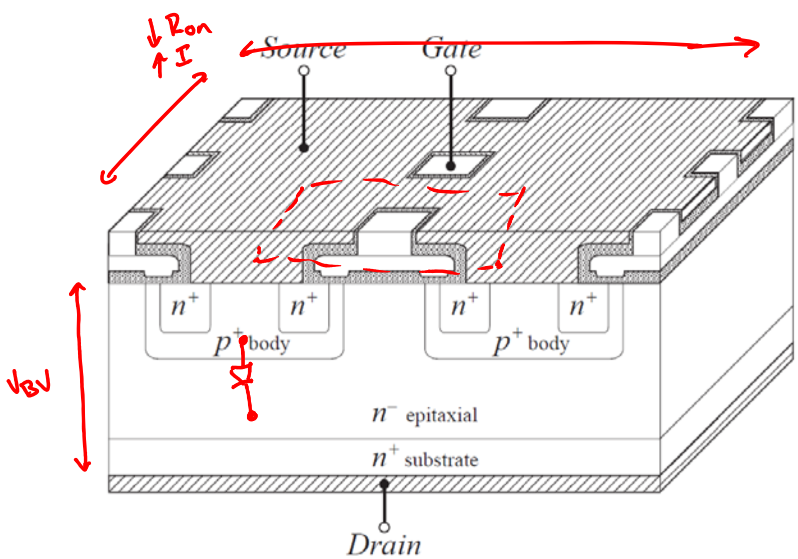
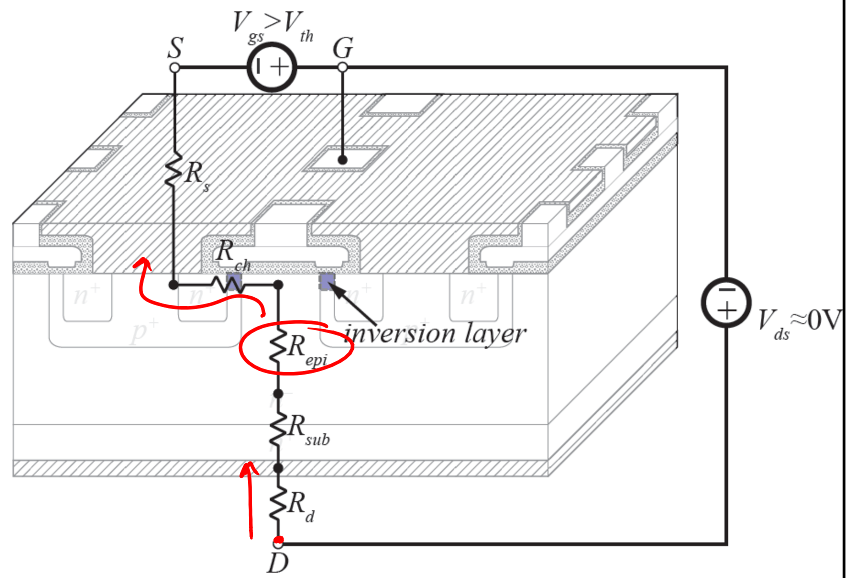
Announcements

MOSFET Cross Section

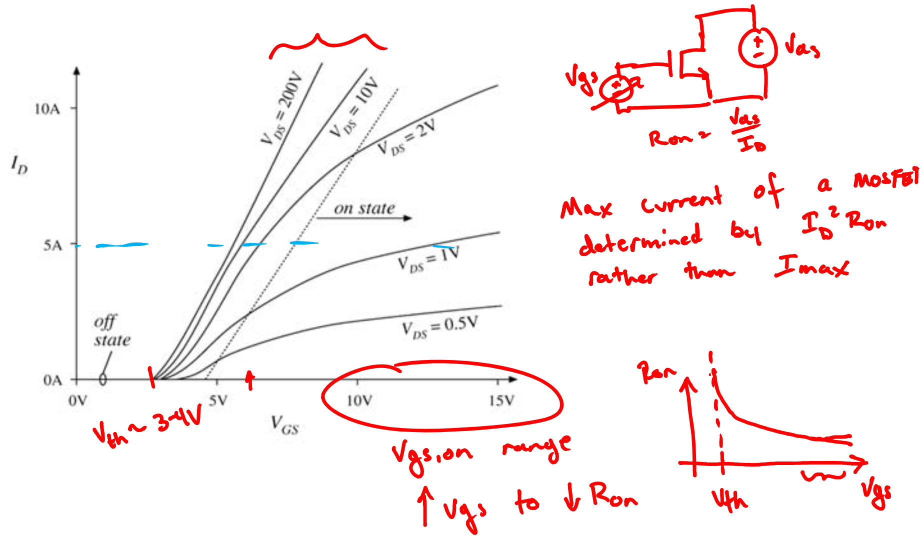


Power MOSFET in Ohmic Region



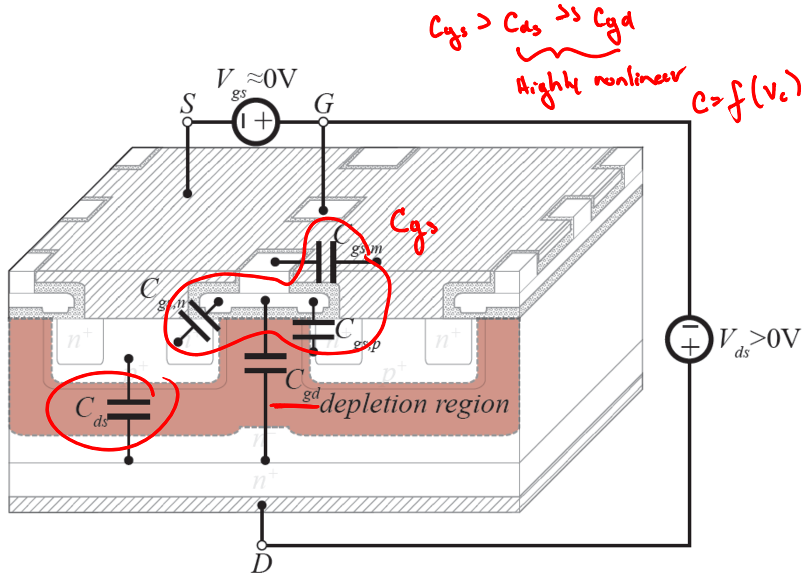
THE UNIVERSITY OF TENNESSEE KNOXVILLE

MOSFET Static Characteristics



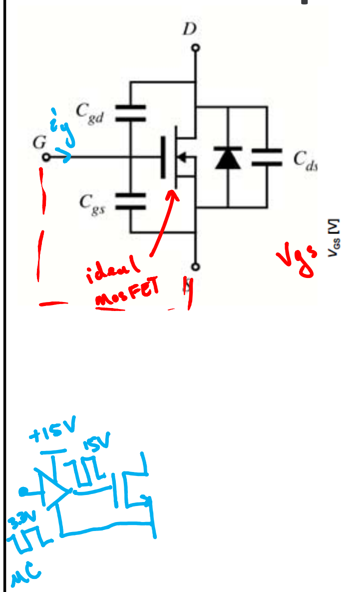
THE UNIVERSITY OF TENNESSEE KNOXVILLE

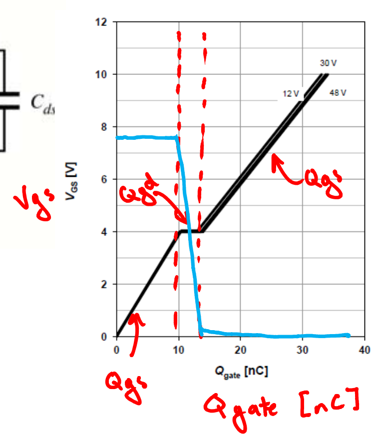
MOSFET Depletion capacitance

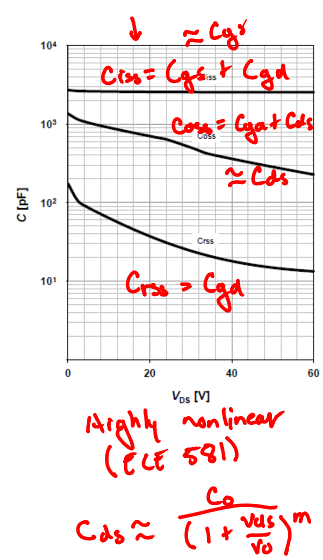


THE UNIVERSITY OF TENNESSEE KNOXVILLE

MOSFET Equivalent Circuit



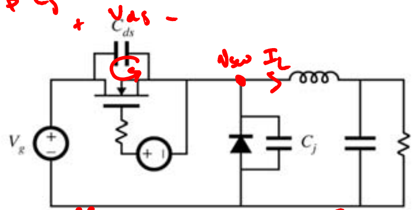


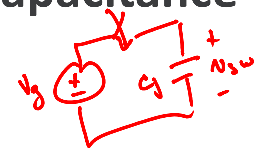


THE UNIVERSITY OF TENNESSEE KNOXVILLE

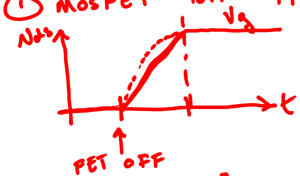
Switching Losses: Output Capacitance

Assume C_{ds} & C_j are linear





① MOSFET Turn-off

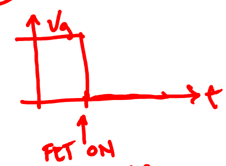


Lossless

$E_{ds} = \frac{1}{2} C_{ds} V_g^2$ → stored in C_{ds}

$E_j = -\frac{1}{2} C_j V_g^2$ → supplied by C_j

② MOSFET Turn-on

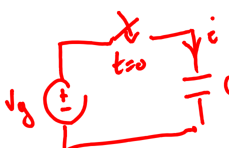


$E_{ds} = \frac{1}{2} C_{ds} V_g^2$ → Now lost in MOSFET

$E_j = \frac{1}{2} C_j V_g^2$ → Also lost in MOSFET

$P_{sw,c} = (E_{ds} + E_j) f_s$

THE UNIVERSITY OF TENNESSEE KNOXVILLE



$v_c(0) = 0$

$i = C \frac{dv_c}{dt}$

$P_{sw} = \int_0^\infty i (V_g - v_c) dt$

$P_{sw} = \int_0^\infty C (V_g - v_c) \frac{dv_c}{dt} dt$

$= \int_0^{V_g} C (V_g - v_c) dv_c$

$= \int_0^{V_g} C V_g dv_c - \int_0^{V_g} C v_c dv_c$

$C V_g \int_0^{V_g} 1 \, dv_c - C \int_0^{V_g} v_c \, dv_c$

$= C V_g^2 - C \frac{V_g^2}{2} = \frac{1}{2} C V_g^2$

Power losses due to capacitive switching even in an ideal switch!

THE UNIVERSITY OF TENNESSEE KNOXVILLE

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 UNIVERSITY OF TENNESSEE KNOXVILLE

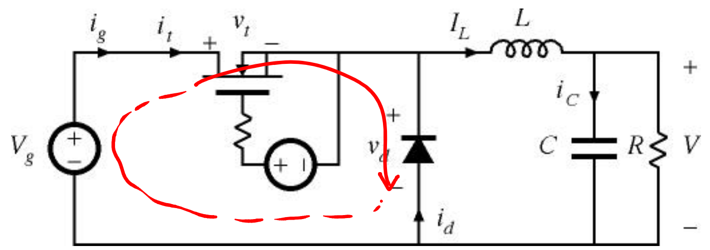
The Modeling Approach

- 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

THE UNIVERSITY OF TENNESSEE KNOXVILLE

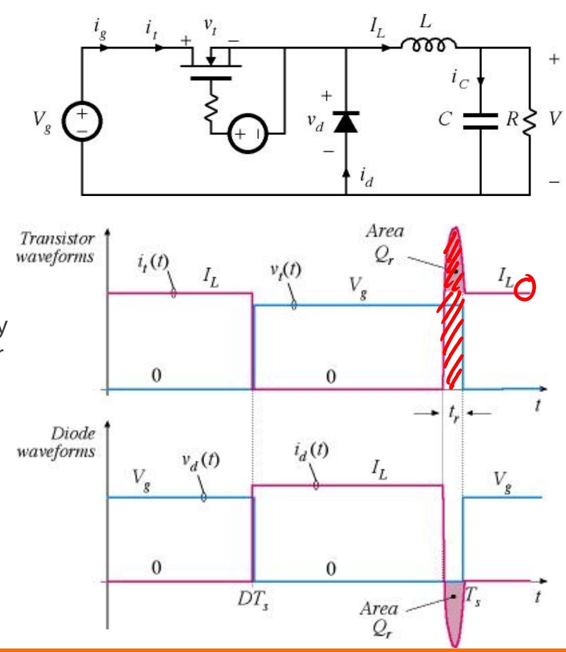
Buck Converter Example

- 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

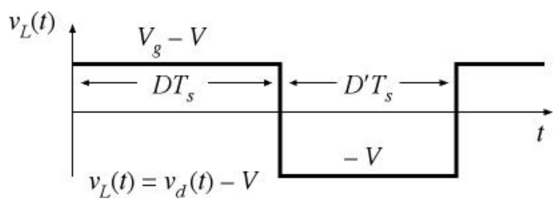


Assumed waveforms

- 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



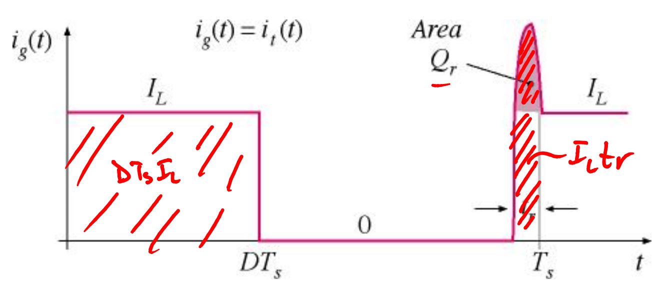
Inductor volt-second & Cap-Charge balance



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



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

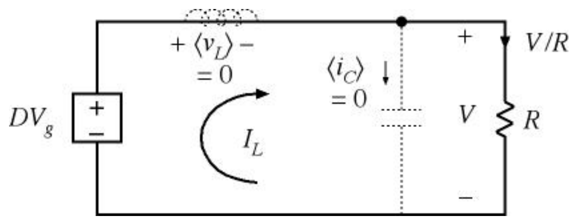
$$= (DT_sI_L + t_rI_L + Q_r)/T_s$$

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

Construction of Equivalent Circuit Model

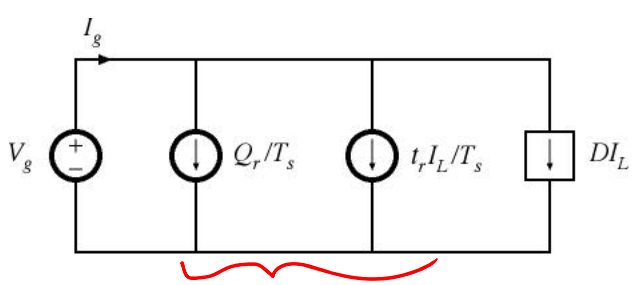
From inductor volt-second balance: $\langle v_L \rangle = 0 = DV_g - V$

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

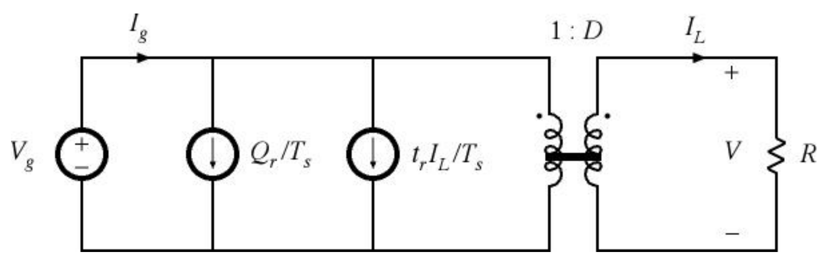


Input port of model

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



Combine for complete model



The two independent current sources consume power

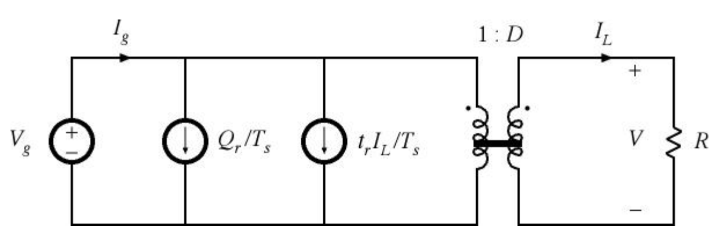
$$V_g\,(t_r I_L/T_s + Q_r/T_s)$$

equal to the switching loss induced by diode reverse recovery

Solution of model

Output:

$V = DV_g$



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

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

Combine and simplify:

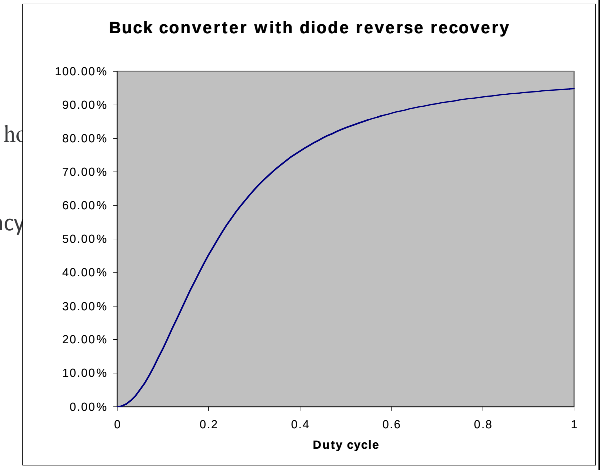
$$\eta = 1 / [1 + f_s(t_r/D + Q_r R/D^2 V_g)]$$

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 how reverse recovery depends on inductor current)

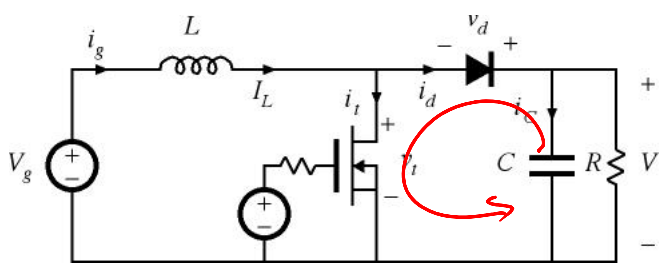
- Substantial degradation of efficiency
- Poor efficiency at low duty cycle



THE UNIVERSITY OF TENNESSEE KNOXVILLE

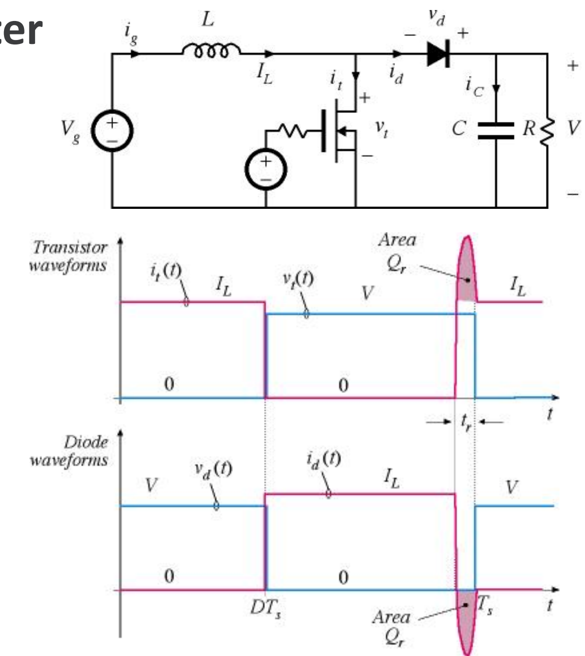
Boost Converter Example

- 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

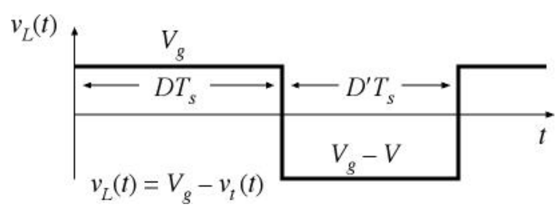


THE UNIVERSITY OF TENNESSEE KNOXVILLE

Boost converter



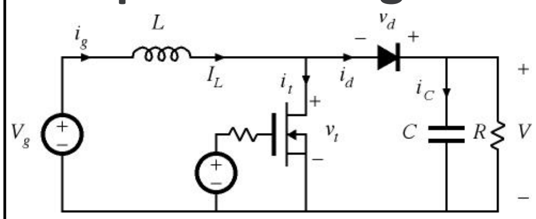
Inductor volt-second balance and average input current

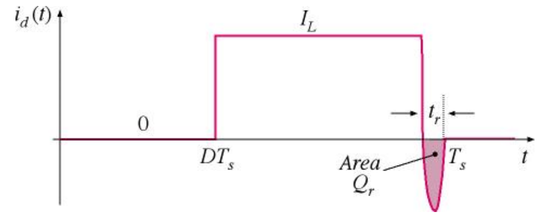


As usual: $\langle v_L \rangle = 0 = V_g - D'V$

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

Capacitor charge balance





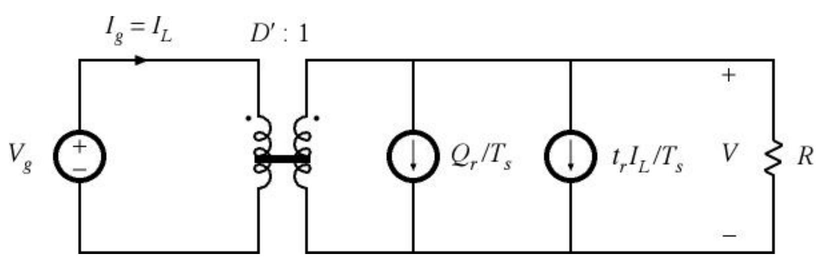
$$\langle i_C \rangle = \langle i_d \rangle - V/R = 0$$

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

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

Construct model

The result is:



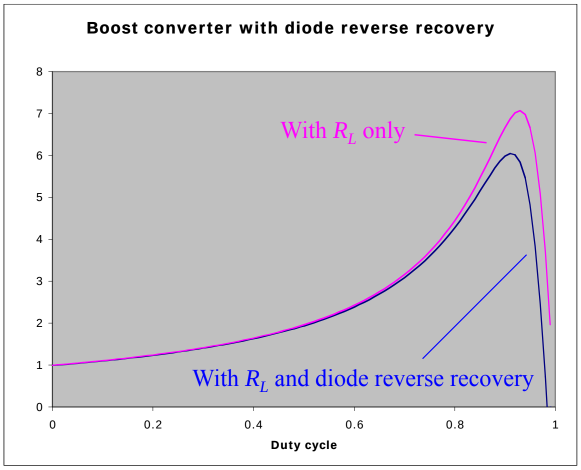
The two independent current sources consume power

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

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)



THE UNIVERSITY OF TENNESSEE KNOXVILLE