Inclusion of Switching Loss in the Averaged Equivalent Circuit Model

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
- These are modeled in ECEN 5817, Resonant and Soft-Switching Phenomena in Power Electronics

The Modeling Approach
Extension of Chapter 3 Methods

Sketch the converter waveforms

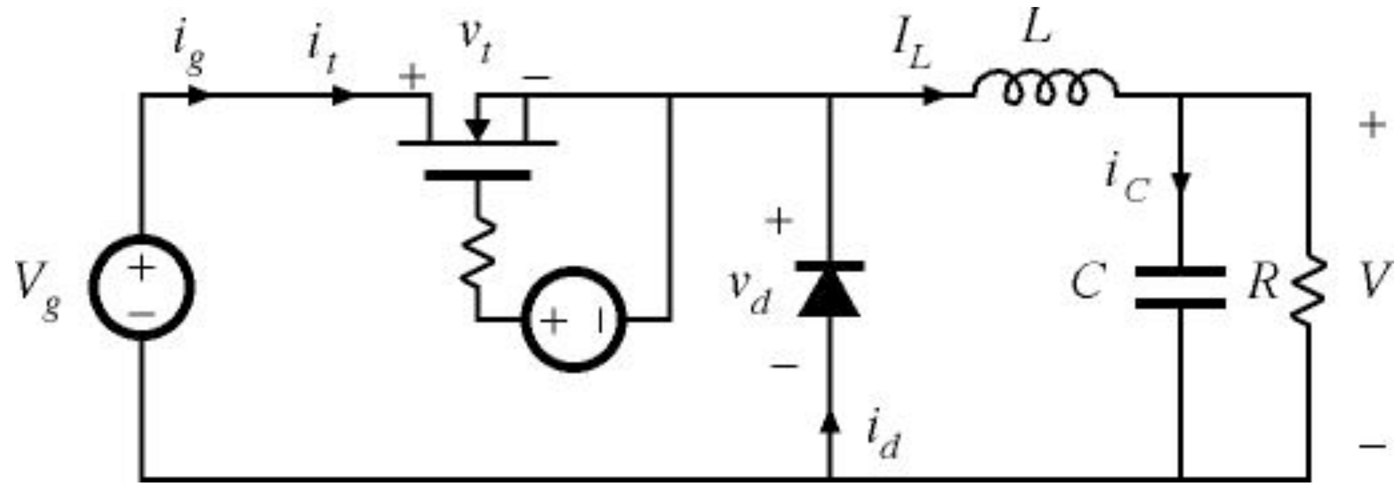
- Including the switching transitions (idealizing assumptions are made to lead to tractable results)
- In particular, sketch inductor voltage, capacitor current, and input current waveforms

The usual steady-state relationships:

$$\langle v_L \rangle = 0, \langle i_C \rangle = 0, \langle i_g \rangle = I_g$$

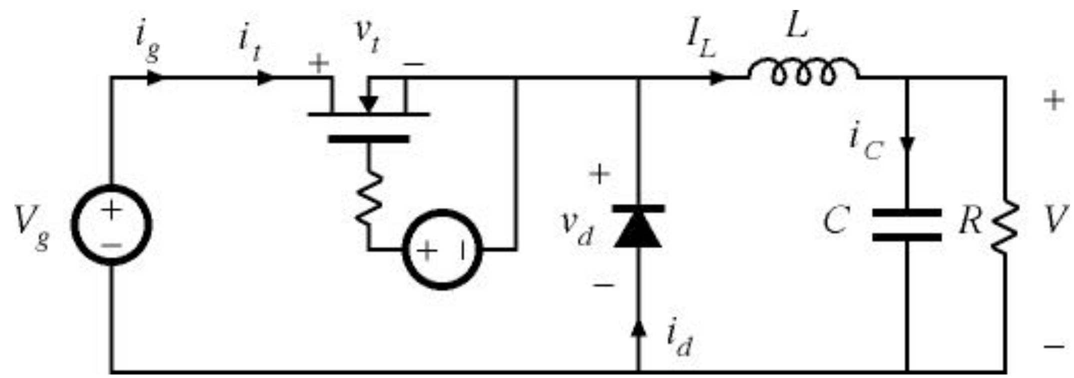
Use the resulting equations to construct an equivalent circuit model, as usual

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

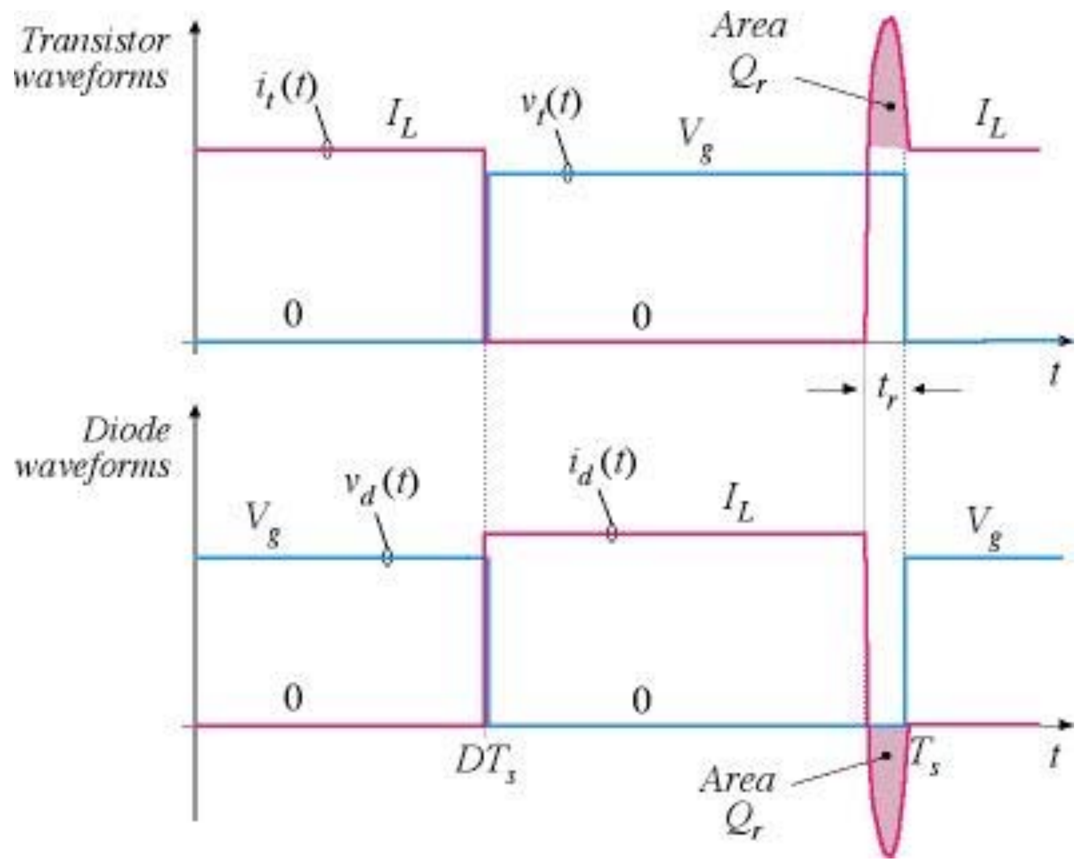
Assumed waveforms



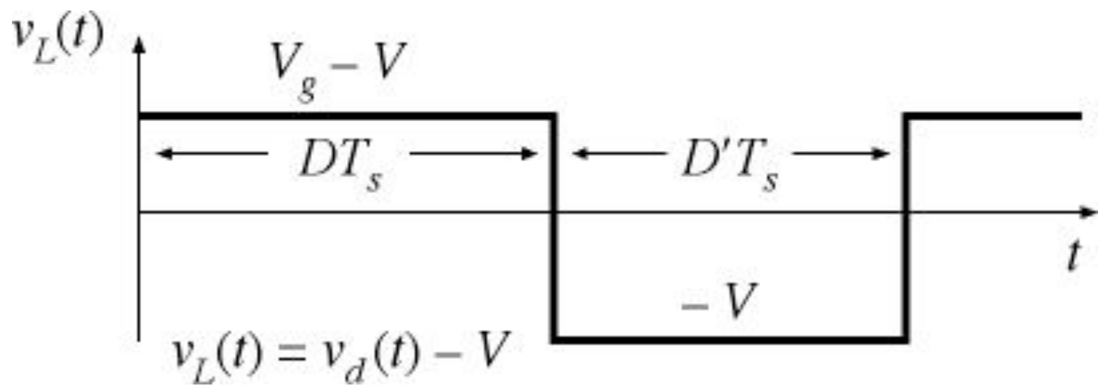
Diode recovered charge Q_r, reverse recovery time t_r

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



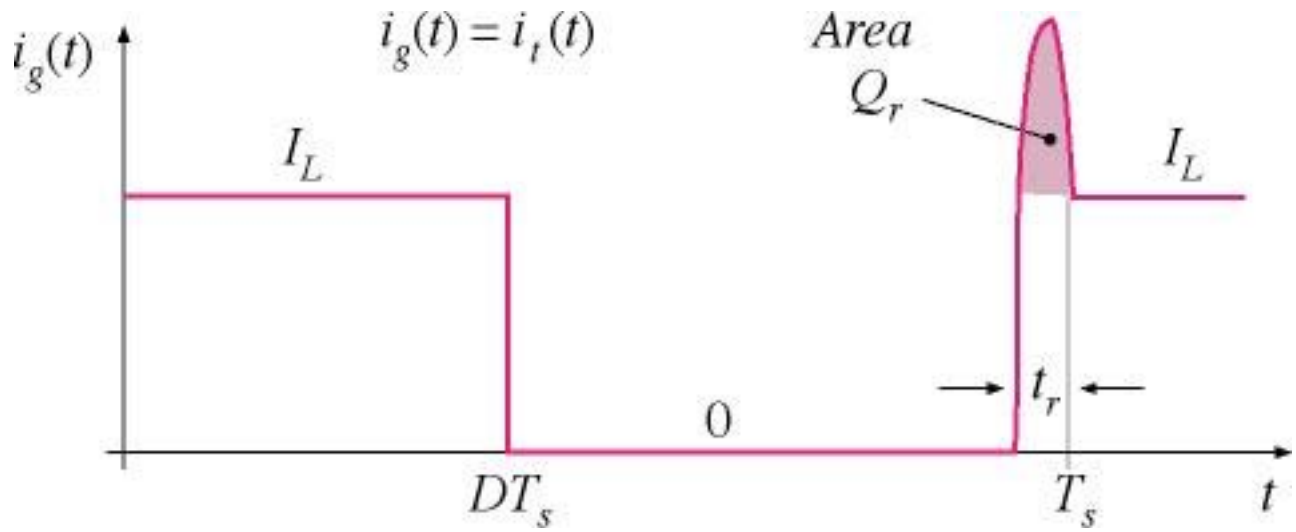
Inductor volt-second balance and capacitor charge balance



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



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

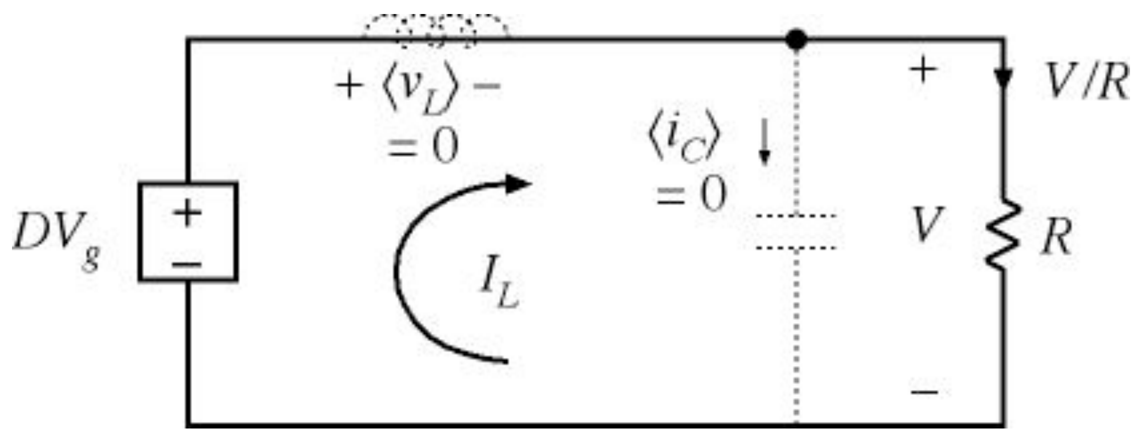
$$= (DT_s I_L + t_r I_L + Q_r)/T_s$$

$$= DI_L + t_r I_L/T_s + Q_r/T_s$$

Construction of Equivalent Circuit Model

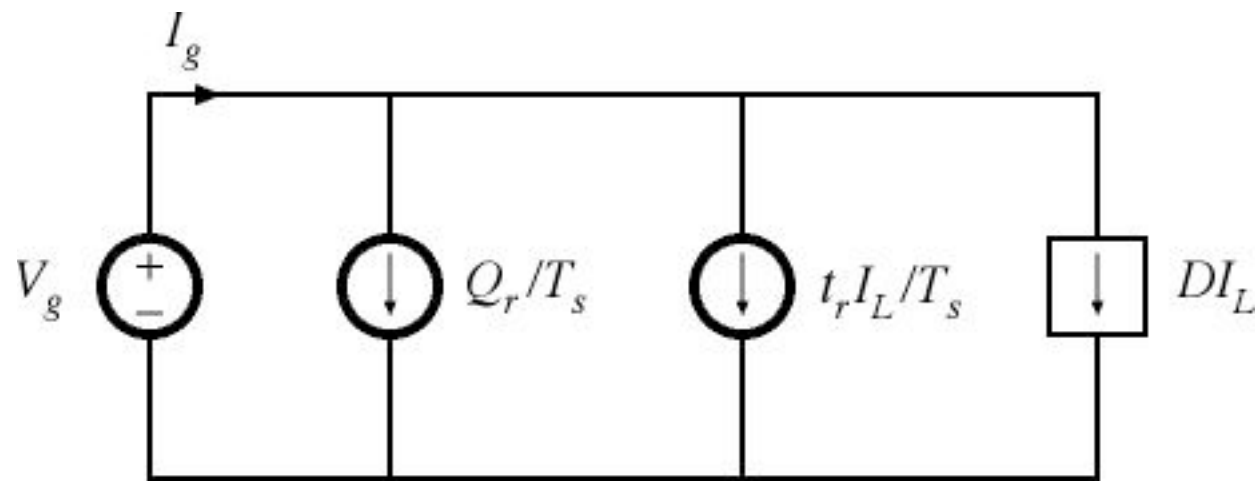
From inductor volt-second balance: $\langle v_L \rangle = 0 = DV_g - V$

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

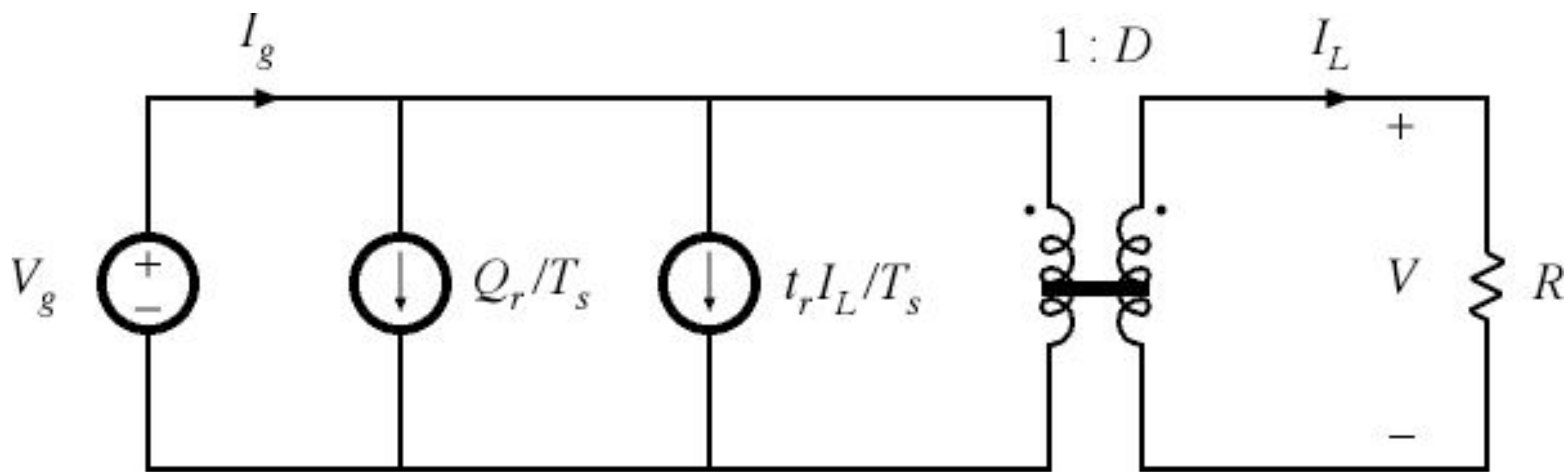


Input port of model

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



Combine for complete model



The two independent current sources consume power

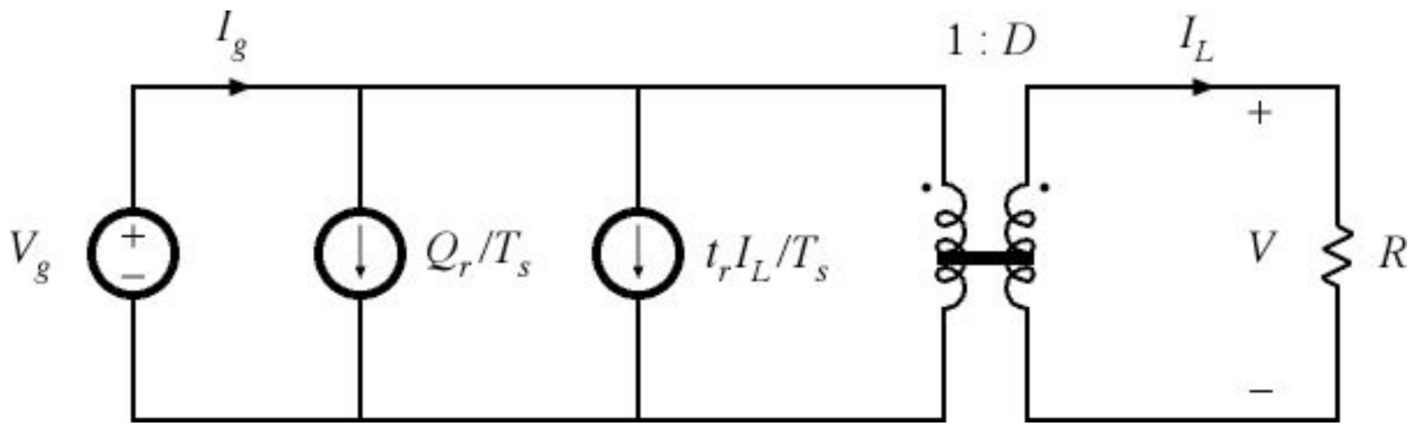
$$V_g \, (t_r I_L/T_s + Q_r/T_s)$$

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:

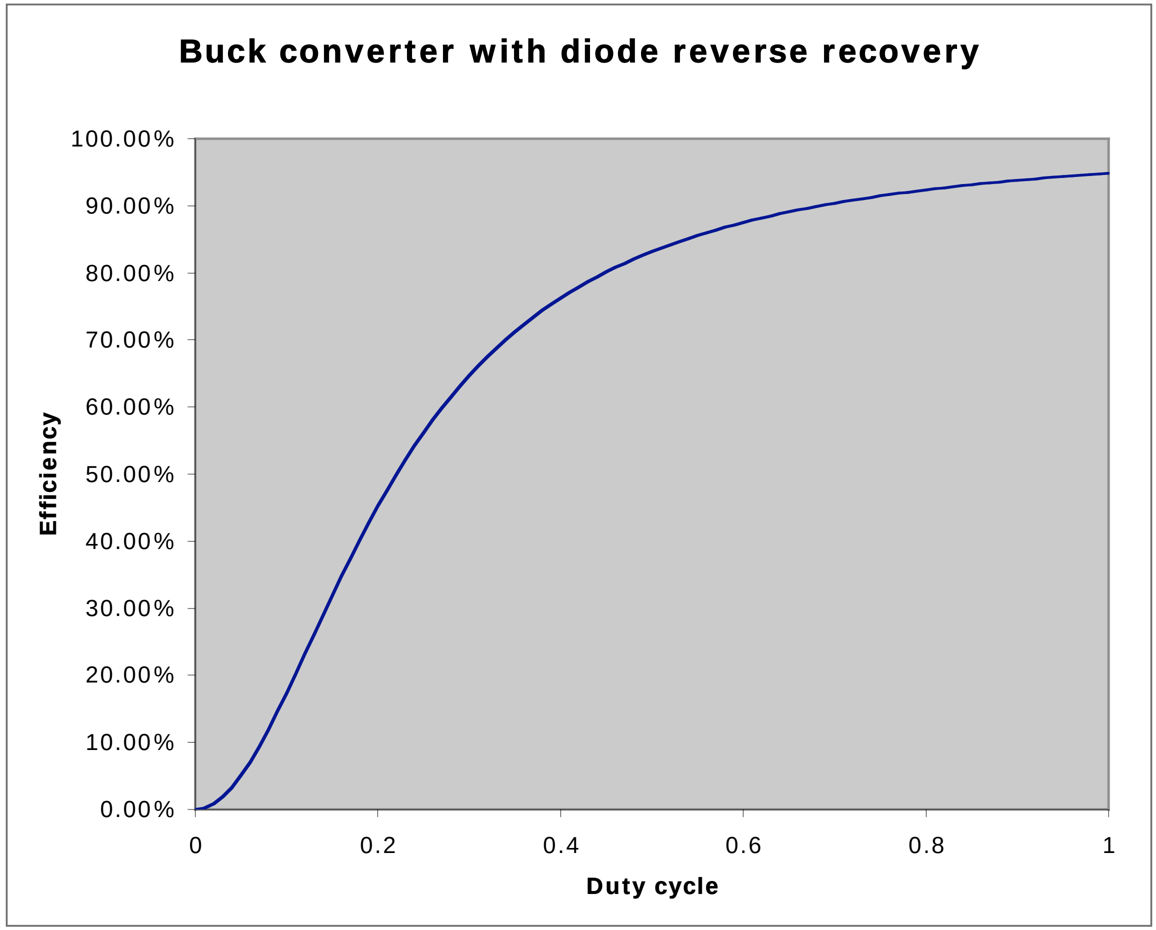
$\eta = 1 \,/\, [1 + f_s \,(t_r / D + Q_r R / D^2 V_g\,)]$

Predicted Efficiency vs Duty Cycle

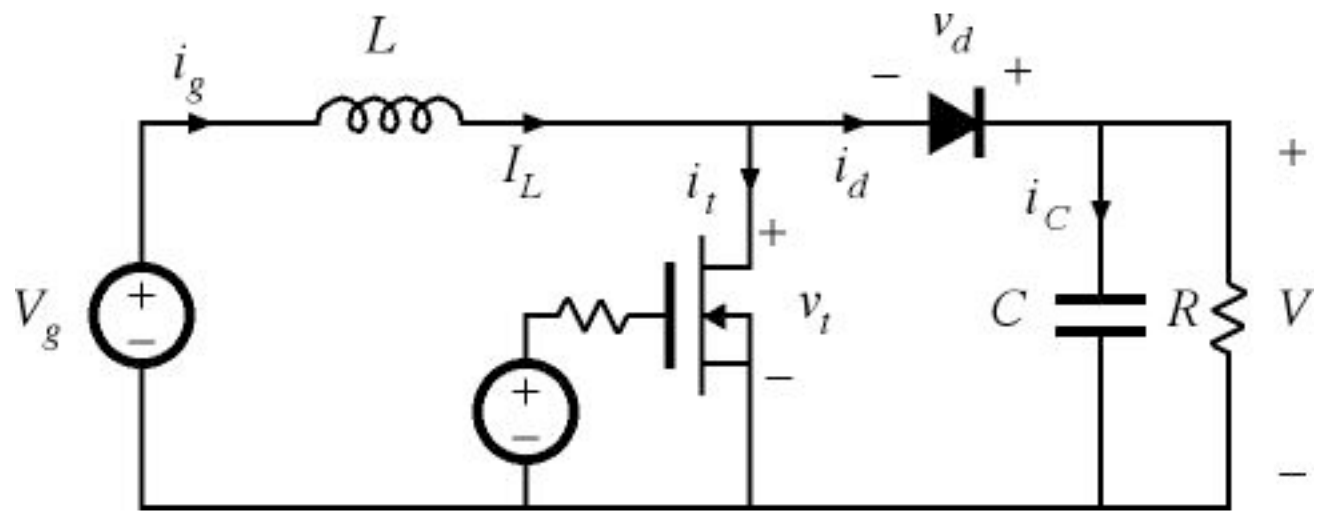
Switching frequency 100 kHz
Input voltage 24 V
Load resistance 15 Ω
Recovered charge 0.75 μCoul
Reverse recovery time 75 nsec

(no attempt is made here to model how the reverse recovery process varies with inductor current)

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



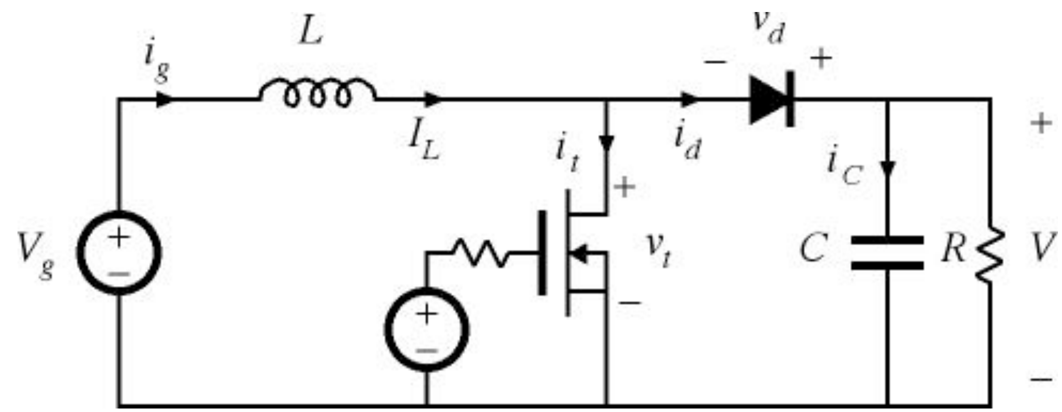
Boost Converter Example



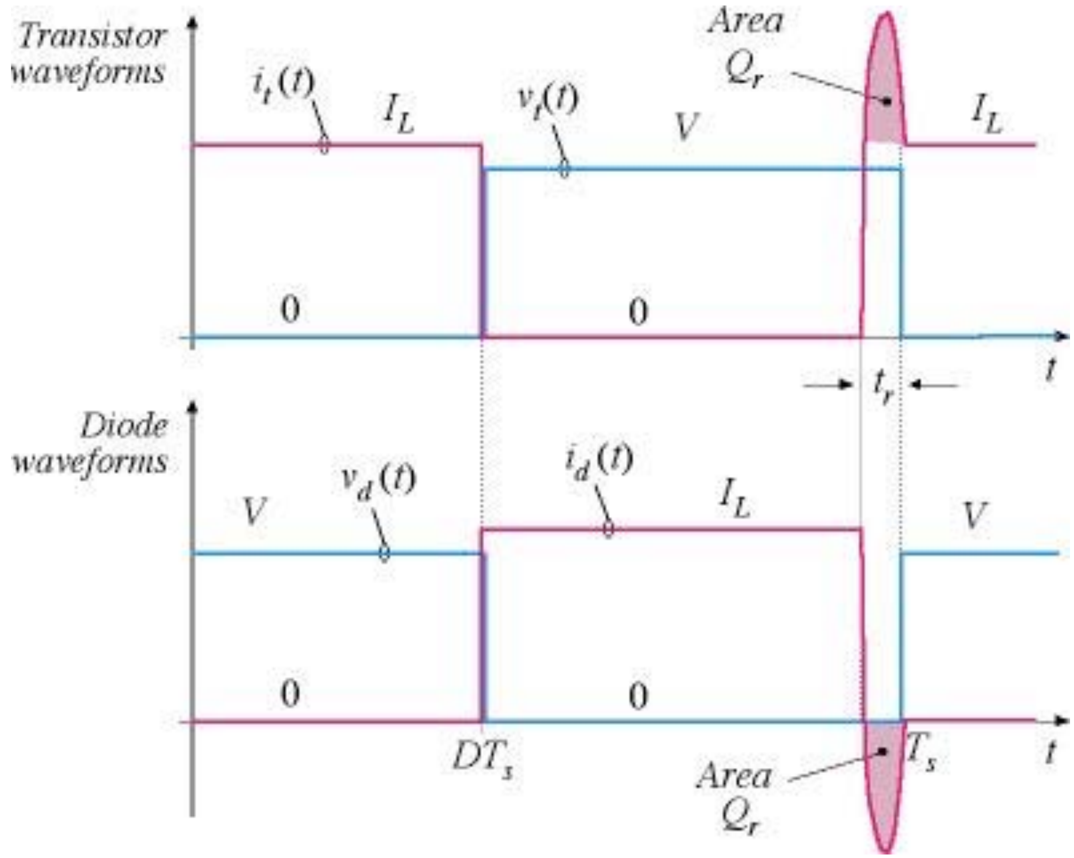
Model same effects as in previous buck converter example:

- 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

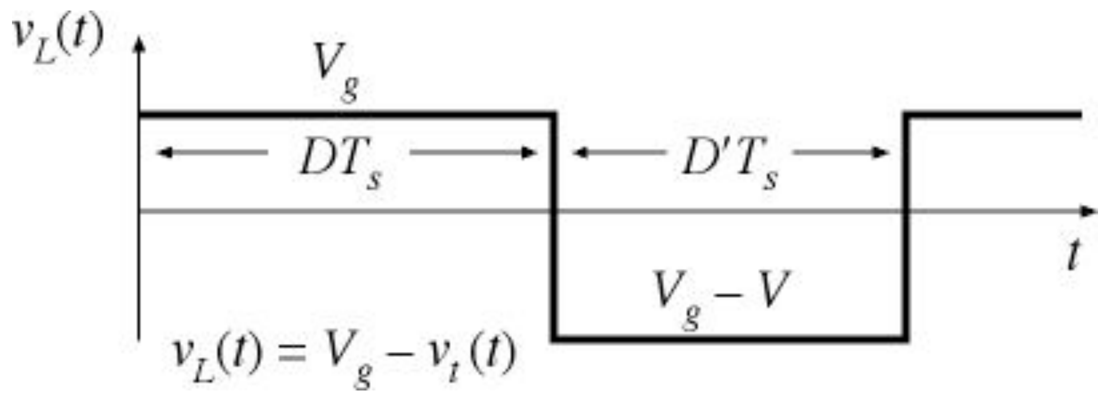
Boost converter



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



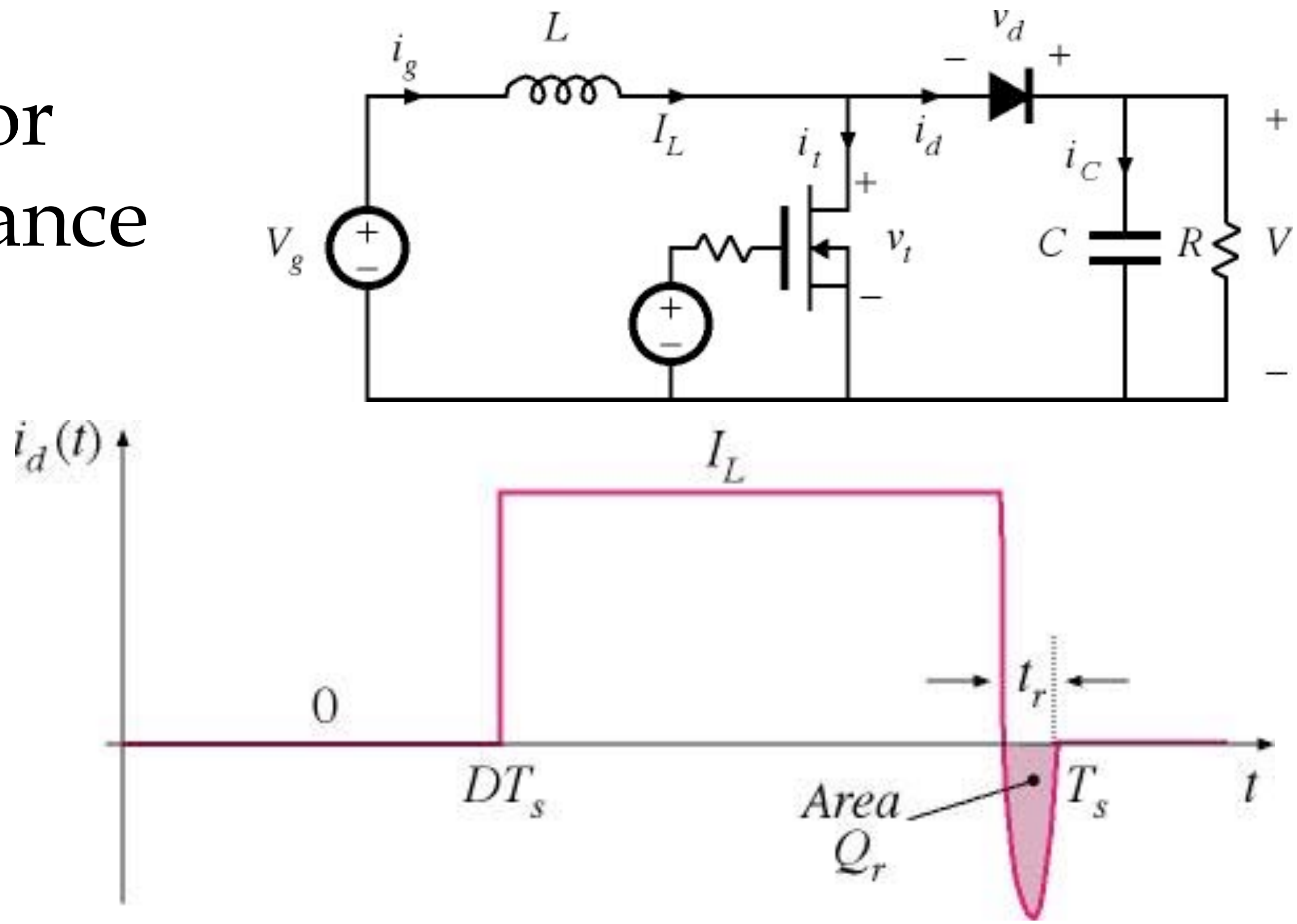
Inductor volt-second balance and average input current



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

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

Capacitor charge balance



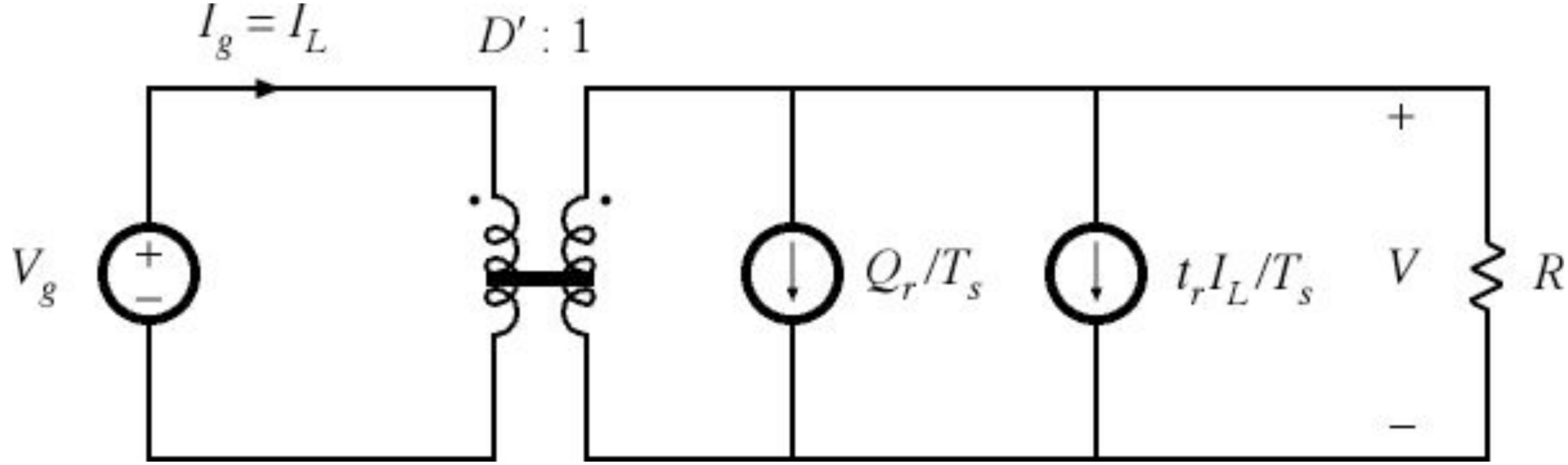
$$\langle i_C \rangle = \langle i_d \rangle - V/R = 0$$

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

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

Construct model

The result is:



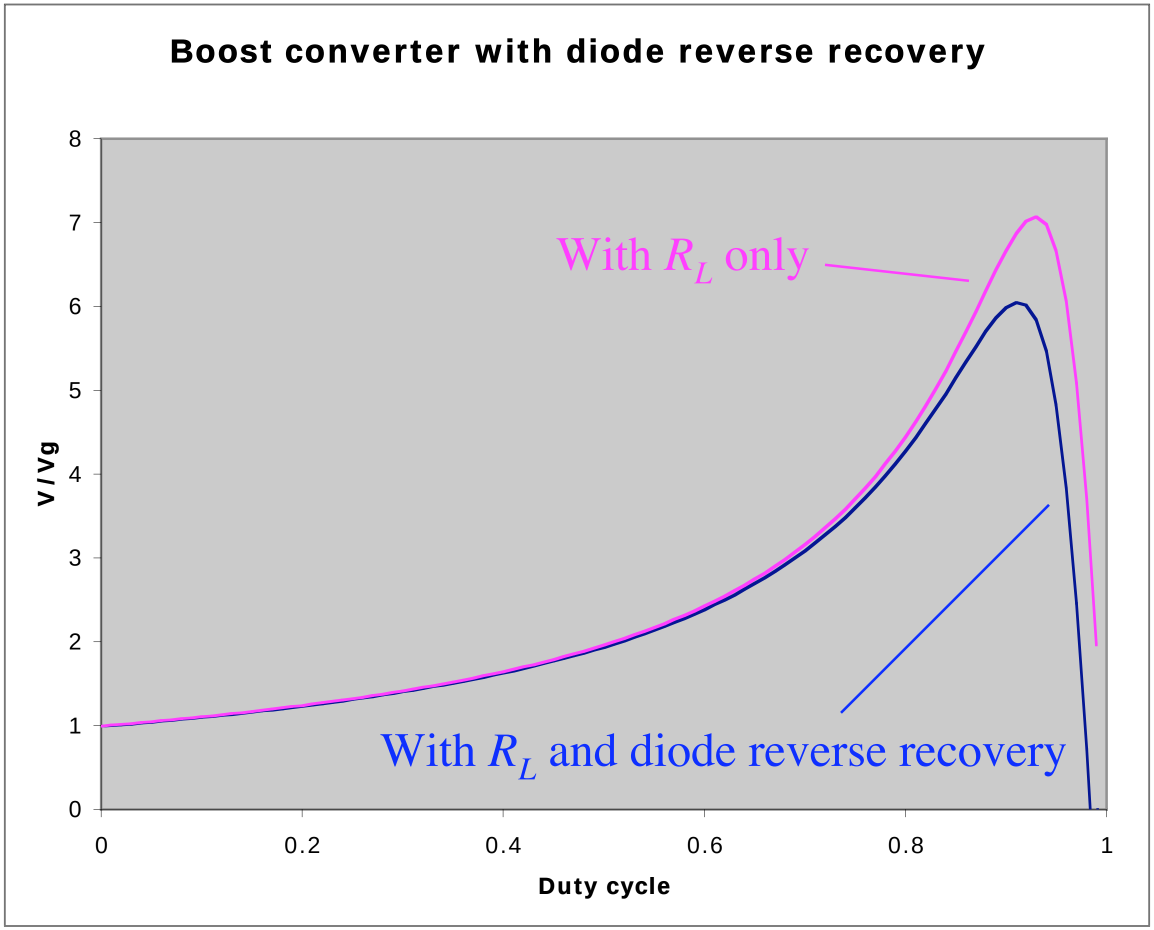
The two independent current sources consume power

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

equal to the switching loss induced by diode reverse recovery

Predicted V/V_g 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 $R_L = 0.3\ \Omega$
(inductor resistance also inserted into averaged model here)



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