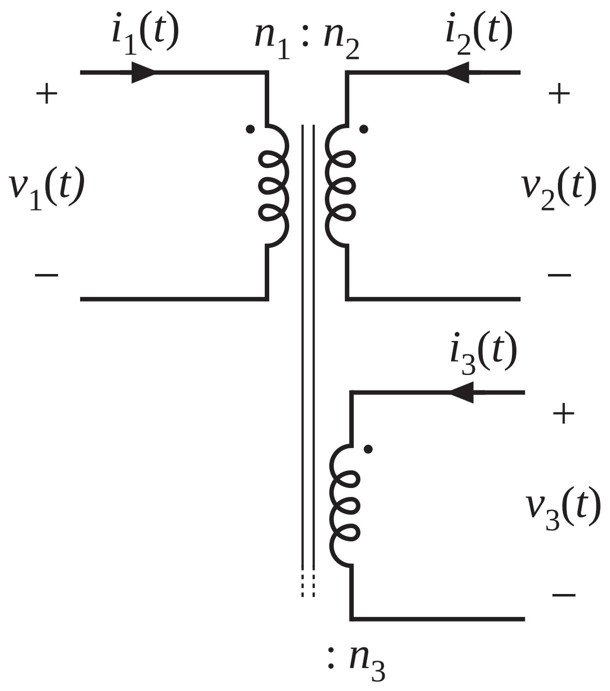
6.3. Transformer isolation

Objectives:

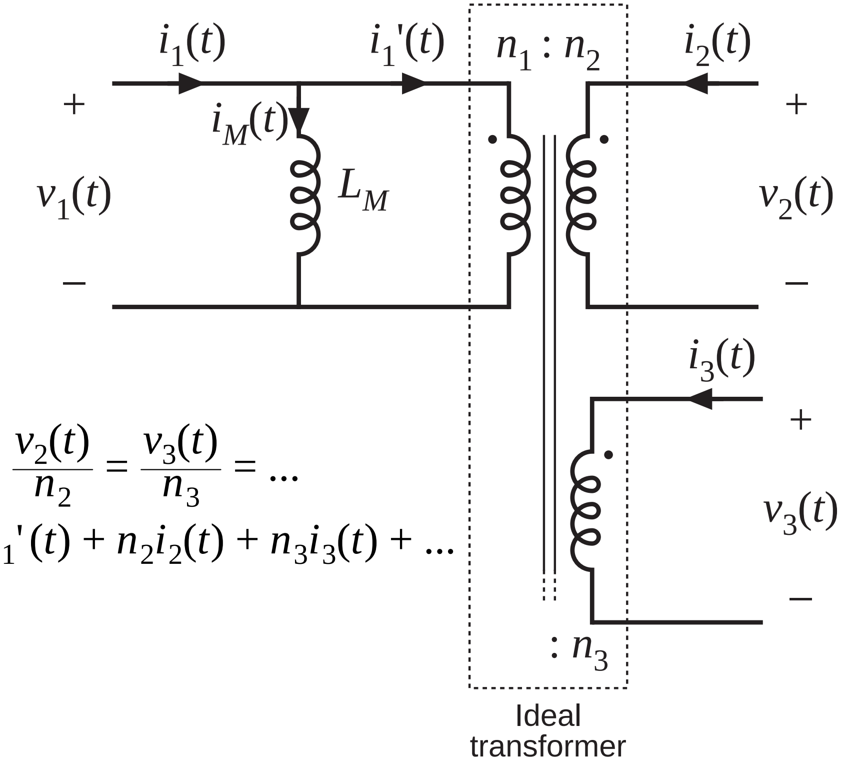
- Isolation of input and output ground connections, to meet safety requirements
- Reduction of transformer size by incorporating high frequency isolation transformer inside converter
- Minimization of current and voltage stresses when a large step-up or step-down conversion ratio is needed —use transformer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



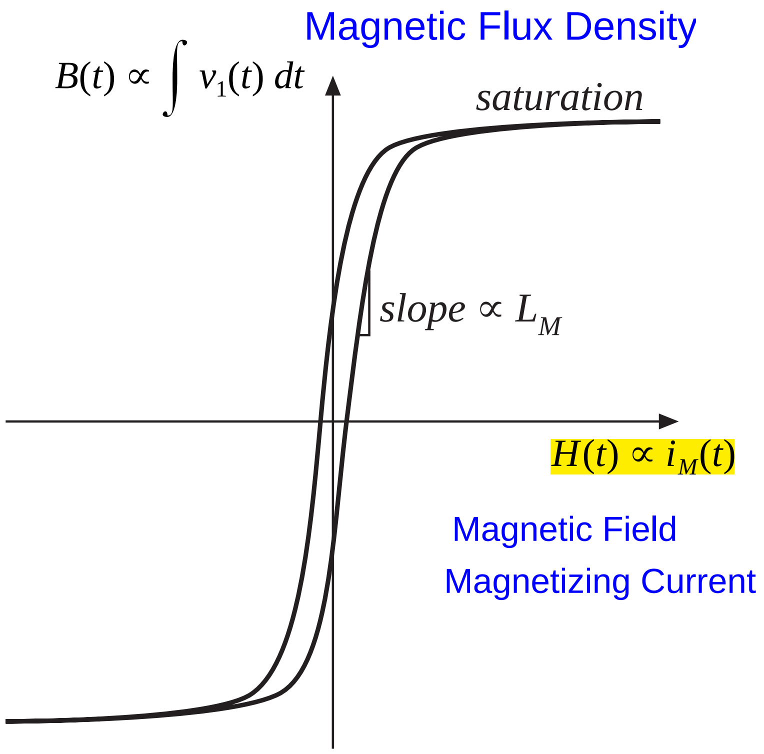
$$\frac{v_1(t)}{n_1} = \frac{v_2(t)}{n_2} = \frac{v_3(t)}{n_3} = \ldots$$

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

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

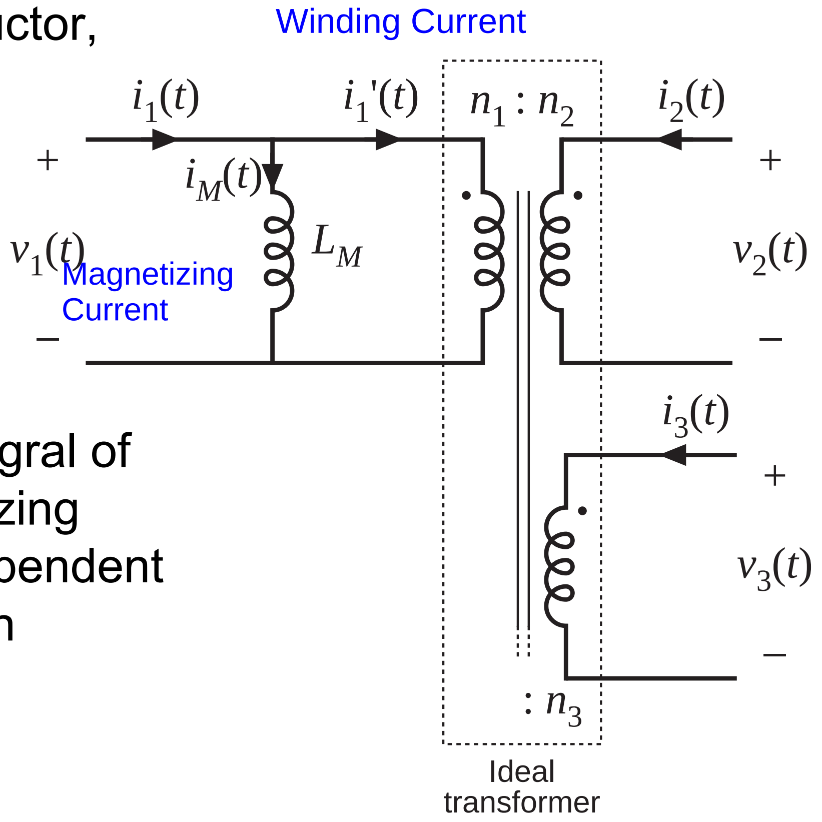
$$v_1(t) = L_M \frac{di_M(t)}{dt}$$

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

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

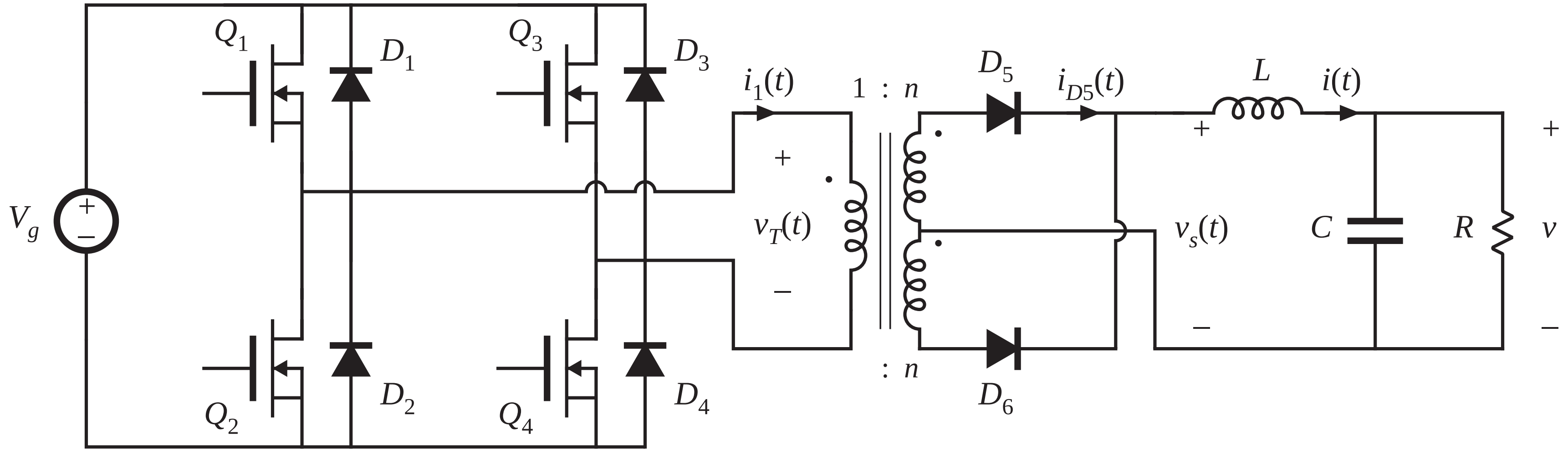


Transformer reset

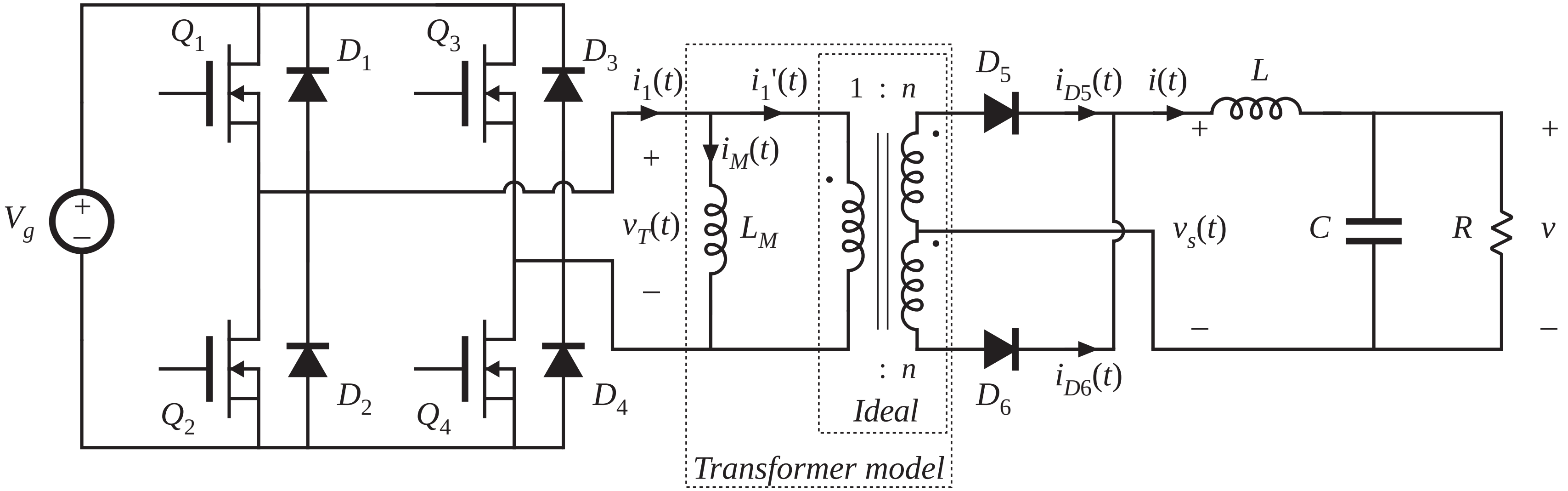
- “Transformer reset” is the mechanism by which magnetizing inductance volt-second balance is obtained
- The need to reset the transformer volt-seconds to zero by the end of each switching period adds considerable complexity to converters
- To understand operation of transformer-isolated converters: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

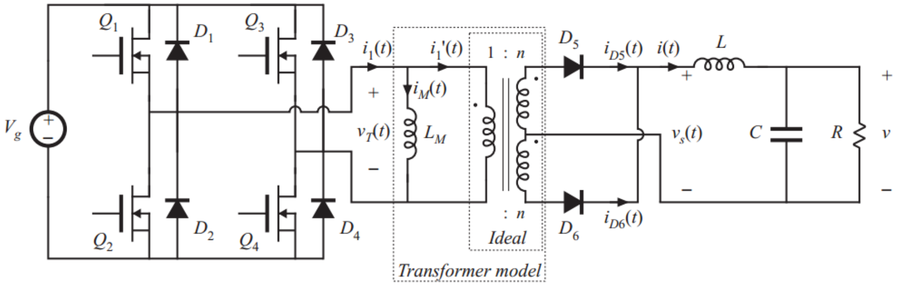
6.3.1. Full-bridge and half-bridge isolated buck converters

Full-bridge isolated buck converter

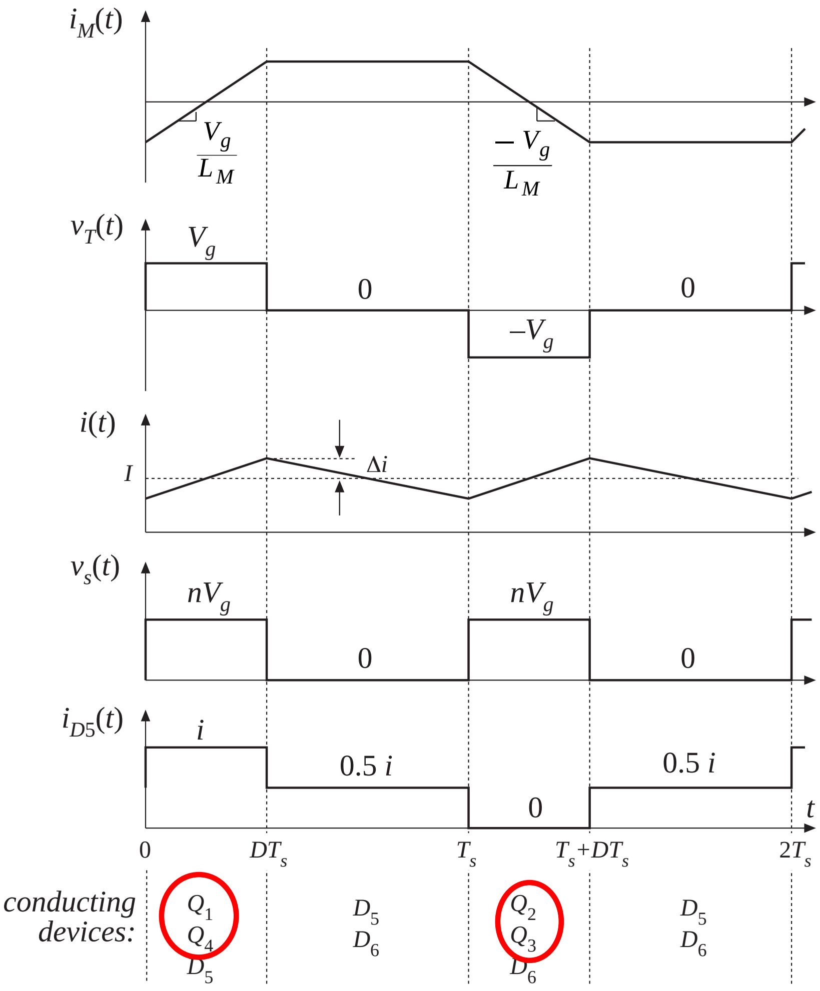


Full-bridge, with transformer equivalent circuit





waveforms



- During first switching period: transistors Q_1 and Q_4 conduct for time DT_s , applying volt-seconds $V_g\ DT_s$ to primary winding
- During next switching period: transistors Q_2 and Q_3 conduct for time DT_s , applying volt-seconds $-V_g\ DT_s$ to primary winding
- Transformer volt-second balance is obtained over two switching periods
- Effect of nonidealities?

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:

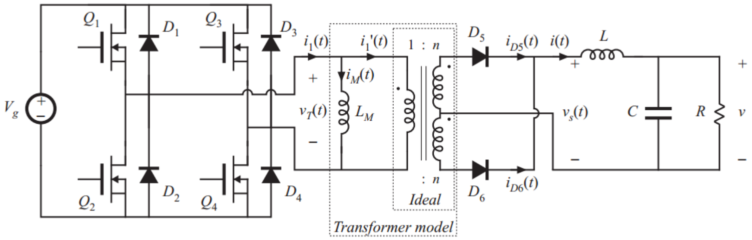
$$-(V_g - (Q_2 \text{ and } Q_3 \text{ forward voltage drops}))(\,Q_2 \text{ and } Q_3 \text{ conduction time})$$

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

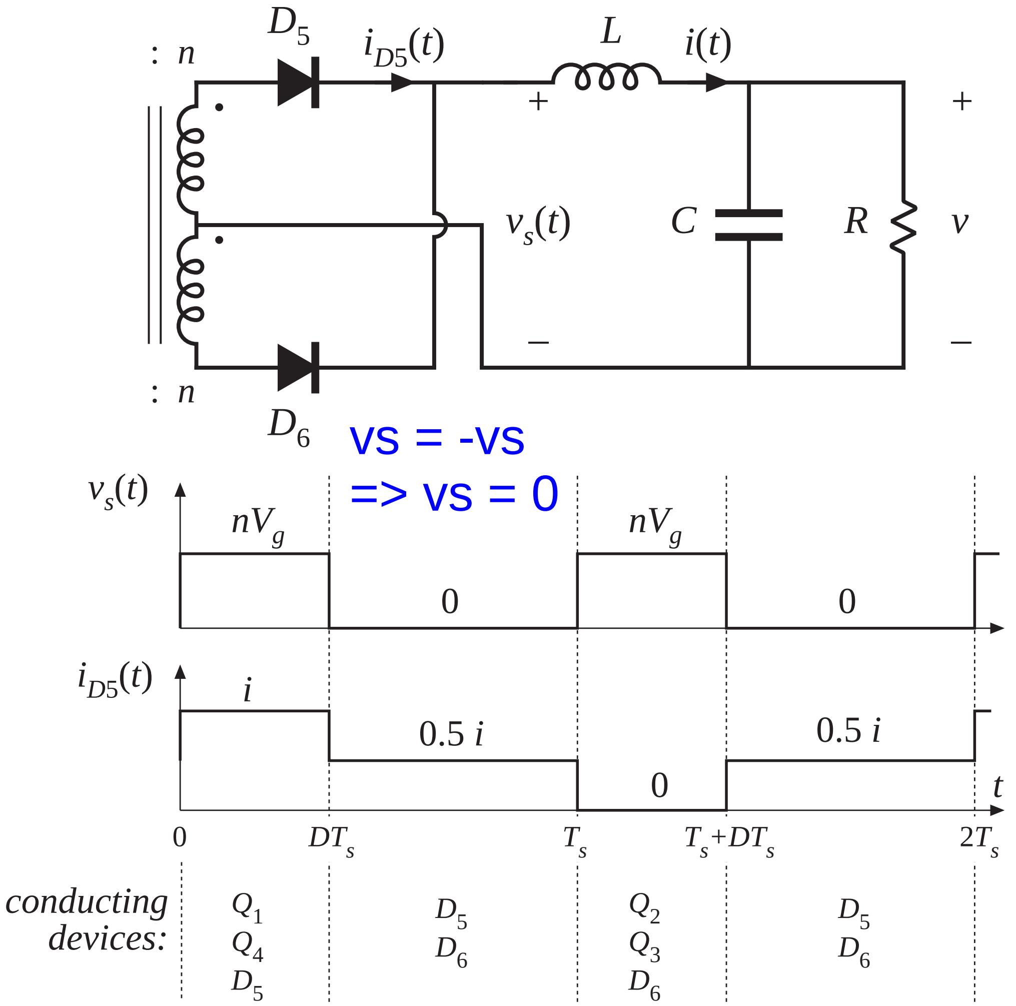
Net volt-seconds are applied to primary winding

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)



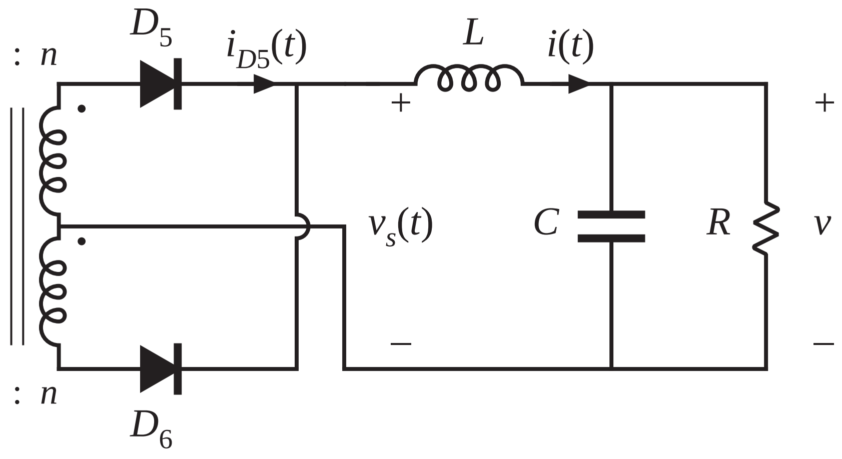
Operation of secondary-side diodes

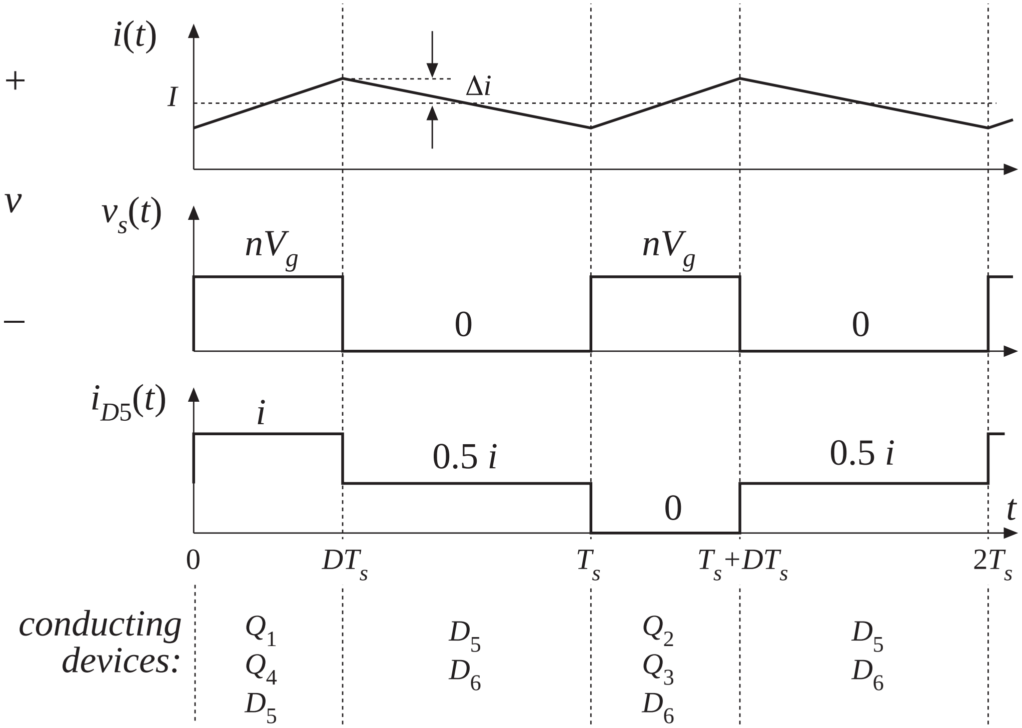


vs = -vs
=> vs = 0

- 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

Volt-second balance on output filter inductor



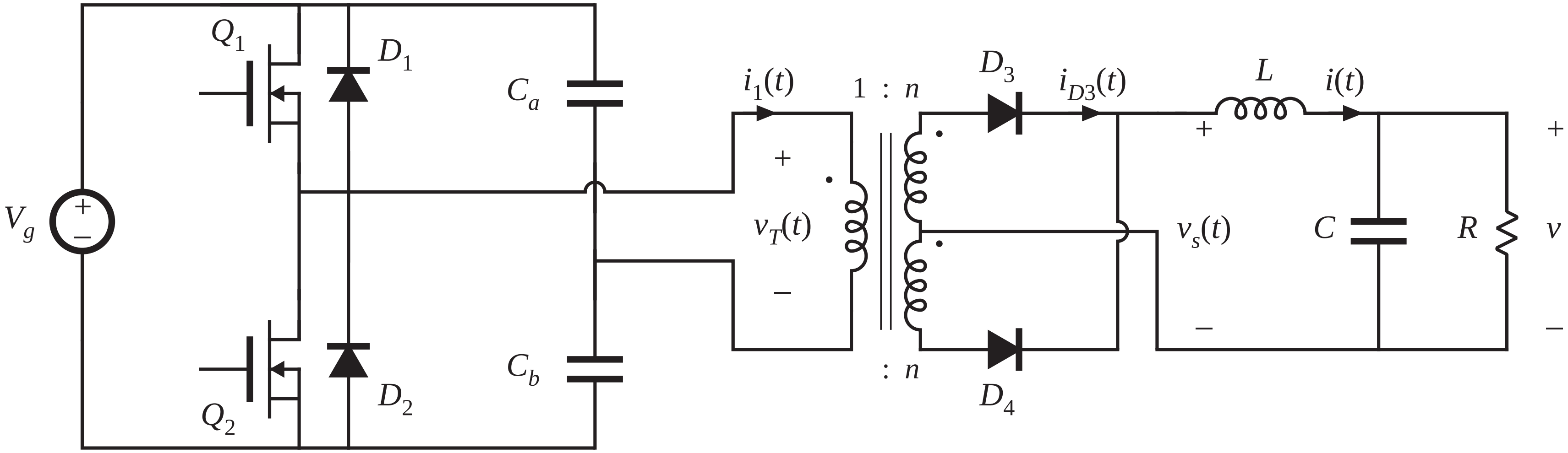


$$V = \left\langle v_s \right\rangle$$

$$V = nDV_g$$

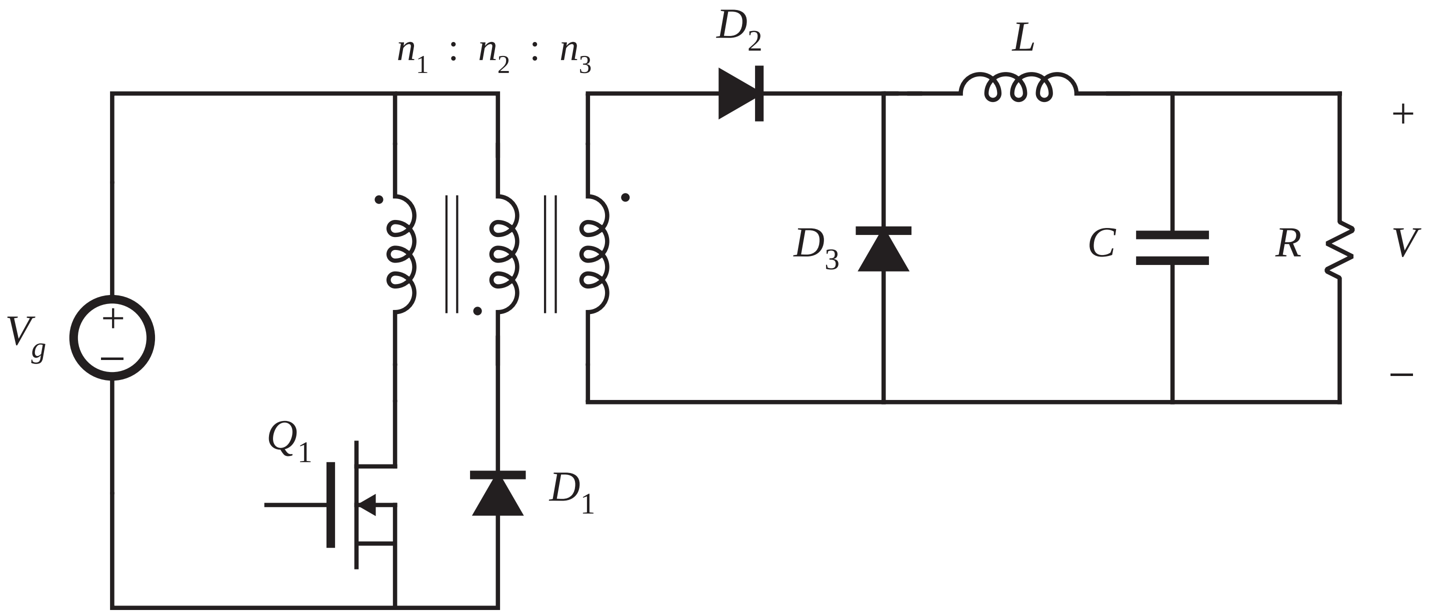
$M(D) = nD$ buck converter with turns ratio

Half-bridge isolated buck converter



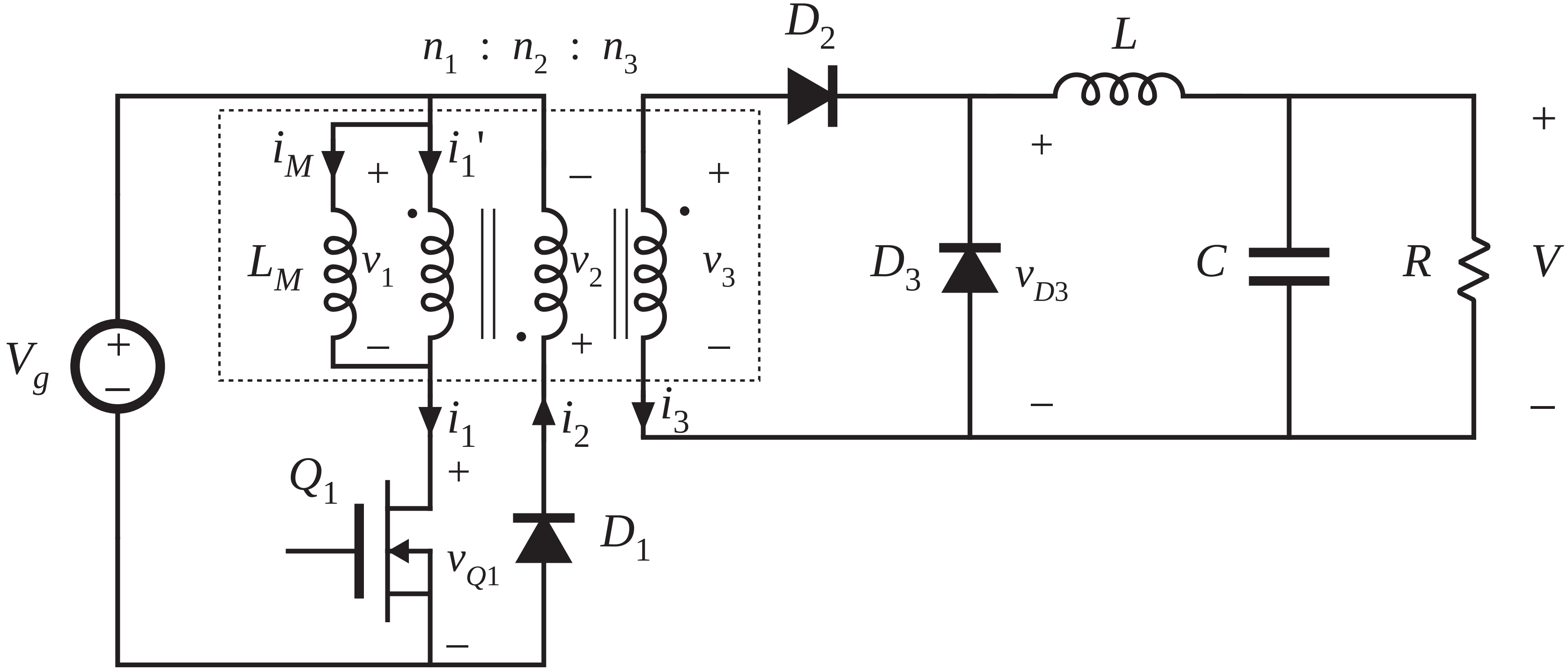
- Replace transistors Q_3 and Q_4 with large capacitors
- Voltage at capacitor centerpoint is $0.5V_g$
- $v_s(t)$ is reduced by a factor of two
- $M = 0.5\ nD$

6.3.2. Forward converter

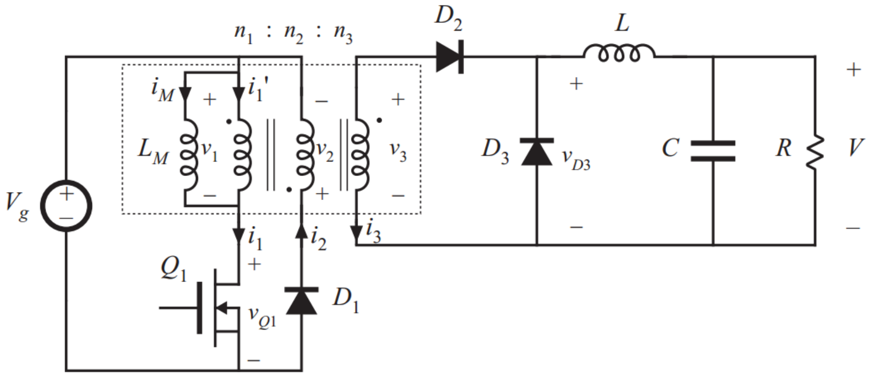


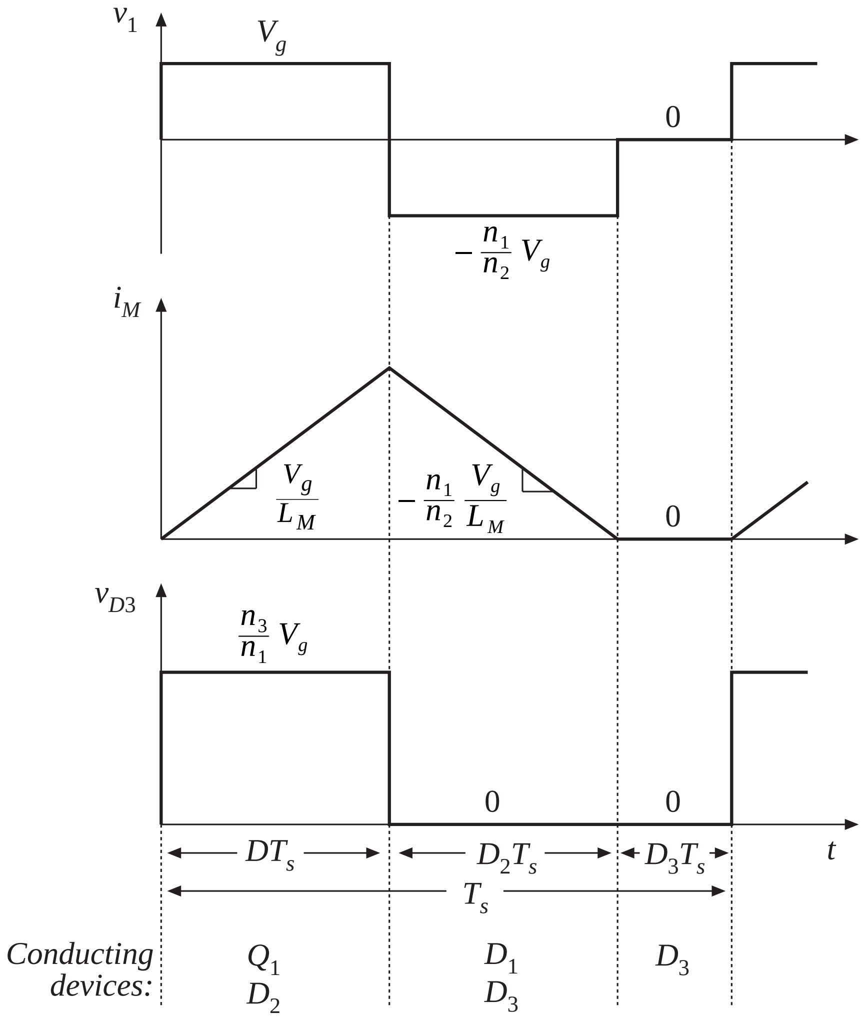
- Buck-derived transformer-isolated converter
- Single-transistor and two-transistor versions
- Maximum duty cycle is limited
- Transformer is reset while transistor is off

Forward converter with transformer equivalent circuit



waveforms

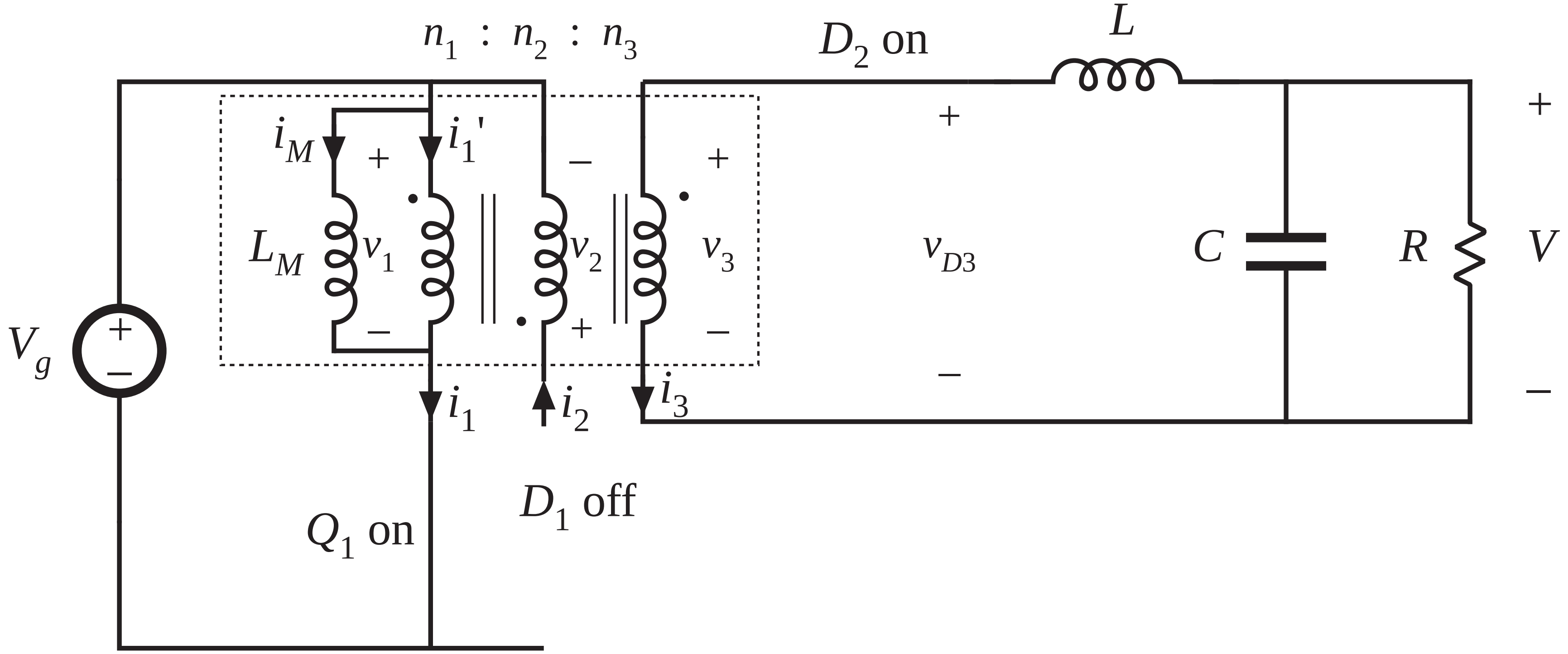




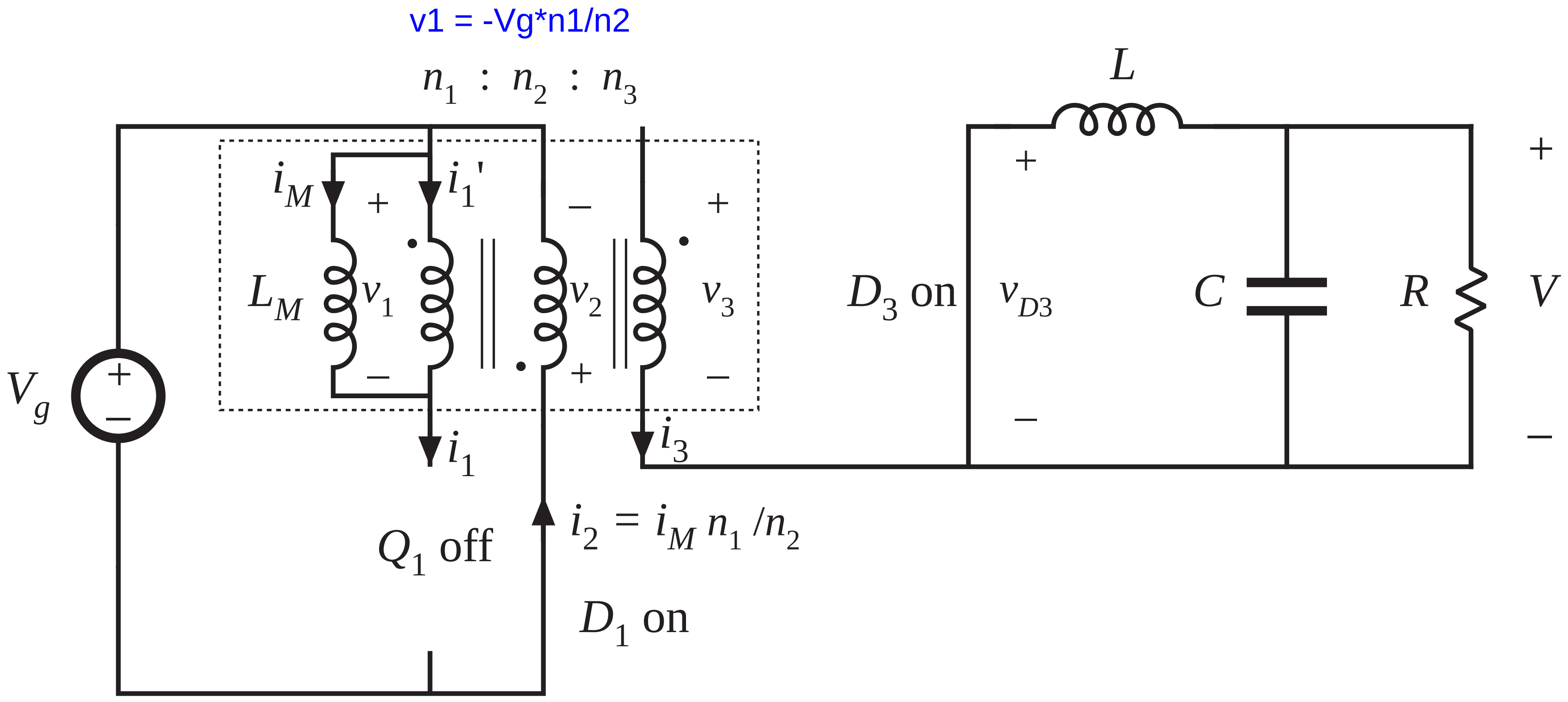
- Magnetizing current, in conjunction with diode D_1, operates in discontinuous conduction mode
- Output filter inductor, in conjunction with diode D_3, may operate in either CCM or DCM

Subinterval 1: transistor conducts

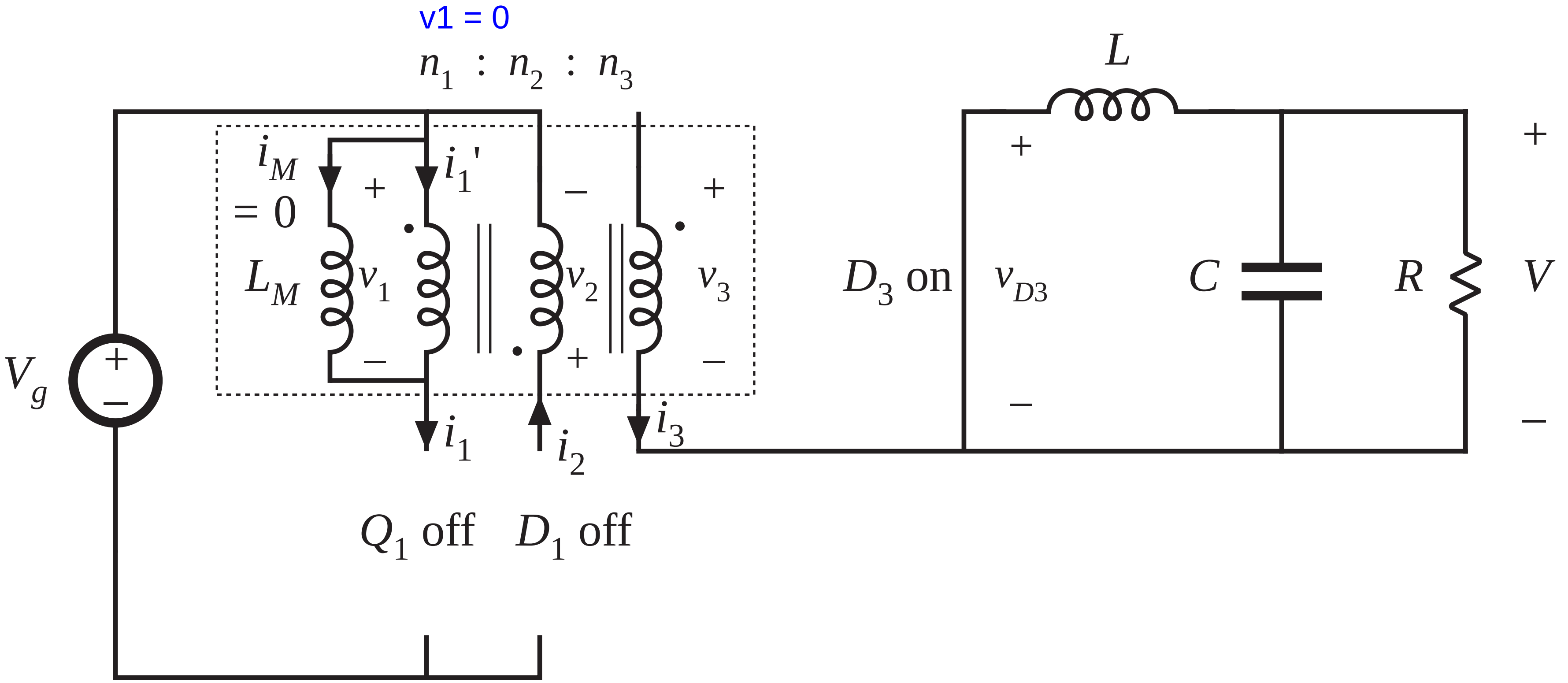
v1 = Vg



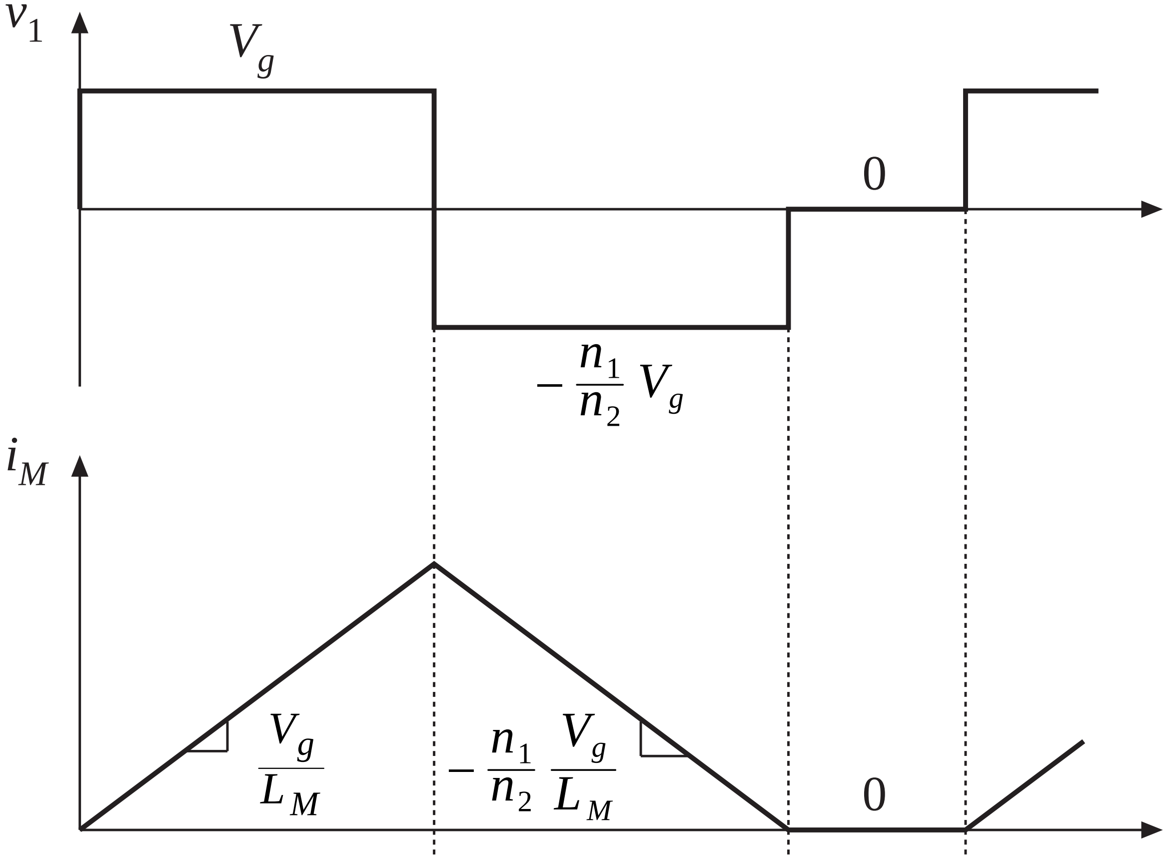
Subinterval 2: transformer reset



Subinterval 3



Magnetizing inductance volt-second balance



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

Transformer reset

From magnetizing current volt-second balance:

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

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

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

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

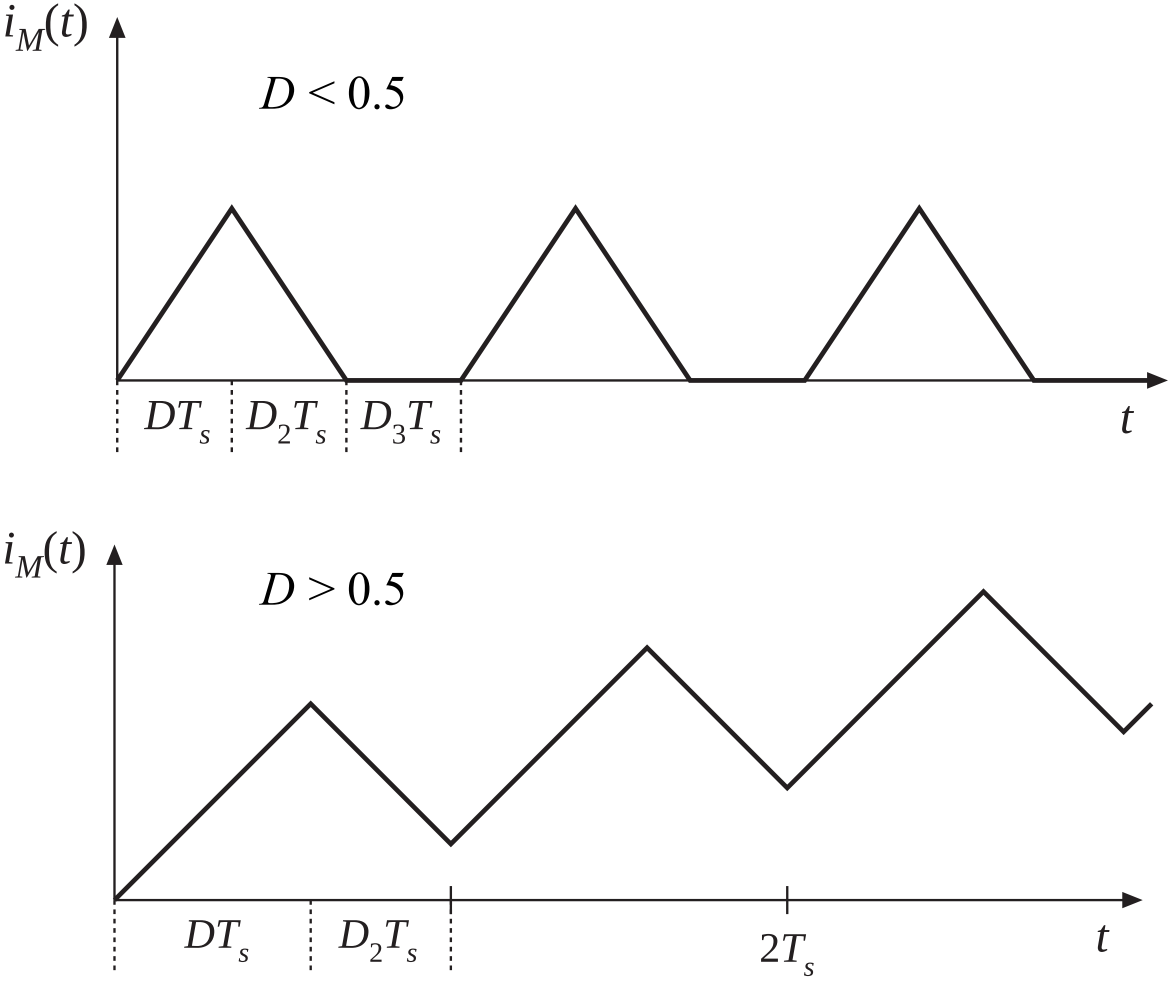
Solve for D

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

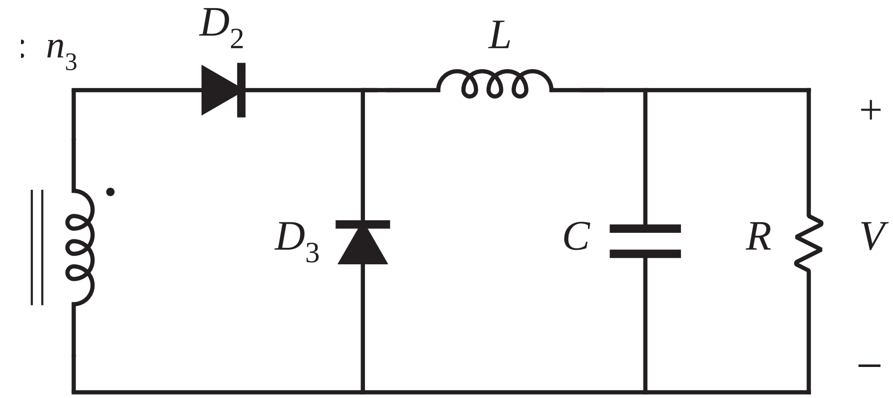
for $n_1 = n_2$: $D \leq \frac{1}{2}$

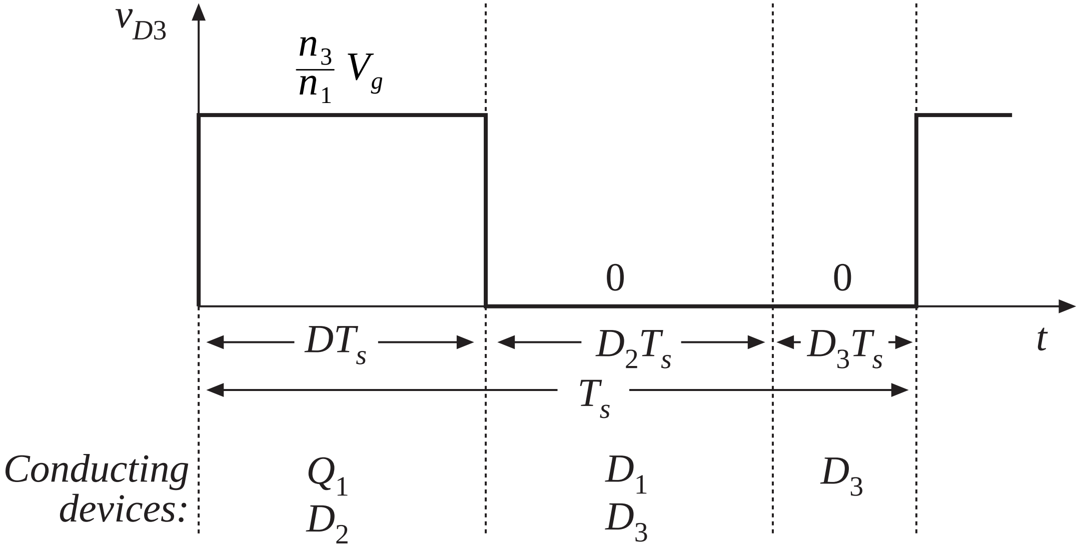
What happens when $D > 0.5$

magnetizing current waveforms,
for $n_1 = n_2$



Conversion ratio *M(D)*





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

Maximum duty cycle vs. transistor voltage stress

Maximum duty cycle limited to

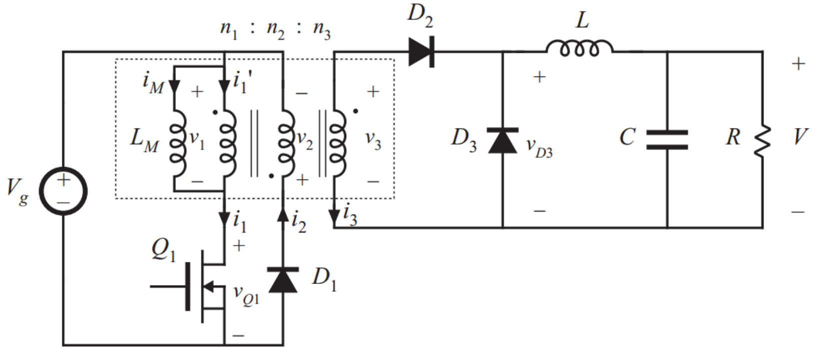
$$D \leq \frac{1}{1 + \frac{n_2}{n_1}}$$

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

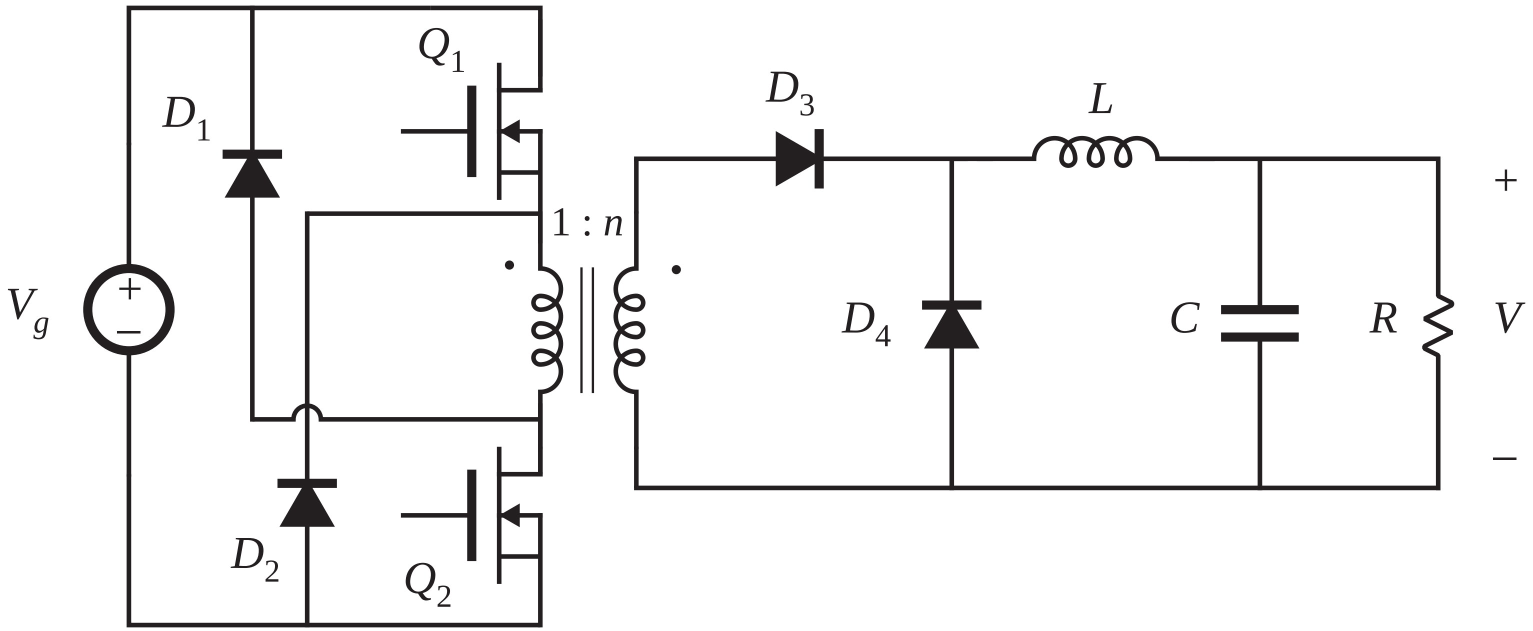
$$\max\left(v_{Q1}\right) = V_g\left(1 + \frac{n_1}{n_2}\right)$$

For $n_1 = n_2$

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

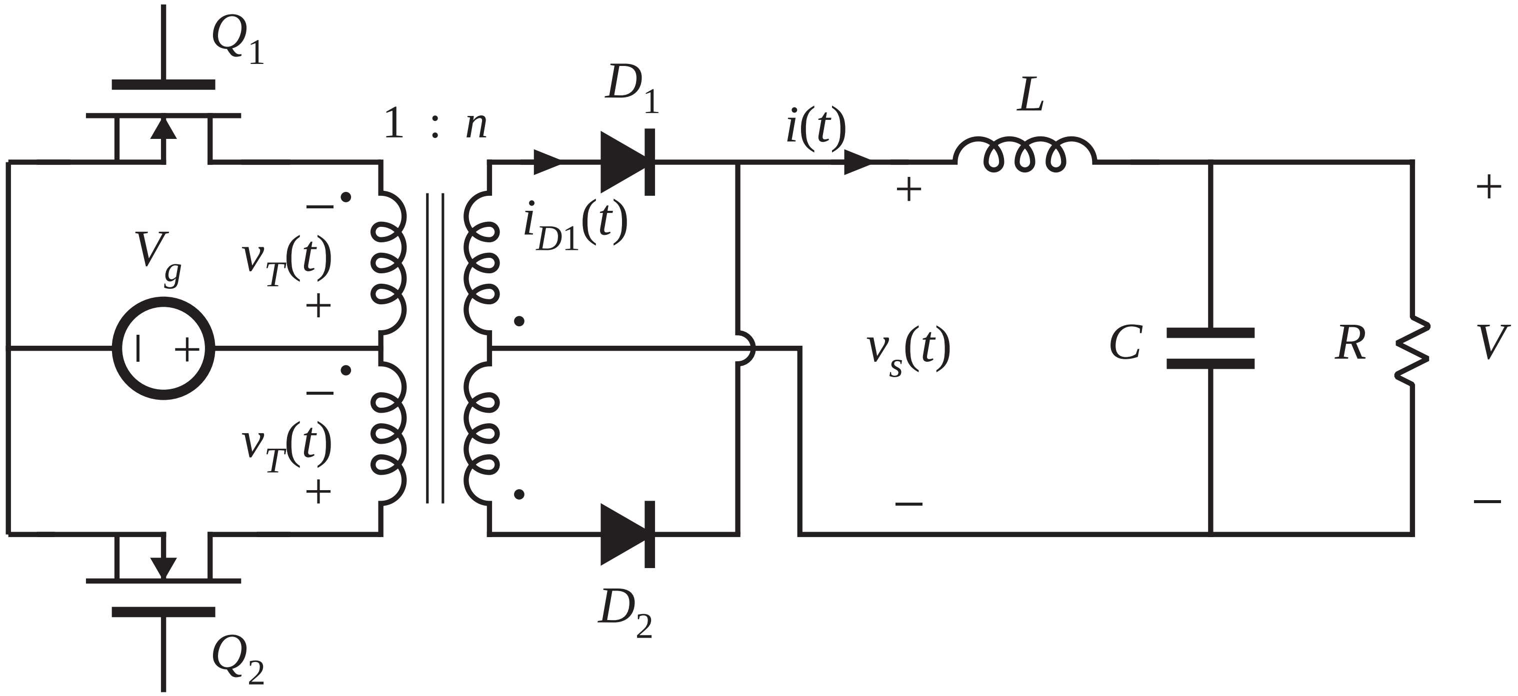


The two-transistor forward converter

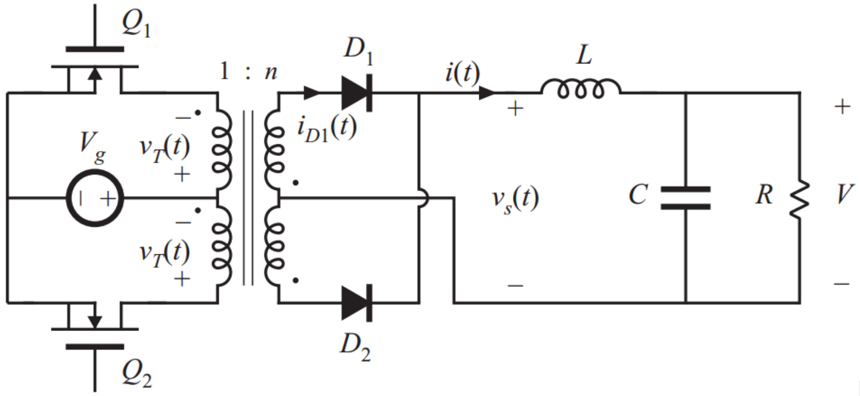


$$V = nDV_g \qquad D \le \frac{1}{2} \qquad \max(v_{Q1}) = \max(v_{Q2}) = V_g$$

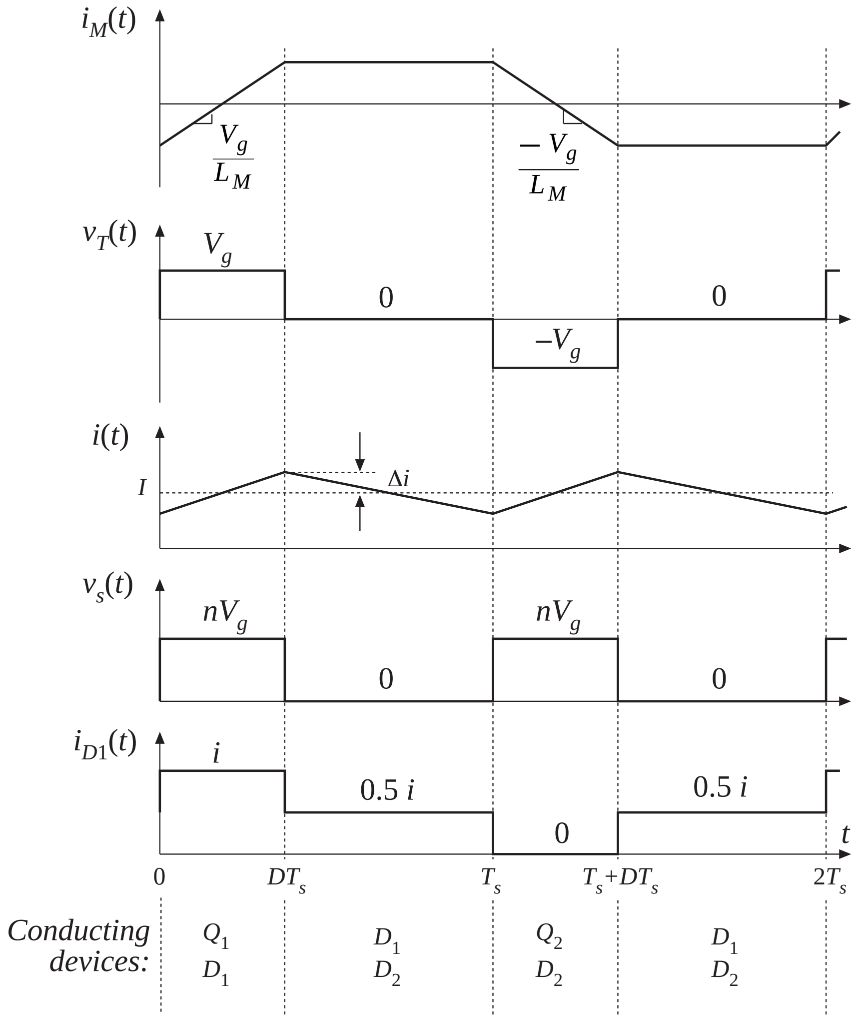
6.3.3. Push-pull isolated buck converter



$$\boxed{V = nDV_g \qquad 0 \le D \le 1}$$



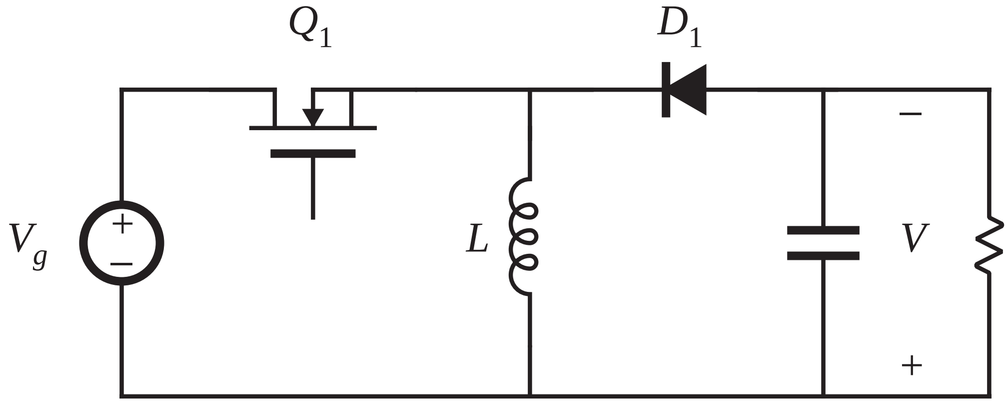
push-pull



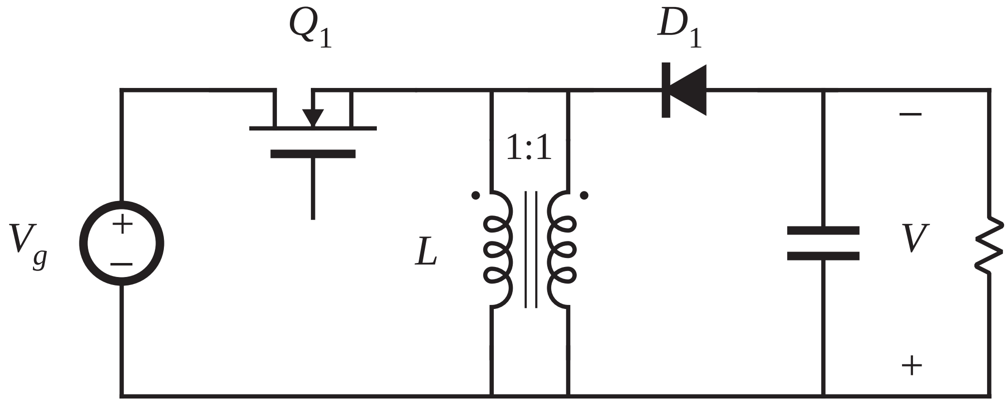
- Used with low-voltage inputs
- Secondary-side circuit identical to full bridge
- As in full bridge, transformer volt-second balance is obtained over two switching periods
- Effect of nonidealities on transformer volt-second balance?
- Current programmed control can be used to mitigate transformer saturation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

6.3.4. Flyback converter

buck-boost converter:

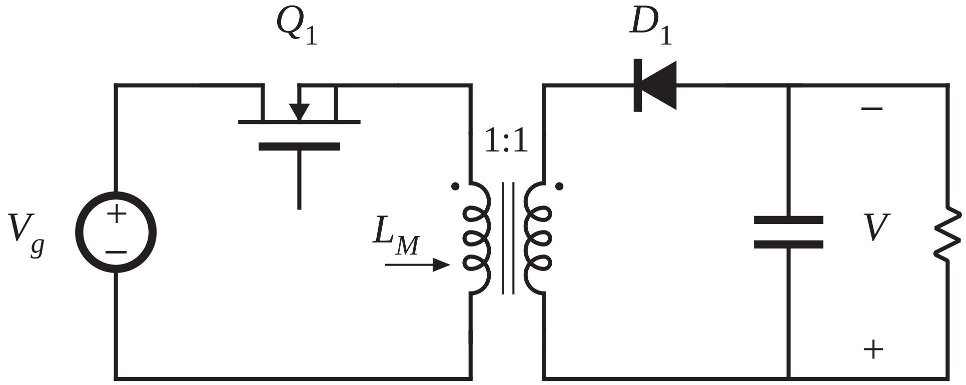


construct inductor winding using two parallel wires:

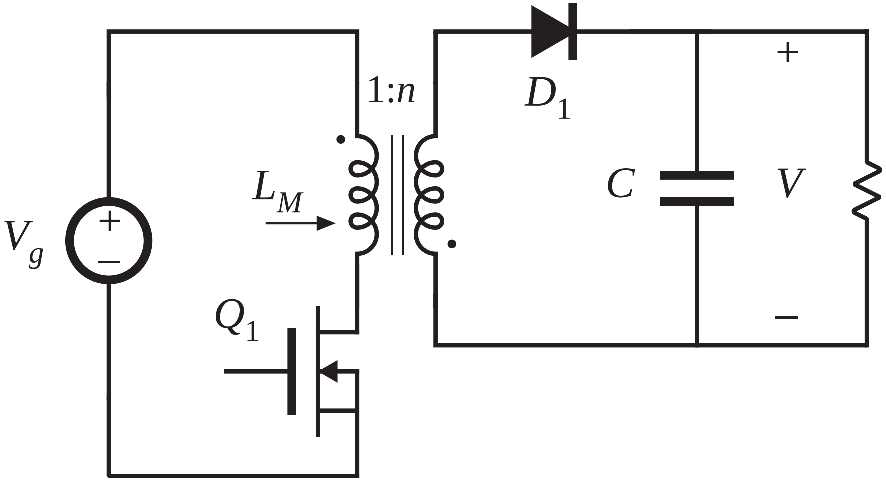


Derivation of flyback converter, cont.

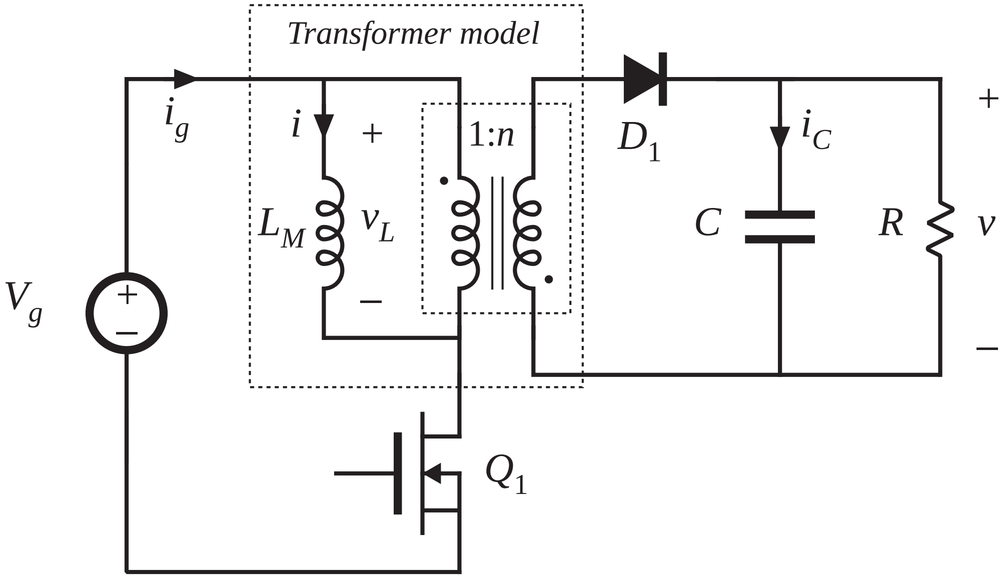
Isolate inductor windings: the flyback converter



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

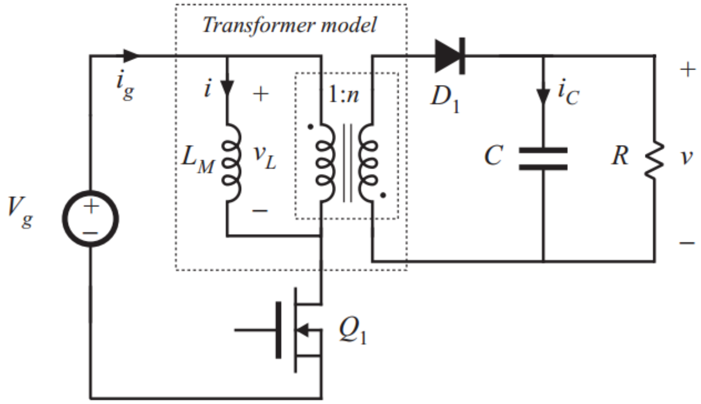


The “flyback transformer”

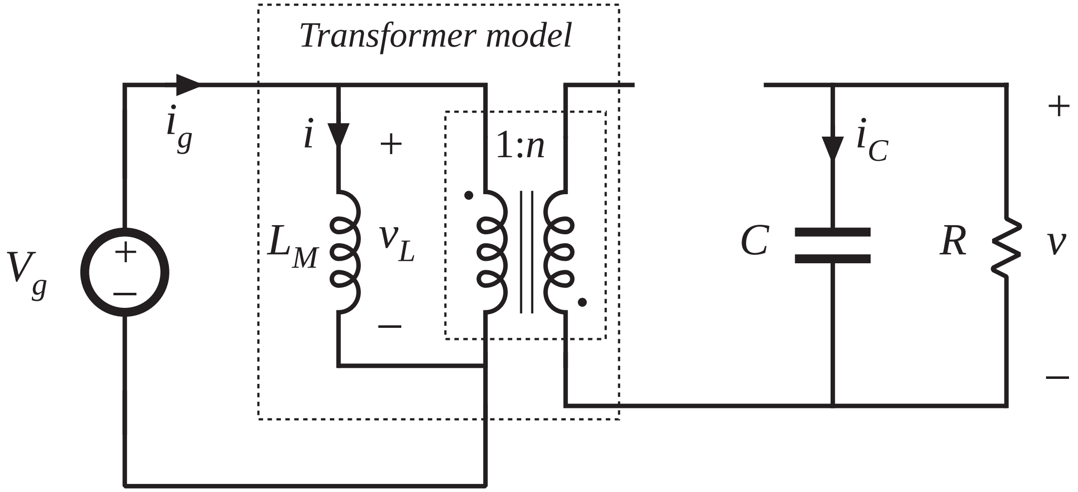


- A two-winding inductor
- Symbol is same as transformer, but function differs significantly from ideal transformer
- Energy is stored in magnetizing inductance
- Magnetizing inductance is relatively small

- 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

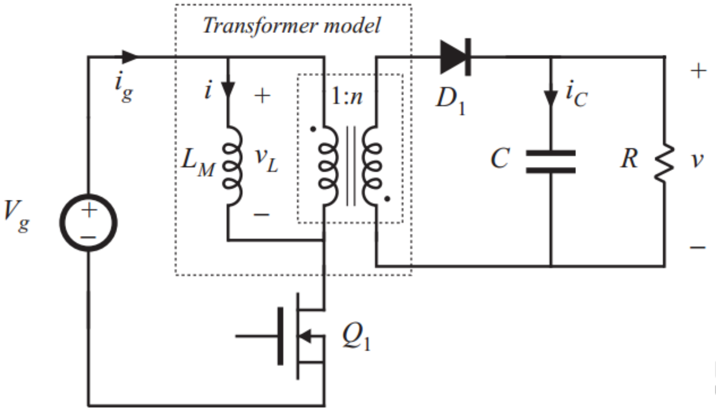


$$v_L = V_g$$
$$i_C = -\frac{v}{R}$$
$$i_g = i$$

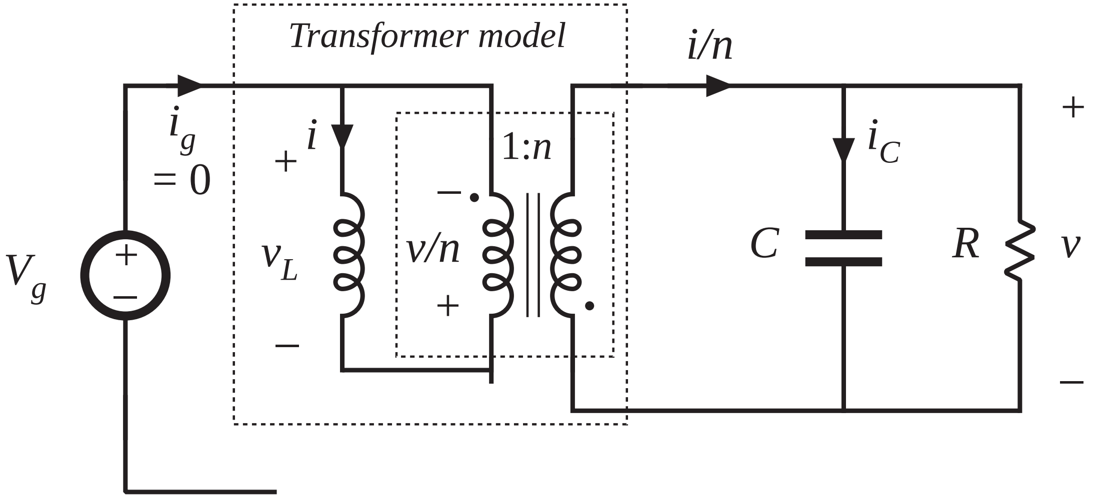
Q_1 on, D_1 off

CCM: small ripple approximation leads to

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



Subinterval 2



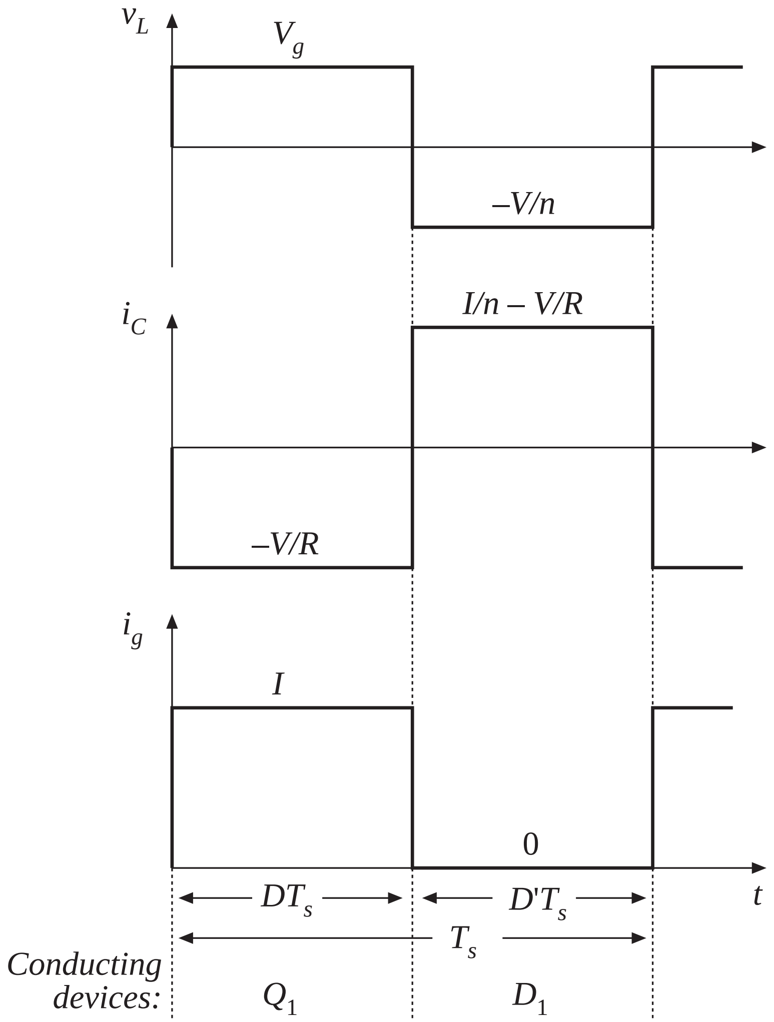
$$v_L = -\frac{v}{n}$$
$$i_C = \frac{i}{n} - \frac{v}{R}$$
$$i_g = 0$$

CCM: small ripple approximation leads to

Q_1 off, D_1 on

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

CCM Flyback waveforms and solution



Volt-second balance:

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

Conversion ratio is

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

Buck-Boost with turns ratio n

Charge balance:

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

Dc component of magnetizing current is

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

Dc component of source current is

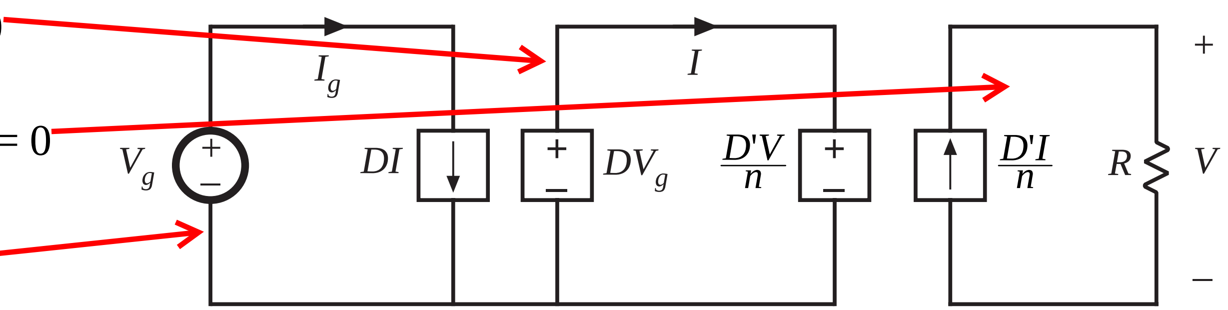
$$I_g = \left\langle i_g \right\rangle = D\left(I\right) + D'\left(0\right)$$

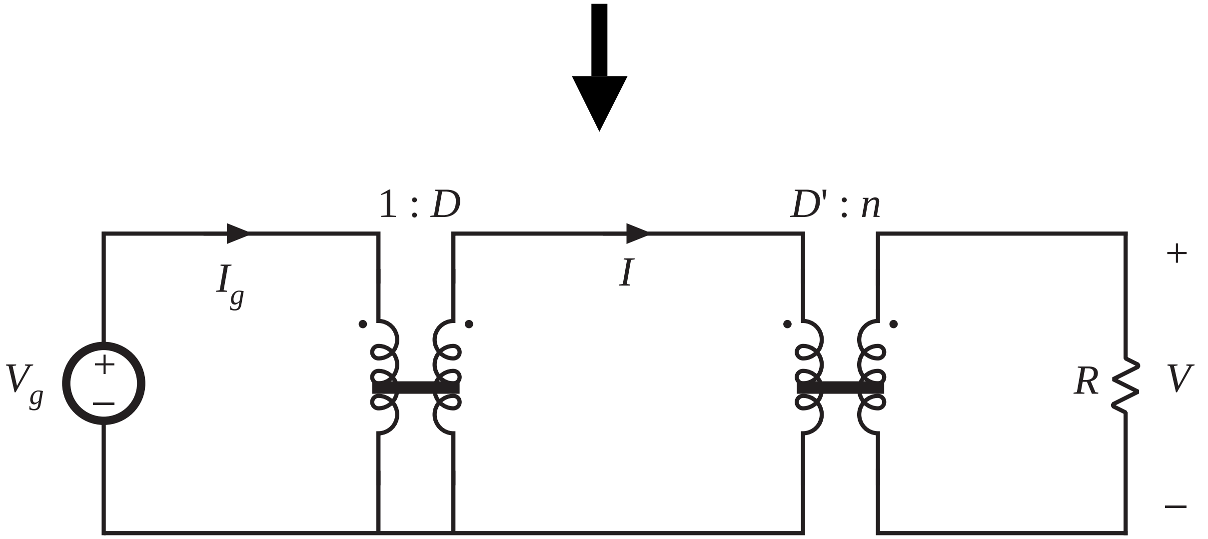
Equivalent circuit model: CCM Flyback

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

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

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





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

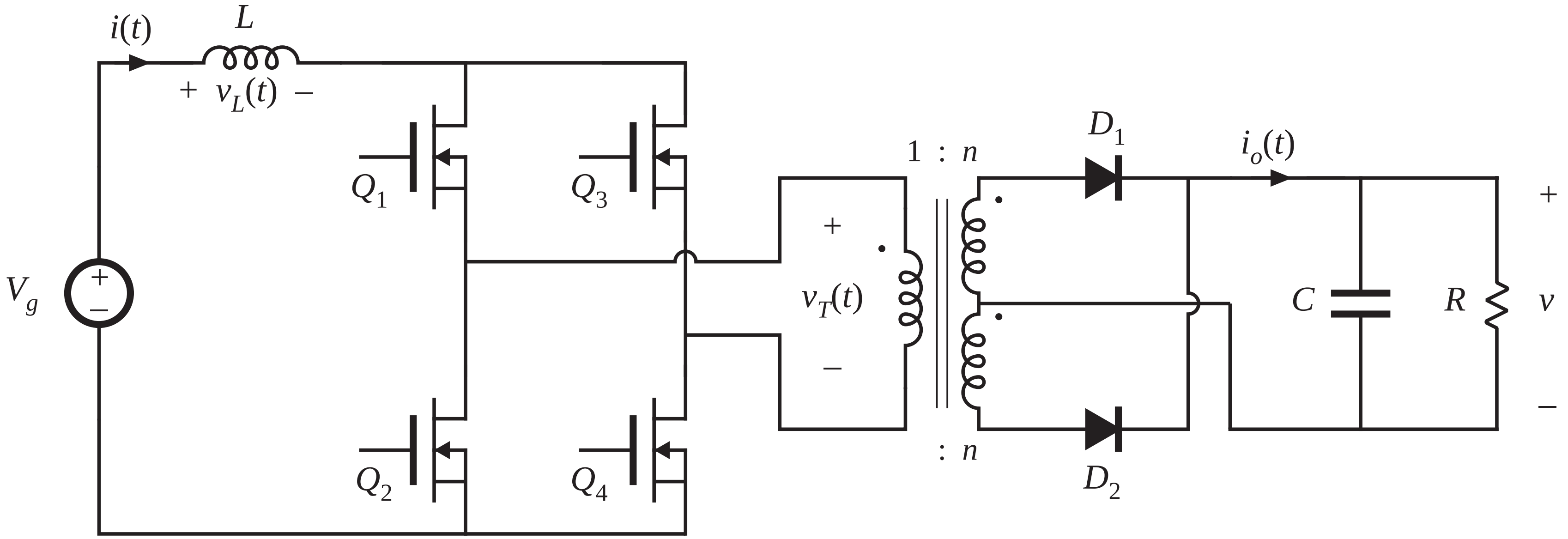
- DCM analysis: DCM buck-boost with turns ratio

6.3.5. Boost-derived isolated converters

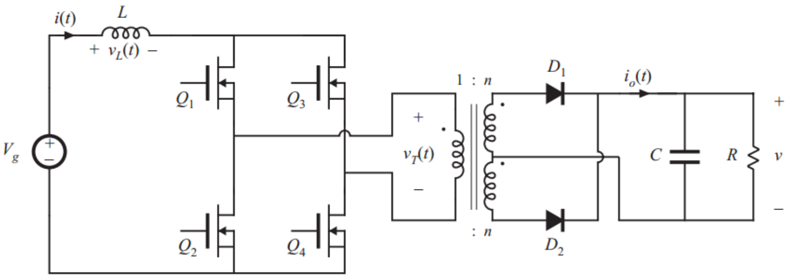
- A wide variety of boost-derived isolated dc-dc converters can be derived, by inversion of source and load of buck-derived isolated converters:
  - full-bridge and half-bridge isolated boost converters
  - inverse of forward converter: the “reverse” converter
  - push-pull boost-derived converter

Of these, the full-bridge and push-pull boost-derived isolated converters are the most popular, and are briefly discussed here.

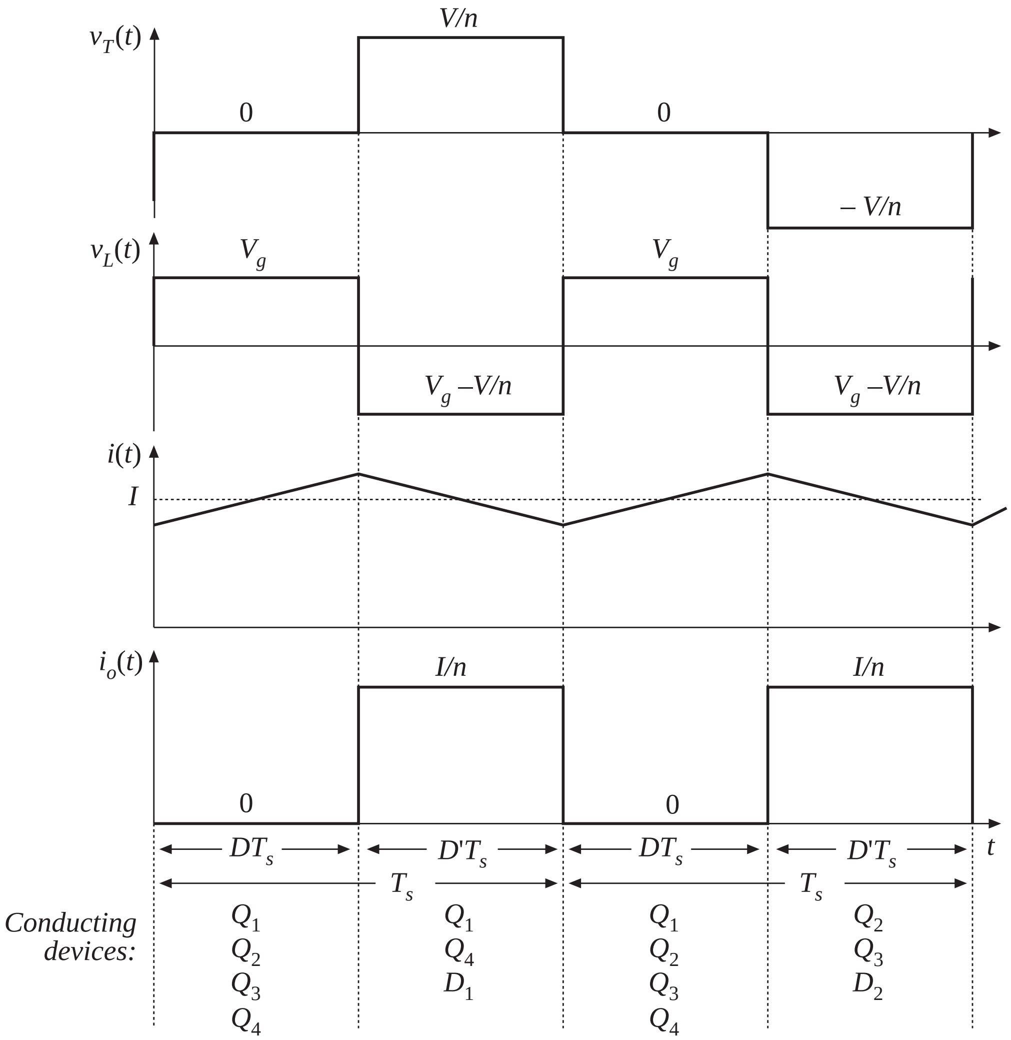
Full-bridge transformer-isolated boost-derived converter



- Circuit topologies are equivalent to those of nonisolated boost converter
- With 1:1 turns ratio, inductor current $i(t)$ and output current $i_o(t)$ waveforms are identical to nonisolated boost converter

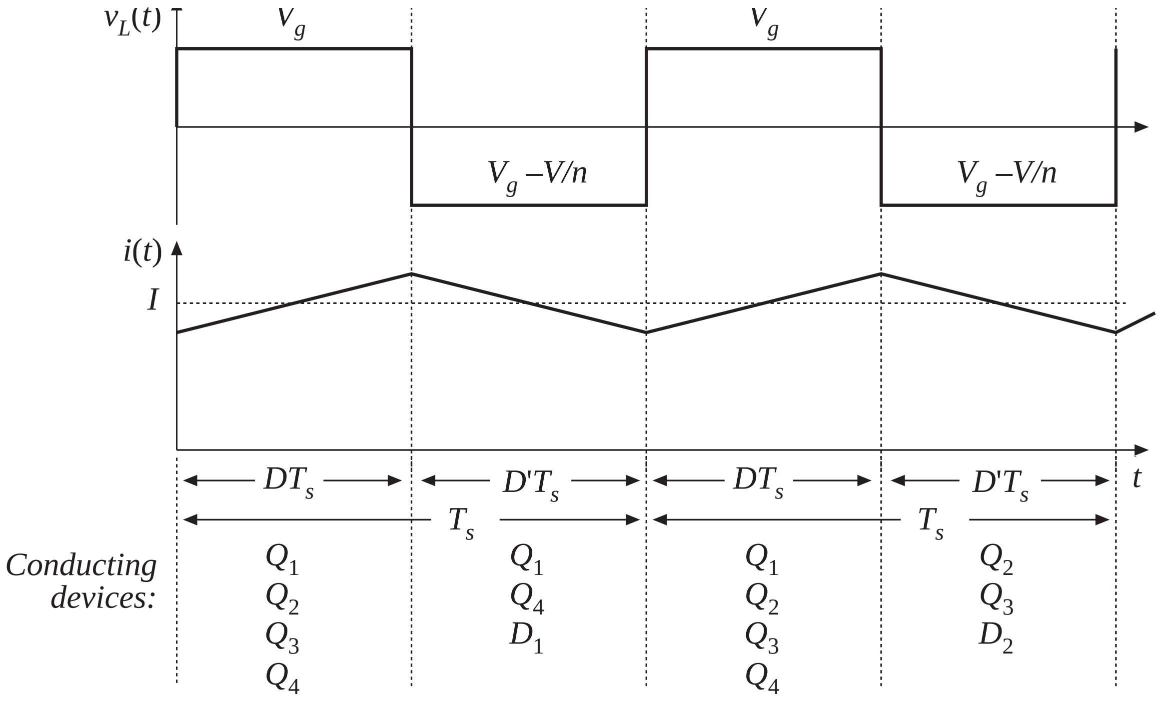


rmer reset mechanism



- As in full-bridge buck topology, transformer volt-second balance is obtained over two switching periods.
- During first switching period: transistors Q_1 and Q_4 conduct for time DT_s , applying volt-seconds VDT_s to secondary winding.
- During next switching period: transistors Q_2 and Q_3 conduct for time DT_s , applying volt-seconds $-VDT_s$ to secondary winding.

Conversion ratio $M(D)$



Application of volt-second balance to inductor voltage waveform:

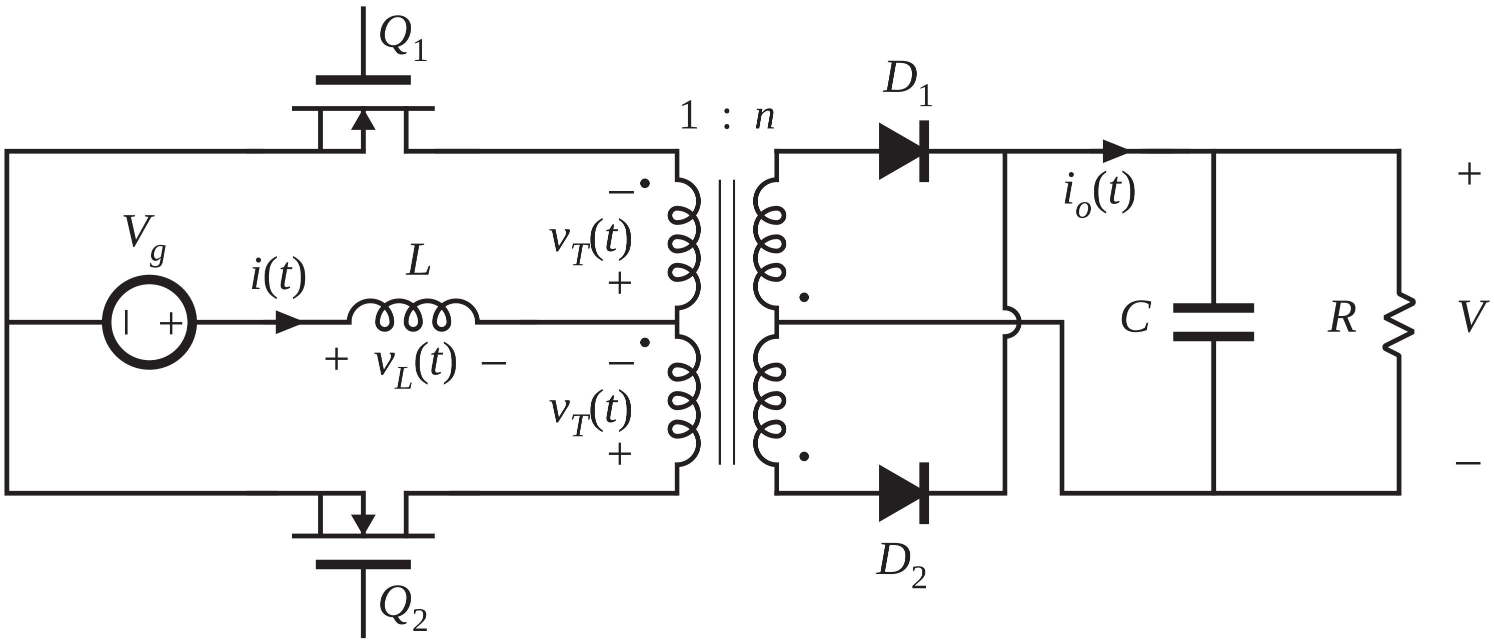
$$\left\langle v_L \right\rangle = D\left(V_g\right) + D'\left(V_g - \frac{V}{n}\right) = 0$$

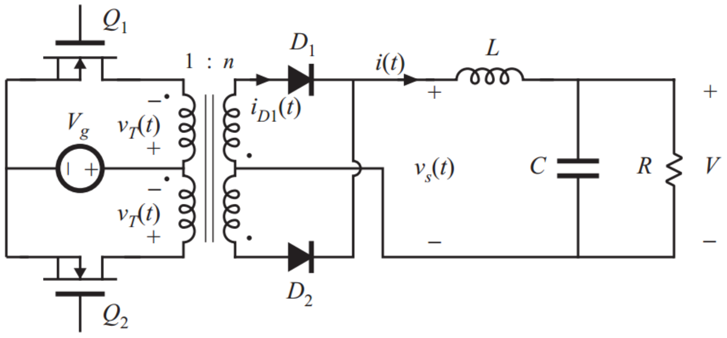
Solve for $M(D)$:

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

—boost with turns ratio n

Push-pull boost-derived converter

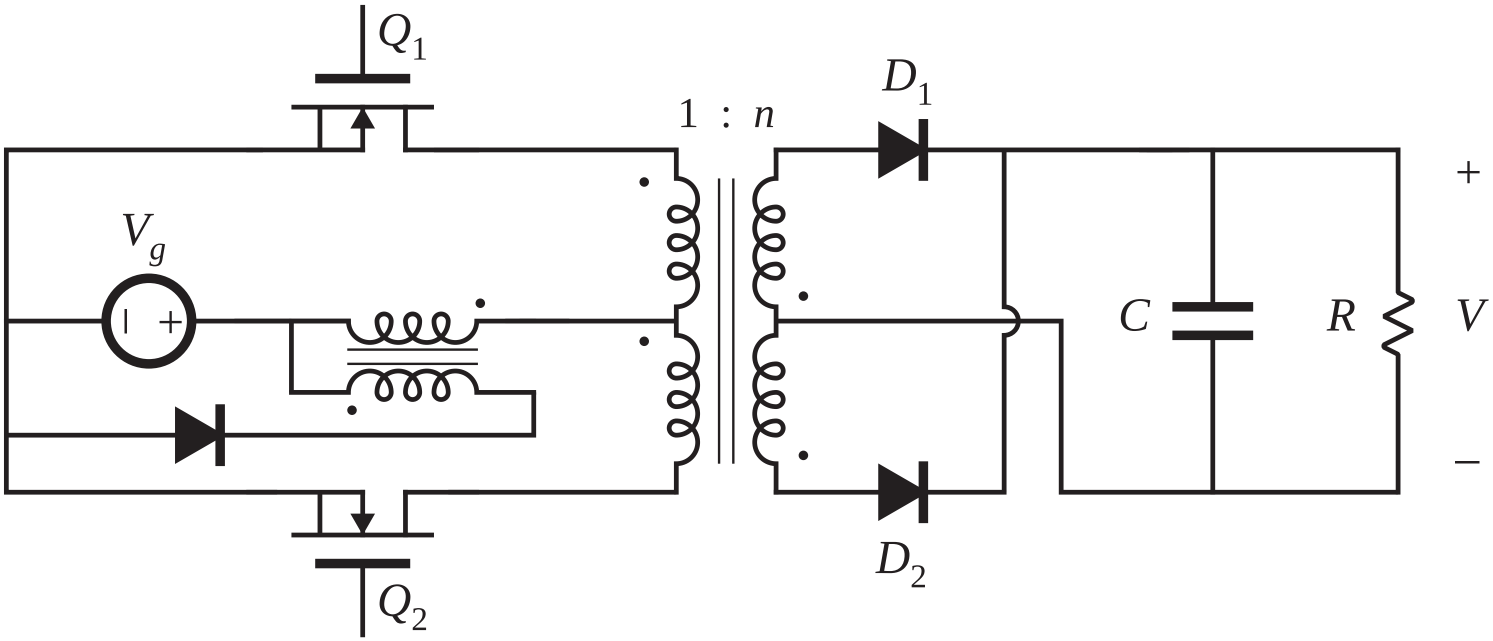




Push-pull buck

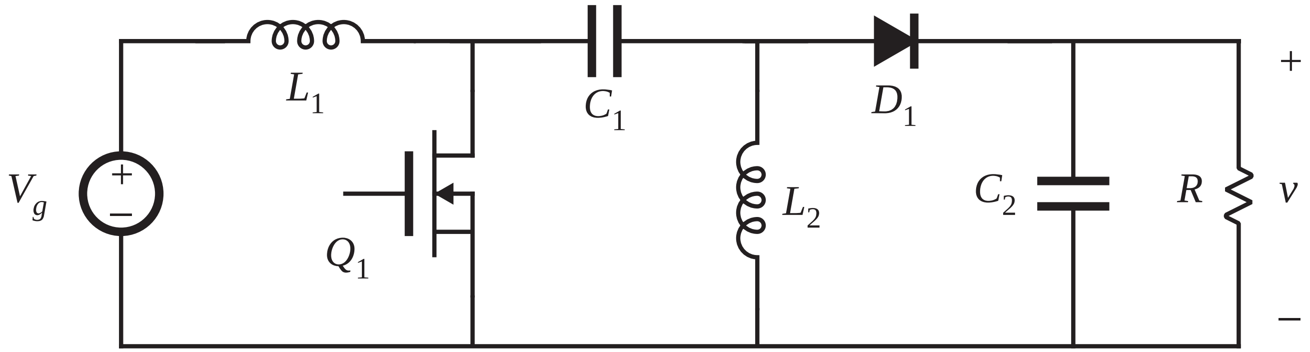
$$M(D) = \frac{V}{V_g} = \frac{n}{D'}$$

Push-pull converter based on Watkins-Johnson converter

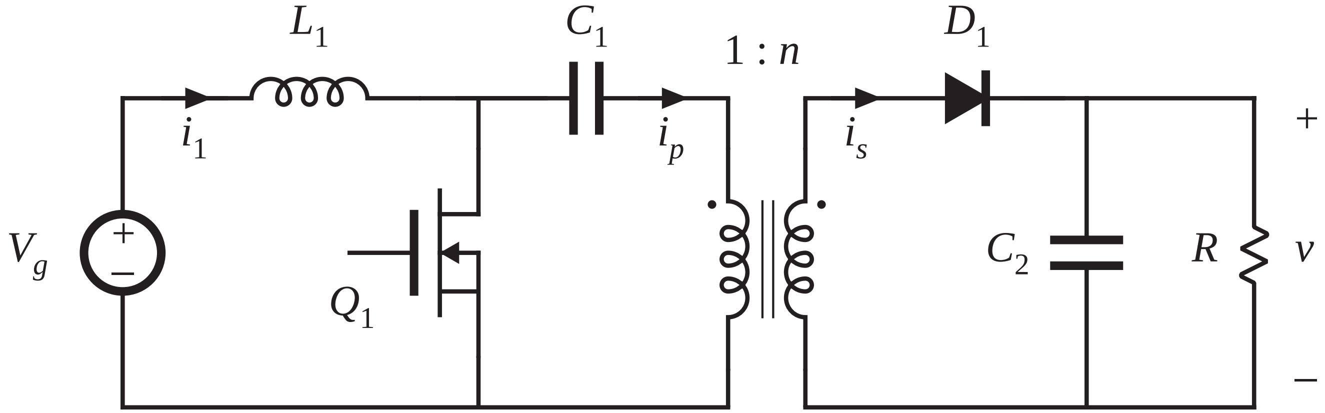


6.3.6. Isolated versions of the SEPIC and Cuk converter

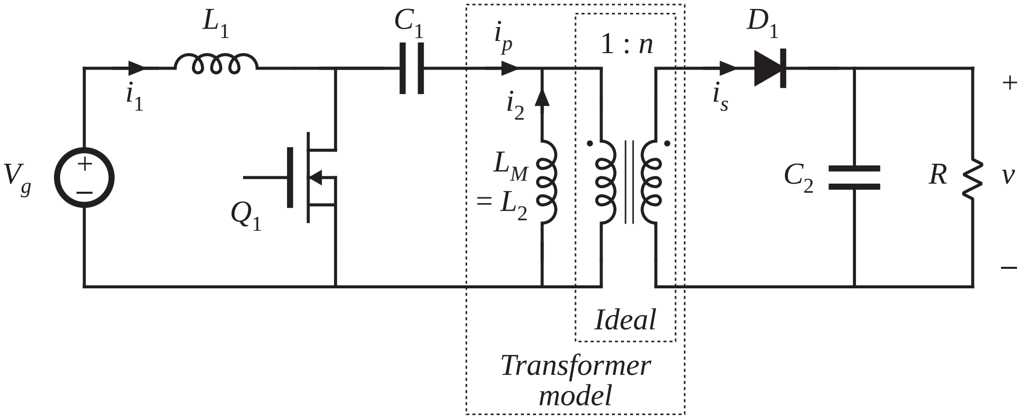
Basic nonisolated SEPIC



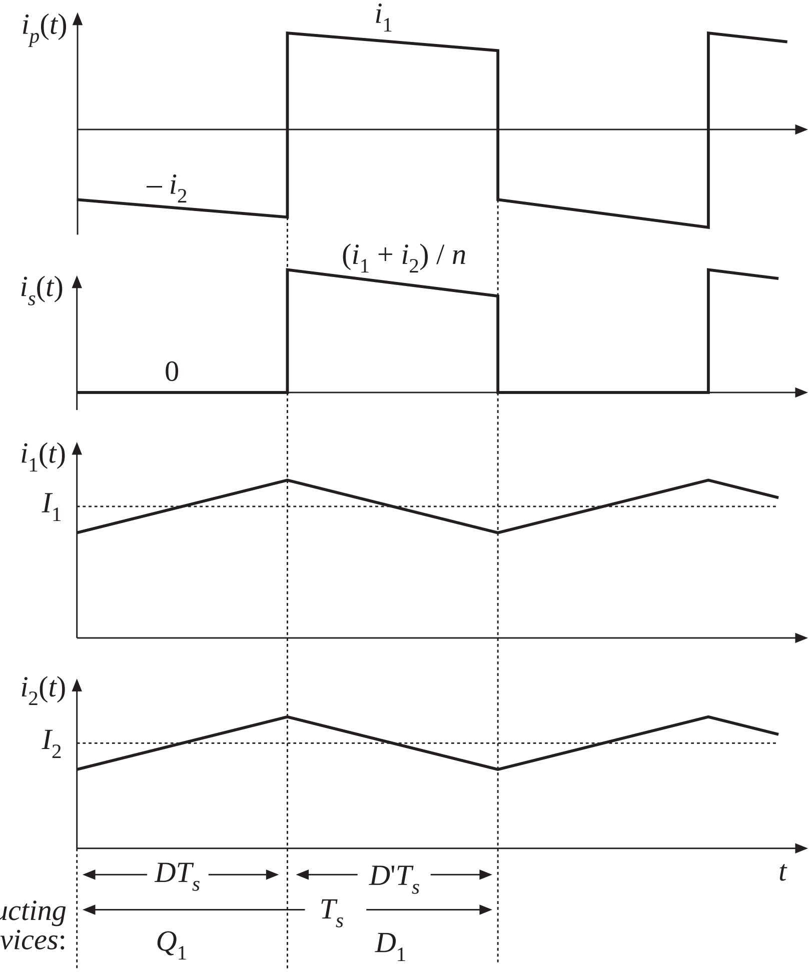
Isolated SEPIC



Isolated SEPIC



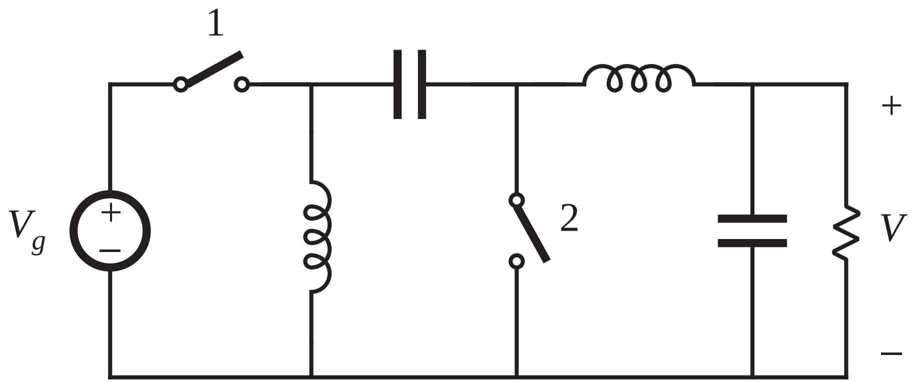
$$\boxed{M(D) = \frac{V}{V_g} = \frac{nD}{D'}}$$



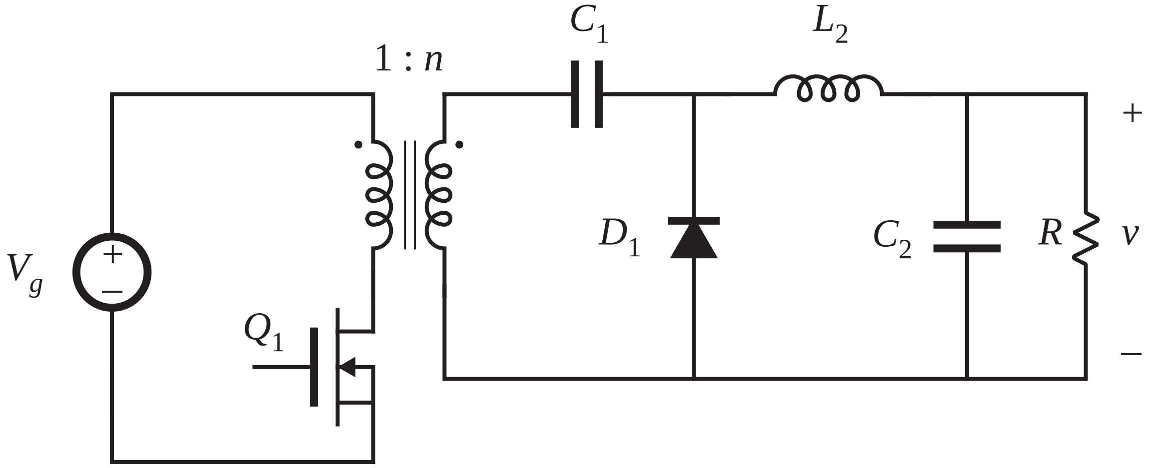
Inverse SEPIC

Nonisolated inverse SEPIC

Inverse the source and load

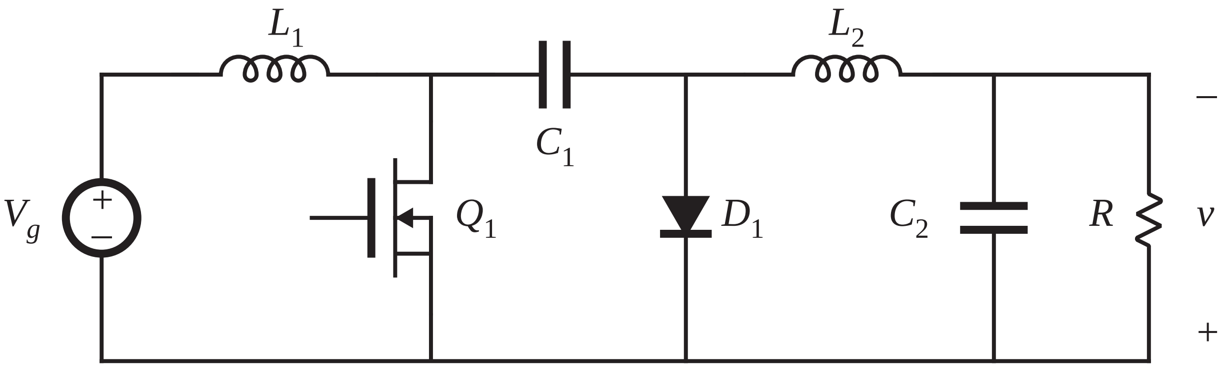


Isolated inverse SEPIC

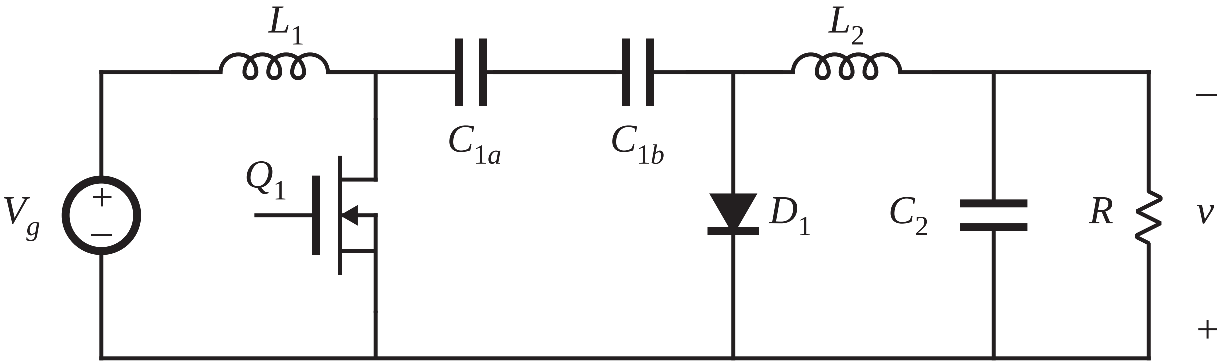


Obtaining isolation in the Cuk converter

Nonisolated Cuk converter



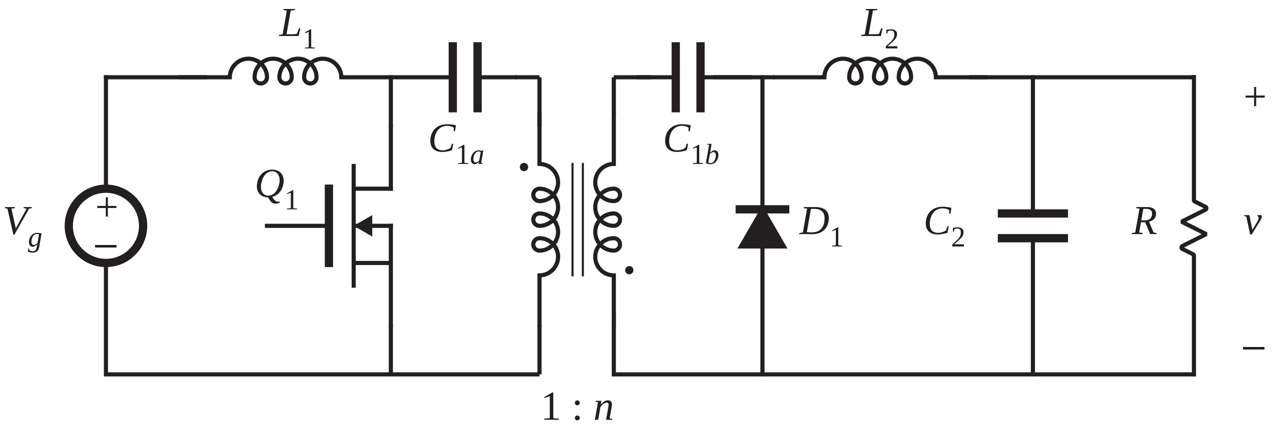
Split capacitor C_1 into series capacitors C_{1a} and C_{1b}



Isolated Cuk converter

Insert transformer between capacitors C_{1a} *and* C_{1b}

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



Discussion

- Capacitors C_{1a} *and* C_{1b} ensure that no dc voltage is applied to transformer primary or secondary windings
- Transformer functions in conventional manner, with small magnetizing current and negligible energy storage within the magnetizing inductance

large magnetizing inductance => large impedance => small magnetizing current