Lecture 8: Flyback Example

ECE 481: Power Electronics
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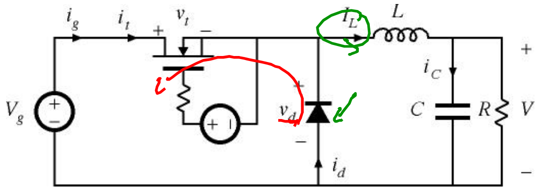
Fall 2013

Announcements

- Homework #3 due today
- Midterm exam “handed out” on Thursday

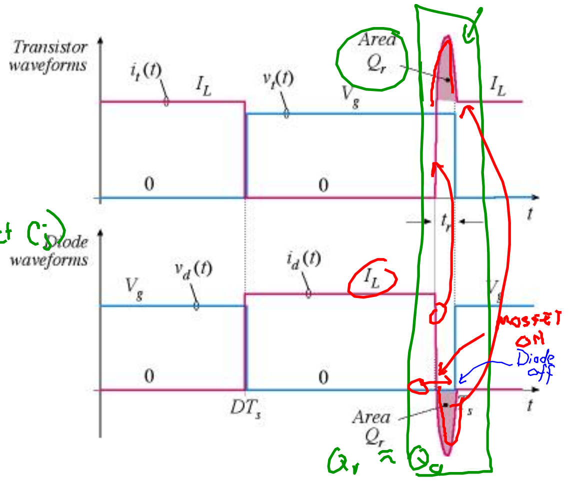
Assumed waveforms



Diode recovered charge Q_r, reverse recovery time t_r

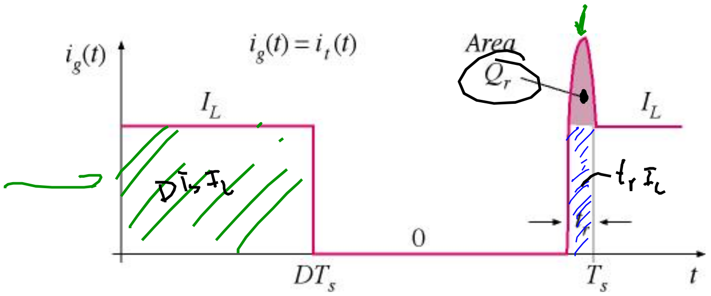
These waveforms assume that the diode voltage changes at the end of the reverse recovery transient

- a "snappy" diode (Neglect C_j)
- Voltage of soft-recovery diodes changes sooner
- Leads to a pessimistic estimate of induced switching loss



$Q_r \approx Q_d$

Average input current



$\langle i_g \rangle = I_g = (\text{area under curve})/T_s$

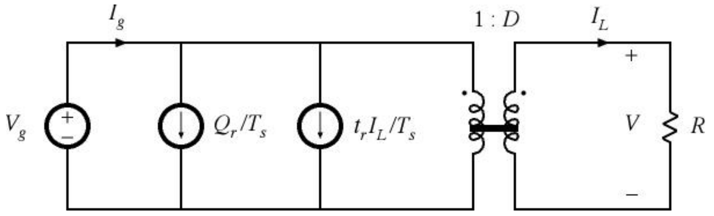
$= (DT_s I_L + t_r I_L + Q_r)/T_s$

$\boxed{= DI_L + t_r I_L / T_s + Q_r / T_s} = \langle i_g \rangle$

Solution of model

Output:

$V = DV_g$



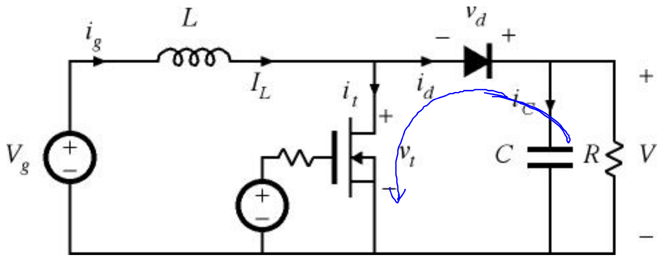
Efficiency: $\eta = P_{out} / P_{in}$

$P_{out} = VI_L$ $\quad$ $P_{in} = V_g\,(DI_L + t_r I_L/T_s + Q_r/T_s)$

Combine and simplify:

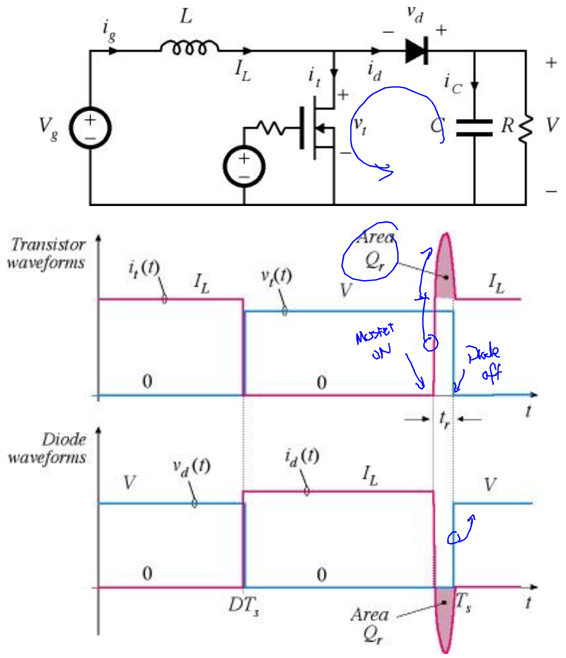
$\eta = 1 / [1 + f_s\,(t_r/D + Q_r R/D^2 V_g)]$

Boost Converter Example



- Model same effects as in previous buck converter example:
- Ideal MOSFET, *p–n* diode with reverse recovery
- Neglect semiconductor device capacitances, MOSFET switching times, etc.
- Neglect conduction losses
- Neglect ripple in inductor current and capacitor voltage

Boost converter



Transistor and diode waveforms have same shapes as in buck example, but depend on different quantities

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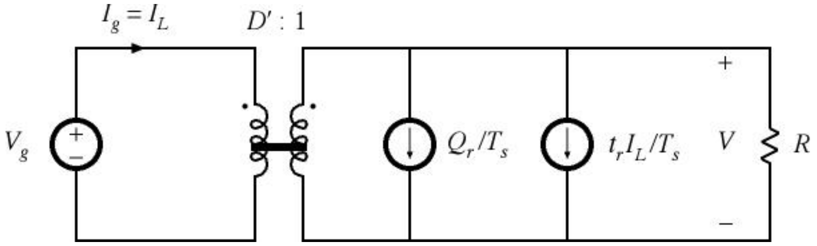
Construct model

The result is:



The two independent current sources consume power

$$V\,(t_r I_L/T_s + Q_r/T_s)$$

equal to the switching loss induced by diode reverse recovery

Summary

- The averaged modeling approach can be extended to include effects of switching loss
- Transistor and diode waveforms are constructed, including the switching transitions. The effects of the switching transitions on the inductor, capacitor, and input current waveforms can then be determined
- Inductor volt-second balance and capacitor charge balance are applied
- Converter input current is averaged
- Equivalent circuit corresponding to the the averaged equations is constructed

6.2. A short list of converters

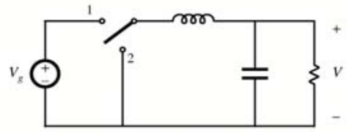
An infinite number of converters are possible, which contain switches embedded in a network of inductors and capacitors

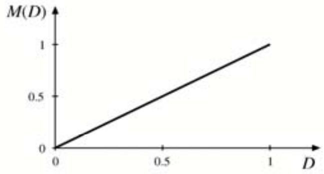
Two simple classes of converters are listed here:

- Single-input single-output converters containing a single inductor. The switching period is divided into two subintervals. This class contains eight converters.
- Single-input single-output converters containing two inductors. The switching period is divided into two subintervals. Several of the more interesting members of this class are listed.

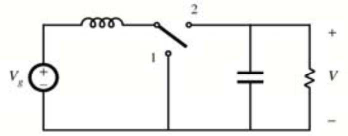
Converters producing a unipolar output voltage

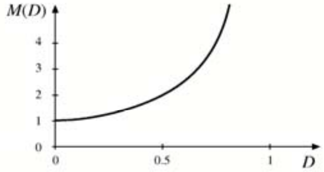
1. *Buck* $M(D) = D$





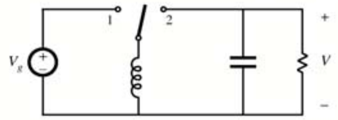
2. *Boost* $M(D) = \frac{1}{1-D}$

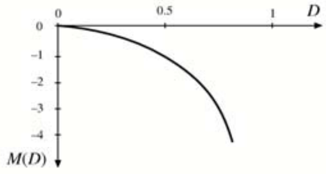




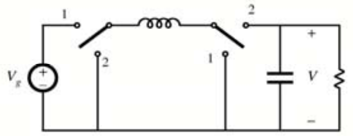
Converters producing a unipolar output voltage

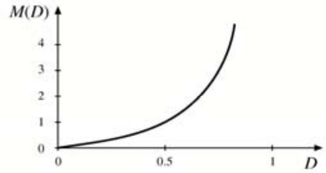
3. *Buck-boost* $M(D) = -\frac{D}{1-D}$





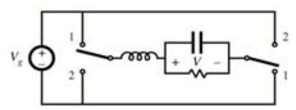
4. *Noninverting buck-boost* $M(D) = \frac{D}{1-D}$

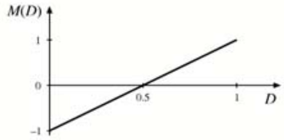




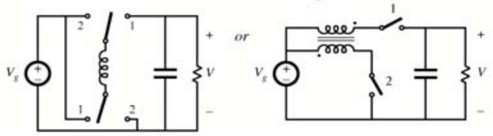
Converters producing a bipolar output voltage suitable as dc-ac inverters

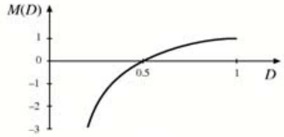
5. *Bridge* $M(D) = 2D - 1$





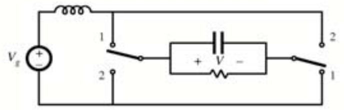
6. *Watkins-Johnson* $M(D) = \frac{2D-1}{D}$

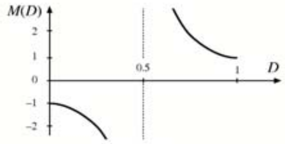




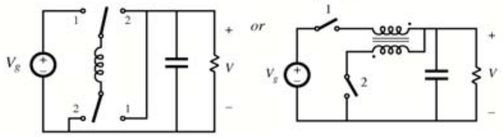
Converters producing a bipolar output voltage suitable as ac-dc rectifiers

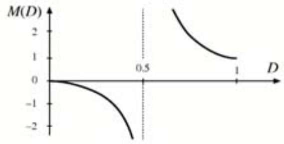
7. *Current-fed bridge* $M(D) = \frac{1}{2D-1}$





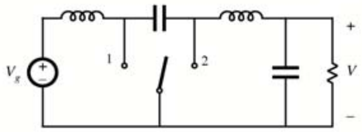
8. *Inverse of Watkins-Johnson* $M(D) = \frac{D}{2D-1}$

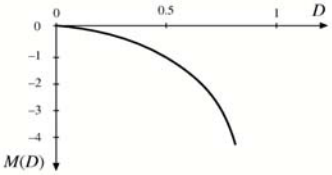




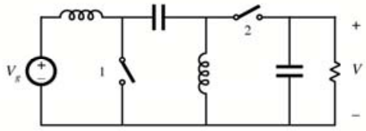
Several members of the class of two-inductor converters

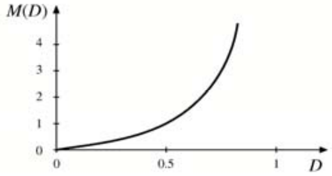
1. *Ćuk* $M(D) = -\frac{D}{1-D}$





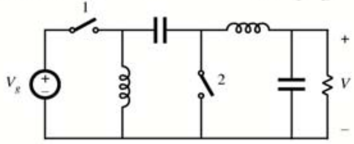
2. *SEPIC* $M(D) = \frac{D}{1-D}$

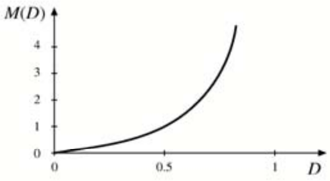




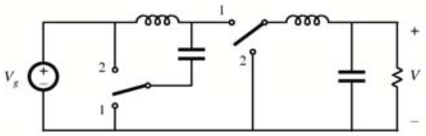
Several members of the class of two-inductor converters

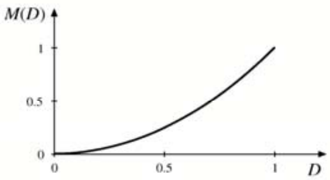
3. *Inverse of SEPIC* $M(D) = \frac{D}{1-D}$



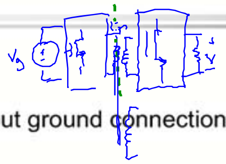


4. *Buck* ^{2} $M(D) = D^2$





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

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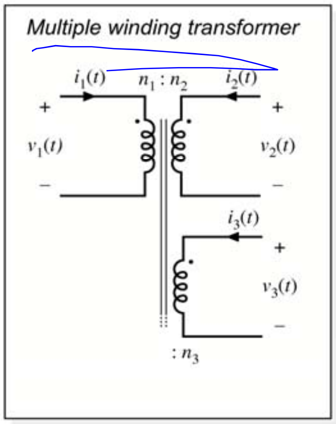
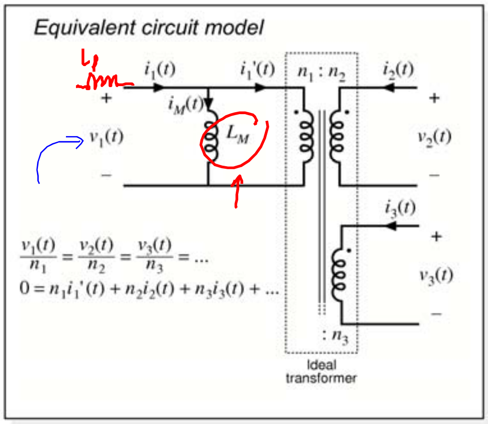
A simple transformer model



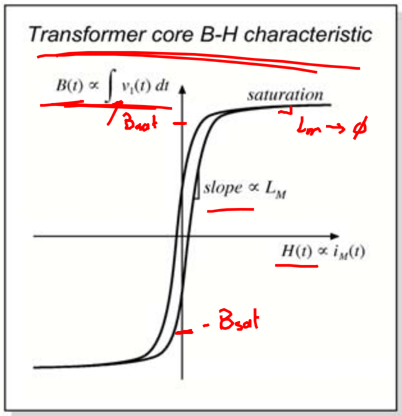


$$\frac{v_1(t)}{n_1} = \frac{v_2(t)}{n_2} = \frac{v_3(t)}{n_3} = \dots$$

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

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

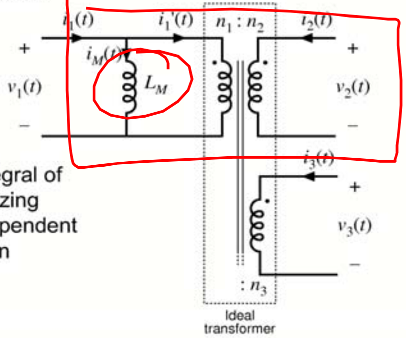
$$v_1(t) = L_M \frac{di_M(t)}{dt}$$

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

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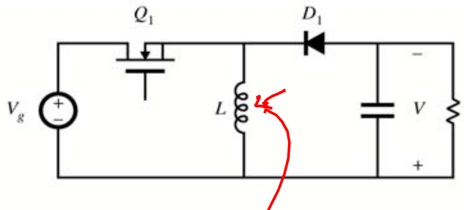
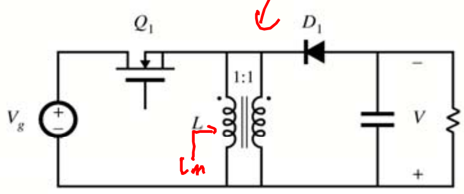
6.3.4. Flyback converter

buck-boost converter:

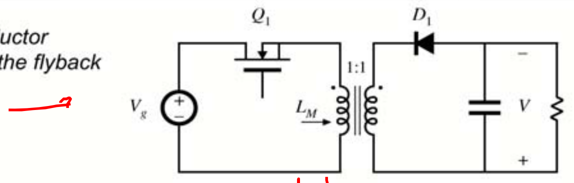


construct inductor winding using two parallel wires:

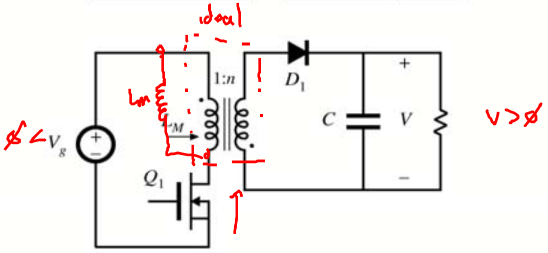


Derivation of flyback converter, cont.

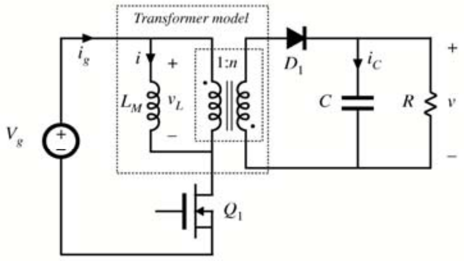
Isolate inductor windings: the flyback converter



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



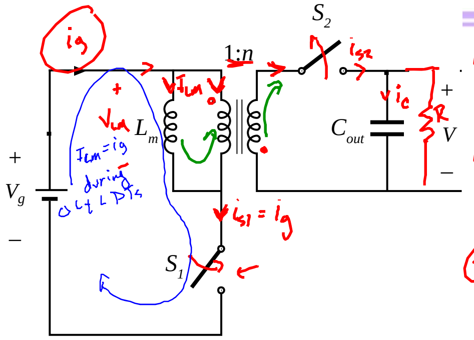
The "flyback transformer"



- 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

Flyback Converter Example



① Volt-second balance

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

② cap-charge balance

$\langle i_c\rangle = D\left(\frac{-V}{R}\right) + D'\left(\frac{-V}{R} + \underbrace{\frac{I_{Lm}}{n}}_{i_{s2}}\right) = 0$

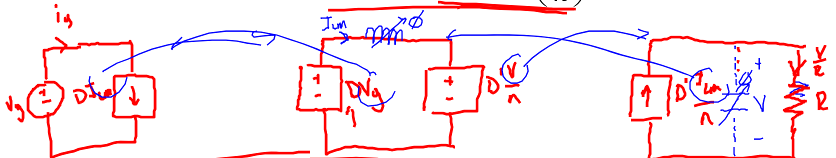
③ input current averaging

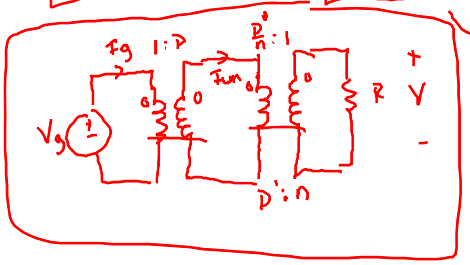
$\langle i_g\rangle = I_g = DI_{Lm}$

Equivalent Circuit Model

③ ① ②

$$\langle i_g\rangle = DI_{lm} \qquad \langle v_{lm}\rangle = 0 = DV_g - D'\left(\frac{V}{n}\right) \qquad \langle i_{co}\rangle = 0 = D'\frac{I_{lm}}{n} - \frac{V}{R}$$

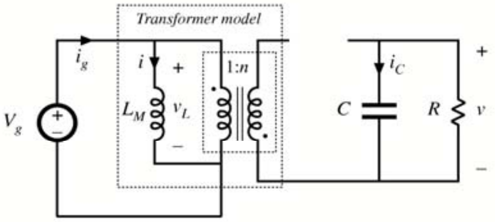




$\frac{V}{V_g} = \frac{nD}{D'}$

ref: Buck-Boost $M(D) = \frac{D}{D'}$

Subinterval 1



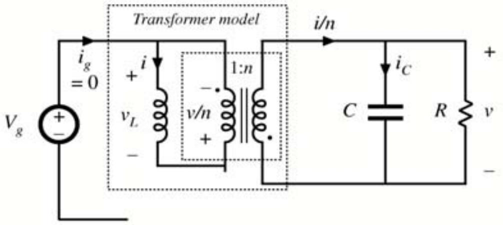
$$v_L = V_g$$
$$i_C = -\frac{v}{R}$$
$$i_g = i$$

CCM: small ripple approximation leads to

Q_1 on, D_1 off

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

Subinterval 2



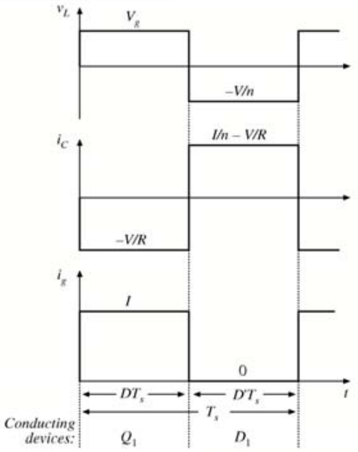
$$v_L = -\frac{v}{n}$$
$$i_C = \frac{i}{n} - \frac{v}{R}$$
$$i_g = 0$$

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:

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

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

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

Equivalent circuit model: CCM Flyback

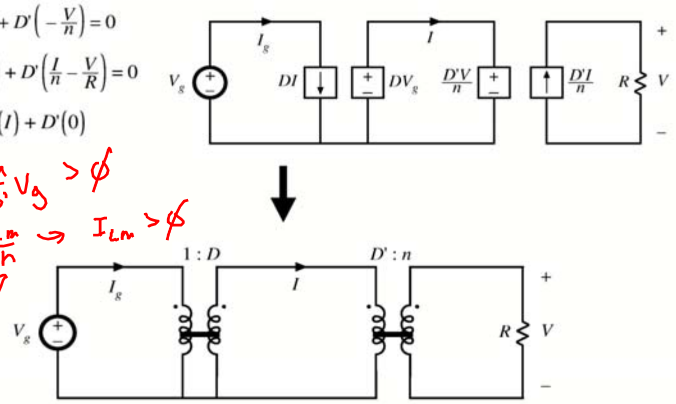
$$\langle v_L \rangle = D(V_g) + D'\left(-\frac{V}{n}\right) = 0$$

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

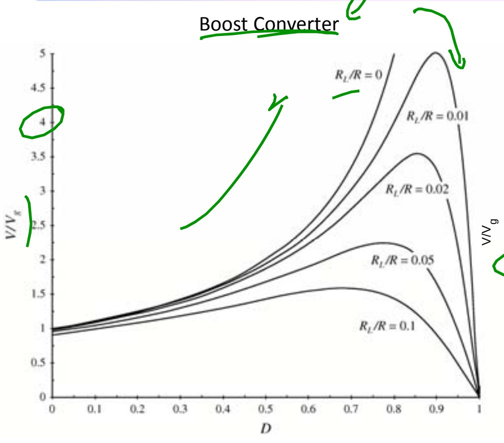
$$I_g = \langle i_g \rangle = D(I) + D'(0)$$

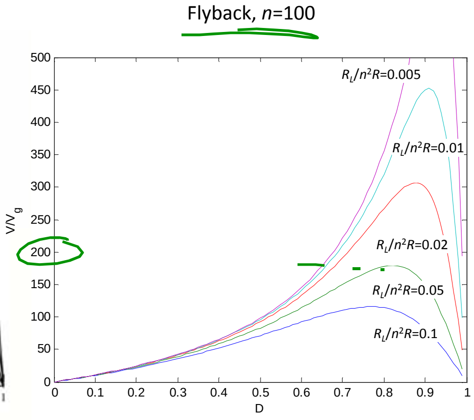
$V = \frac{Dn}{D'} V_g > 0$

$\frac{V}{R} = D' \frac{I_{Lm}}{n} \rightarrow I_{Lm} > 0$

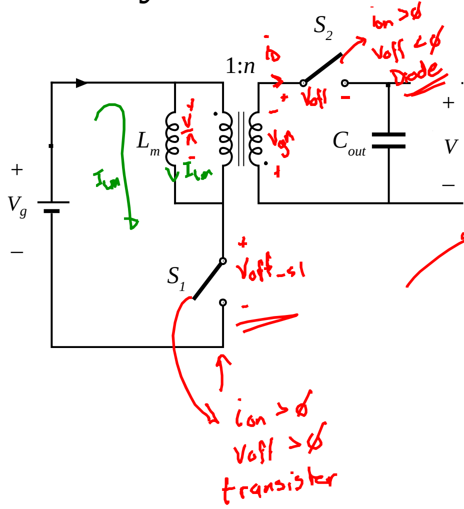


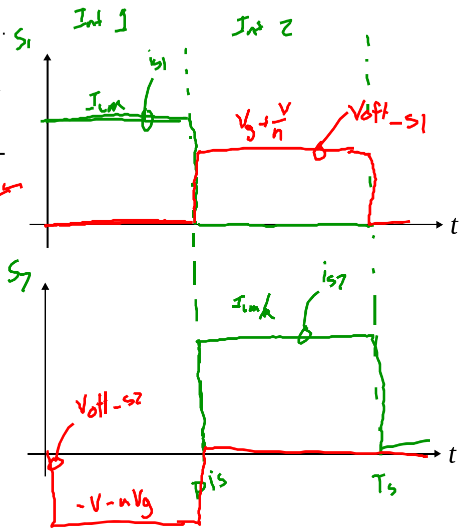
Large Step Conversion Ratio



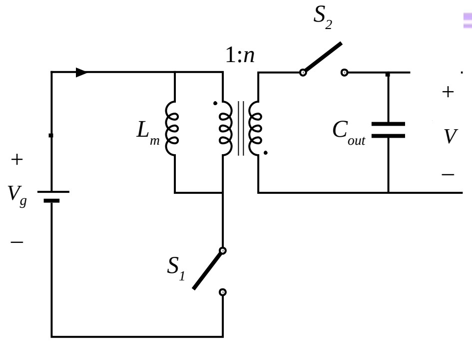


Flyback Semiconductor Waveforms



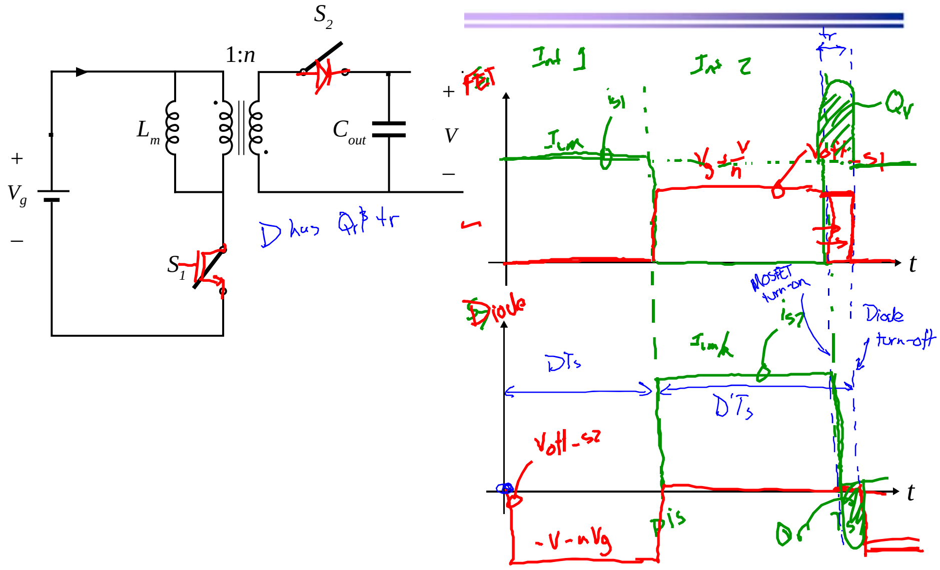


Flyback Switch Implementation

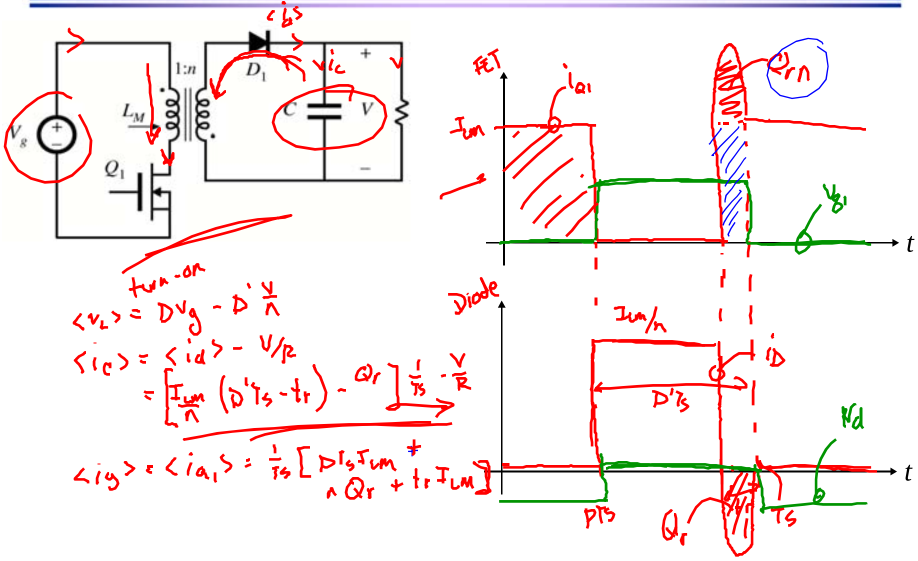


Reverse Recovery

Flyback ~~Semiconductor Waveforms~~



Flyback Reverse Recovery



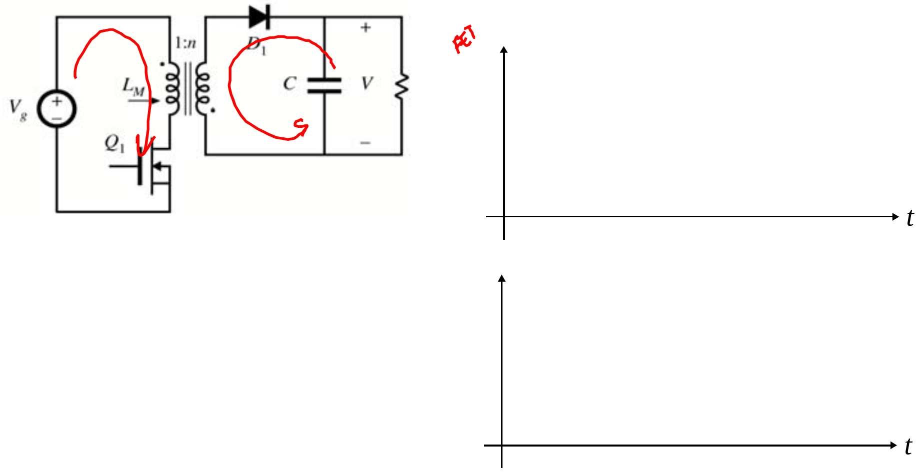
$\langle v_L \rangle = D V_g - D' \frac{V}{n}$

$\langle i_C \rangle = \langle i_d \rangle - V/R$

$= \left[\frac{I_{LM}}{n} \left(D' T_s - t_r \right) - Q_r \right] \frac{1}{T_s} - \frac{V}{R}$

$\langle i_g \rangle = \langle i_{Q1} \rangle = \frac{1}{T_s} \left[D T_s I_{LM} + n Q_r + t_r I_{LM} \right]$

Flyback Reverse Recovery

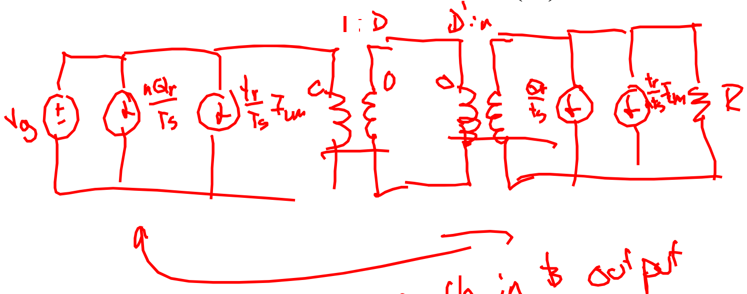


Flyback Reverse Recovery

$$\langle i_g \rangle = DI_{lm} + \underbrace{\frac{t_r}{T_s} I_{lm} + \frac{Q_r\, n}{T_s}}$$

$$\langle i_{co} \rangle = 0 = D' \frac{I_{lm}}{n} - \frac{V}{R} \underbrace{- \frac{t_r}{nT_s} I_{lm} - \frac{Q_r}{\cancel{n}T_s}}$$

$$\langle v_{lm} \rangle = 0 = DV_g - D'\left(\frac{V}{n}\right)$$



Both in & output