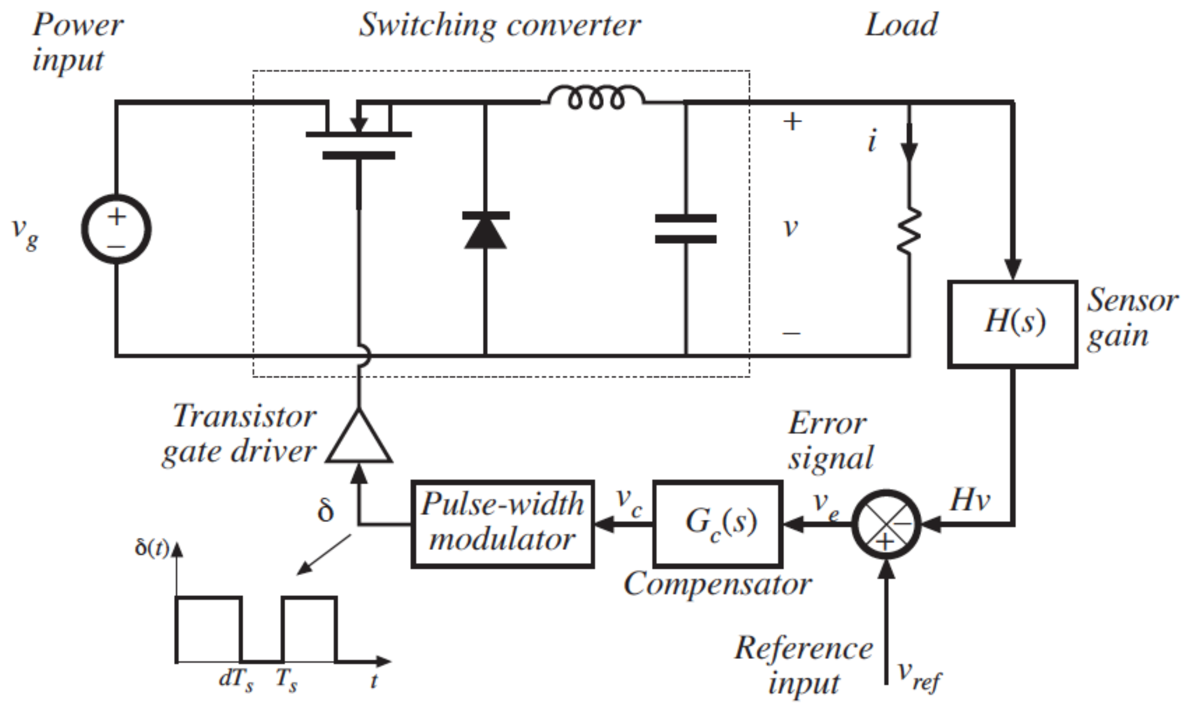
Plan du Cours

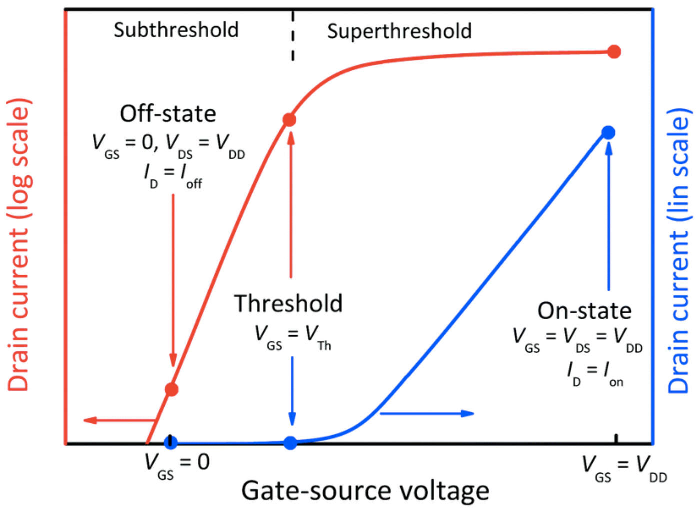
- Calcul de pertes
- Calcul de l'éfficacité versus fréquence de commutation

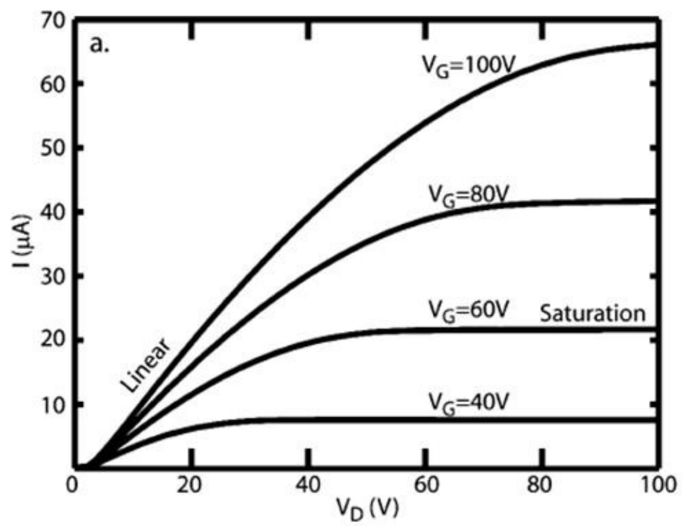
References additionelles:
Fundamentals of Power Electronics, Robert W. Erickson, Dragan Maksimović, SECOND EDITION University of Colorado Boulder, Colorado
Electronique de puissance, Philippe Barrade, presses polytechniques et universitaires romandes

Need for gate driver:

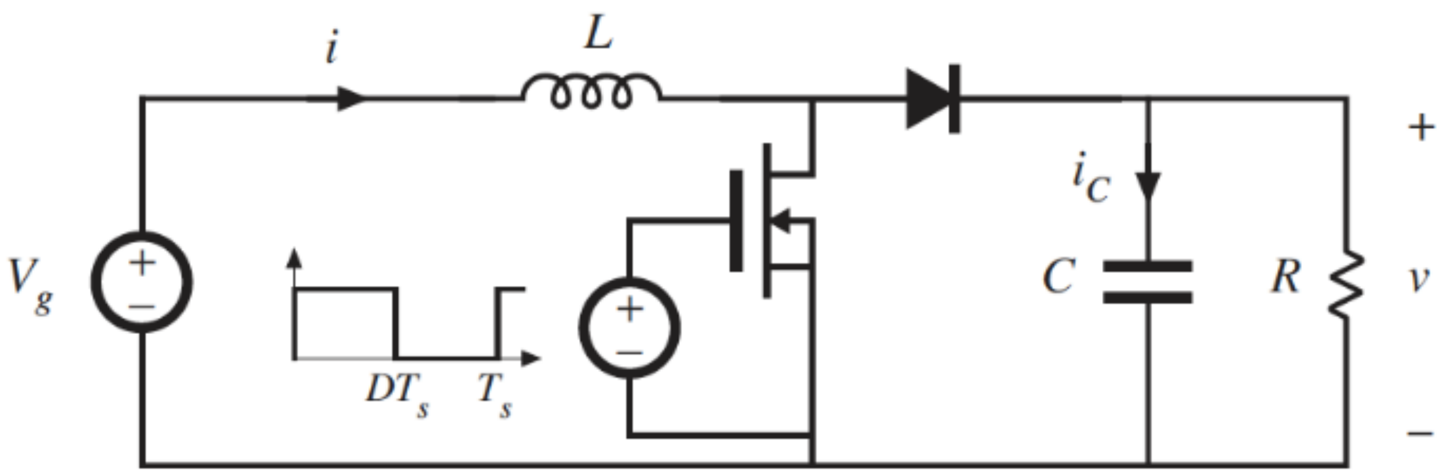


MOSFET characteristics:





What is the efficiency of the circuit that you simulated/calculated?

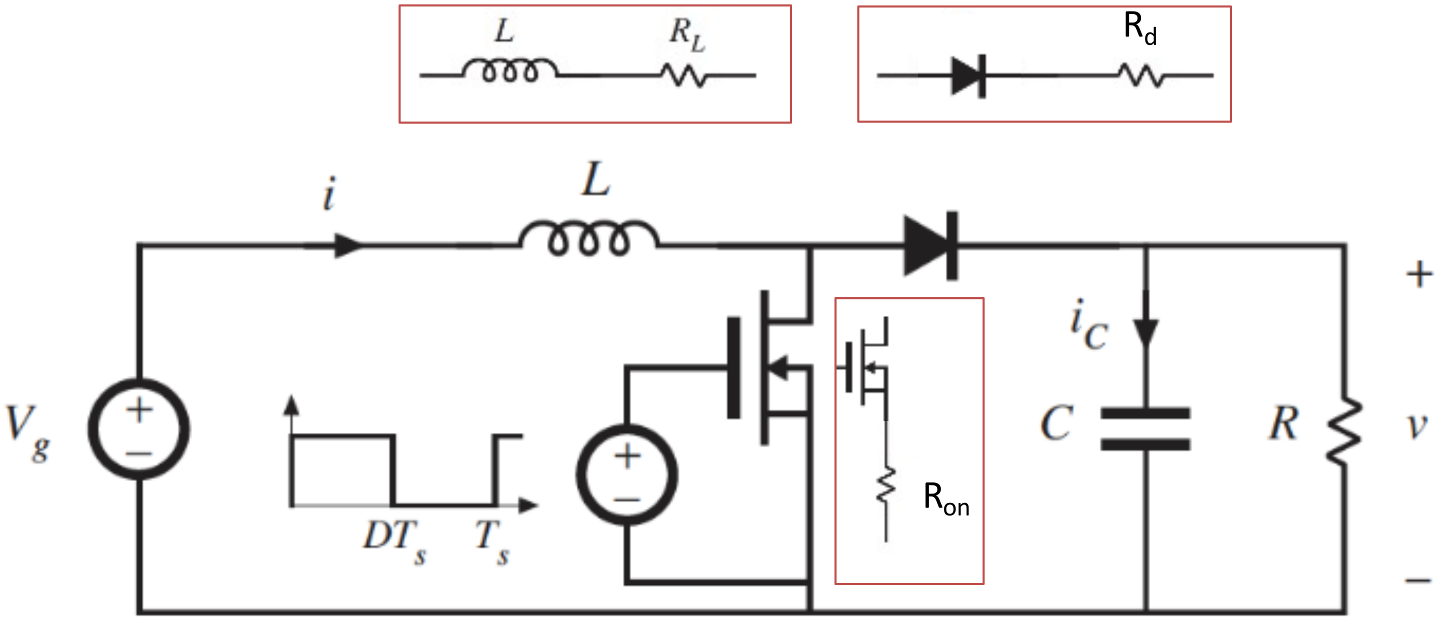


Introduction de pertes

1. Pertes en conduction: se passe pendant la conduction

- Semiconductor forward bias
- Parasitics: inductances, capacitances, resistances

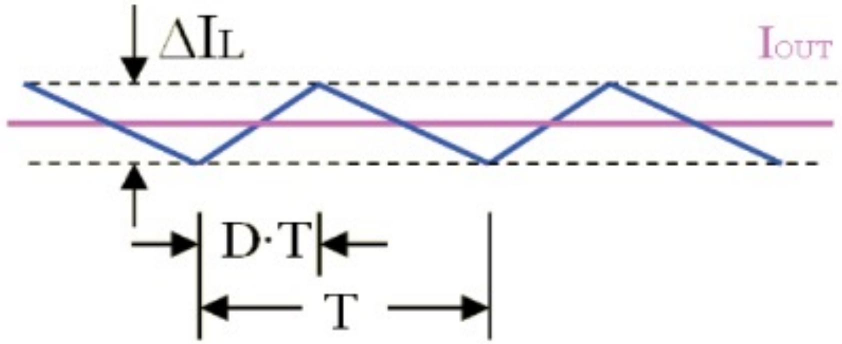
2. Pertes en commutation: se passe à chaque commutation



Pertes en conduction

Pertes en conduction

Power dissipated in the inductor



The inductor conduction loss is given by:

$$P_L = I^2_{RMS\_L} \times R_{DCR} \quad (1)$$

Where R_{DCR} is the DC-Resistance of the inductor.

The rms inductor current is given by:

$$I^2_{RMS\_L} = I^2_O + \frac{\Delta I^2}{12} \quad (2)$$

Where ΔI = ripple current

Typically ΔI is about 30% of the output current. Therefore, the inductor current can be calculated to be:

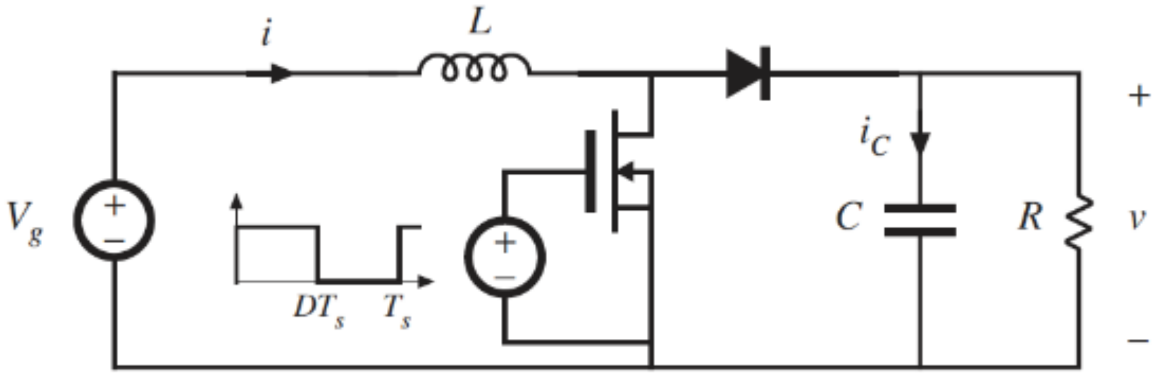
$$I_{RMS\_L} = I_O \times 1.00375 \quad (3)$$

Puissance dissipée (pertes): $P_L = I_{RMS}^2 \times R_{DC}$
For small ripple: $P_L = I_{DC}^2 \times R_{DC}$

Pertes en conduction

Power dissipated in the transistor and diodes:

Boost converter example



Models of on-state semiconductor devices:

MOSFET: on-resistance R_{on}

Diode: constant forward voltage V_D plus on-resistance R_D

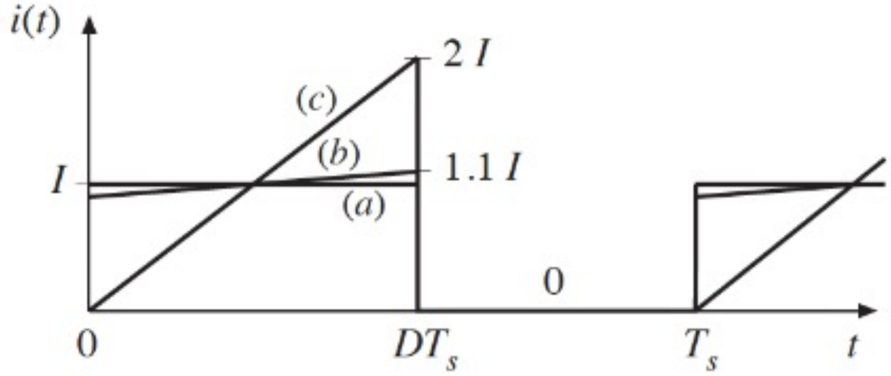
Insert these models into subinterval circuits

Pertes en conduction

Power dissipated in the transistor:

- Model uses average currents and voltages
- To correctly predict power loss in a resistor, use rms values
- Result is the same, provided ripple is small

MOSFET current waveforms, for various ripple magnitudes:



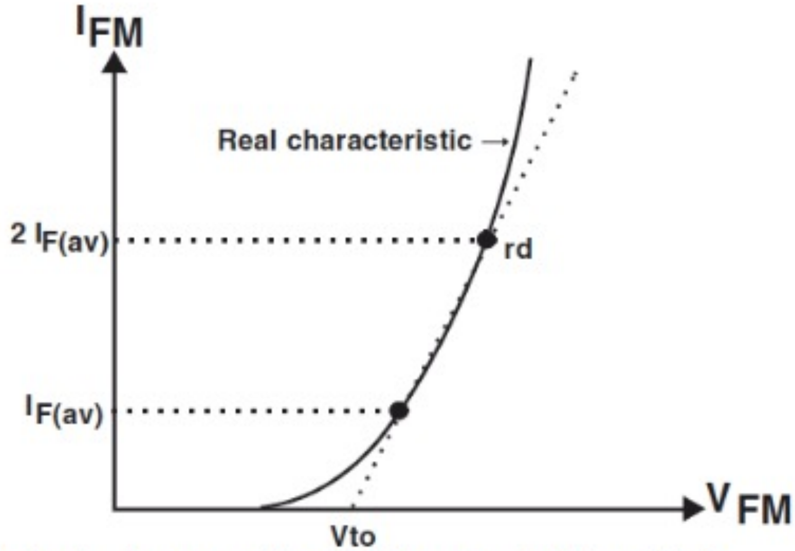
Inductor current ripple	*MOSFET rms current*	*Average power loss in* R_{on}
(a) $\Delta i = 0$	$I\sqrt{D}$	$D\, I^2 R_{on}$
(b) $\Delta i = 0.1\, I$	$(1.00167)\, I\sqrt{D}$	$(1.0033)\, D\, I^2 R_{on}$
(c) $\Delta i = I$	$(1.155)\, I\sqrt{D}$	$(1.3333)\, D\, I^2 R_{on}$

- To predict the power loss in a resistor R, we must calculate the root-mean-square current I_{RMS}, rather than the average current. The average power loss is then given by RI_{RMS}^2
- If inductor current ripple is small: average model correctly predicts average power loss
- DC (average) model correctly predicts losses in the component non-idealities, provided that the inductor current ripple is small.

Pertes en conduction

Power dissipated in diodes:

In spite of the high operating frequency, the conduction losses remain the main cause of the junction's temperature increase in the majority of the applications. Therefore, it is important to accurately estimate these losses.



$I_F(av)$: Average forward current of the diode

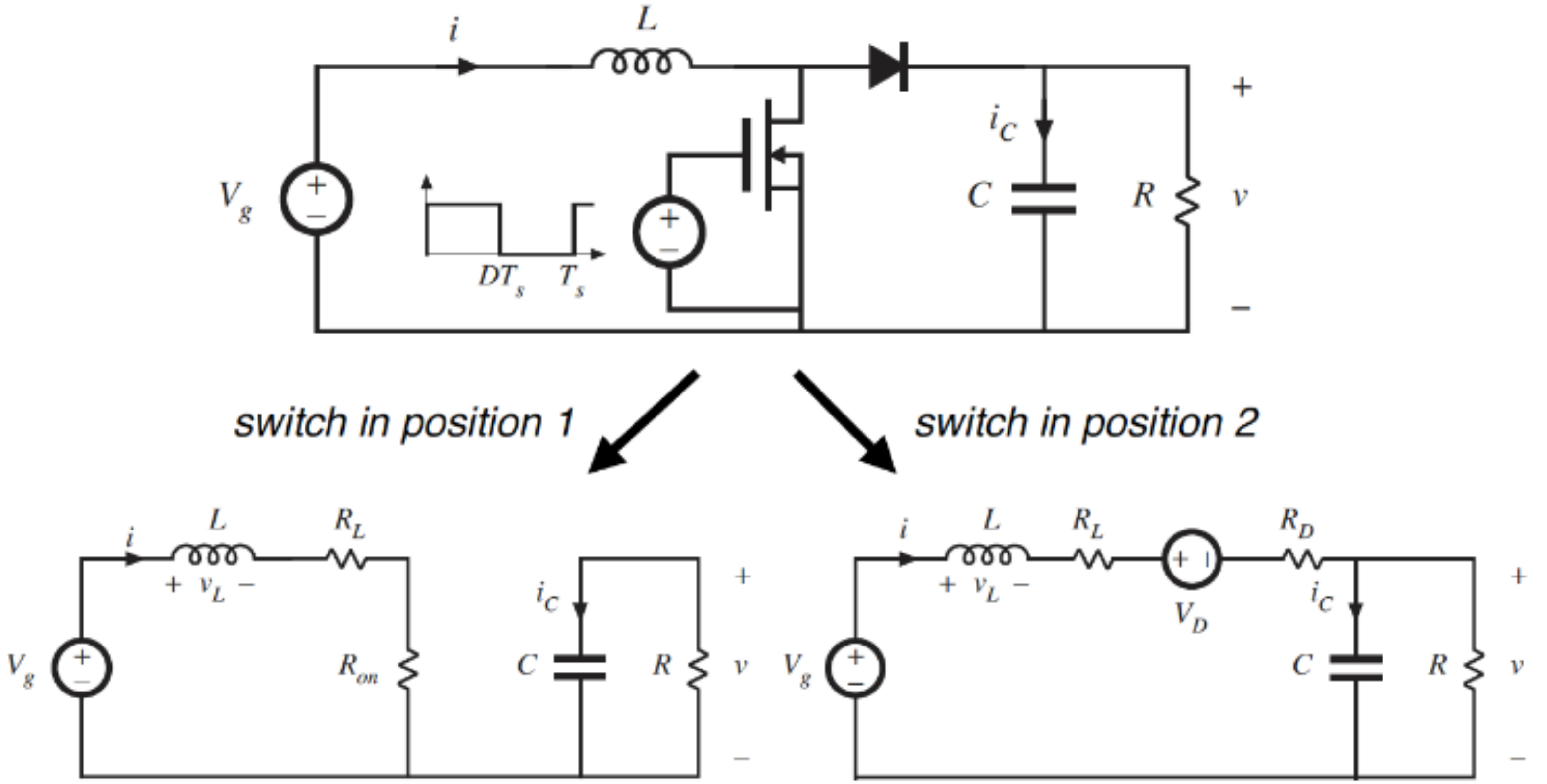
The forward voltage can be expressed by: $V_{FM} = V_{to} + r_d\, I_{FM}$
V_{to} and r_d are given in the datasheet for each part

$$P_{cond} = V_{to}\, I_F(av) + r_d\, I_F\,(RMS)^2$$

$I_F(av)$: average forward current in the diode
$I_F(RMS)$: RMS forward current in the diode

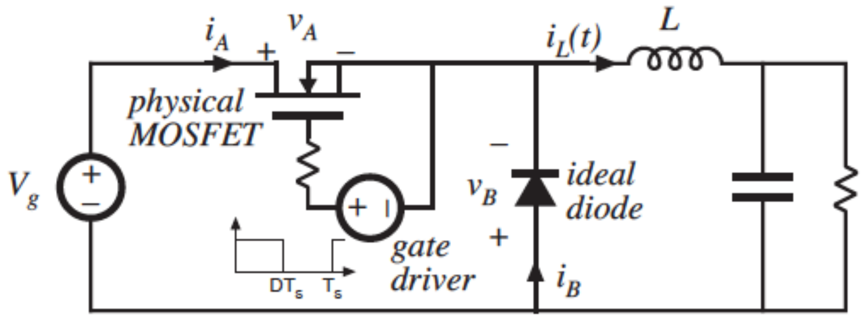
Pertes en conduction

Power dissipated in the transistor:



Pertes en commutation

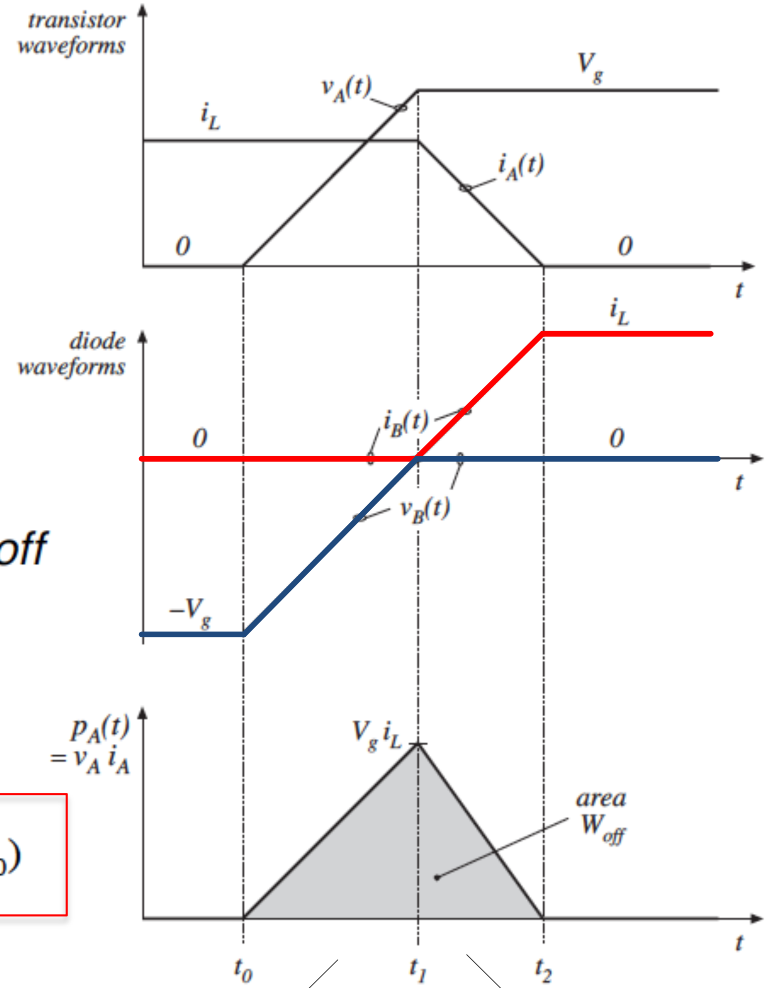
Pertes en commutation: MOSFET



Buck converter example

$$v_B(t) = v_A(t) - V_g$$
$$i_A(t) + i_B(t) = i_L$$

transistor turn-off transition



$$W_{off} = \frac{1}{2} V_g i_L (t_2 - t_0)$$

Temps pour charger le C_{GD} du MOSFET

Temps pour décharger le C_{gs} du MOSFET

Pertes en commutation: MOSFET

Energy lost during transistor turn-off transition:

$$W_{off} = \frac{1}{2} V_g i_L (t_2 - t_0)$$

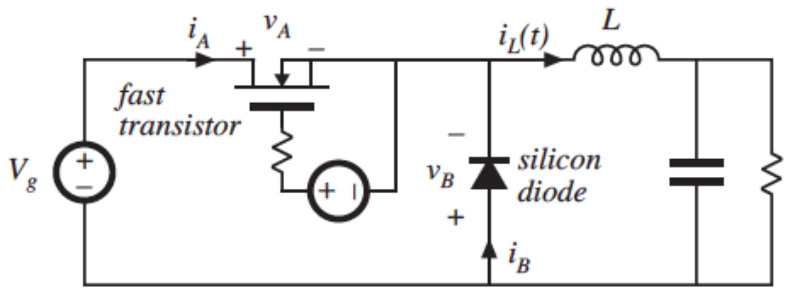
Similar result during transistor turn-on transition.
Average power loss:

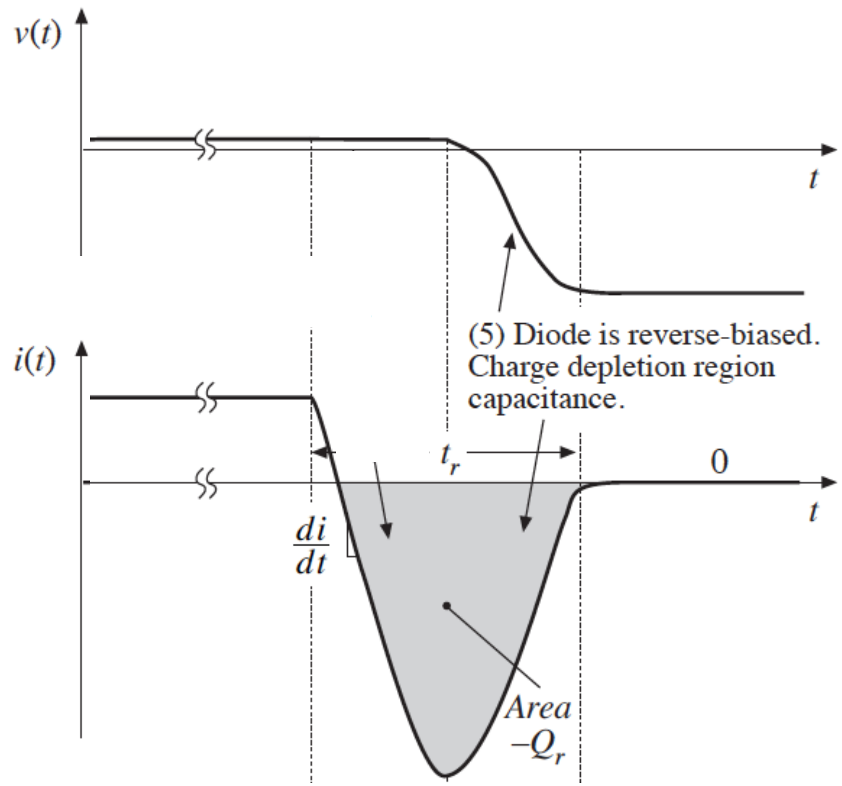
$$P_{sw} = \frac{1}{T_s} \int_{\substack{switching \\ transitions}} p_A(t)\, dt = (W_{on} + W_{off})\, f_s$$

Perte en commutation: proportionnelle à la fréquence de commutation

Introduction: Pertes sur les diodes

Pertes en commutation: Diode

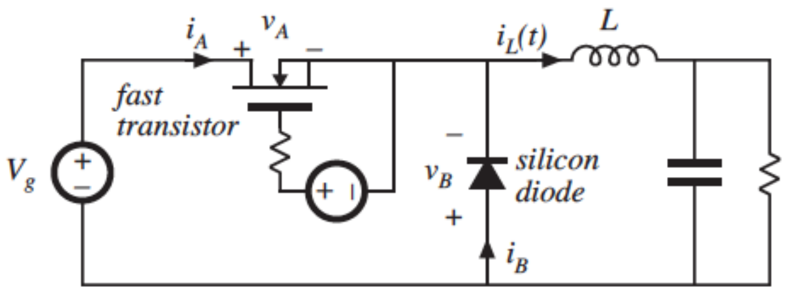


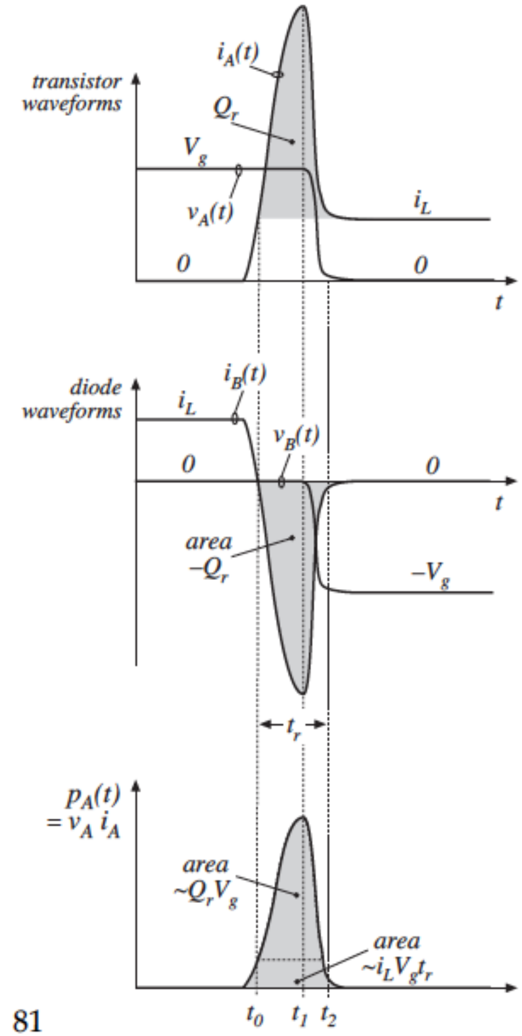


Under forward bias:

- substantial amount of charges is stored in the n^- region
- Increases conductivity
- Reduces R_{ON}

Pertes en commutation: Diode





- Diode recovered stored charge Q_r flows through transistor during transistor turn-on transition, inducing switching loss
- Q_r depends on diode on-state forward current, and on the rate-of-change of diode current during diode turn-off transition

Efficacité versus fréquence de commutation

Add up all of the energies lost during the switching transitions of one switching period:

$$W_{tot} = W_{on} + W_{off} + W_D + W_C + W_L + \ldots$$

Average switching power loss is

$$P_{sw} = W_{tot}\, f_{sw}$$

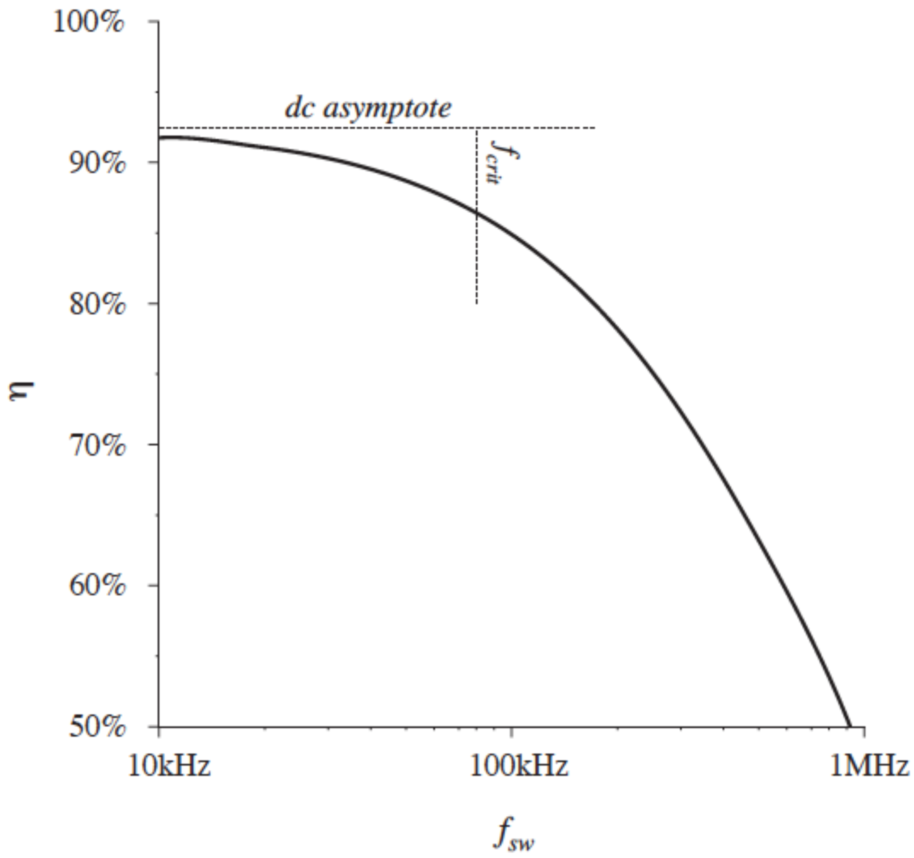
Total converter loss can be expressed as

$$P_{loss} = P_{cond} + P_{fixed} + W_{tot}\, f_{sw}$$

where P_{fixed} = fixed losses (independent of load and f_{sw})
P_{cond} = conduction losses

Efficacité versus fréquence de commutation

$$P_{loss} = P_{cond} + P_{fixed} + W_{tot}\, f_{sw}$$



Switching losses are equal to the other converter losses at the critical frequency

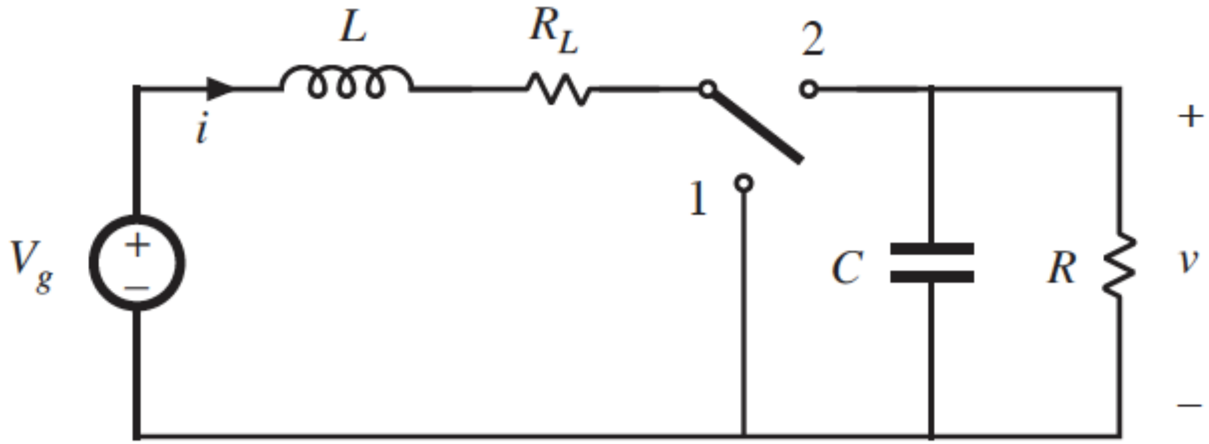
$$f_{crit} = \frac{P_{cond} + P_{fixed}}{W_{tot}}$$

This can be taken as a rough upper limit on the switching frequency of a practical converter. For $f_{sw} > f_{crit}$, the efficiency decreases rapidly with frequency.

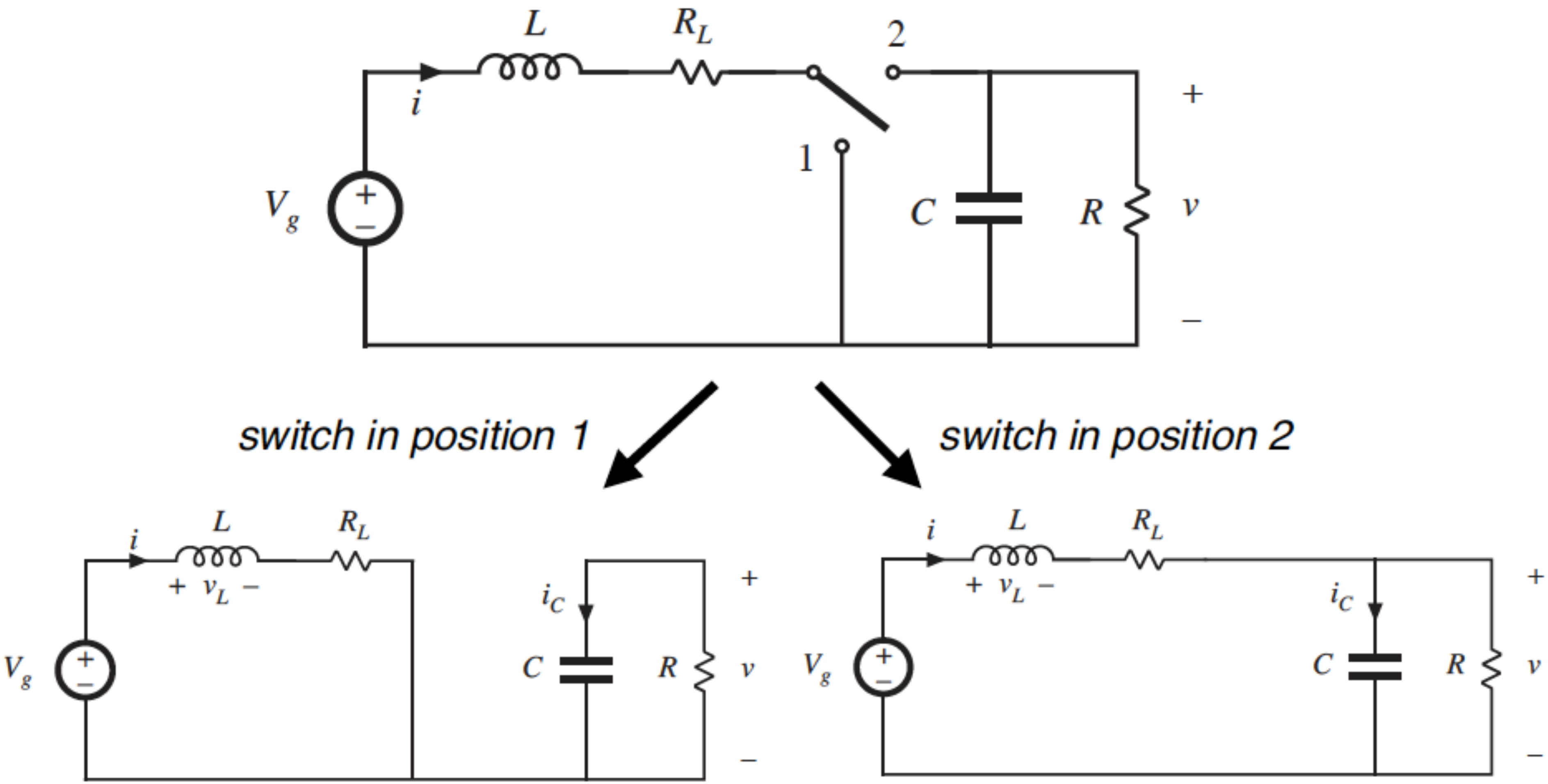
Exemple: Effet des pertes en conduction sur le convertisseur boost

Example: inductor copper loss (resistance of winding):

Insert this inductor model into boost converter circuit:



Introduction de pertes

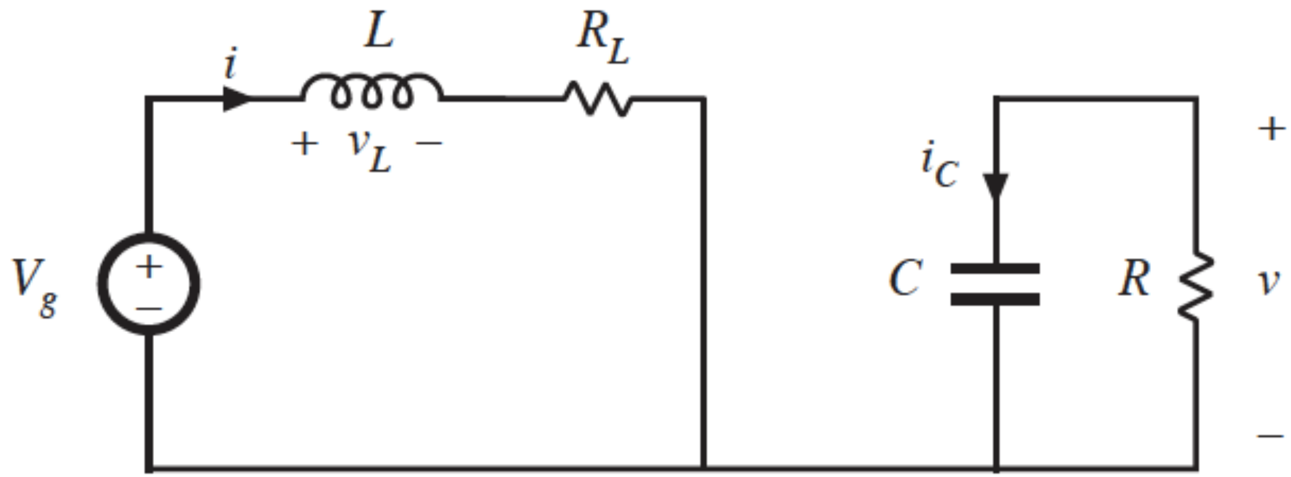


Introduction de pertes

Inductor current and capacitor voltage:

$$v_L(t) = V_g - i(t)\, R_L$$

$$i_C(t) = -v(t) \,/\, R$$

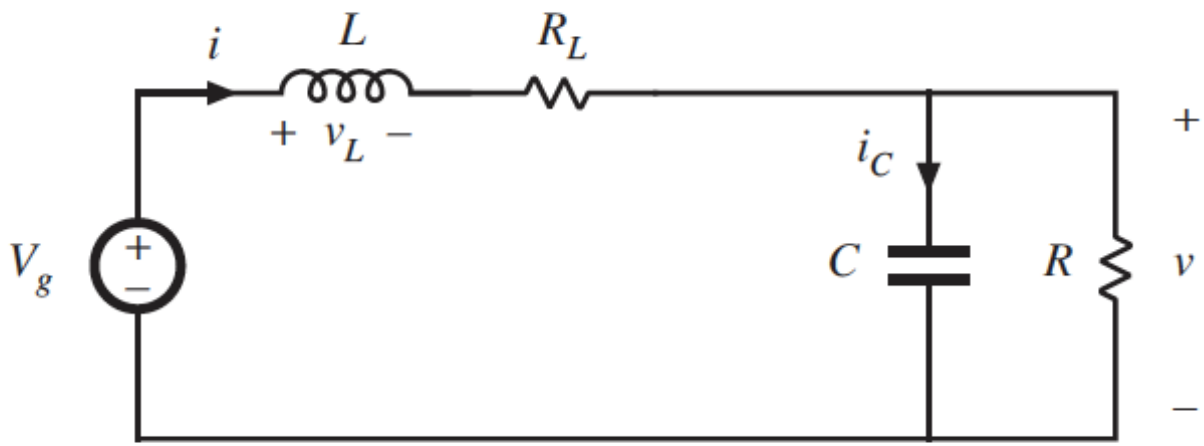


Small ripple approximation:

$$v_L(t) = V_g - I\, R_L$$

$$i_C(t) = -V \,/\, R$$

Introduction de pertes



$$v_L(t) = V_g - i(t)\, R_L - v(t) \approx V_g - I\, R_L - V$$
$$i_C(t) = i(t) - v(t) / R \approx I - V / R$$

Introduction de pertes

Average inductor voltage:

$$\langle v_L(t) \rangle = \frac{1}{T_s} \int_0^{T_s} v_L(t) dt$$
$$= D(V_g - I\,R_L) + D'(V_g - I\,R_L - V)$$

Inductor volt-second balance:

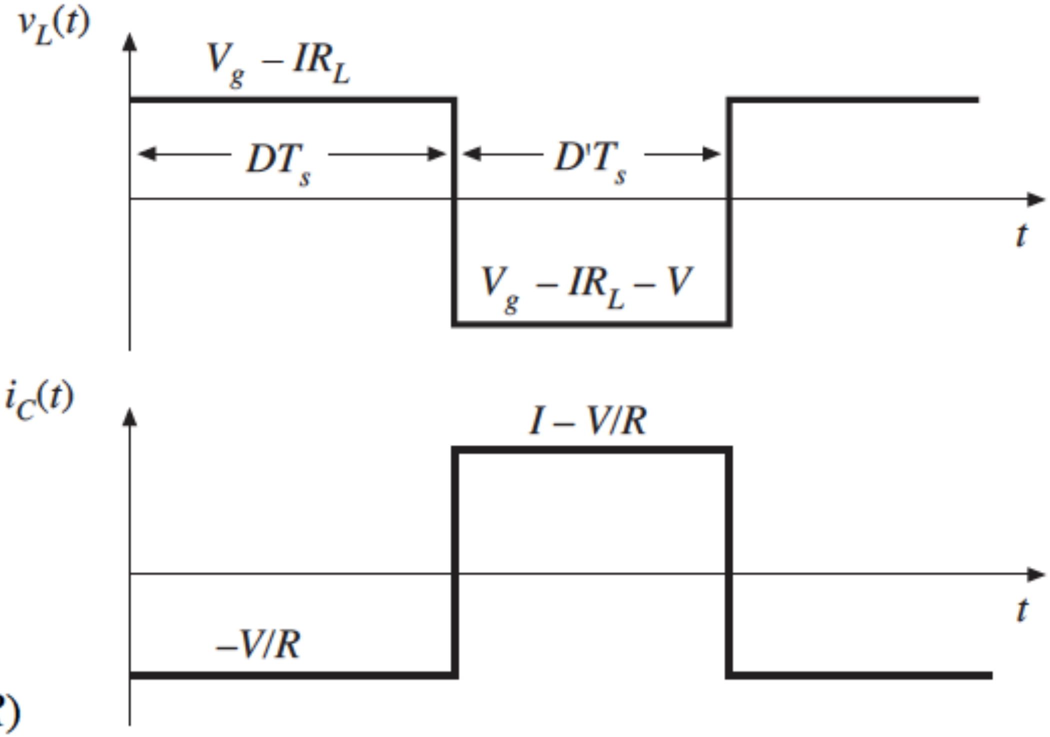
$$0 = V_g - I\,R_L - D'V$$

Average capacitor current:

$$\langle i_C(t) \rangle = D\,(-V/R) + D'\,(I - V/R)$$

Capacitor charge balance:

$$0 = D'I - V/R$$



Introduction de pertes

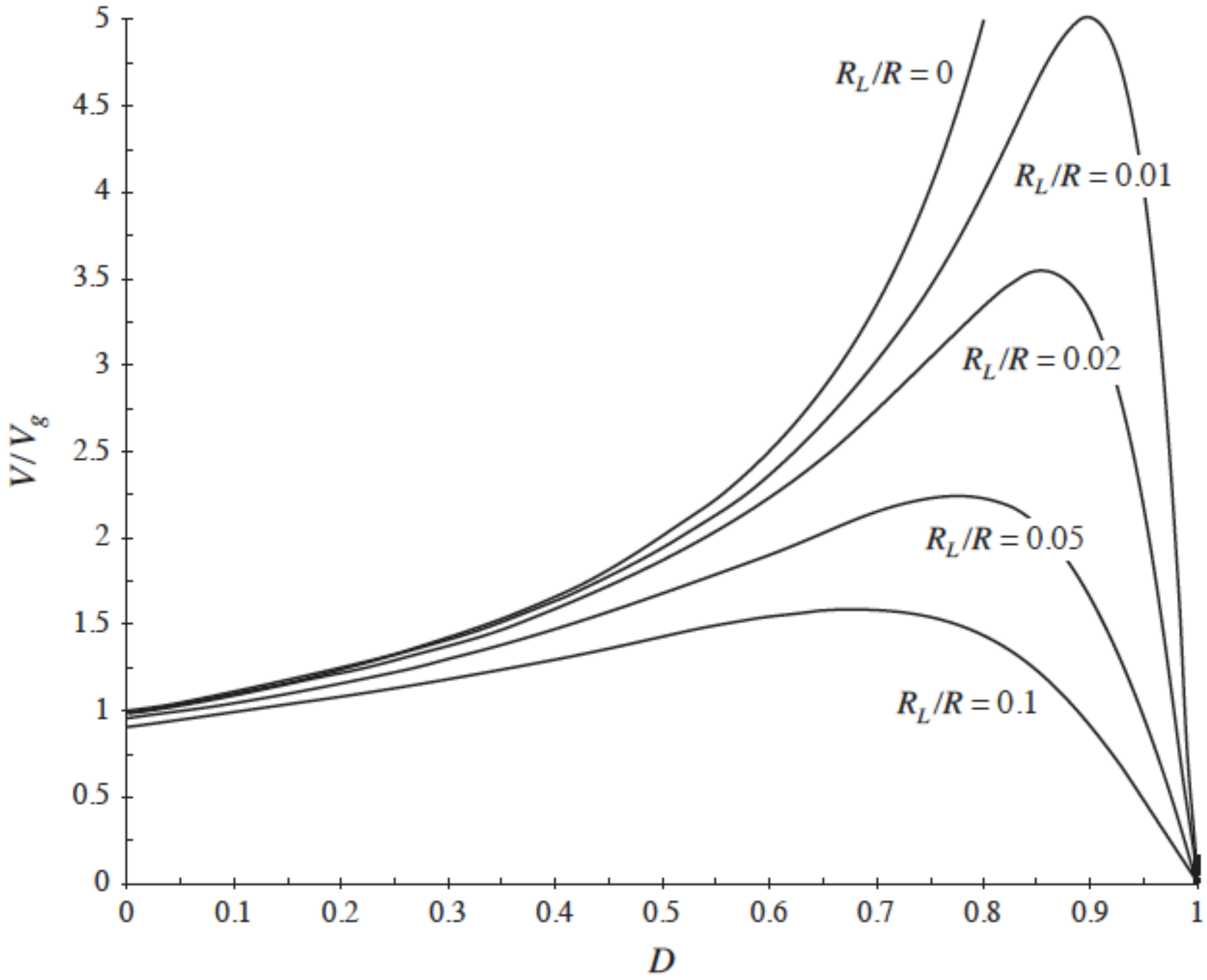
We now have two equations and two unknowns:

$$0 = V_g - I\,R_L - D'V$$

$$0 = D'I - V / R$$

Eliminate I and solve for V:

$$\frac{V}{V_g} = \frac{1}{D'} \frac{1}{(1 + R_L / D'^2 R)}$$



Dispositifs de puissance: Wide-band-gap semiconductors

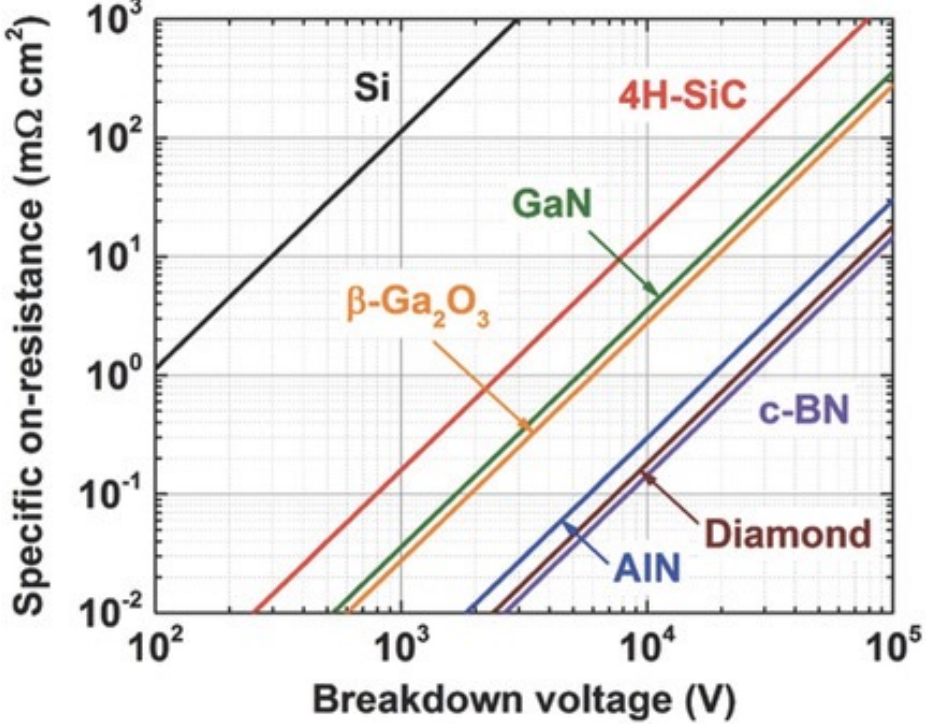
$$R_{ON,SP} = \frac{4BV^2}{\varepsilon_S \mu_n E_C^3}$$

$R_{on,sp}$ is related to material properties

Baliga's figure of merit

$$BFOM = \varepsilon_S \mu_n E_C^3 = \frac{4BV^2}{R_{ON,SP}}$$

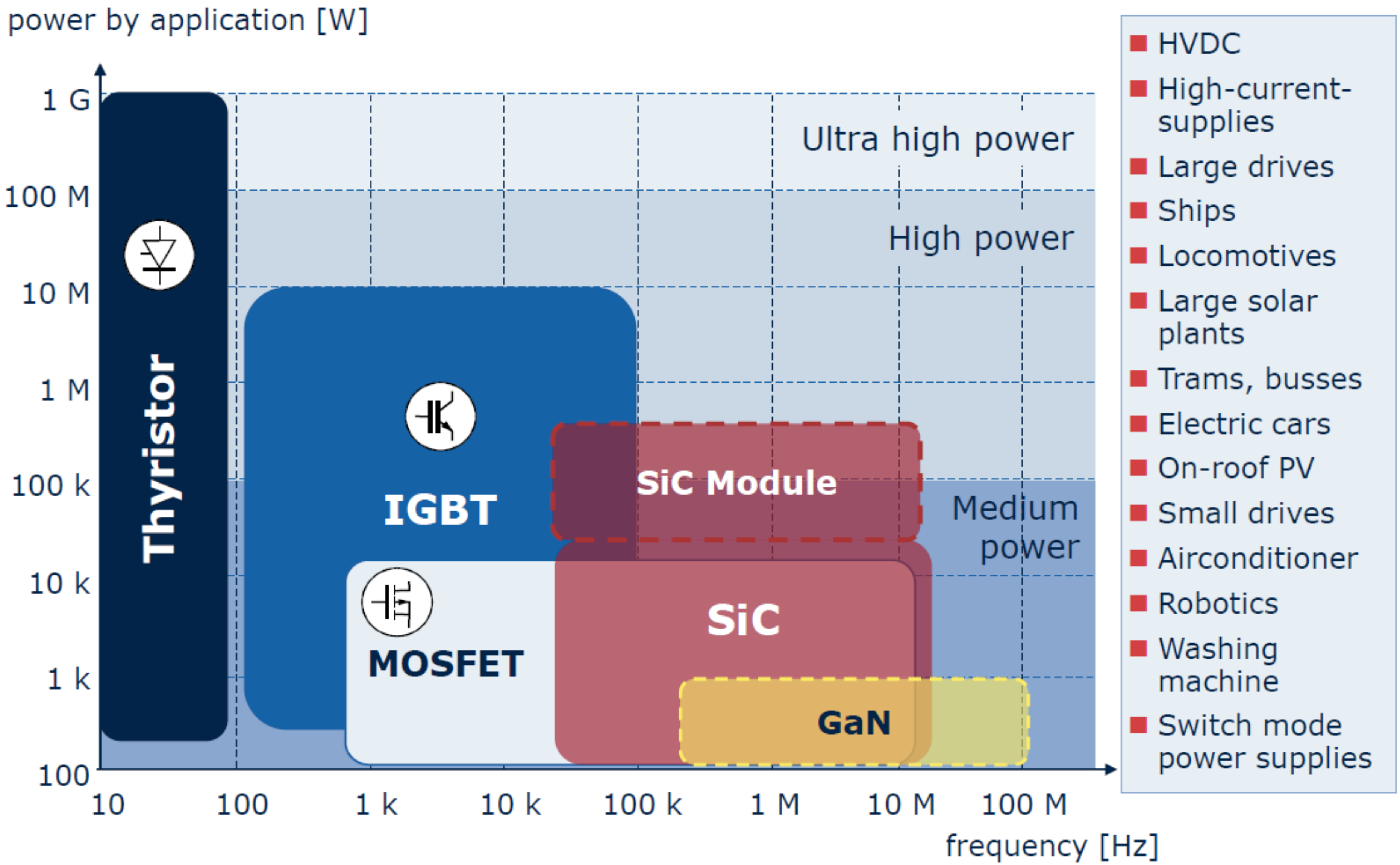
Wide-band-gap materials



Parameter	Silicon	4H-SiC	GaN	Diamond
W_g, eV	1.12	3.26	3.39	5.47
E_{crit}, MV/cm	0.23	2.2	3.3	5.6
ε_r	11.8	9.7	9.0	5.7
μ_n, cm^2/V·s	1400	950	800/1700[b]	1800
BFoM[a] relative to Si	1	500	1300/2700[b]	9000
n_i, cm^{-3}	$1{\cdot}10^{10}$	$8{\cdot}10^{-9}$	$2{\cdot}10^{-10}$	$1{\cdot}10^{-20}$
λ, W/cm·K	1.5	3.8	1.3/3[c]	20

B.J. Baliga, *Fundamentals of Power Semiconductor Devices*, Springer 2008

Synthèse


power by application [W]
1 G
100 M
10 M
1 M
100 k
10 k
1 k
100
10
100
1 k
10 k
100 k
1 M
10 M
100 M
frequency [Hz]
Thyristor
IGBT
MOSFET
SiC Module
SiC
GaN
Ultra high power
High power
Medium power
HVDC
High-current-supplies
Large drives
Ships
Locomotives
Large solar plants
Trams, busses
Electric cars
On-roof PV
Small drives
Airconditioner
Robotics
Washing machine
Switch mode power supplies