

Johns Hopkins Engineering

Power Electronics 525.725

Module 4 Lecture 4
Transformer Isolation



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

Multiple winding transformer

The diagram illustrates a multiple winding transformer with three windings. The primary winding (1) has n_1 turns, with current $i_1(t)$ flowing into the top terminal and voltage $v_1(t)$ across it. The secondary winding (2) has n_2 turns, with current $i_2(t)$ flowing into the top terminal and voltage $v_2(t)$ across it. The tertiary winding (3) has n_3 turns, with current $i_3(t)$ flowing into the top terminal and voltage $v_3(t)$ across it. All windings are magnetically coupled, as indicated by the dots on the top terminal of each winding. The turns ratio is given as $n_1 : n_2$ and $: n_3$.

Equivalent circuit model

The diagram shows an equivalent circuit model of a transformer. The primary winding is connected to a voltage source $v_1(t)$ and has current $i_1(t)$. A magnetizing inductor L_M is in parallel with the primary winding. The secondary windings are connected to loads with voltages $v_2(t)$ and $v_3(t)$, and currents $i_2(t)$ and $i_3(t)$. The transformer is enclosed in a dashed box labeled "ideal transformer".

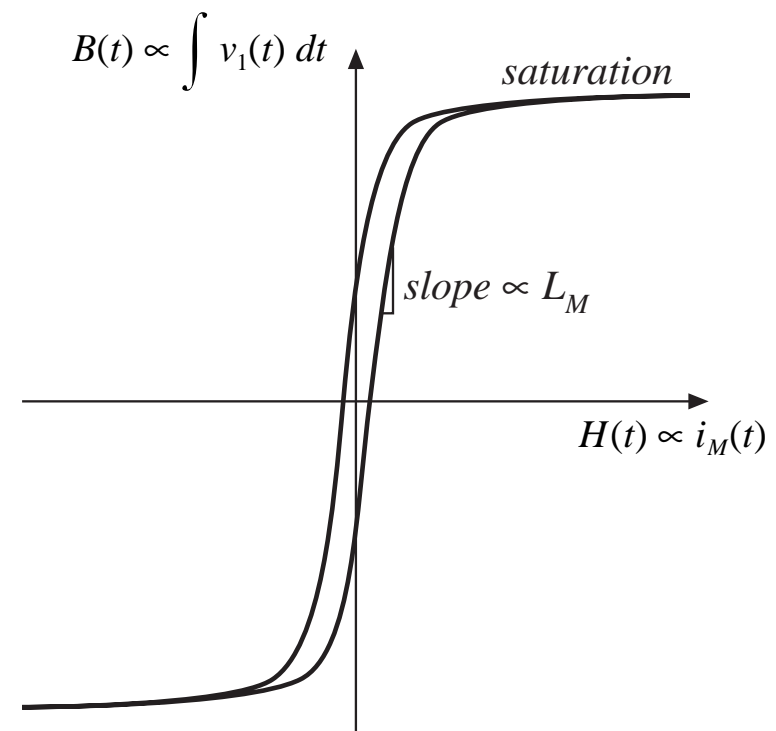
$$\frac{v_1(t)}{n_1} = \frac{v_2(t)}{n_2} = \frac{v_3(t)}{n_3} = \dots$$

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

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

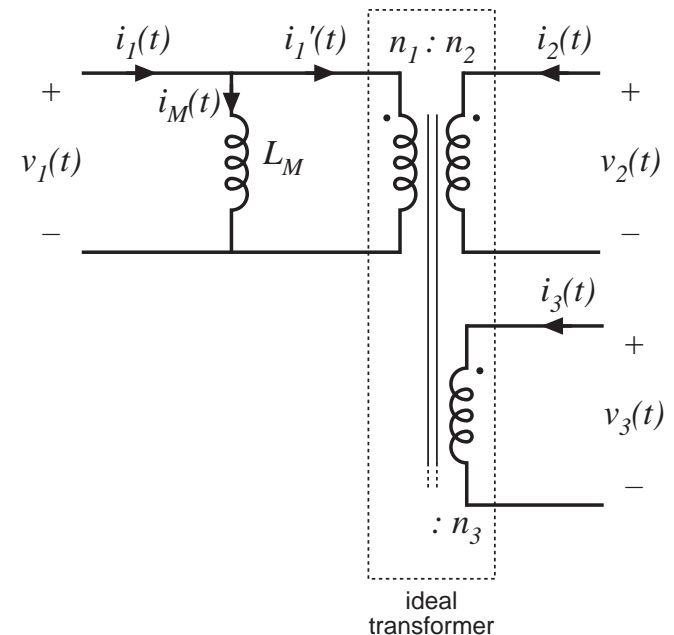
$$v_1(t) = L_M \frac{di_M(t)}{dt}$$

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

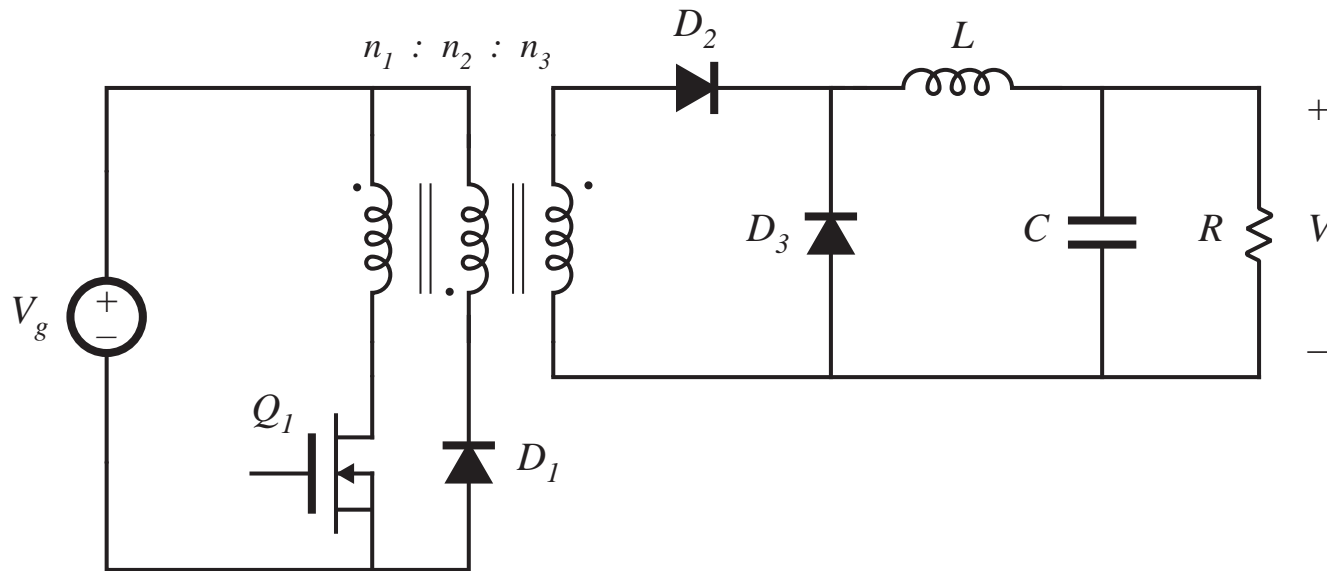
$$0 = \frac{1}{T_s} \int_0^{T_s} v_1(t) dt$$



Transformer reset

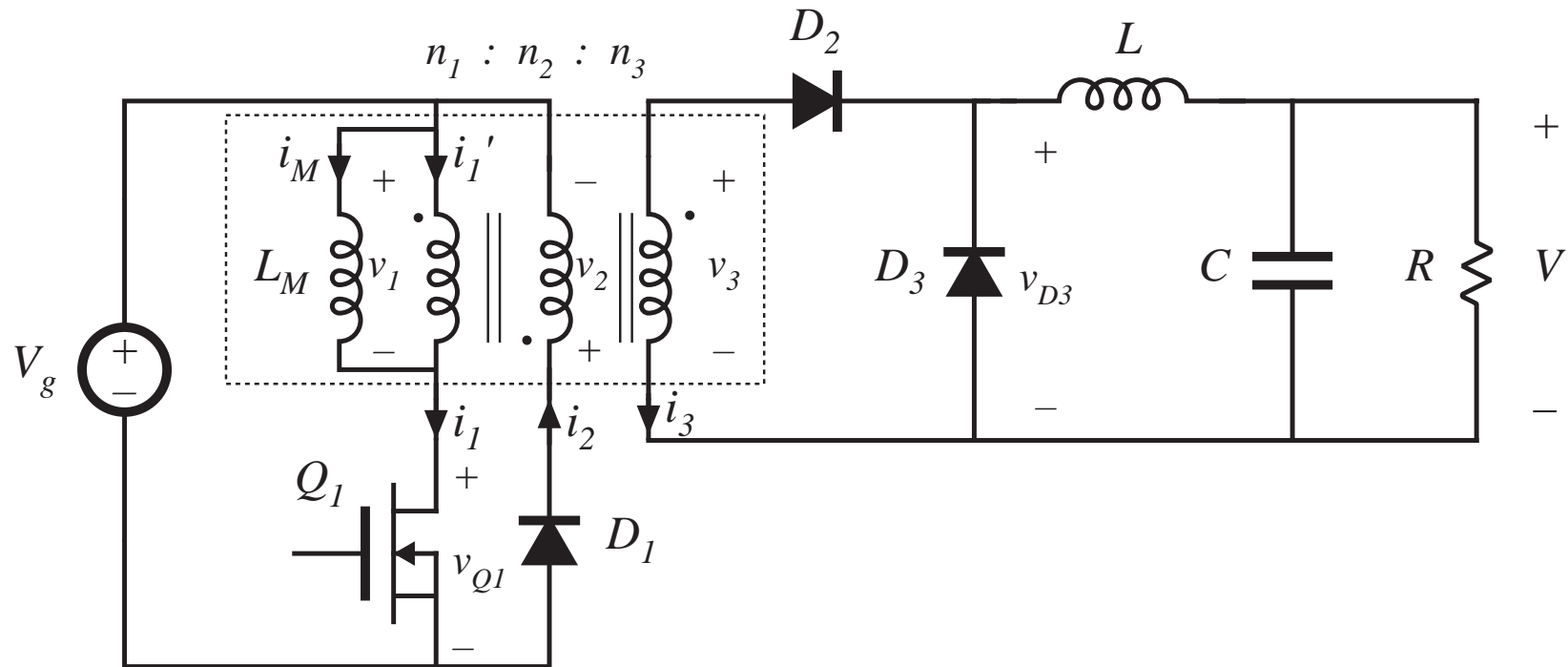
- “Transformer reset” is the mechanism by which magnetizing inductance volt-second balance is obtained
- The need to reset the transformer volt-seconds to zero by the end of each switching period adds considerable complexity to converters
- To understand operation of transformer-isolated converters: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

6.3.2. Forward converter

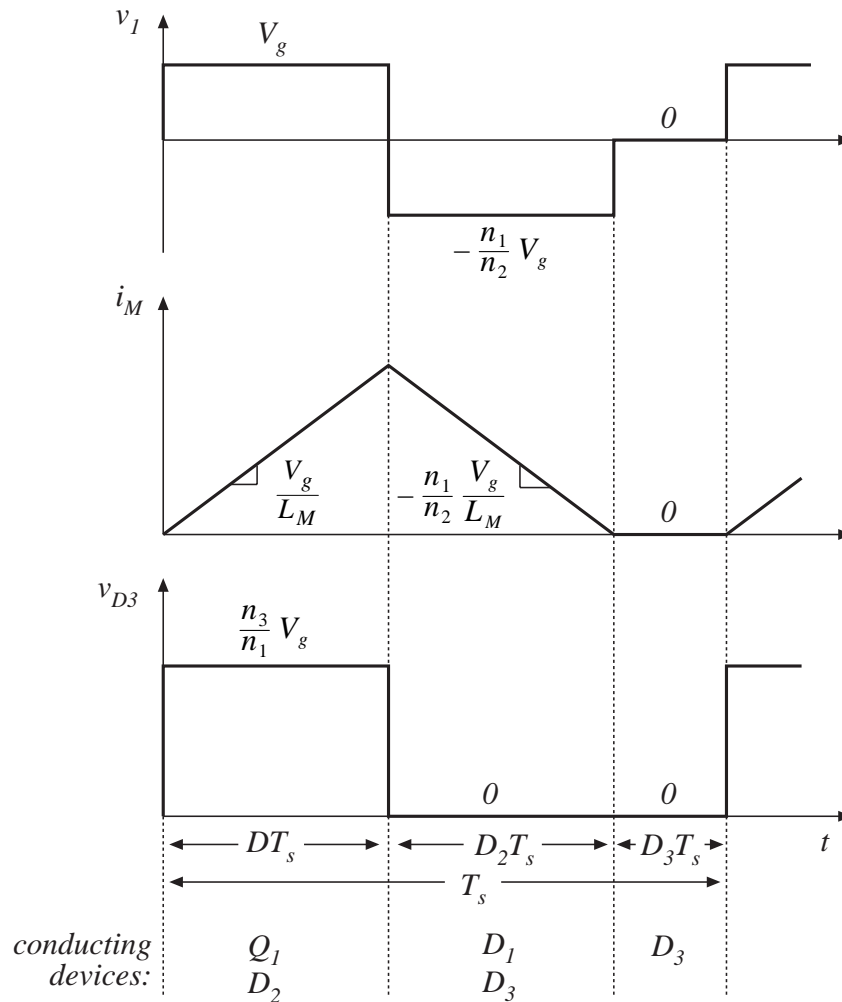


- Buck-derived transformer-isolated converter
- Single-transistor and two-transistor versions
- Maximum duty cycle is limited
- Transformer is reset while transistor is off

Forward converter with transformer equivalent circuit

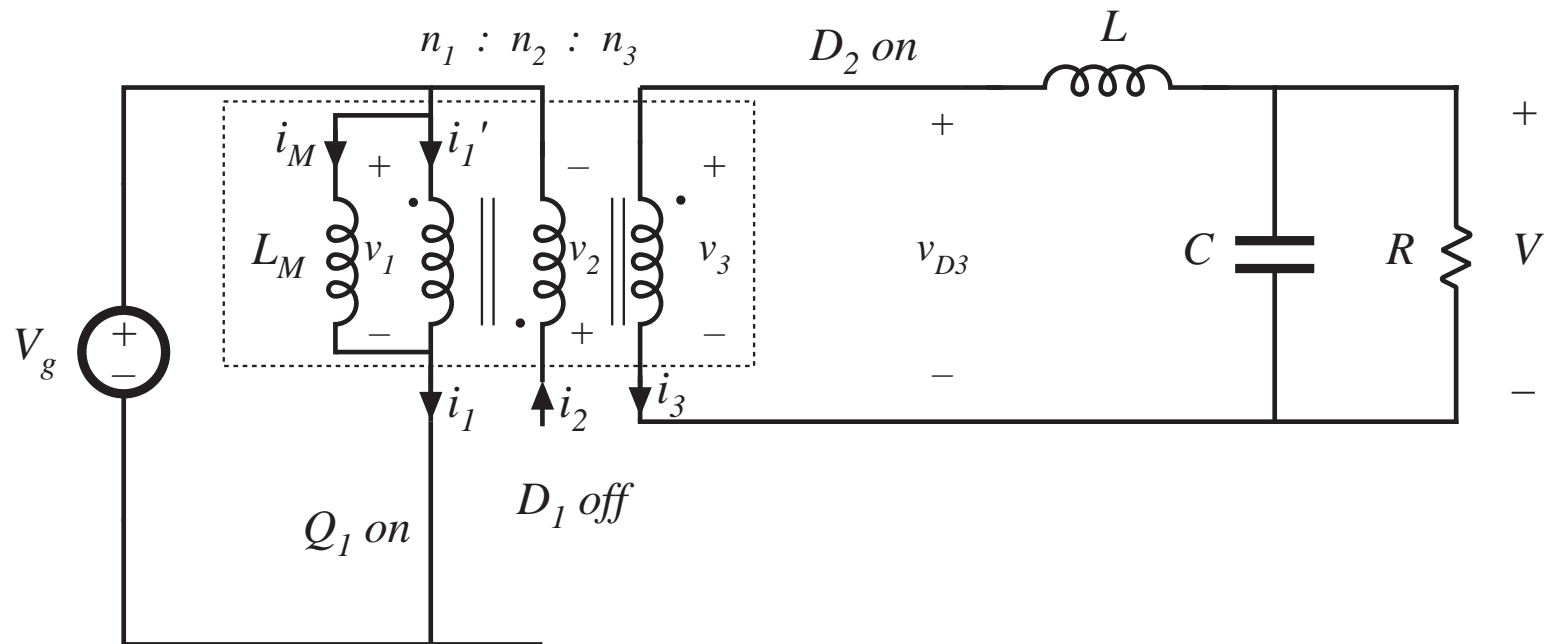


Forward converter: waveforms



- 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

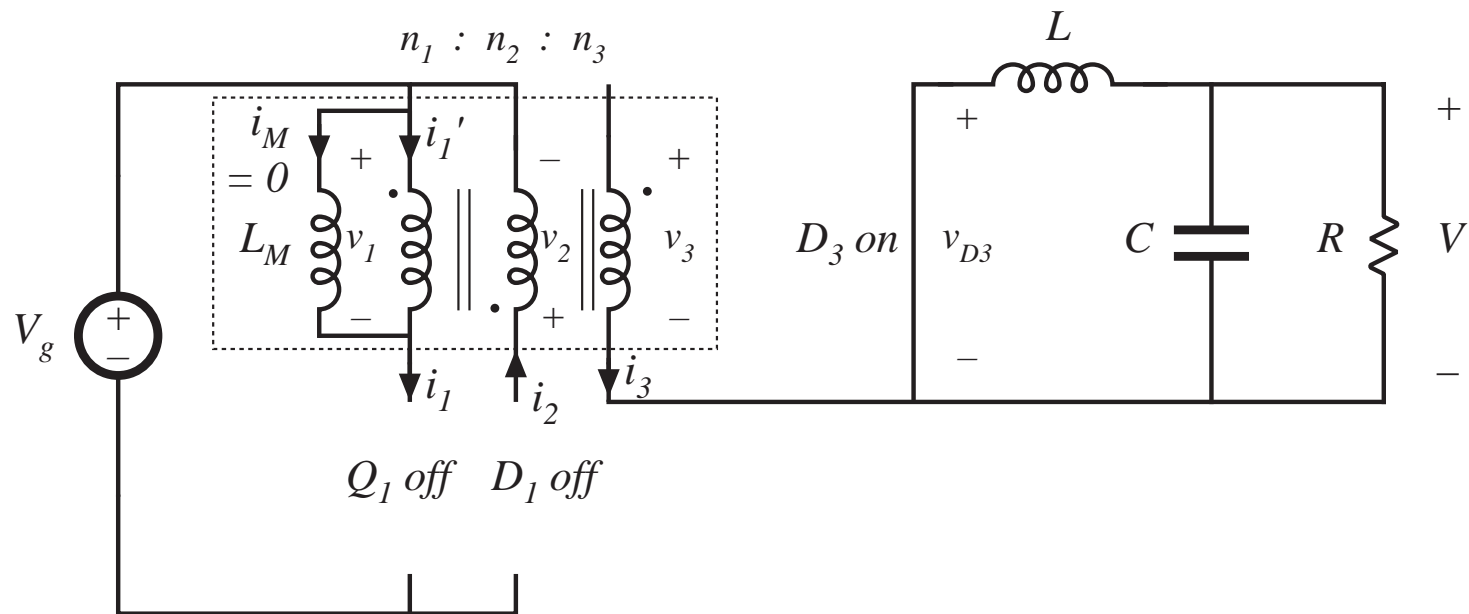
Subinterval 1: transistor conducts



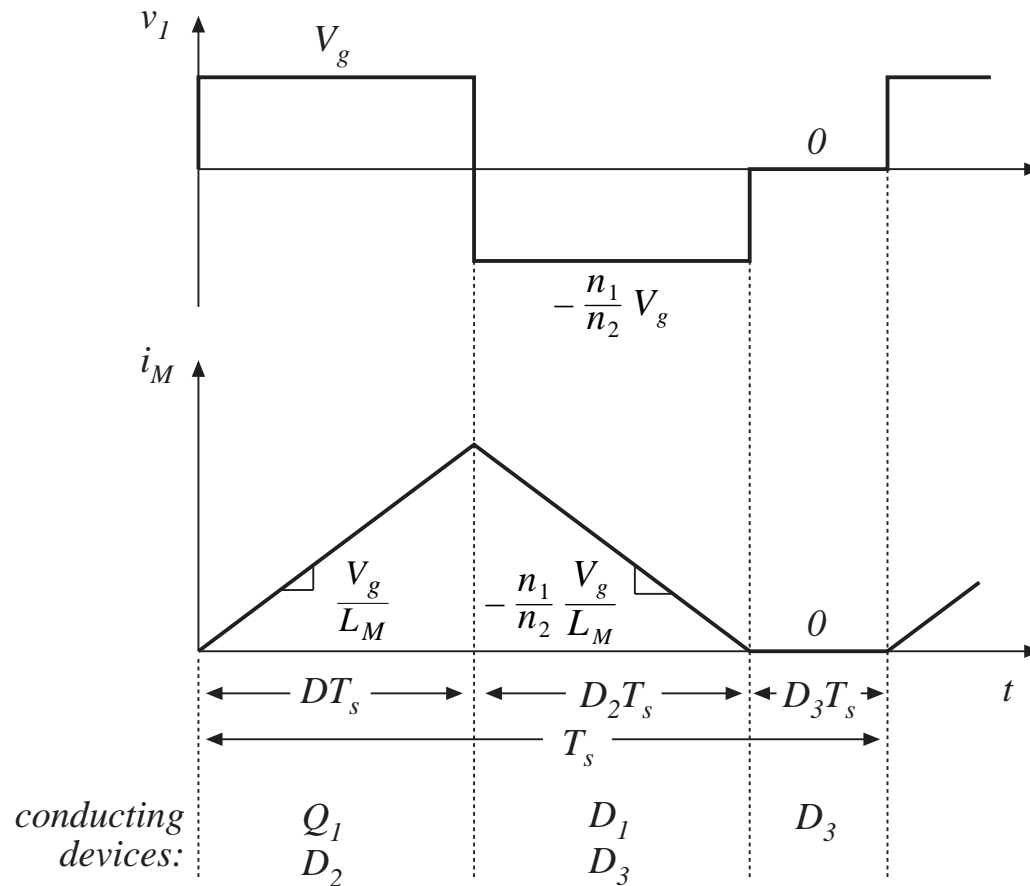
Age Group	Total	Male	Female	Male	Female
18-24	12%	10%	14%	11%	13%
25-34	35%	33%	37%	34%	36%
35-44	28%	26%	30%	27%	29%
45-54	18%	16%	20%	17%	19%
55-64	8%	7%	9%	8%	10%
65-74	3%	2%	4%	3%	5%
75+	1%	0%	2%	1%	3%



Subinterval 3



Magnetizing inductance volt-second balance



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

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

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

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

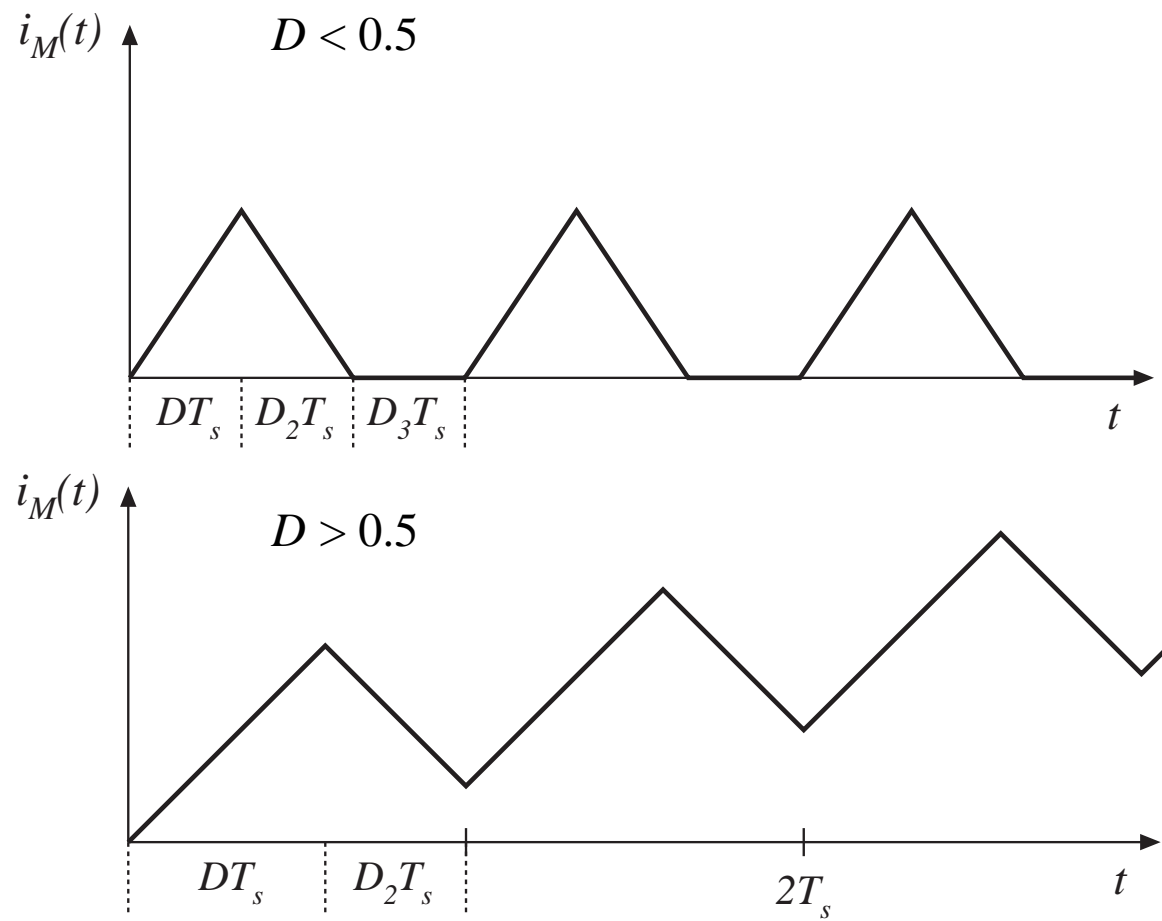
Solve for D

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

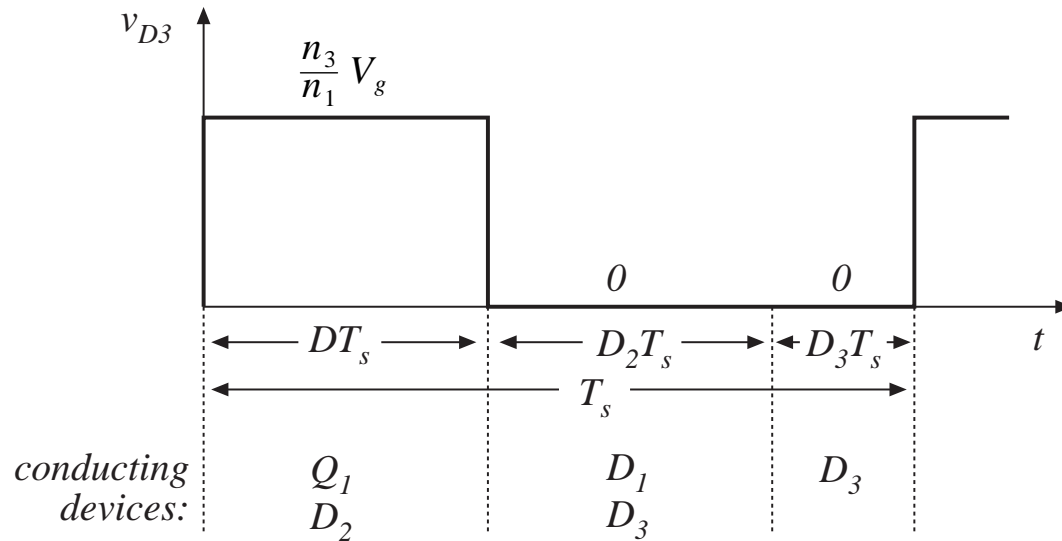
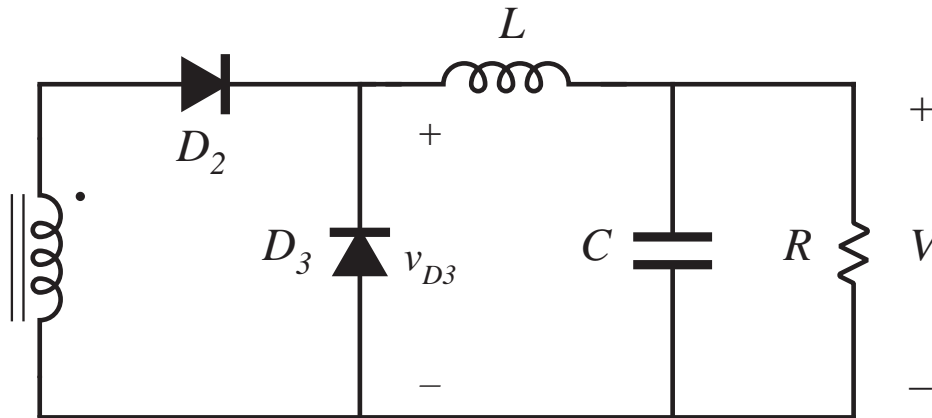
$$\text{for } n_1 = n_2: \quad D \leq \frac{1}{2}$$

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

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

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

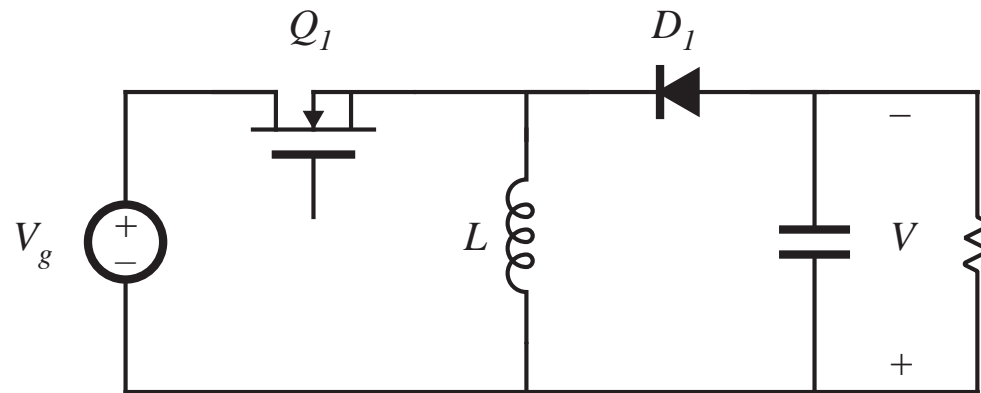
$$\max v_{Q1} = V_g \left(1 + \frac{n_1}{n_2} \right)$$

For $n_1 = n_2$

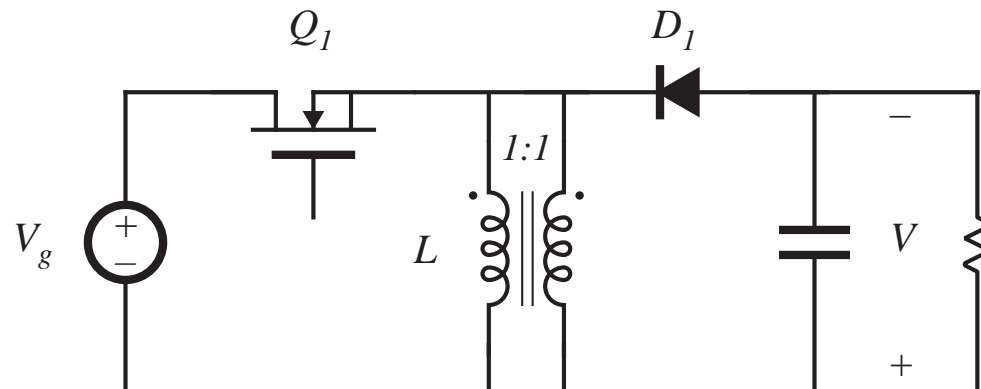
$$D \leq \frac{1}{2} \quad \text{and} \quad \max v_{Q1} = 2V_g$$

6.3.4. Flyback converter

buck-boost converter:

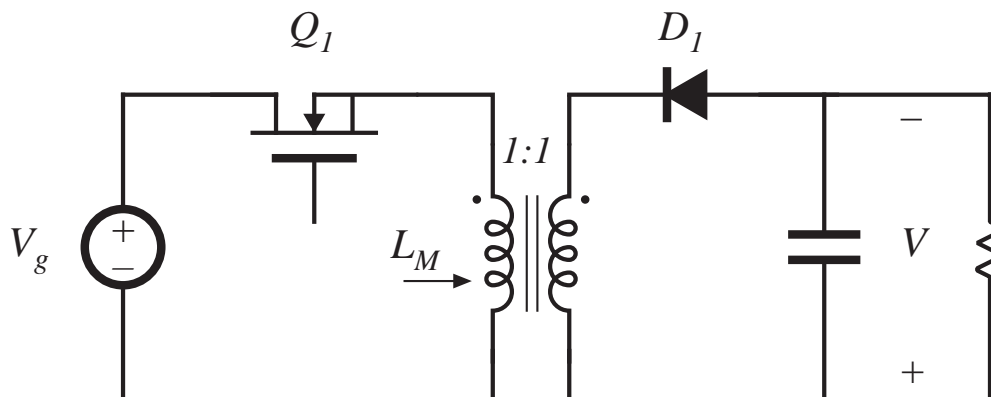


construct inductor winding using two parallel wires:

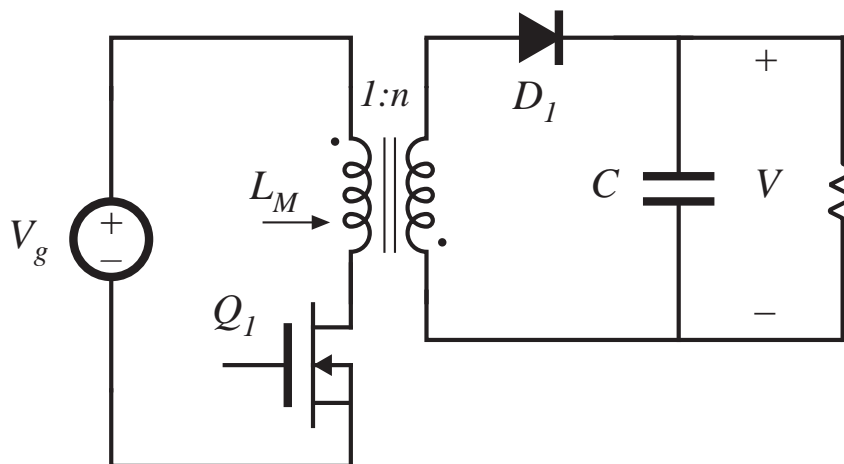


Derivation of flyback converter, cont.

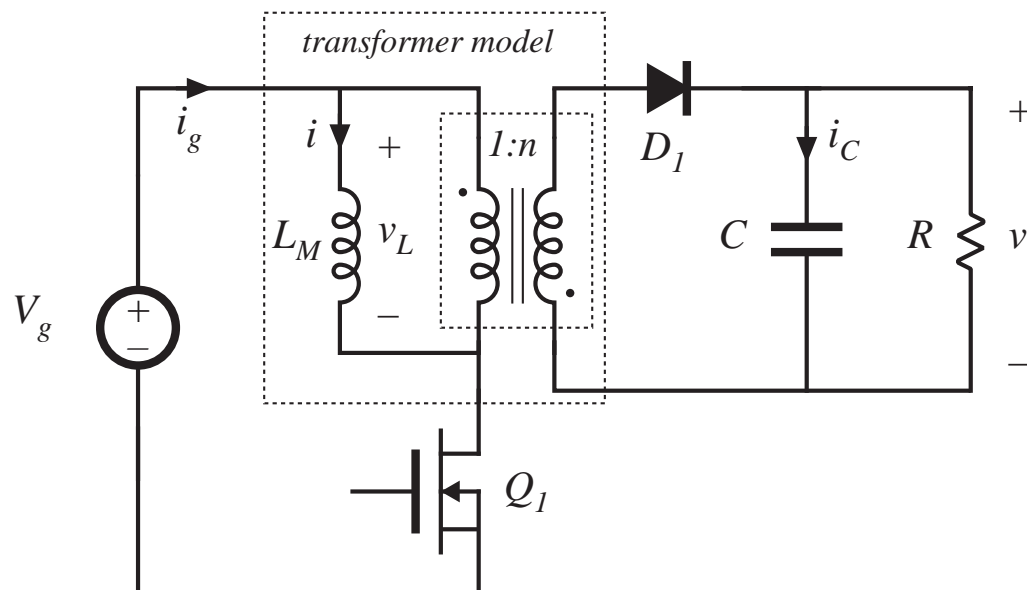
Isolate inductor windings: the flyback converter



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

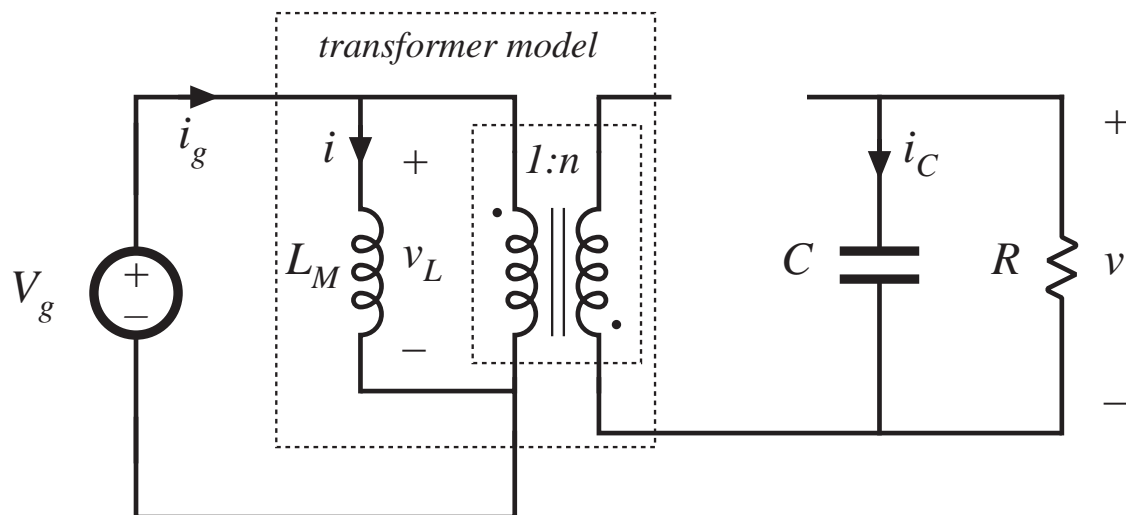


The “flyback transformer”



- 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

Subinterval 1

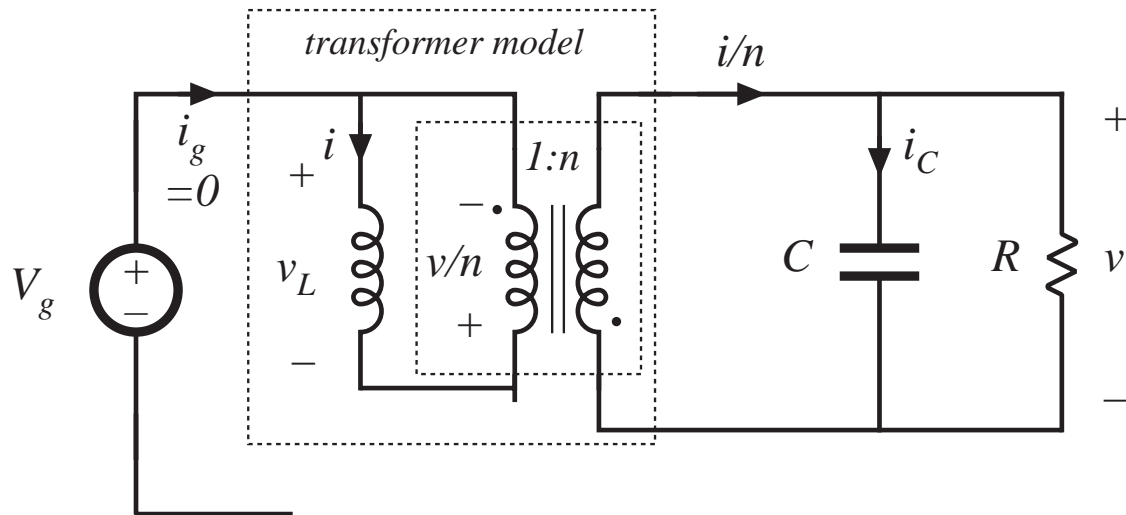


$$\begin{aligned} v_L &= V_g \\ i_C &= -\frac{v}{R} \\ i_g &= i \end{aligned}$$

CCM: small ripple approximation leads to

$$\begin{aligned} v_L &= V_g \\ i_C &= -\frac{V}{R} \\ i_g &= I \end{aligned}$$

Subinterval 2

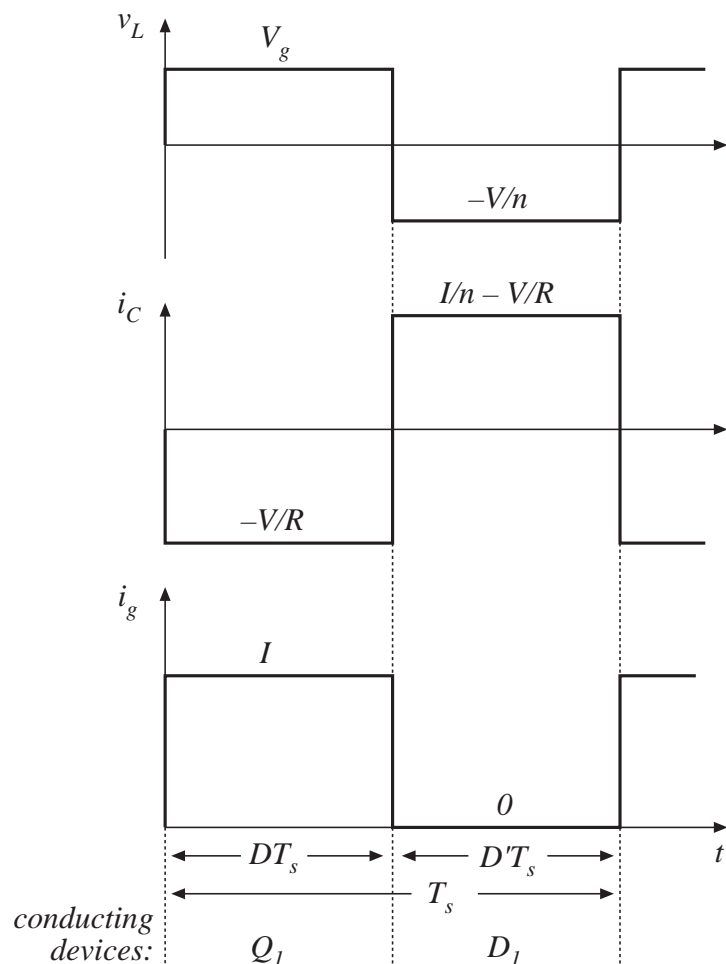


$$\begin{aligned} v_L &= -\frac{v}{n} \\ i_C &= \frac{i}{n} - \frac{v}{R} \\ i_g &= 0 \end{aligned}$$

CCM: small ripple approximation leads to

$$\begin{aligned} v_L &= -\frac{V}{n} \\ i_C &= \frac{I}{n} - \frac{V}{R} \\ i_g &= 0 \end{aligned}$$

CCM Flyback waveforms and solution



Volt-second balance:

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

Conversion ratio is

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

Charge balance:

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

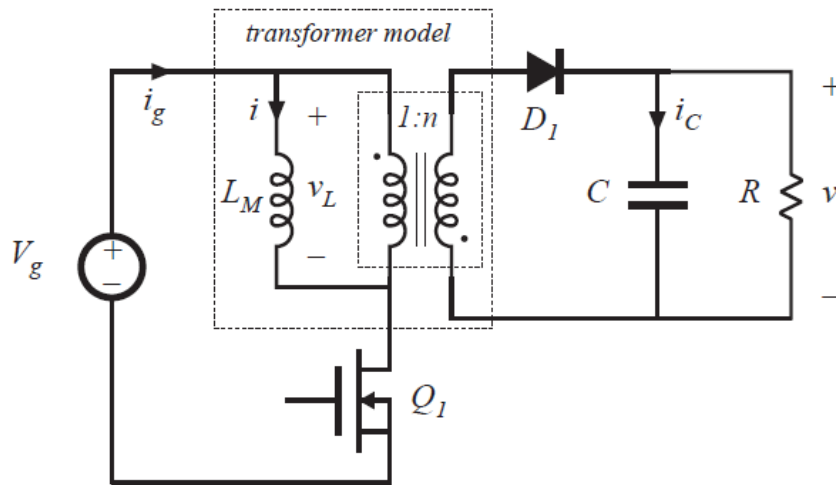
Dc component of magnetizing current is

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

Dc component of source current is

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

SIMULINK SIMULATION FLYBACK CONVERTER



$$V_g = 48 \text{ V}$$

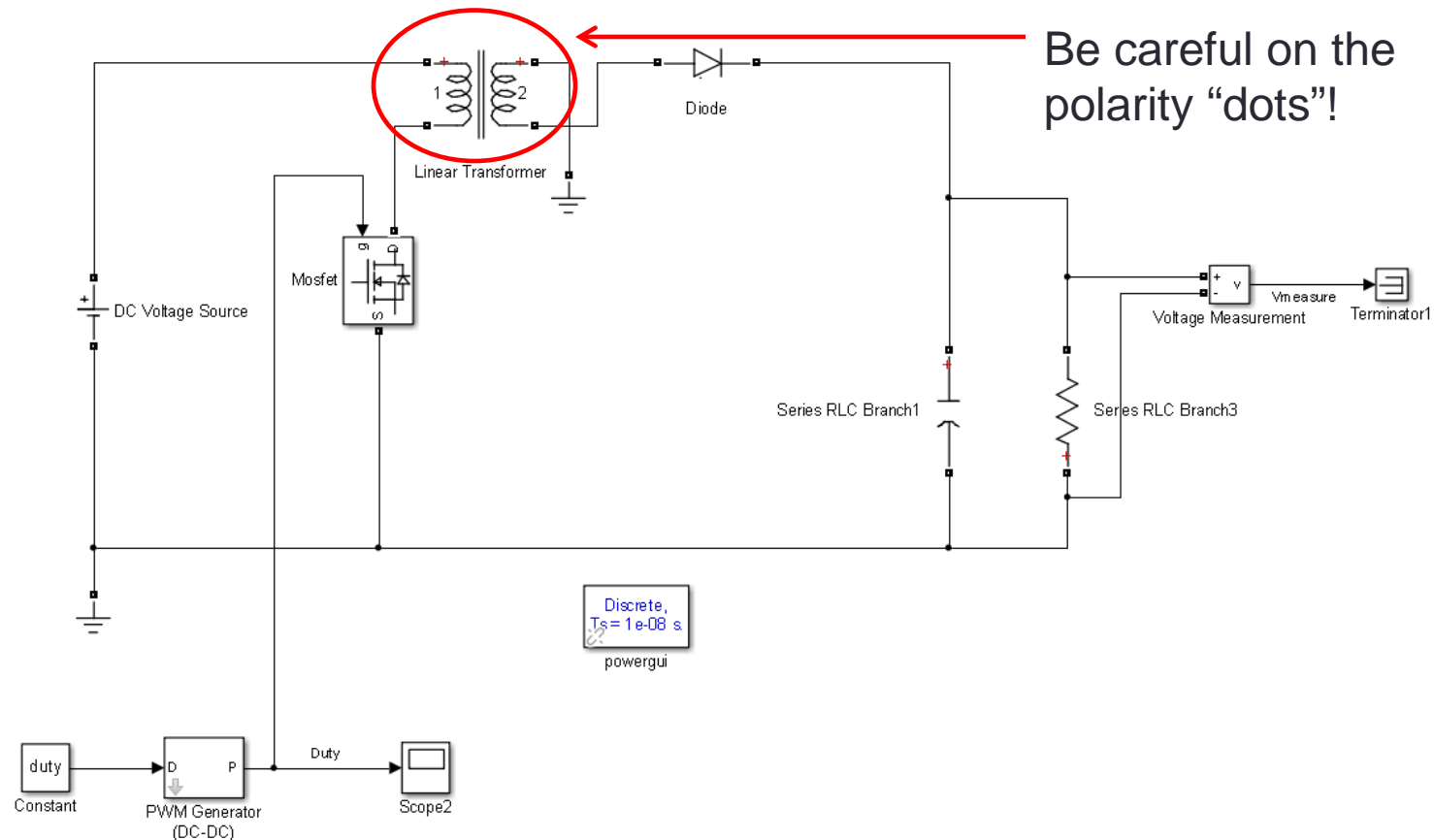
$$V = 12 \text{ V}$$

$$P_{\text{out}} = 150 \text{ W}$$

$$f_{\text{sw}} = 100 \text{ kHz}$$

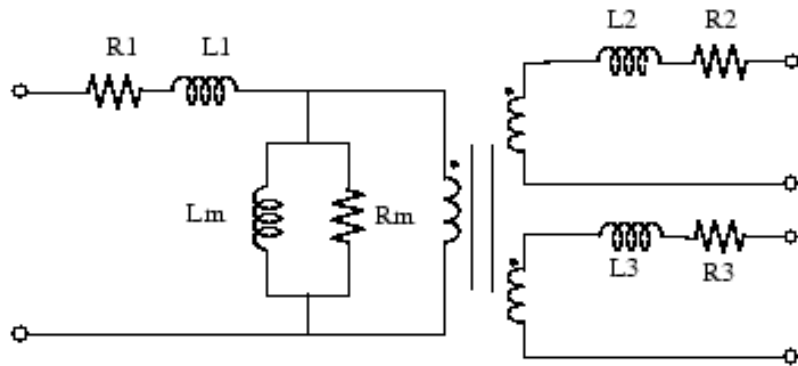
$$L_m = 250 \text{ uH}$$

Build Simulink Simulation



Linear Transformer Model

The Linear Transformer block model shown consists of three coupled windings wound on the same core.



- Use SI units for simplicity
- Uncheck three winding transformer
- To model as ideal transformer, set $R1, L1, R2, L2$ to 0
- Turns ratio “n” incorporated when setting the V1 and V2 values.
- Set magnetizing inductance as Lm

Block Parameters: Linear Transformer

Linear Transformer (mask) (link)
Implements a three windings linear transformer.

Click the Apply or the OK button after a change to the Units popup to confirm the conversion of parameters.

Parameters

Units SI

Nominal power and frequency [Pn(VA) fn(Hz)]:
[250e6 60]

Winding 1 parameters [V1(Vrms) R1(ohm) L1(H)]:
[7.35e+05 0 0]

Winding 2 parameters [V2(Vrms) R2(ohm) L2(H)]:
[n*7.35e+05 0 0]

☐ Three windings transformer

Winding 3 parameters [V3(Vrms) R3(ohm) L3(H)]:
[3.15e+05 0.7938 0.084225]

Magnetization resistance and inductance [Rm(ohm) Lm(H)]:
[1.0805e+06 Lm]

Measurements Magnetization current

☒ Use SI units

OK Cancel Help Apply

Use Idealized Diode and MOSFET Models

Block Parameters: Diode

Diode (mask) (link)

Implements a diode in parallel with a series RC snubber circuit.
In on-state the Diode model has an internal resistance (R_{on}) and inductance (L_{on}).
For most applications the internal inductance should be set to zero.
The Diode impedance is infinite in off-state mode.

Parameters

Resistance R_{on} (Ohms) :

Inductance L_{on} (H) :

Forward voltage V_f (V) :

Initial current I_c (A) :

Snubber resistance R_s (Ohms) :

Snubber capacitance C_s (F) :

OK Cancel Help Apply

Block Parameters: Mosfet

Mosfet (mask) (link)

MOSFET and internal diode in parallel with a series RC snubber circuit. When a gate signal is applied the MOSFET conducts and acts as a resistance (R_{on}) in both directions. If the gate signal falls to zero when current is negative, current is transferred to the antiparallel diode.

For most applications, L_{on} should be set to zero.

Parameters

FET resistance R_{on} (Ohms) :

internal diode inductance L_{on} (H) :

Internal diode resistance R_d (Ohms) :

Internal diode forward voltage V_f (V) :

Initial current I_c (A) :

Snubber resistance R_s (Ohms) :

Snubber capacitance C_s (F) :

Simulate Converter 2 ms

- Use same configuration parameters as lab 1
 - Power gui set to discrete “Tustin” since using PWM generator
 - Ode23tb for main simulation parameters
- What is the required duty cycle? – verify correct output voltage (12V)
- What is the average DC component of the magnetizing current? - verify
- Adjust Lmag until discontinuous mode
 - What happens to output voltage?