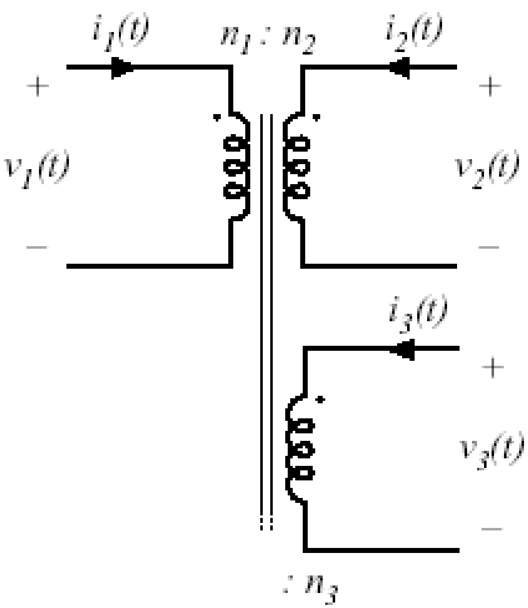
4.2 Transformer isolation

Objectives:

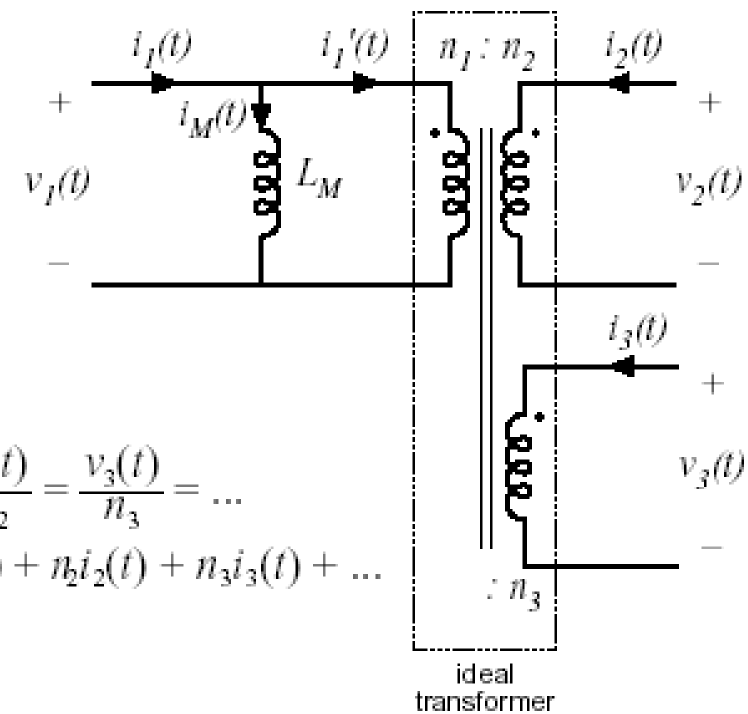
- Isolation of input and output ground connections, to meet safety requirements
- Reduction of transformer size by incorporating high frequency isolation transformer inside converter
- Minimization of current and voltage stresses when a large step-up or step-down conversion ratio is needed — use transformer turns ratio
- Obtain multiple output voltages via multiple transformer secondary windings and multiple converter secondary circuits

A simple transformer model

Multiple winding transformer



Equivalent circuit model



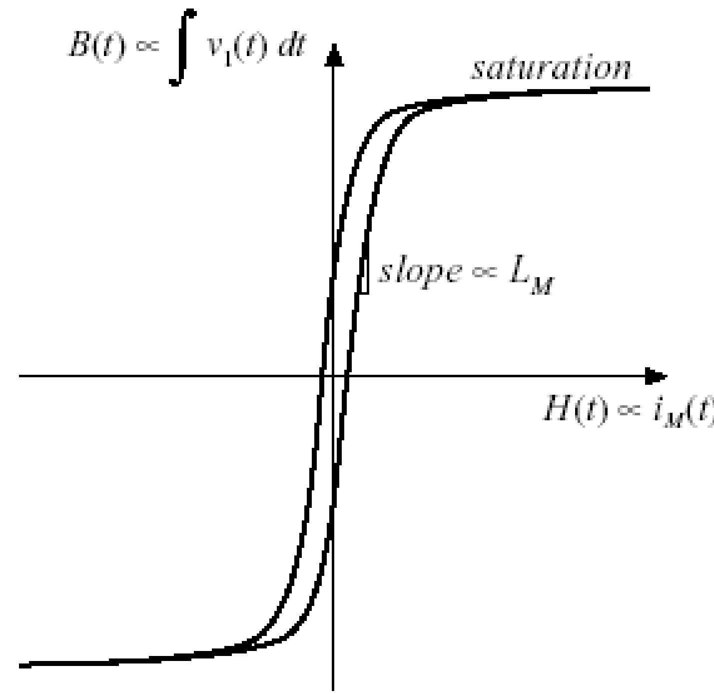
$$\frac{v_1(t)}{n_1} = \frac{v_2(t)}{n_2} = \frac{v_3(t)}{n_3} = \ldots$$

$$0 = n_1 i_1'(t) + n_2 i_2(t) + n_3 i_3(t) + \ldots$$

The magnetizing inductance L_M

- Models magnetization of transformer core material
- Appears effectively in parallel with windings
- If all secondary windings are disconnected, then primary winding behaves as an inductor, equal to the magnetizing inductance
- At dc: magnetizing inductance tends to short-circuit. Transformers cannot pass dc voltages
- Transformer saturates when magnetizing current i_M is too large

Transformer core B-H characteristic



Volt-second balance in L_M

The magnetizing inductance is a real inductor, obeying

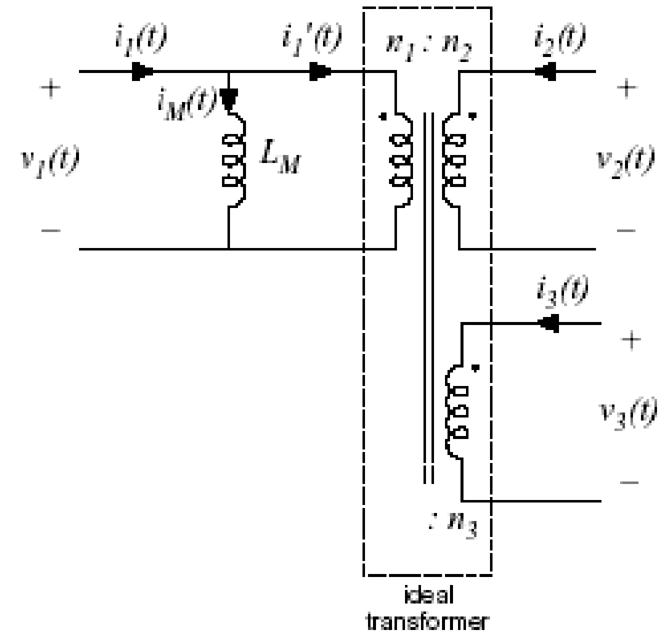
$$v_1(t) = L_M \frac{d\,i_M(t)}{dt}$$

integrate:

$$i_M(t) - i_M(0) = \frac{1}{L_M} \int_0^t v_1(\tau)\, d\tau$$

Magnetizing current is determined by integral of the applied winding voltage. The magnetizing current and the winding currents are independent quantities. Volt-second balance applies: in steady-state, $i_M(T_s) = i_M(0)$, and hence

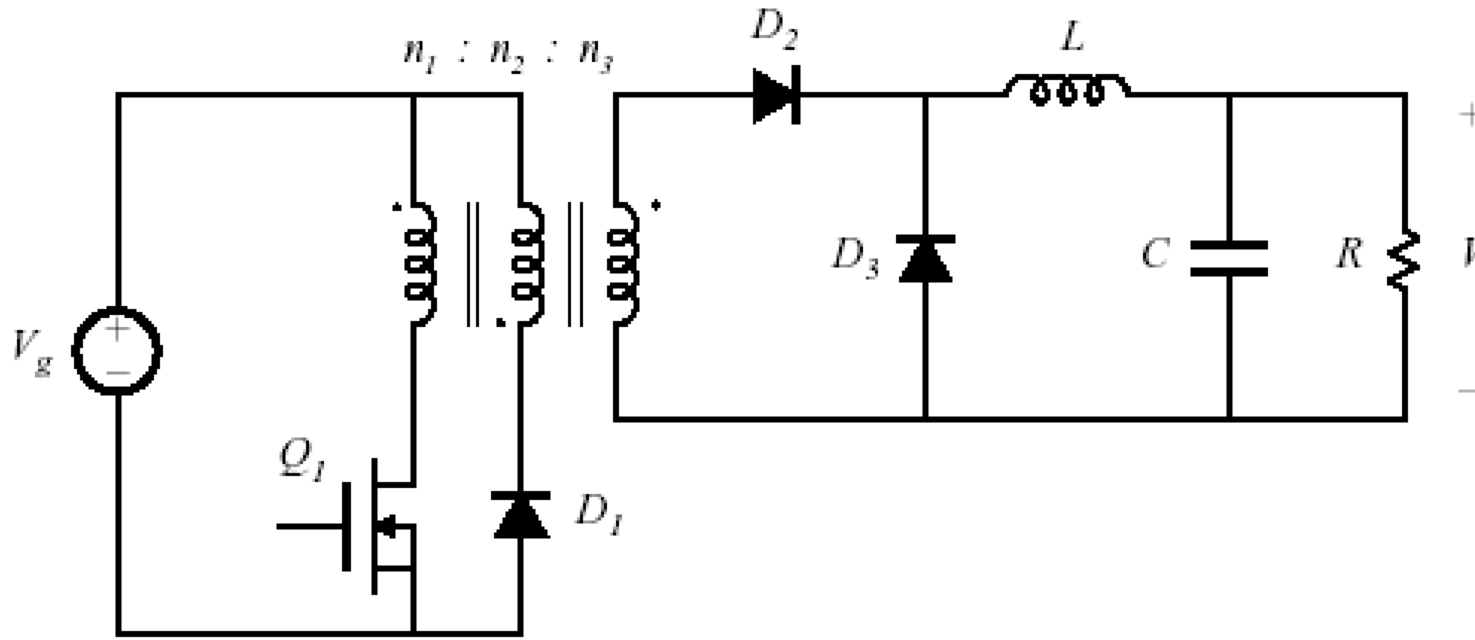
$$0 = \frac{1}{T_s} \int_0^{T_s} v_1(t)\, dt$$



Transformer reset

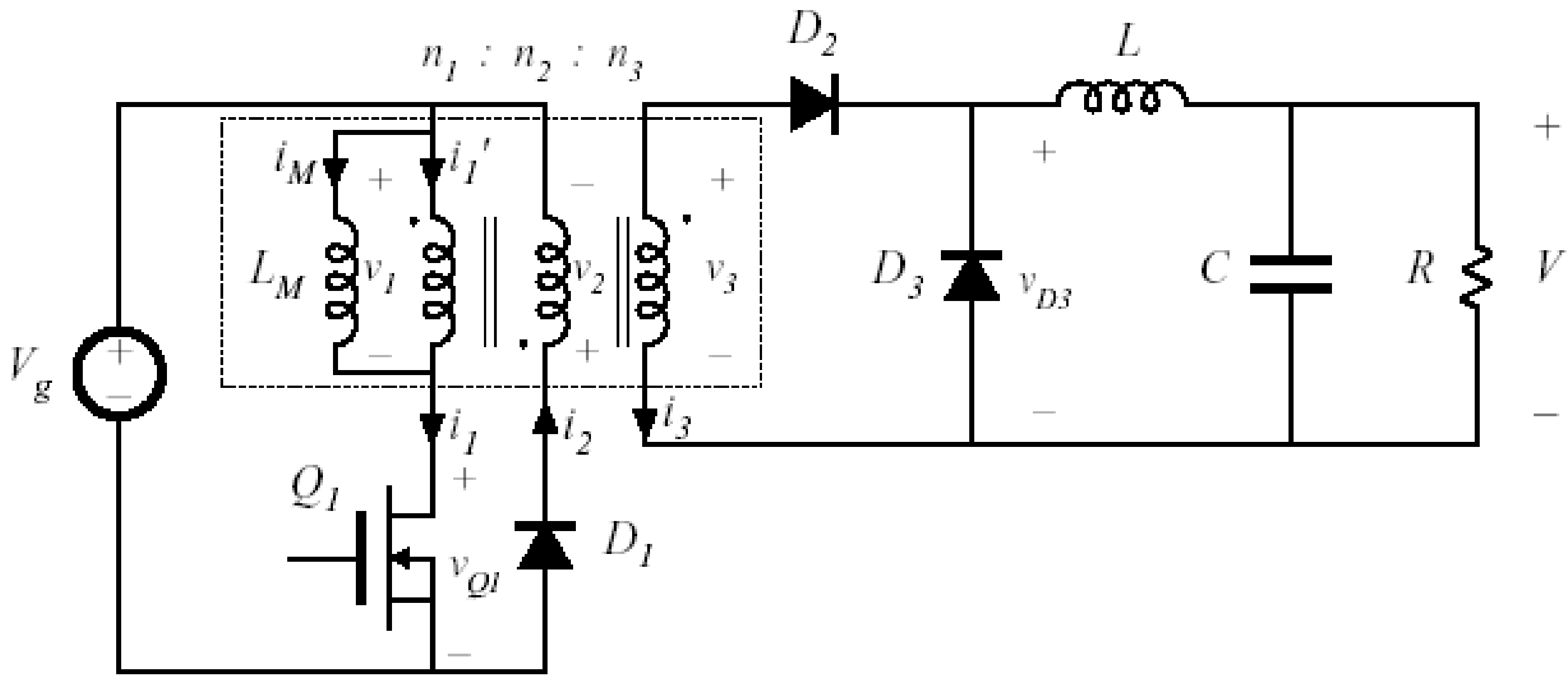
- "Transformer reset" is the mechanism by which magnetizing inductance volt-second balance is obtained
- The need to reset the transformer volt-seconds to zero by the end of each switching period adds considerable complexity to converters
- To understand operation of transformer-isolated converters:
    - 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

4.2.2. Forward converter

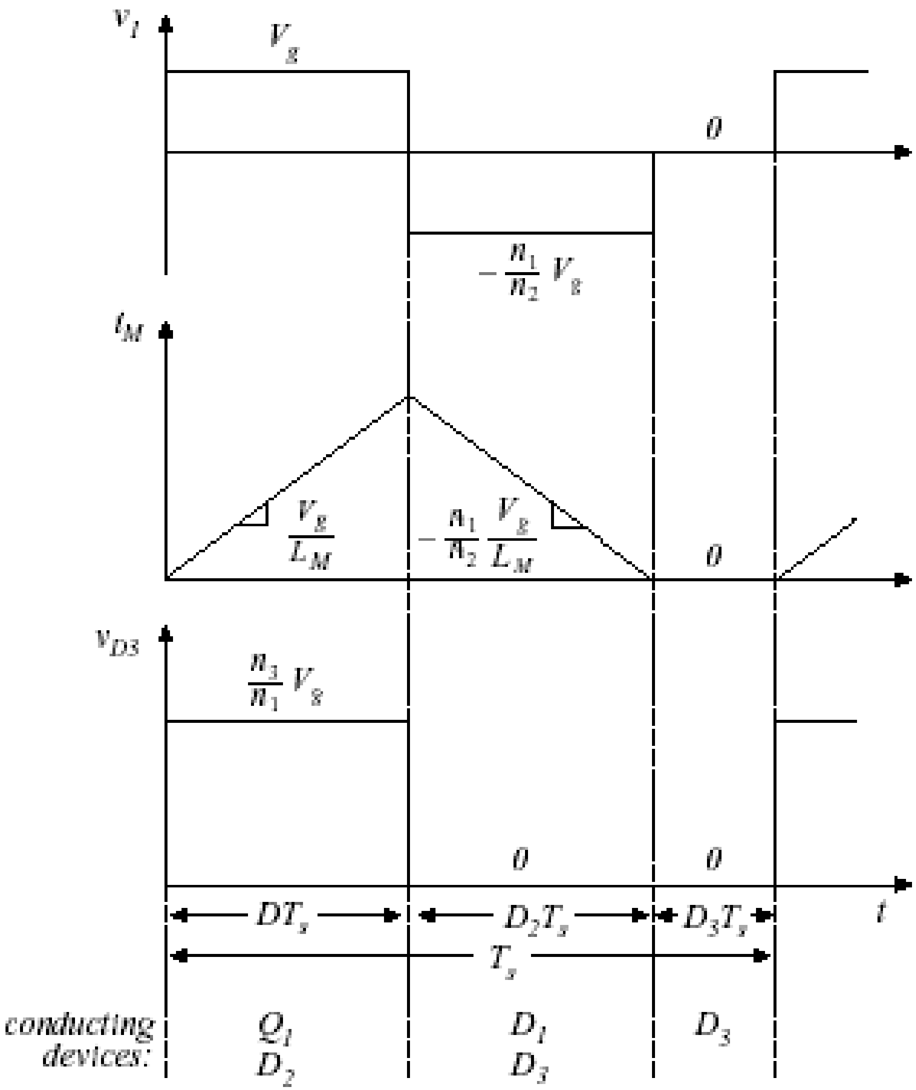


- Buck-derived transformer-isolated converter
- Single-transistor and two-transistor versions
- Maximum duty cycle is limited
- Transformer is reset while transistor is off

Forward converter with transformer equivalent circuit

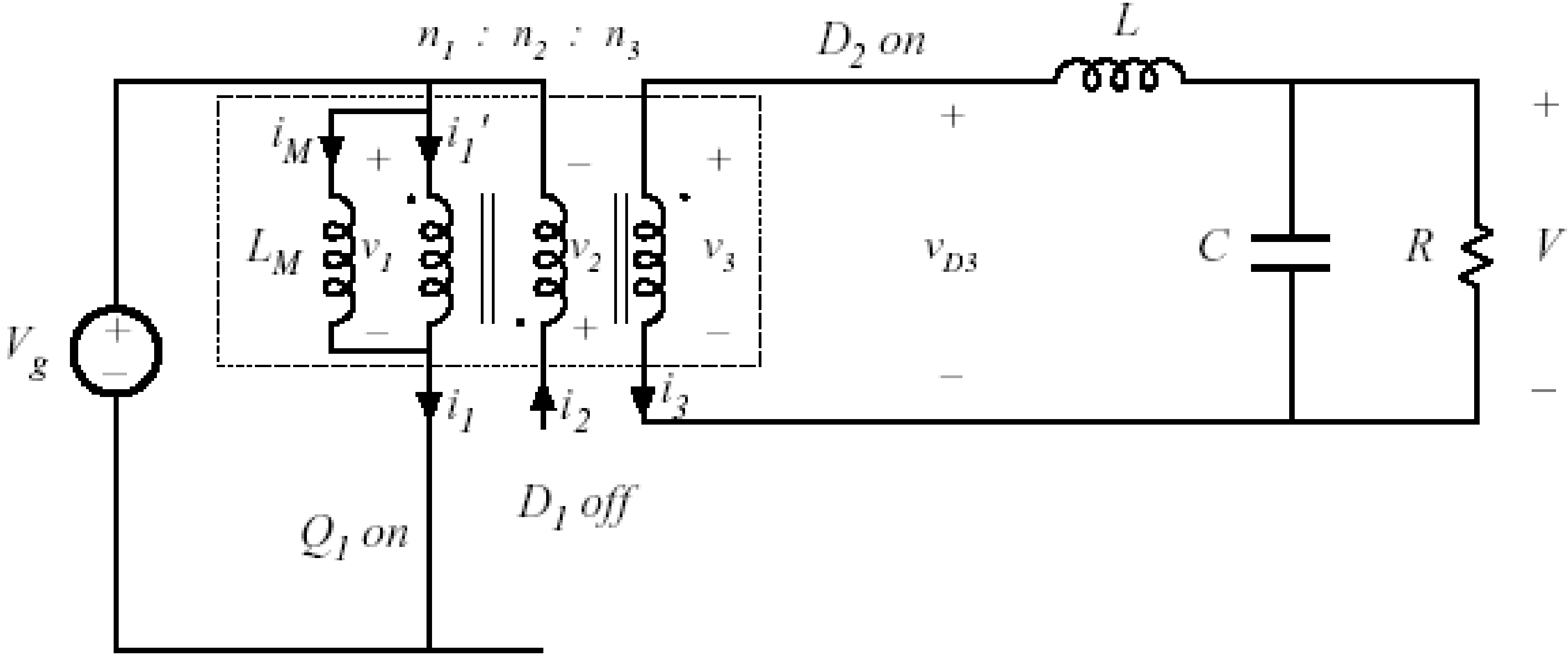


Forward converter: waveforms

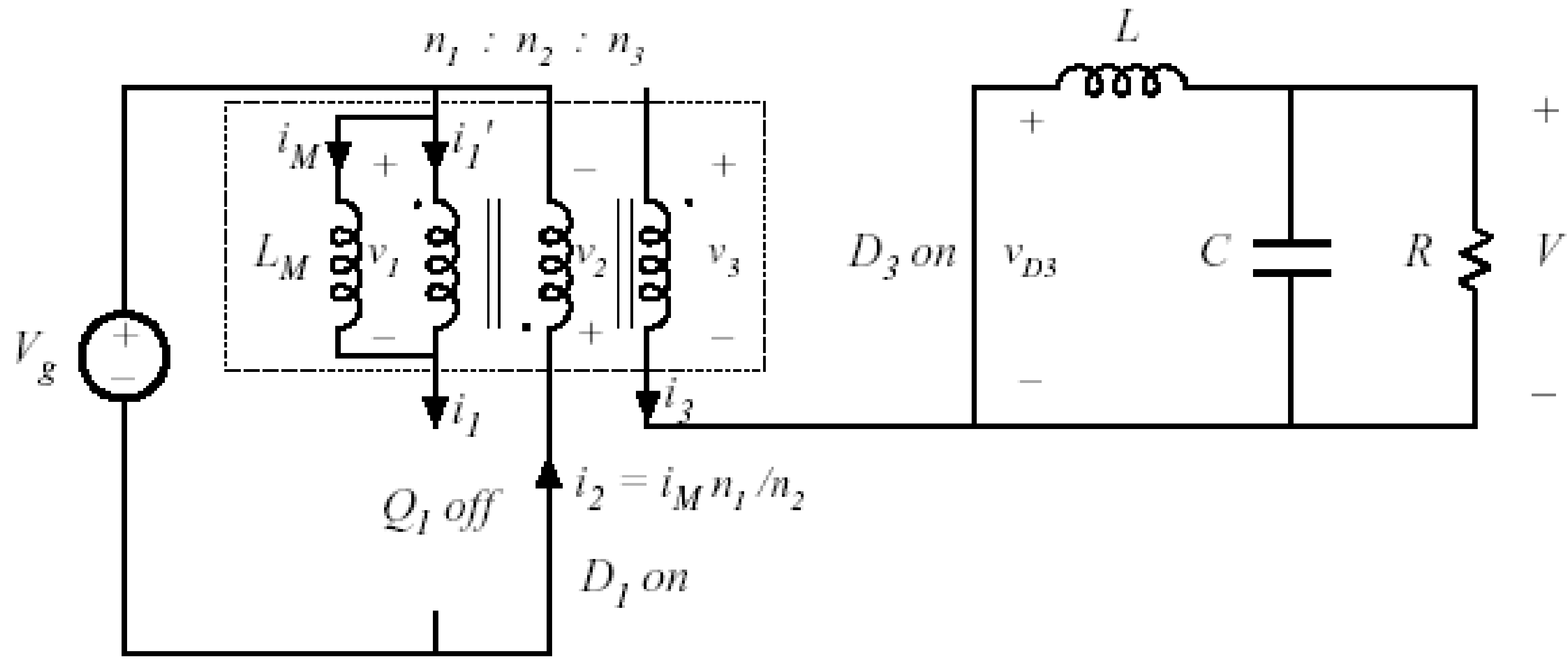


- Magnetizing current, in conjunction with diode D_1, operates in discontinuous conduction mode
- Output filter inductor, in conjunction with diode D_3, may operate in either CCM or DCM

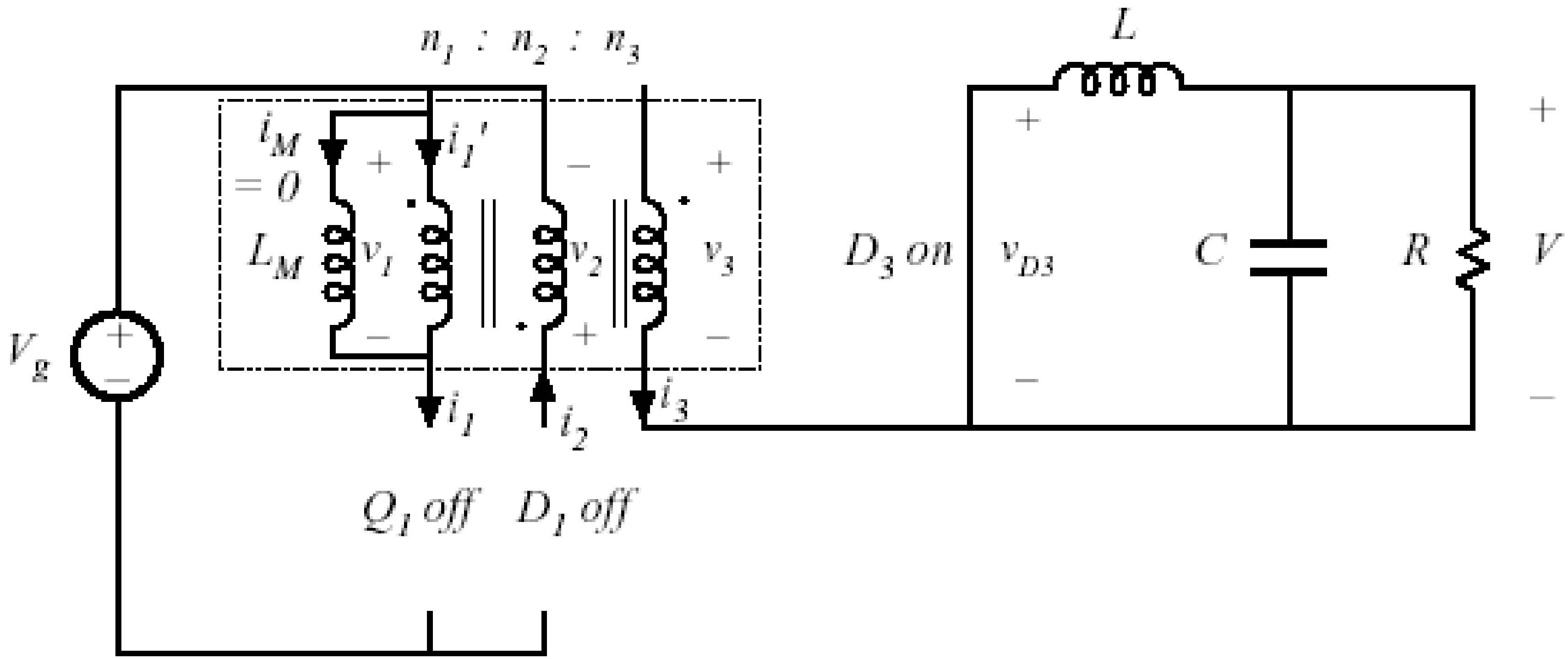
Subinterval 1: transistor conducts



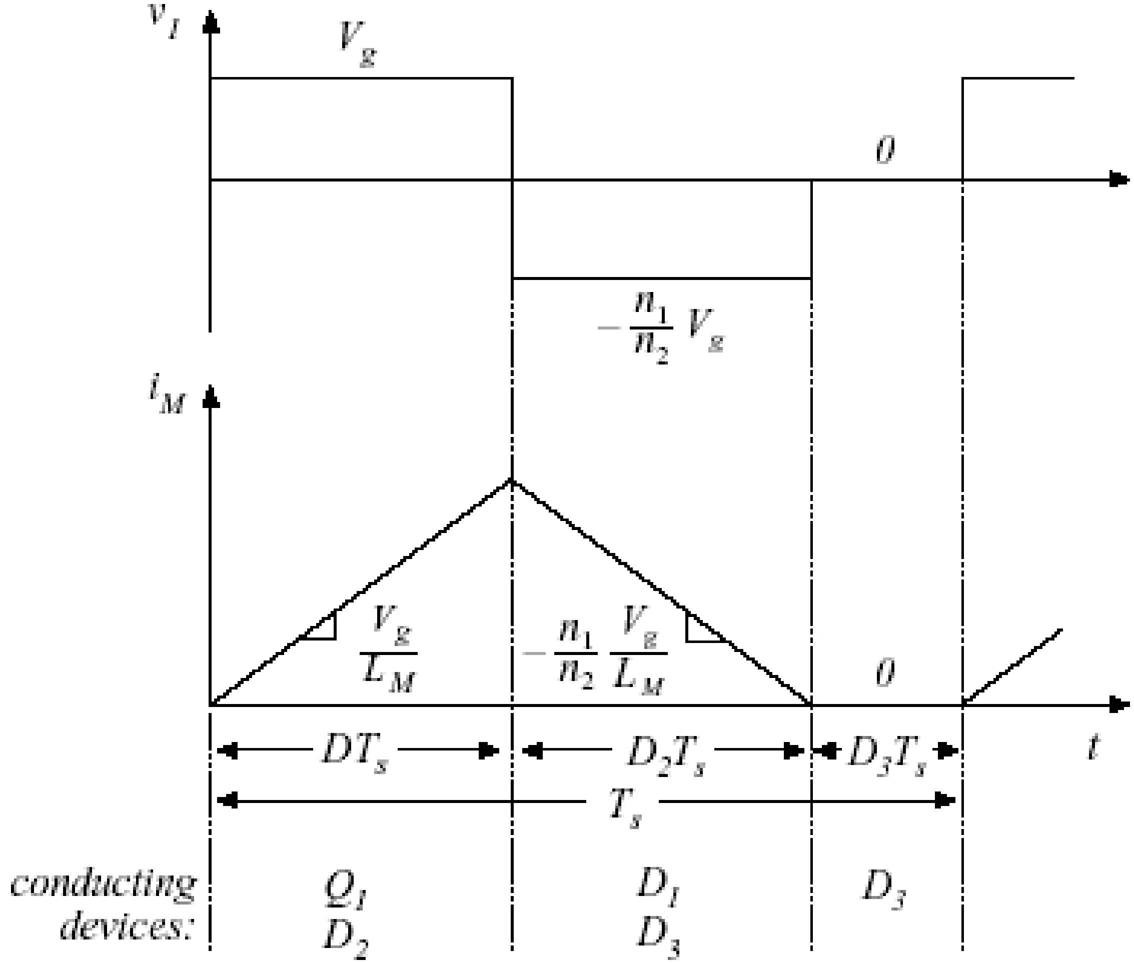
Subinterval 2: transformer reset



Subinterval 3



Magnetizing inductance volt-second balance



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

Transformer reset

From magnetizing current volt-second balance:

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

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

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

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

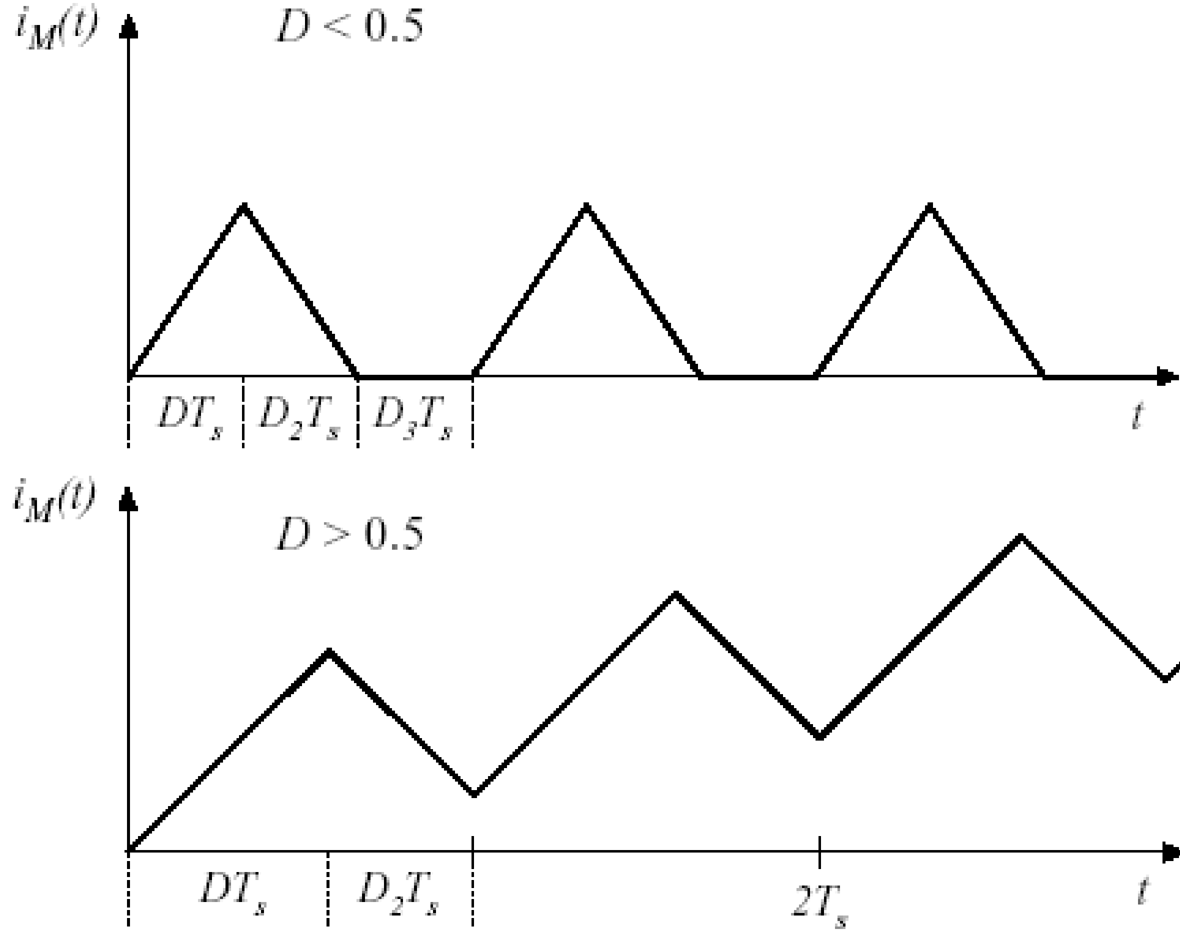
Solve for D

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

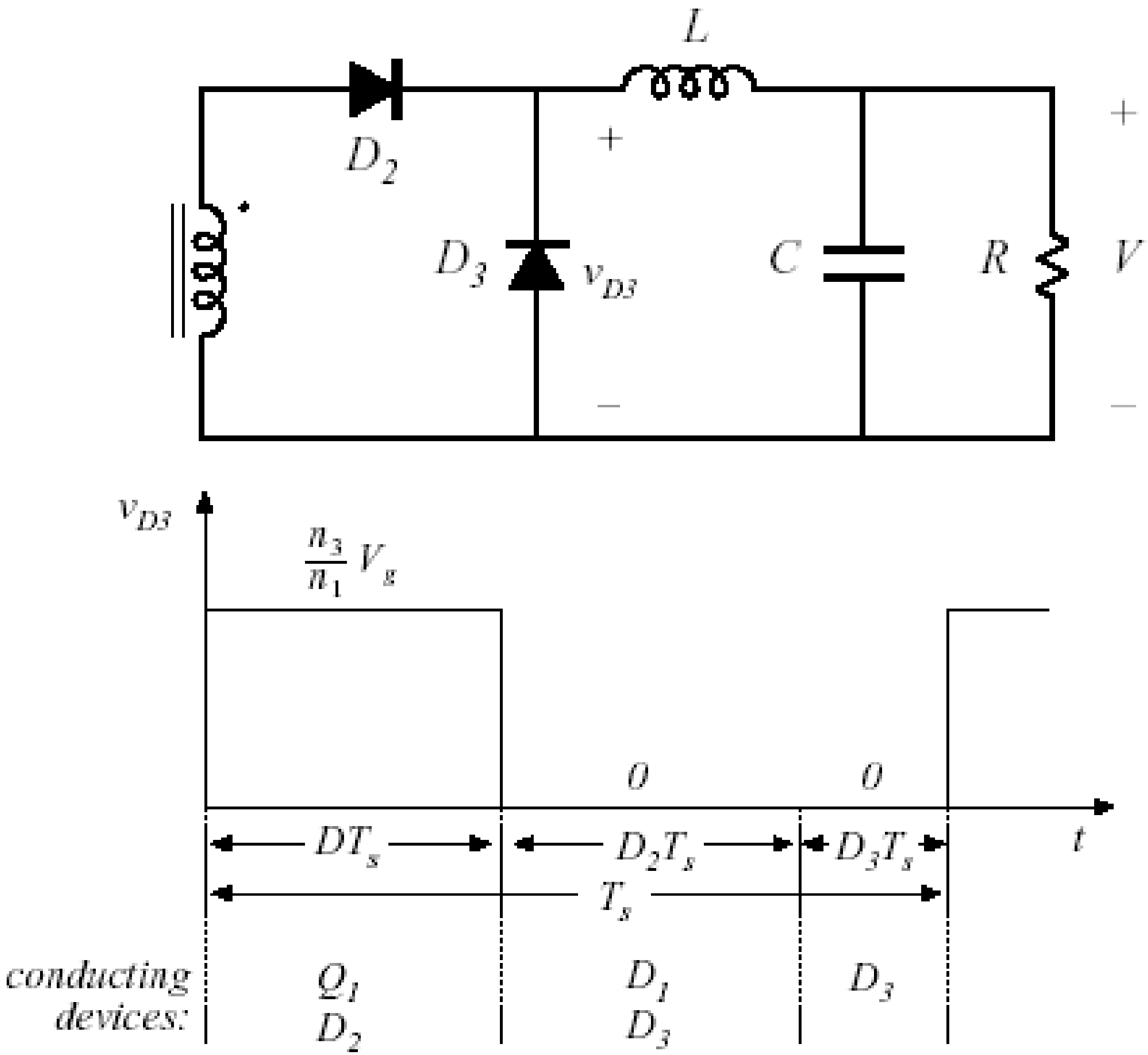
for $n_1 = n_2$: $D \leq \frac{1}{2}$

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

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

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

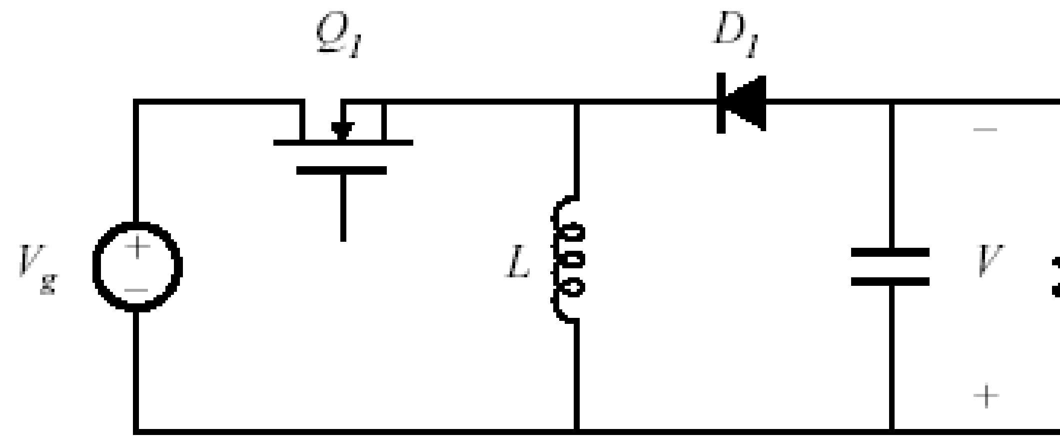
$$\max v_{Q1} = V_g \left(1 + \frac{n_1}{n_2}\right)$$

For $n_1 = n_2$

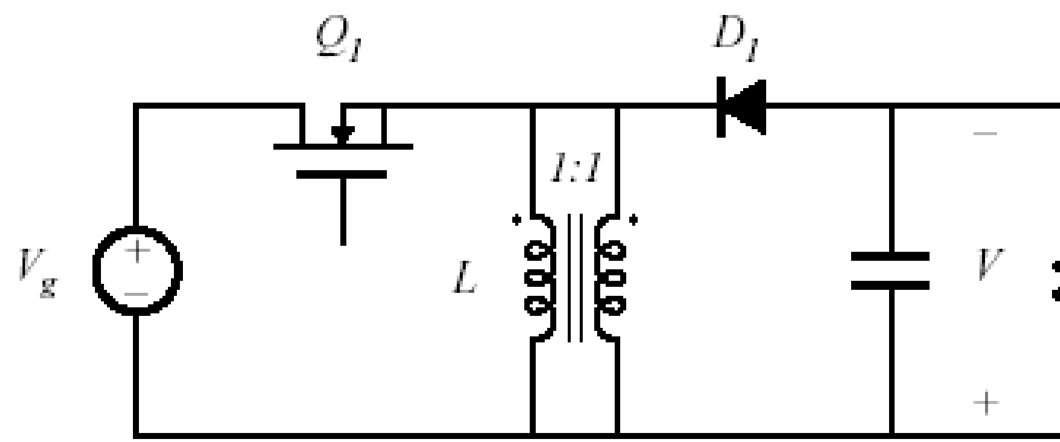
$$D \le \frac{1}{2} \qquad \text{and} \qquad \max v_{Q1} = 2V_g$$

4.2.3. Flyback converter

buck-boost converter:

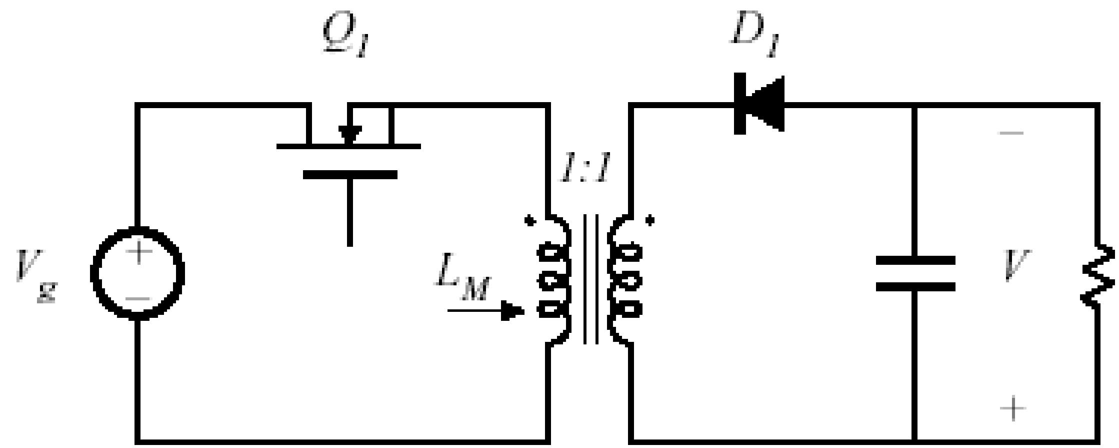


construct inductor winding using two parallel wires:

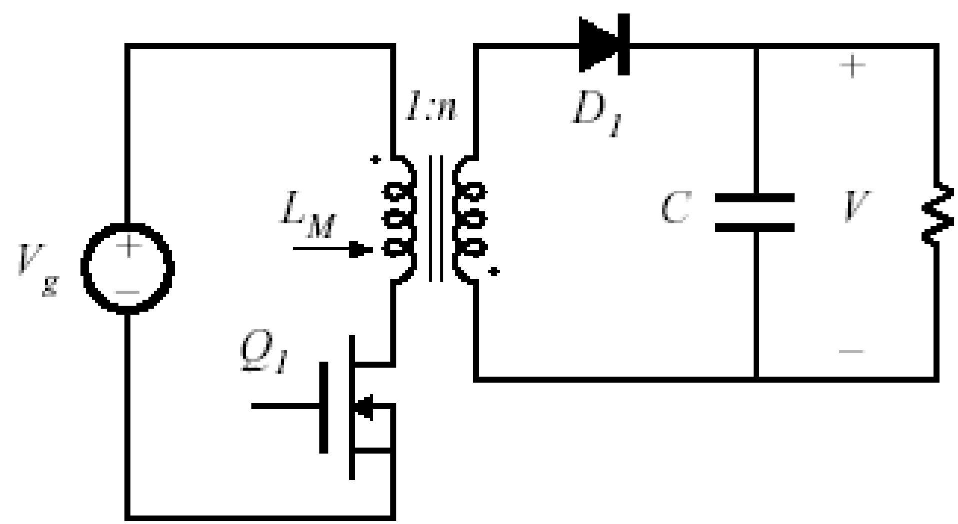


Derivation of flyback converter, cont.

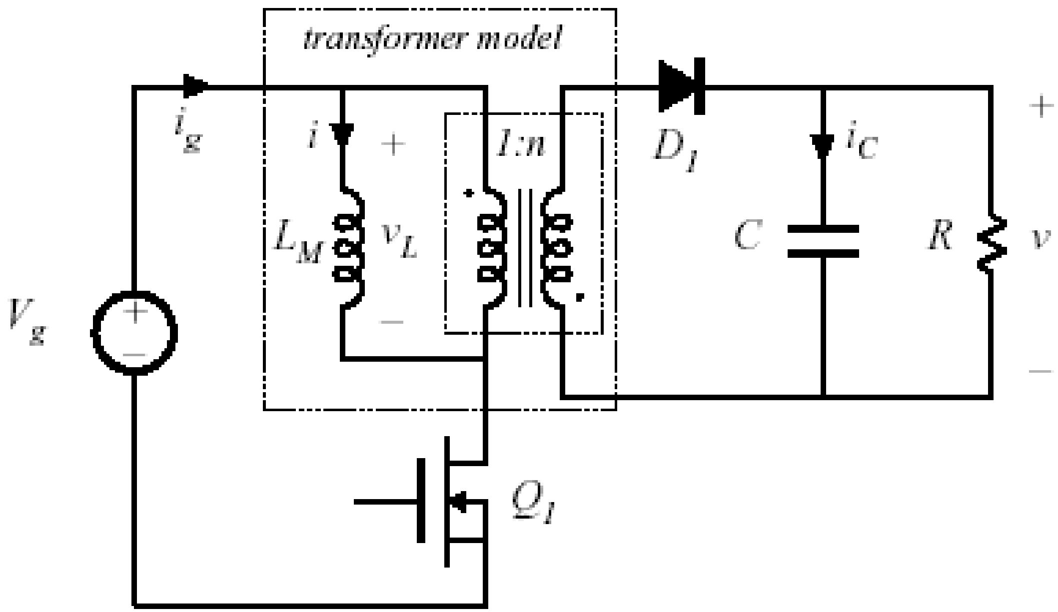
Isolate inductor windings: the flyback converter



Flyback converter having a 1:n turns ratio and positive output:



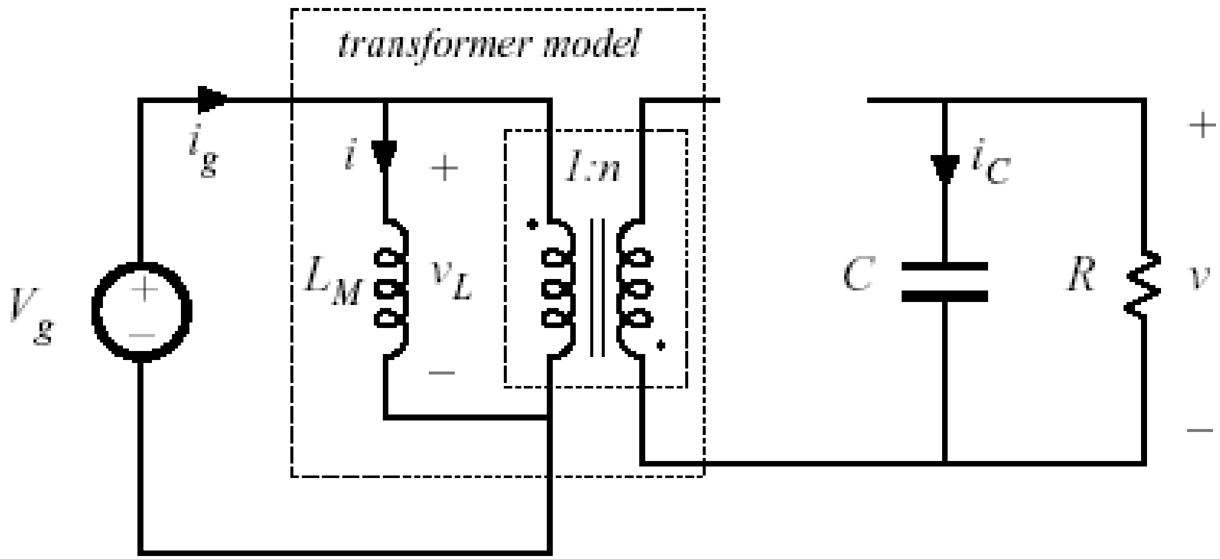
The "flyback transformer"



- A two-winding inductor
- Symbol is same as transformer, but function differs significantly from ideal transformer
- Energy is stored in magnetizing inductance
- Magnetizing inductance is relatively small

- Current does not simultaneously flow in primary and secondary windings
- Instantaneous winding voltages follow turns ratio
- Instantaneous (and rms) winding currents do not follow turns ratio
- Model as (small) magnetizing inductance in parallel with ideal transformer

Subinterval 1

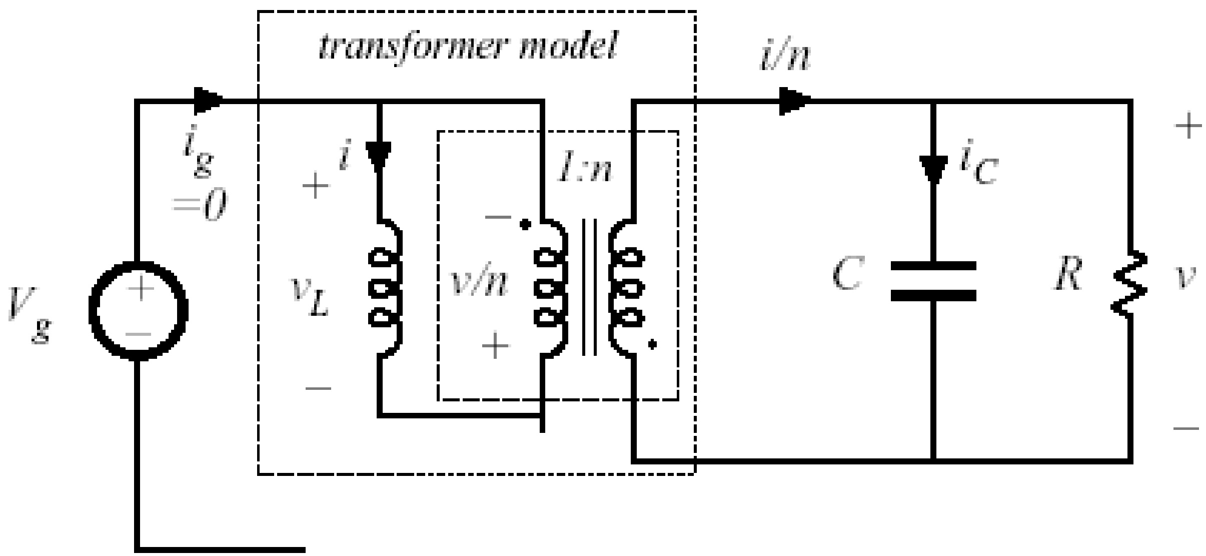


$$v_L = V_g$$
$$i_C = -\frac{v}{R}$$
$$i_g = i$$

CCM: small ripple approximation leads to

$$v_L = V_g$$
$$i_C = -\frac{V}{R}$$
$$i_g = I$$

Subinterval 2

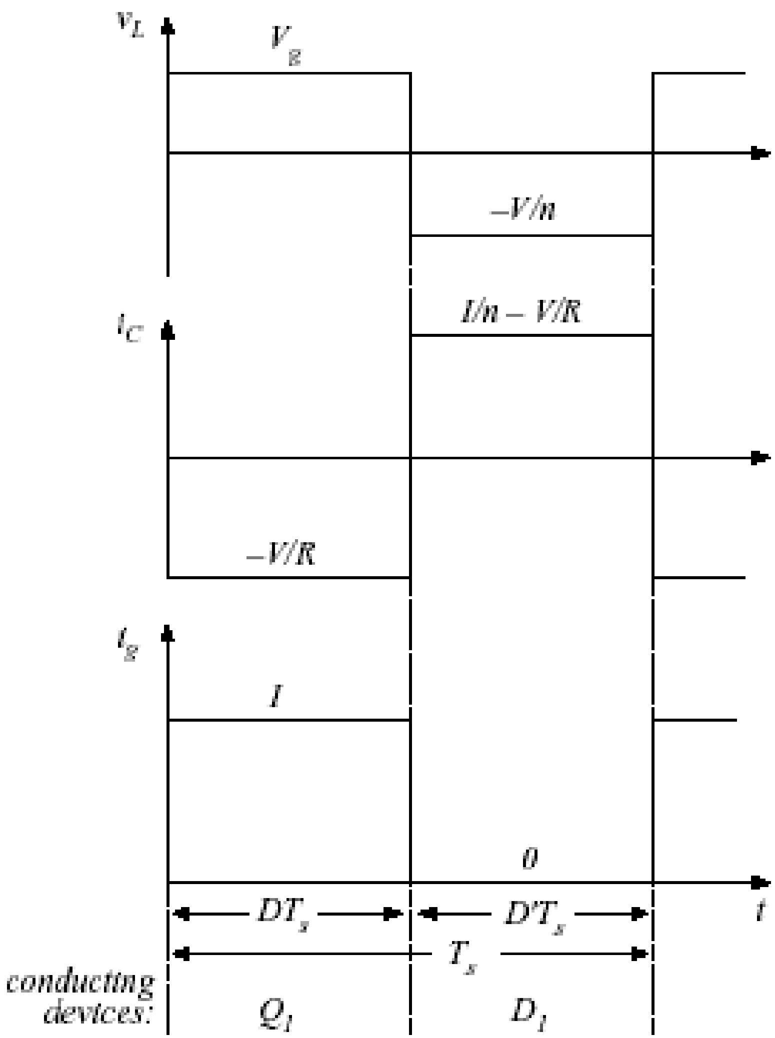


$$v_L = -\frac{v}{n}$$
$$i_C = \frac{i}{n} - \frac{v}{R}$$
$$i_g = 0$$

CCM: small ripple approximation leads to

$$v_L = -\frac{V}{n}$$
$$i_C = \frac{I}{n} - \frac{V}{R}$$
$$i_g = 0$$

CCM Flyback waveforms and solution



Volt-second balance:

$$\langle v_L \rangle = D\,(V_g) + D'\,(-\frac{V}{n}) = 0$$

Conversion ratio is

$$M(D) = \frac{V}{V_g} = n\,\frac{D}{D'}$$

Charge balance:

$$\langle i_C \rangle = D\,(-\frac{V}{R}) + D'\,(\frac{I}{n} - \frac{V}{R}) = 0$$

Dc component of magnetizing current is

$$I = \frac{nV}{D'R}$$

Dc component of source current is

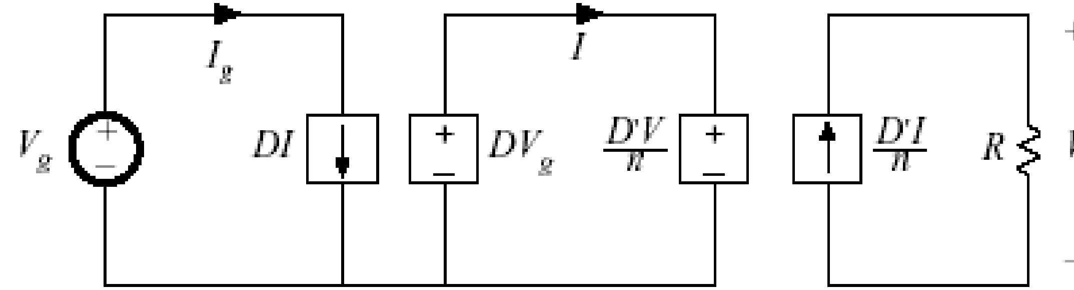
$$I_g = \langle i_g \rangle = D\,(I) + D'\,(0)$$

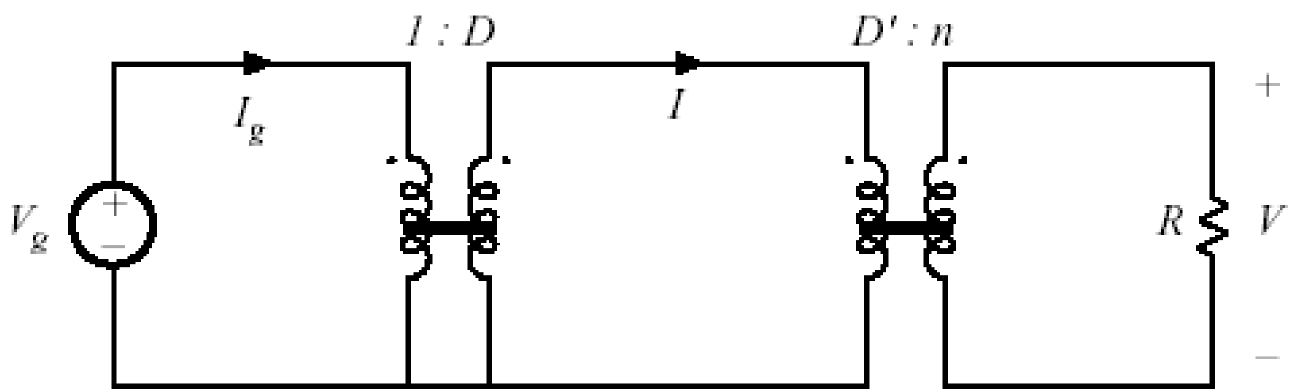
Equivalent circuit model: CCM Flyback

$$\langle v_L \rangle = D\,(V_g) + D'\,(-\frac{V}{n}) = 0$$

$$\langle i_C \rangle = D\,(-\frac{V}{R}) + D'\,(\frac{I}{n} - \frac{V}{R}) = 0$$

$$I_g = \langle i_g \rangle = D\,(I) + D'\,(0)$$





Discussion: Flyback converter

- Widely used in low power and/or high voltage applications
- Low parts count
- Multiple outputs are easily obtained, with minimum additional parts
- Cross regulation is inferior to buck-derived isolated converters
- Often operated in discontinuous conduction mode
- DCM analysis: DCM buck-boost with turns ratio