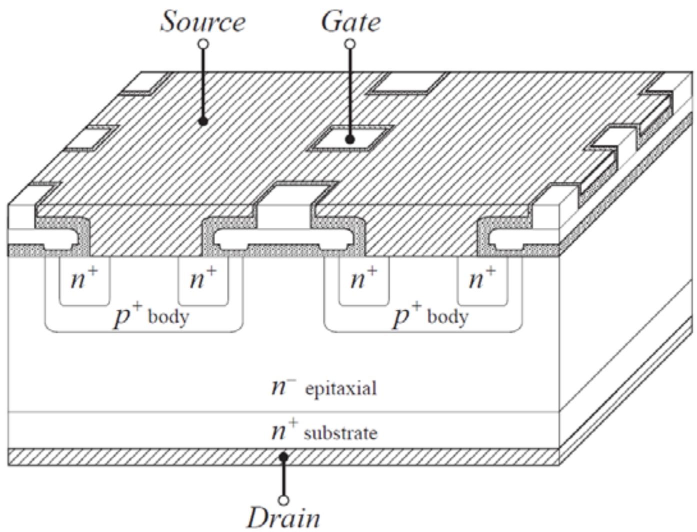
MOSFET Cross Section



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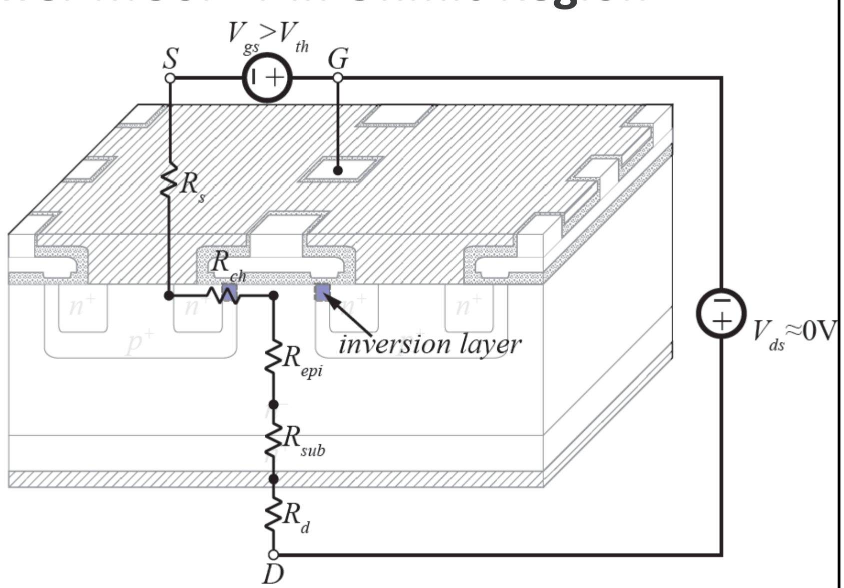
Power MOSFET in Ohmic Region



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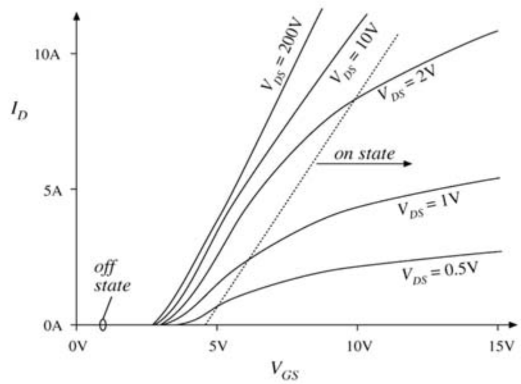
MOSFET Static Characteristics



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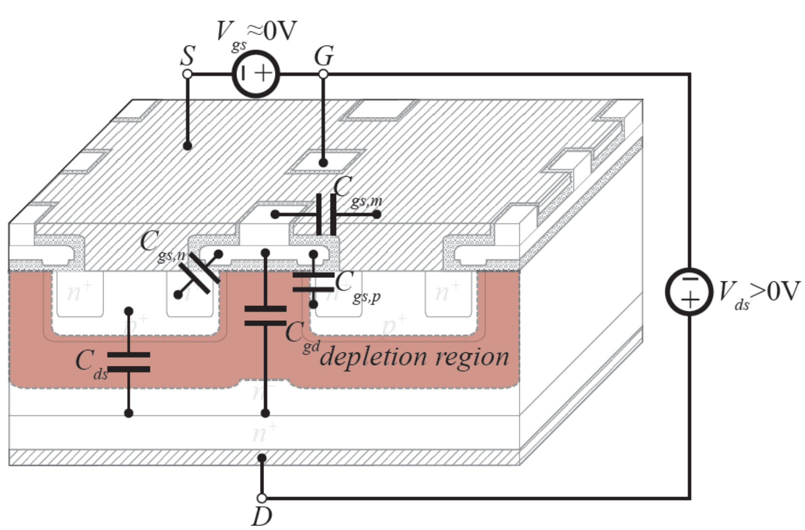
MOSFET Depletion capacitance



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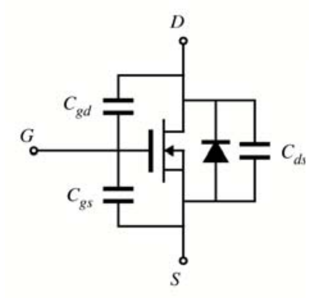
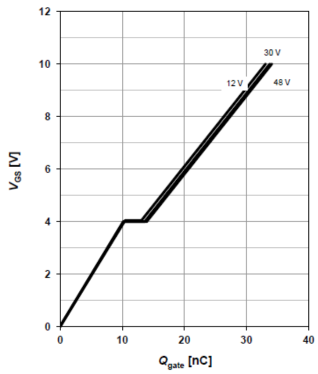
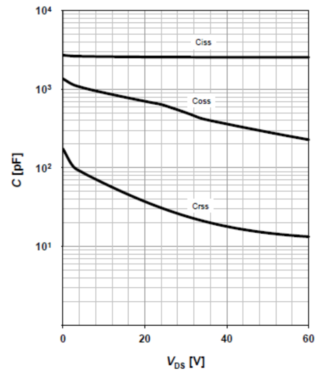
MOSFET Equivalent Circuit







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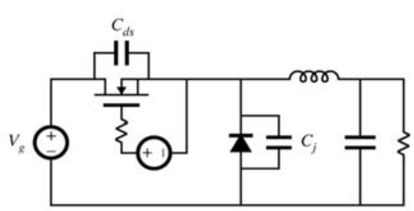
Switching Losses: Output Capacitance



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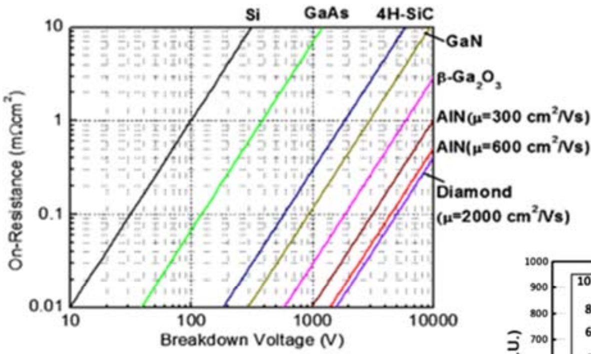
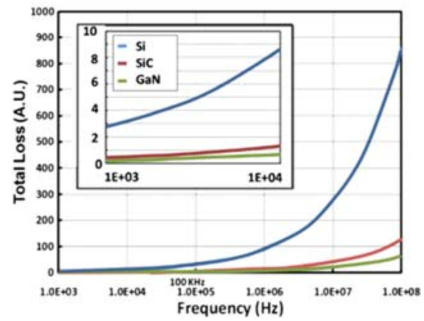
Wide Bandgap Materials





Srabanti Chowdhury *et al* "Current status and scope of gallium nitride-based vertical transistors for high-power electronics application" 2013 *Semicond. Sci. Technol.* 28, 074014

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Power MOSFET: Conclusions

- A majority-carrier device: fast switching speed
- Typical switching frequencies: tens and hundreds of kHz
- On-resistance increases rapidly with rated blocking voltage
- Easy to drive
- The device of choice for blocking voltages less than 500V
- 1000V devices are available, but are useful only at low power levels (100W)
- Part number is selected on the basis of on-resistance rather than current rating

Fundamentals of Power Electronics 55 *Chapter 4: Switch realization*

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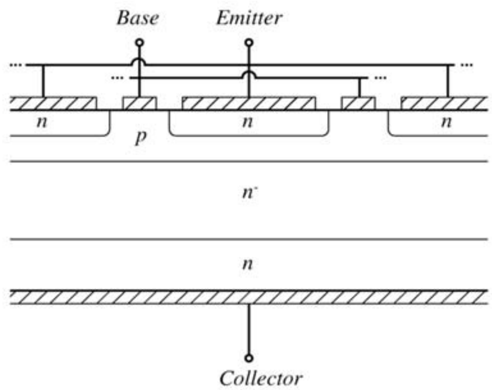
Bipolar Junction Transistor

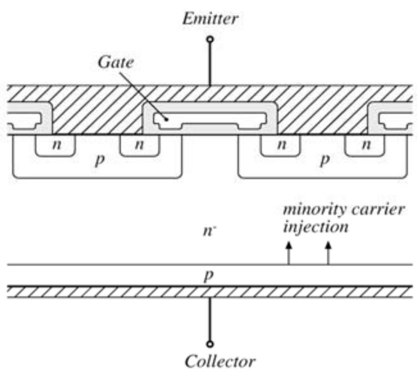


- Interdigitated base and emitter contacts
- Vertical current flow
- npn device is shown
- minority carrier device
- on-state: base-emitter and collector-base junctions are both forward-biased
- on-state: substantial minority charge in *p* and n^- regions, conductivity modulation

BJT: Conclusions

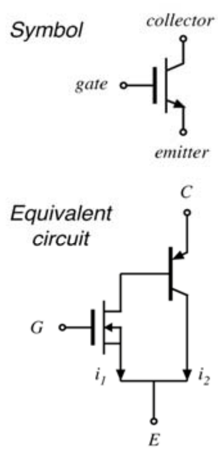
- BJT has been replaced by MOSFET in low-voltage (<500V) applications
- BJT is being replaced by IGBT in applications at voltages above 500V
- A minority-carrier device: compared with MOSFET, the BJT exhibits slower switching, but lower on-resistance at high voltages

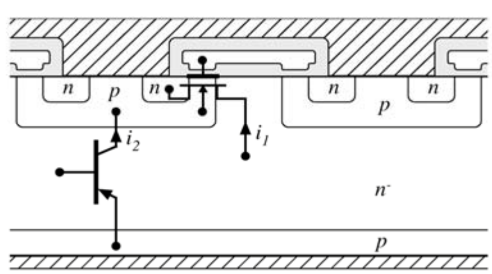
Insulated Gate Bipolar Junction Transistor



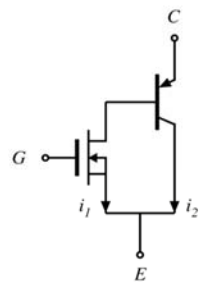
- A four-layer device
- Similar in construction to MOSFET, except extra *p* region
- On-state: minority carriers are injected into n^- region, leading to conductivity modulation
- compared with MOSFET: slower switching times, lower on-resistance, useful at higher voltages (up to 1700V)

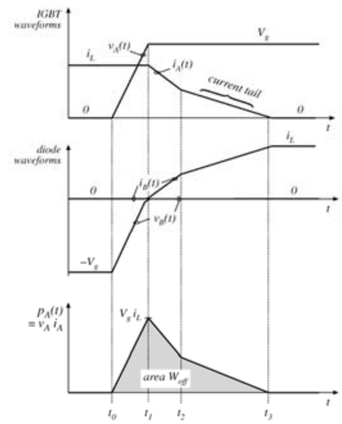
The IGBT





IGBT: Current Tailing





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Conclusions: IGBT

- Becoming the device of choice in 500 to 1700V+ applications, at power levels of 1-1000kW
- Positive temperature coefficient at high current —easy to parallel and construct modules
- Forward voltage drop: diode in series with on-resistance. 2-4V typical
- Easy to drive —similar to MOSFET
- Slower than MOSFET, but faster than Darlington, GTO, SCR
- Typical switching frequencies: 3-30kHz
- IGBT technology is rapidly advancing:
  - 3300 V devices: HVIGBTs
  - 150 kHz switching frequencies in 600 V devices

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Averaged Equivalent Circuit Model – Switching Loss

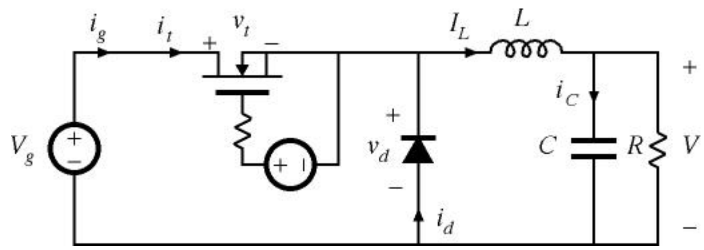
- The methods of Chapter 3 can be extended to include switching loss in the converter equivalent circuit model
  - Include switching transitions in the converter waveforms
  - Model effects of diode reverse recovery, etc.
- To obtain tractable results, the waveforms during the switching transitions must usually be approximated
- Things that can substantially change the results:
  - Ringing caused by parasitic tank circuits
  - Snubber circuits

The Modeling Approach

- Sketch the converter waveforms
  - Including the switching transitions (idealizing assumptions are made to lead to tractable results)
  - In particular, sketch inductor voltage, capacitor current, and input current waveforms
- The usual steady-state relationships:
  - $\langle v_L \rangle = 0, \langle i_C \rangle = 0, \langle i_g \rangle = I_g$
- Use the resulting equations to construct an equivalent circuit model, as usual

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



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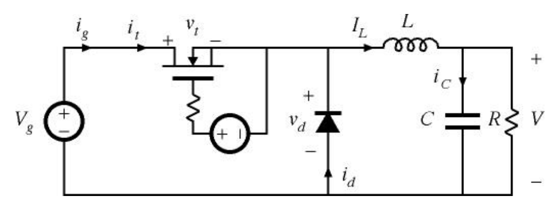
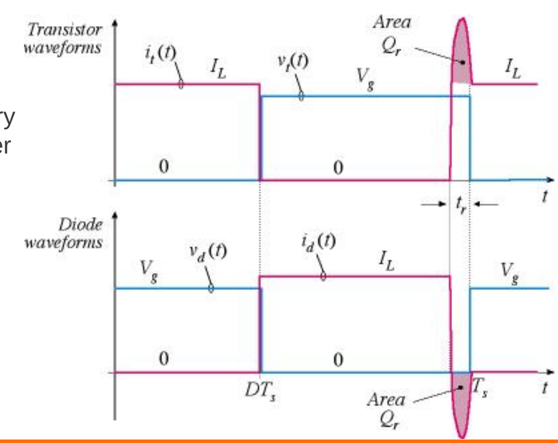
Assumed waveforms

- 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
  - Voltage of soft-recovery diodes changes sooner
  - Leads to a pessimistic estimate of induced switching loss





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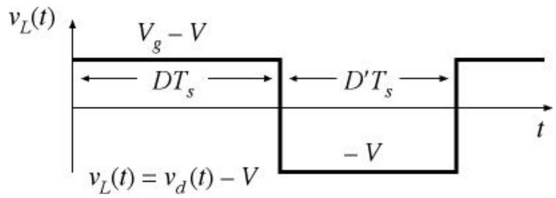
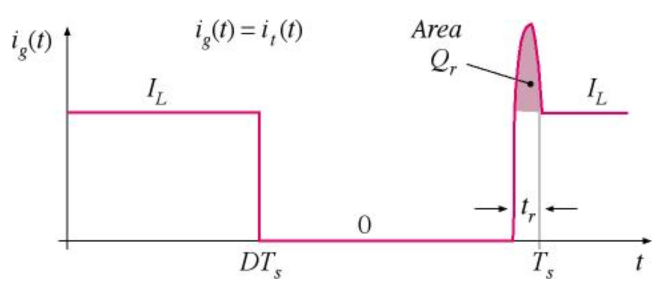
Inductor volt-second & Cap-Charge balance



As usual: $\langle v_L \rangle = 0 = DV_g - V$

Also as usual: $\langle i_C \rangle = 0 = I_L - V/R$

Average input current



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

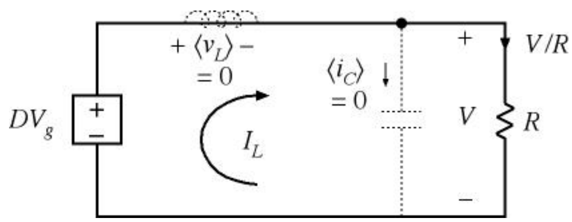
$= (DT_sI_L + t_rI_L + Q_r)/T_s$

$= DI_L + t_rI_L/T_s + Q_r/T_s$

Construction of Equivalent Circuit Model

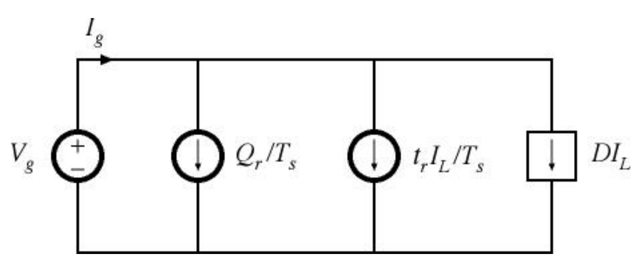
From inductor volt-second balance: $\langle v_L \rangle = 0 = DV_g - V$

From capacitor charge balance: $\langle i_C \rangle = 0 = I_L - V/R$

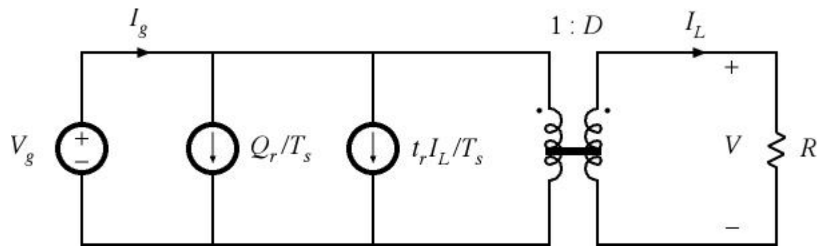


Input port of model

$$\langle i_g \rangle = I_g = DI_L + t_r I_L / T_s + Q_r / T_s$$



Combine for complete model



The two independent current sources consume power

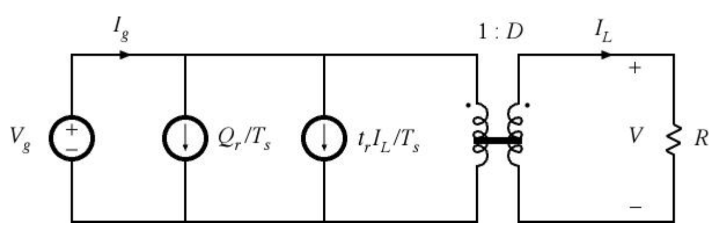
$$V_g\,(t_r I_L/T_s + Q_r/T_s)$$

equal to the switching loss induced by diode reverse recovery

Solution of model

Output:

$V = DV_g$



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

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

Combine and simplify:

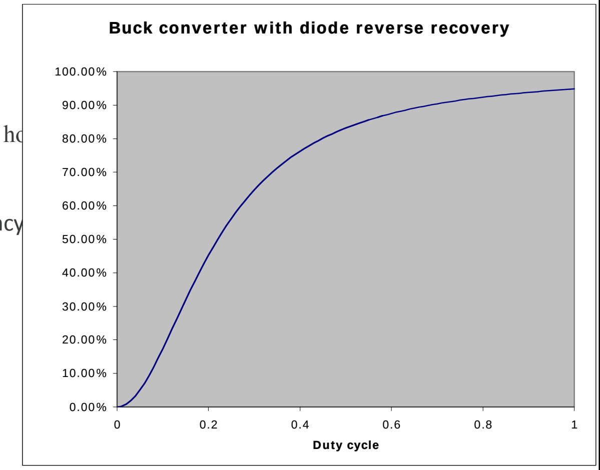
$\eta = 1\,/\,[1 + f_s\,(t_r/D + Q_r R/D^2 V_g)]$

Predicted Efficiency vs Duty Cycle

- Switching frequency 100 kHz
- Input voltage 24 V
- Load resistance 15 Ω
- Recovered charge 0.75 µCoul
- Reverse recovery time 75 nsec

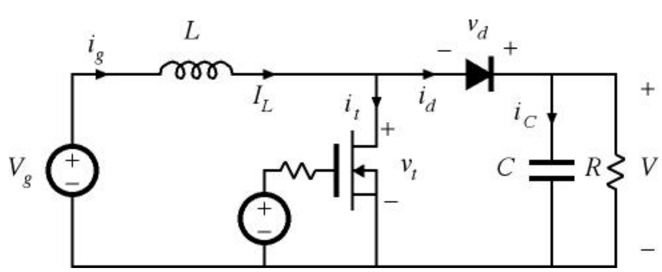
- (no attempt is made here to model h… inductor current)

- Substantial degradation of efficiency…
- Poor efficiency at low duty cycle

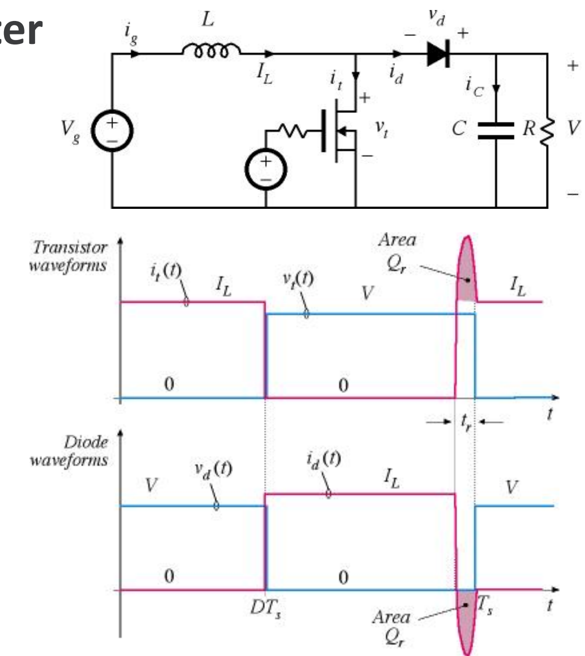


Boost Converter Example

- 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



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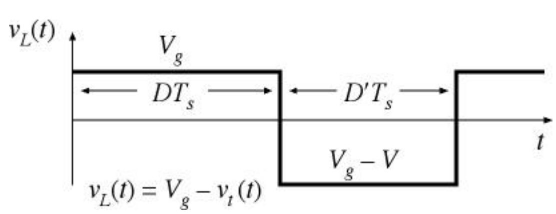
Inductor volt-second balance and average input current



As usual: $\langle v_L \rangle = 0 = V_g - D'V$

Also as usual: $\langle i_g \rangle = I_L$

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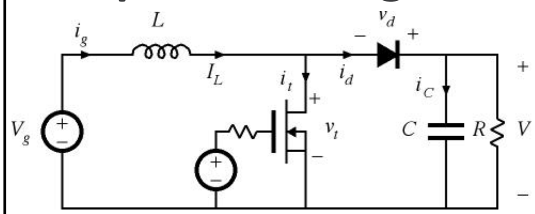
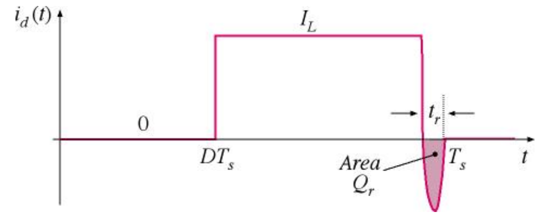
Capacitor charge balance





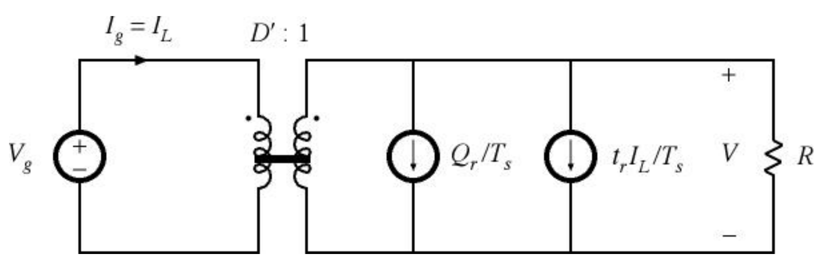
$$\langle i_C \rangle = \langle i_d \rangle - V/R = 0$$

$$= - V/R + I_L(D'T_s - t_r)/T_s - Q_r/T_s$$

Collect terms: $V/R = I_L(D'T_s - t_r)/T_s - Q_r/T_s$

Construct model

The result is:



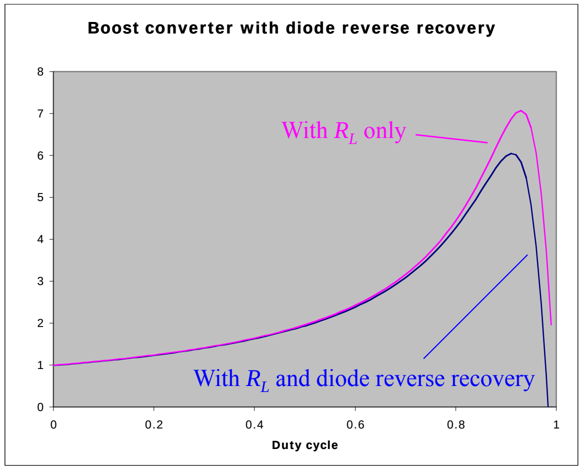
The two independent current sources consume power

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

equal to the switching loss induced by diode reverse recovery

Predicted *M* vs duty cycle

- Switching frequency 100 kHz
- Input voltage 24 V
- Load resistance 60 Ω
- Recovered charge 5 µCoul
- Reverse recovery time 100 nsec
- Inductor resistance R_L = 0.3 Ω
- (inductor resistance also inserted into averaged model here)



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