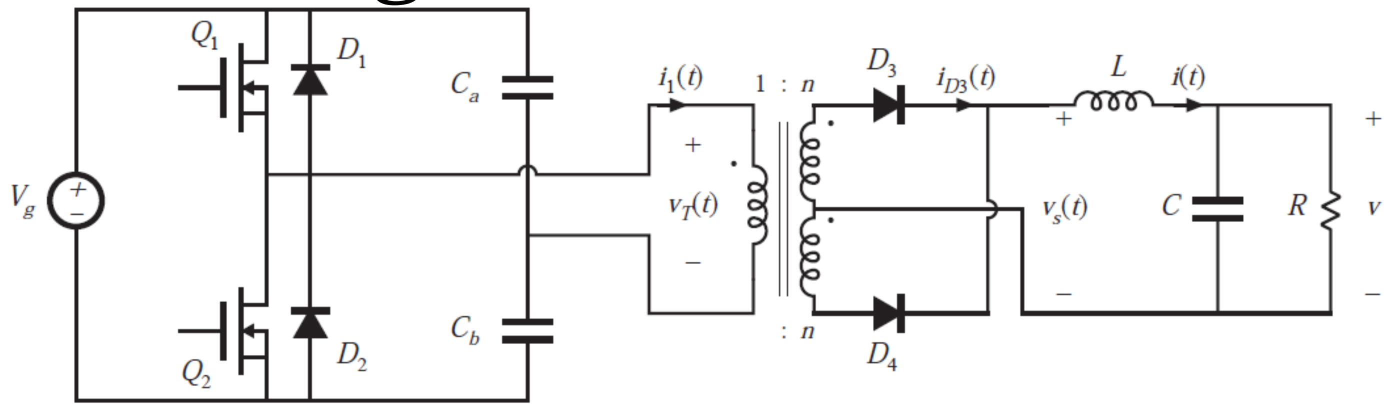
$$v_L = -V_0 \qquad (DT_s < t < T_s/2)$$

$$v_{L,av} = 0 \quad \rightarrow \quad \frac{V_0}{V_d} = 2\frac{N_2}{N_1} D$$

Switch voltage: $\hat{V}_T = V_d$



Half-bridge converter



$$\frac{V_0}{V_d}?$$

$$v_{L,av} = 0$$

$$v_L = \frac{N_2}{N_1}\frac{V_d}{2} - V_0 \qquad (0 < t < t_{on})$$

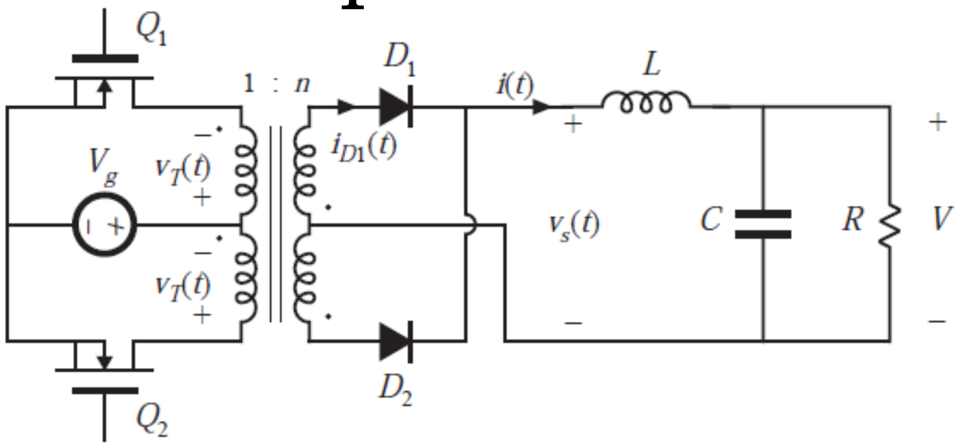
$$v_L = -V_0 \qquad (t_{on} < t < T_s)$$

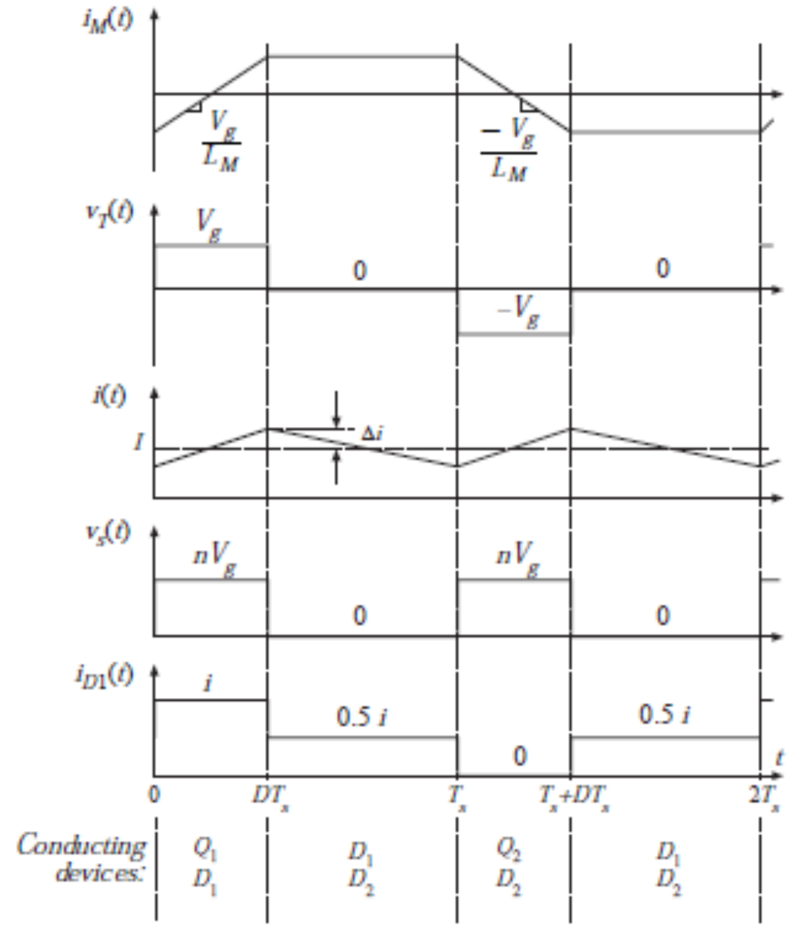
$$v_{L,av} = 0 \;\rightarrow\; \frac{V_0}{V_d} = \frac{N_2}{N_1} D$$

Value of i_T in full bridge is lower than in half bridge with same power rating:

$$(I_T)_{HB} = 2(I_T)_{FB}$$

Push-pull converter





$\frac{V_0}{V_d}$?

$v_{L,av} = 0$

$v_L = \frac{N_2}{N_1} V_d - V_0$ $\quad (0 < t < t_{on})$

$v_L = V_0$ $\quad (t_{on} < t < T_s)$

$v_{L,av} = 0 \;\rightarrow\; \frac{V_0}{V_d} = 2\frac{N_2}{N_1} D$

$(0 < D < 0.5)$

Switch voltage: $\hat{V}_T = 2V_d$

- risk of transformer saturation

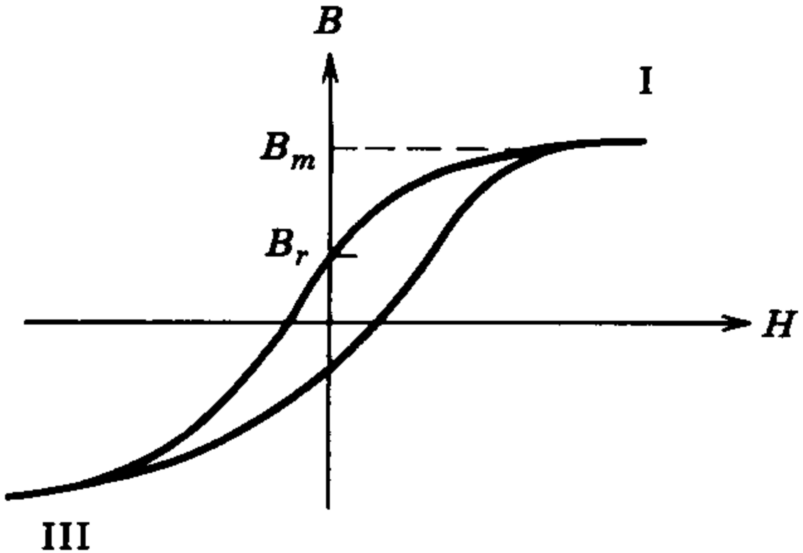
DC-DC converters with electrical isolation

Unidirectional core excitation ($\Delta B_{p\_p} = B_m - B_r$)

- flyback converter
- forward converter

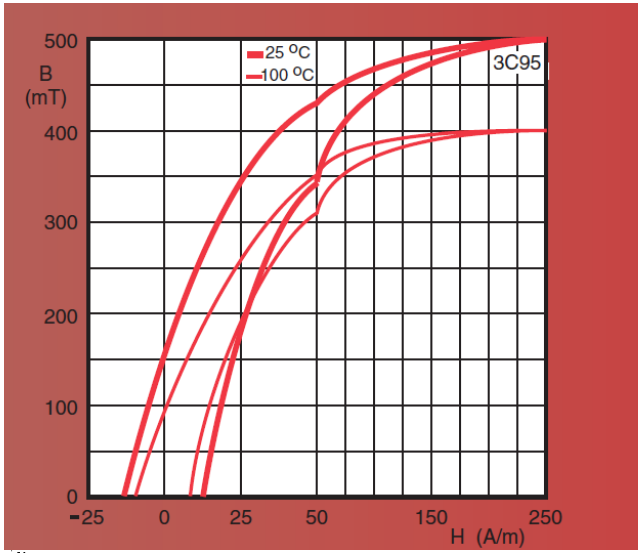
Bidirectional core excitation ($\Delta B_{p\_p} = 2B_m$)

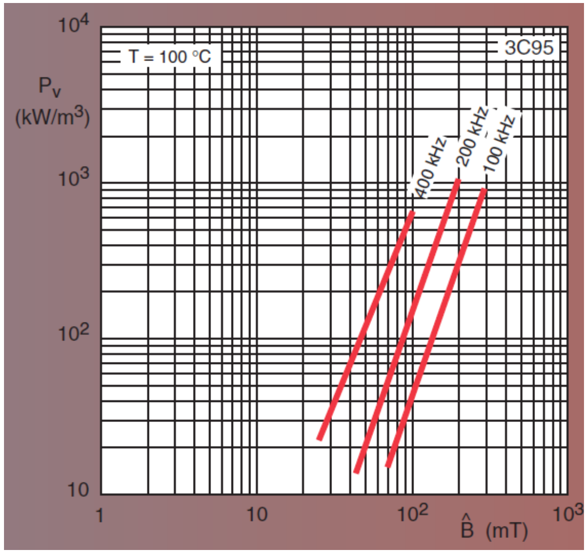
- push-pull converter
- half-bridge converter
- full-bridge converter

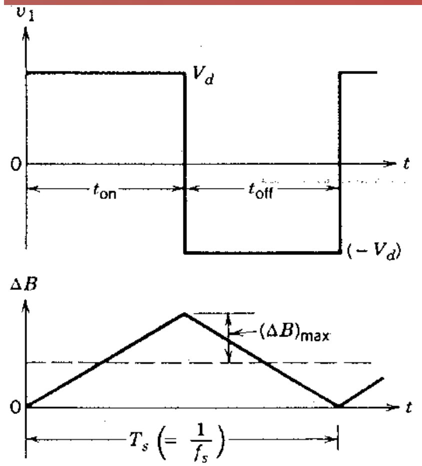


(a)

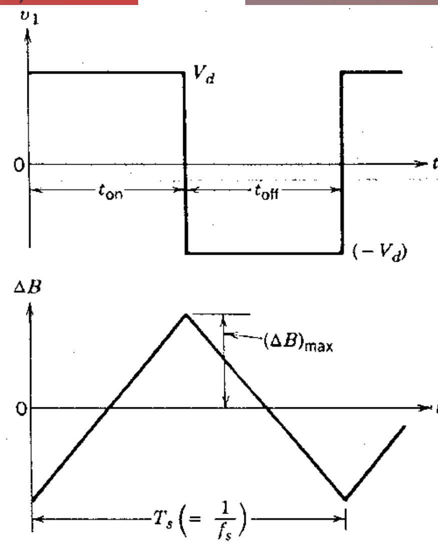
Transformer core selection







(a)

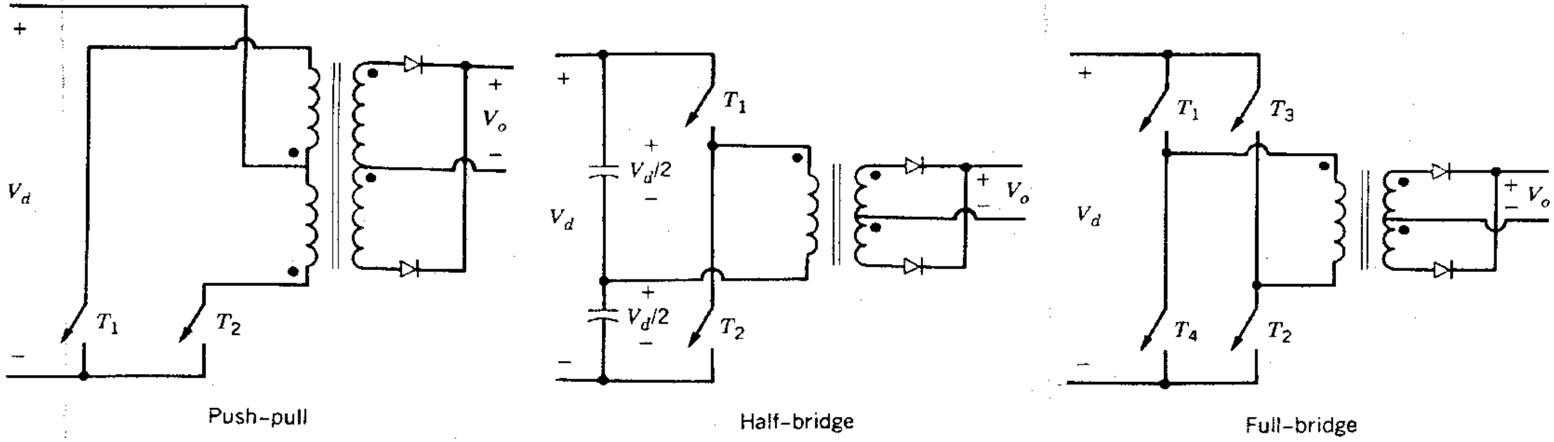


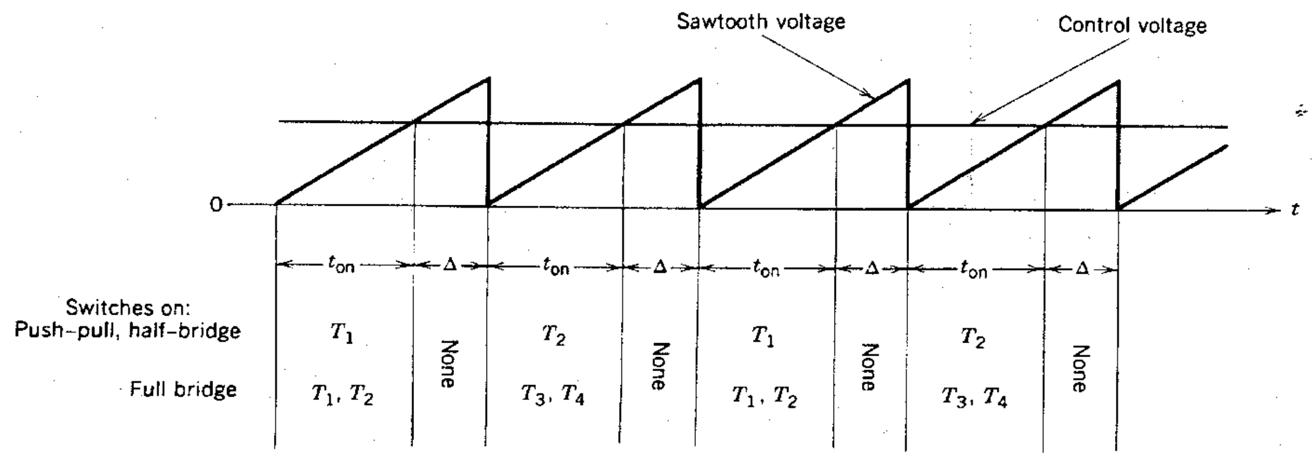
(b)

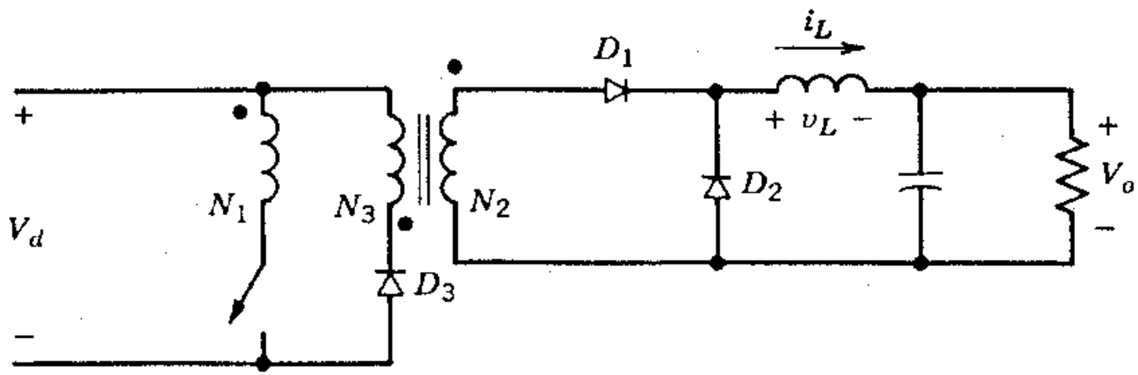
$$\text{Core loss density} = k\, f_s^a\, [\,(\Delta B)_{max}]^b$$

$$(\Delta B)_{max} = \frac{V}{4\, N_1 A_c f_s} \quad (at\ D = 0.5)$$

PWM-control of dc-dc converters with isolation







3. A forward converter shown below is operating in a continuous conduction mode. The demagnetising winding is chosen to be N3=N1. All components can be assumed to be ideal, except for the presence of transformer magnetising inductance.

The converter specifications are:

- Vd=48V±10%
- Vo=5V
- fs=100kHz
- Pload=15-50W

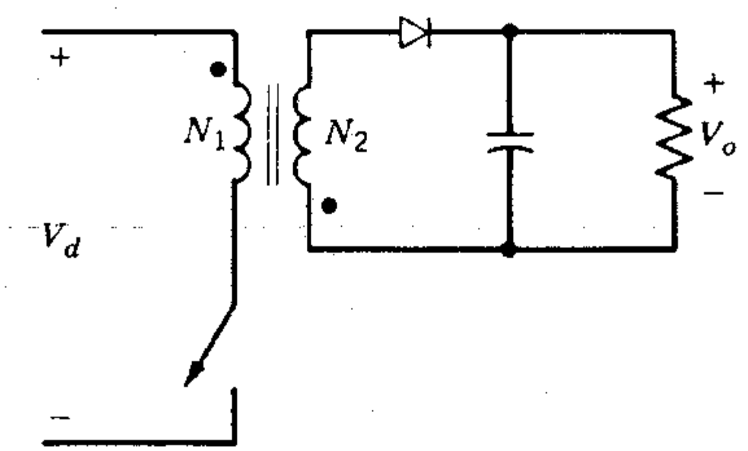
a) (10) Calculate the transformer turns ratio N2/N1 is this turns ratio is desired to be as small as possible.

b) (10) Calculate the minimum value of the filter inductance.

c) (5) Calculate the voltage rating of the switch in terms of the input voltage Vd.

Design a flyback converter operating in the discontinuous conduction mode with the following specifications:

- Input voltage $300V \leq V_d \leq 400V$ (nominal value 400V)
- Output power $0V \leq P_o \leq 50W$ (nominal value 50W)
- Output voltage $20V \leq V_o \leq 30W$ (nominal value 27V)
- Switching frequency f_s=50kHz
- Peak –to-peak voltage ripple ΔV_{0p_p}=20mV.



(b)

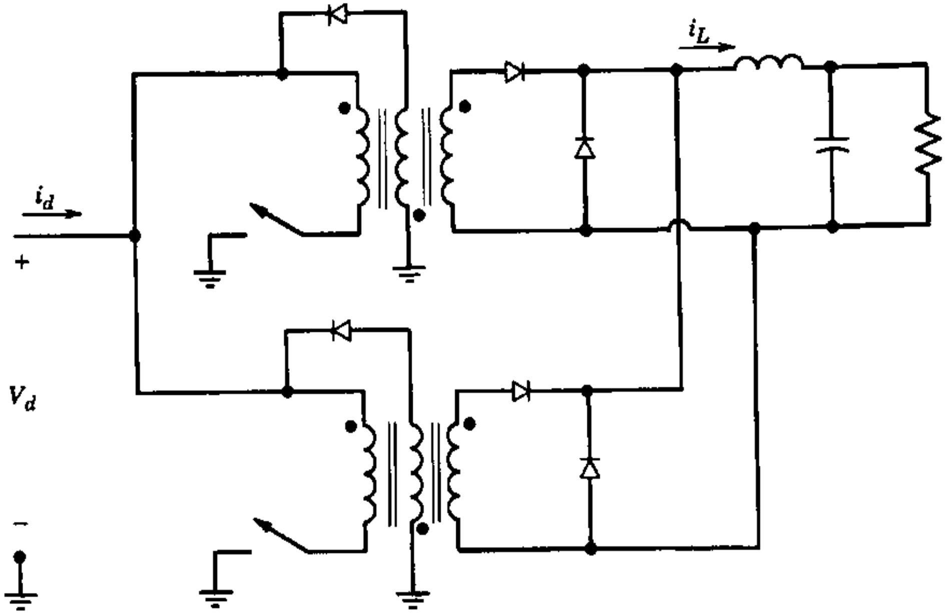
a) (15) Select the transformer turn ratio N_2/N_1, the magnetising inductance L_m and the output capacitance C. You may assume that the maximum duty cycle value is 0.5. The voltage drop across the diode when it is in on-state is 1V.

b) Sketch the waveforms and calculate RMS and DC values of the transistor and output diode current at the nominal operating point.

c) Sketch the waveforms and calculate the maximum voltages across the transistor and output diode.

In the figure below two parallel forward converters are shown. Draw the input current i_d and i_L waveforms if each converter is operating at a duty ratio of 0.3 in a continuous-conduction mode.

Compare these two waveforms with those if a single forward converter (with twice the power rating but with the same value of the output filter inductance as in double forward) is used.



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