Plan du cours

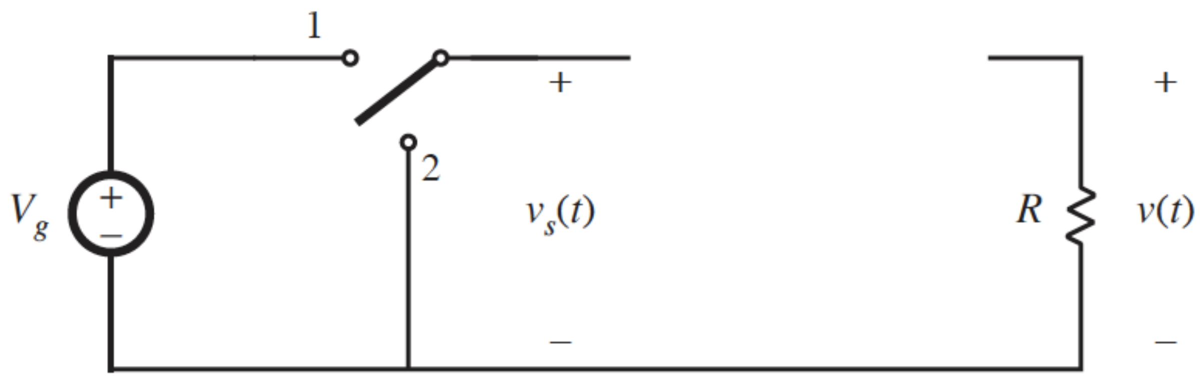
- Circuits convertisseurs
  - Inductor volt-second balance
  - Capacitor charge balance
  - Small-ripple approximation

References additionelles:
Fundamentals of Power Electronics, Robert W. Erickson, Dragan Maksimović, SECOND EDITION University of Colorado Boulder, Colorado
Fundamentals of Power Semiconductor Devices, B. J. Baliga, Springer (2008)
Dispositifs de Puissance à Semiconducteurs: Utilisation en circuits, Prof. A. Rufer, EPFL (2002)

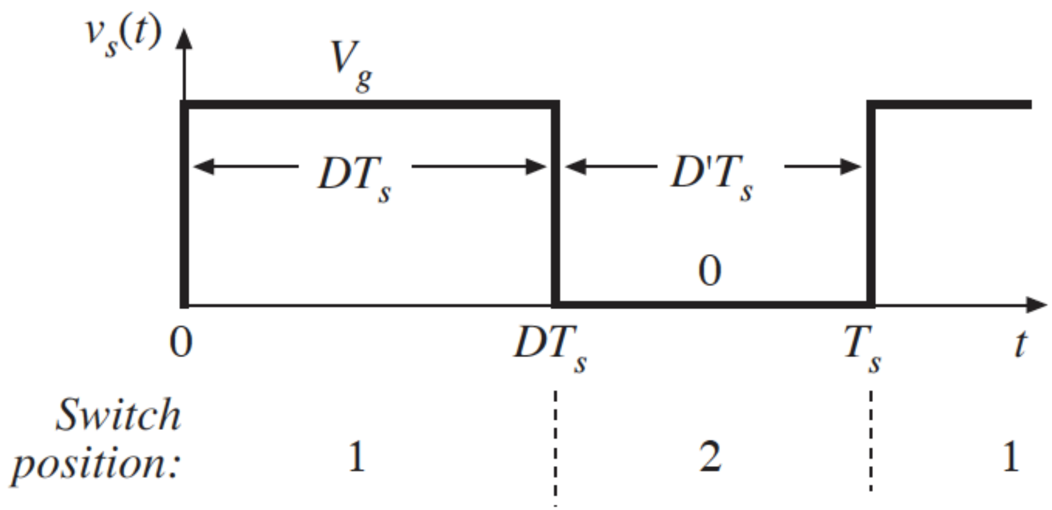
Introduction – buck converter

Single Pole Double Throw (SPDT) Switch

SPDT switch changes dc component



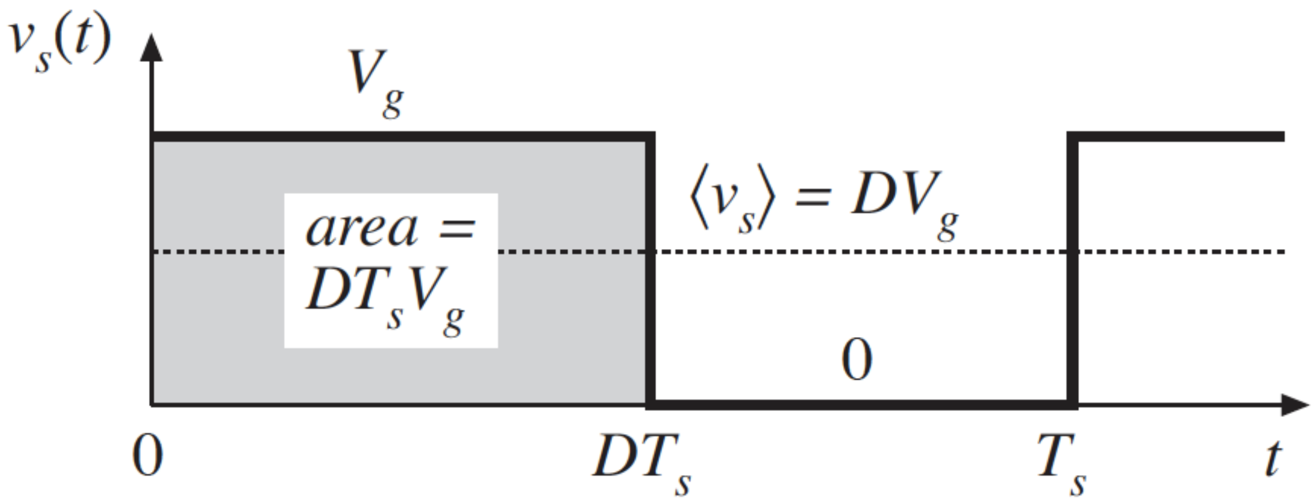
Switch output voltage waveform



Duty cycle *D*:
$0 \le D \le 1$

complement D′:
$D' = 1 - D$

buck converter

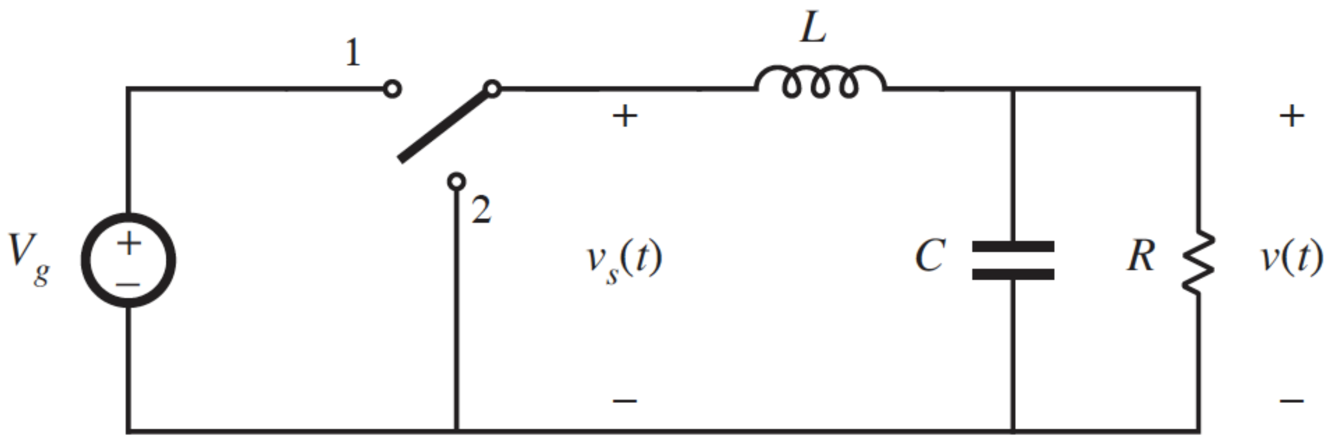


Fourier analysis: Dc component = average value

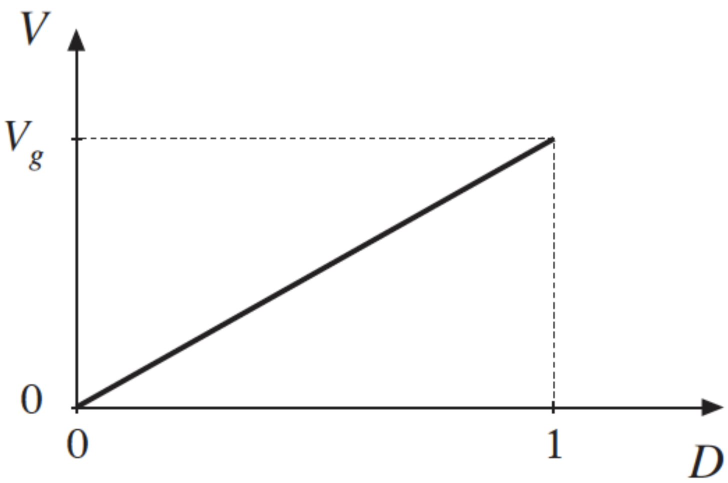
$$\langle v_s \rangle = \frac{1}{T_s}\int_0^{T_s} v_s(t)\, dt$$

$$\langle v_s \rangle = \frac{1}{T_s}(DT_sV_g) = DV_g$$

buck converter



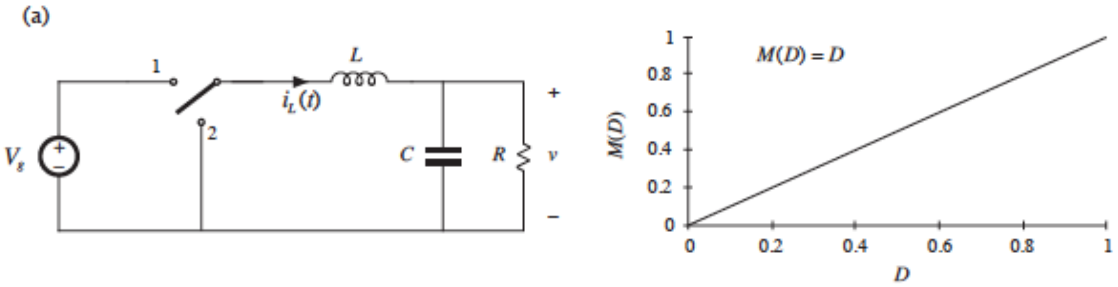
$$v \approx \langle v_s \rangle = DV_g$$



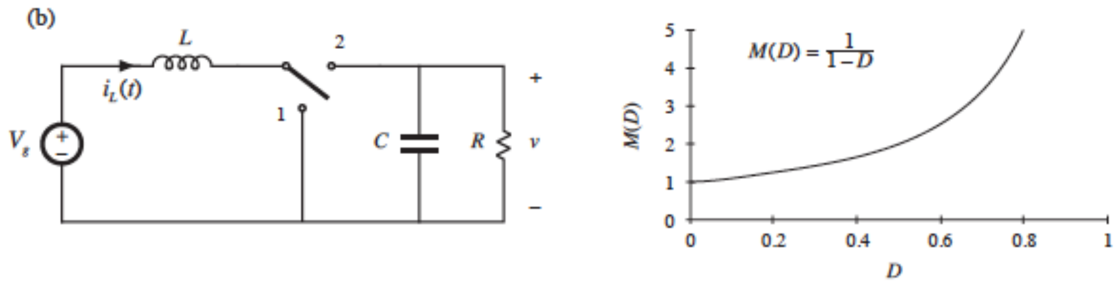
Filtre LC pour éliminer les harmoniques à haute fréquence

Convertisseurs DC/DC

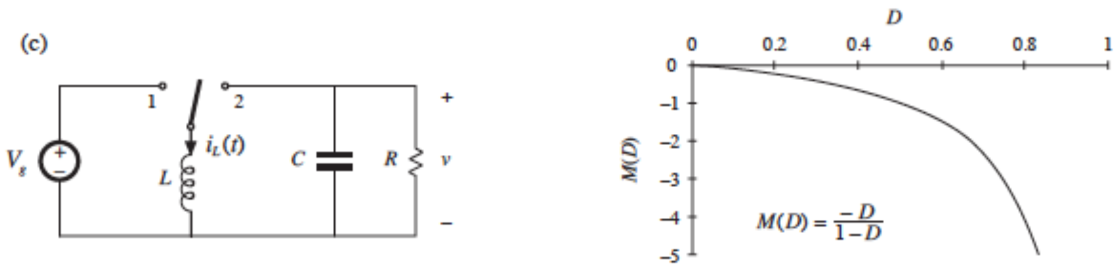
Buck



Boost



Buck-boost



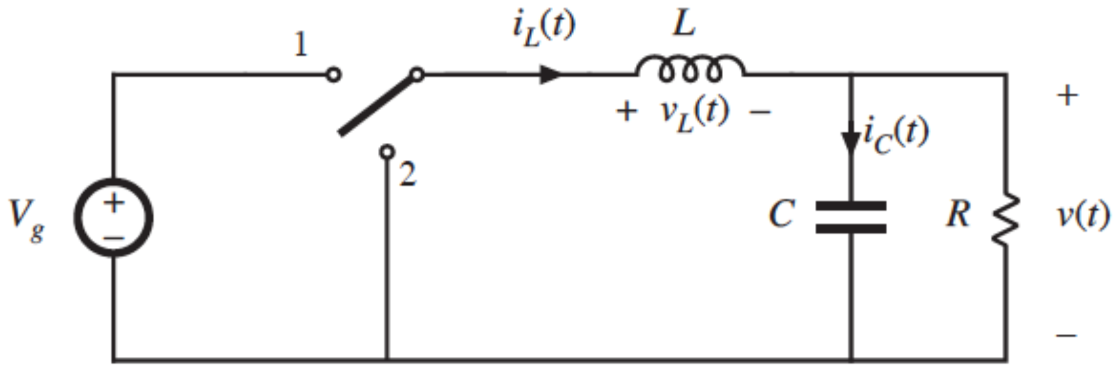
Comment calculer le facteur M(D)?

Introduire les principes de:

- Inductor volt-second balance
- Capacitor charge balance
- Small-ripple approximation

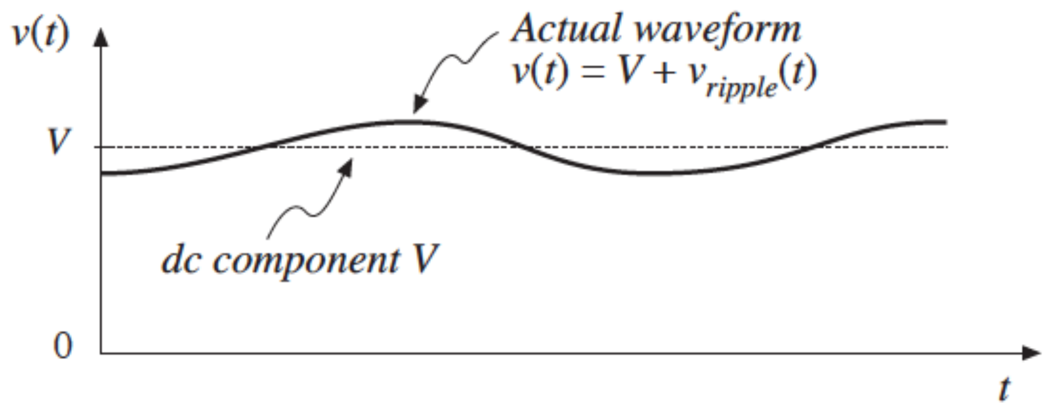
Méthode: volt-second balance et capacitor-charge balance

Buck converter containing practical low-pass filter



Actual output voltage waveform

$$v(t) = V + v_{ripple}(t)$$

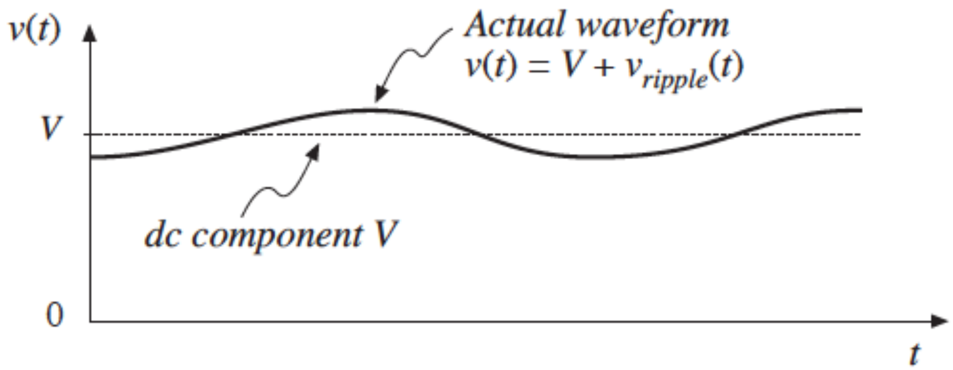


Impossible de construire un filtre passe bas parfait:

- Il y aura toujours des ondulations à la sortie… mais nous les considérons très faibles
- **Approximation de faibles ondulations** (small-ripple approximations)

Approximation de faibles ondulations (small ripple approximation)

$$v(t) = V + v_{ripple}(t)$$



In a well-designed converter, the output voltage ripple is small. Hence, the waveforms can be easily determined by ignoring the ripple:

$$\left\| v_{ripple} \right\| \ll V$$

$$v(t) \approx V$$

- On considère que la composante DC est beaucoup plus grande que l'AC: v(t) ~ V
- Cela élimine la dépendance des variables d'intérêt avec *t*

Approximation de faibles ondulations (small ripple approximation)

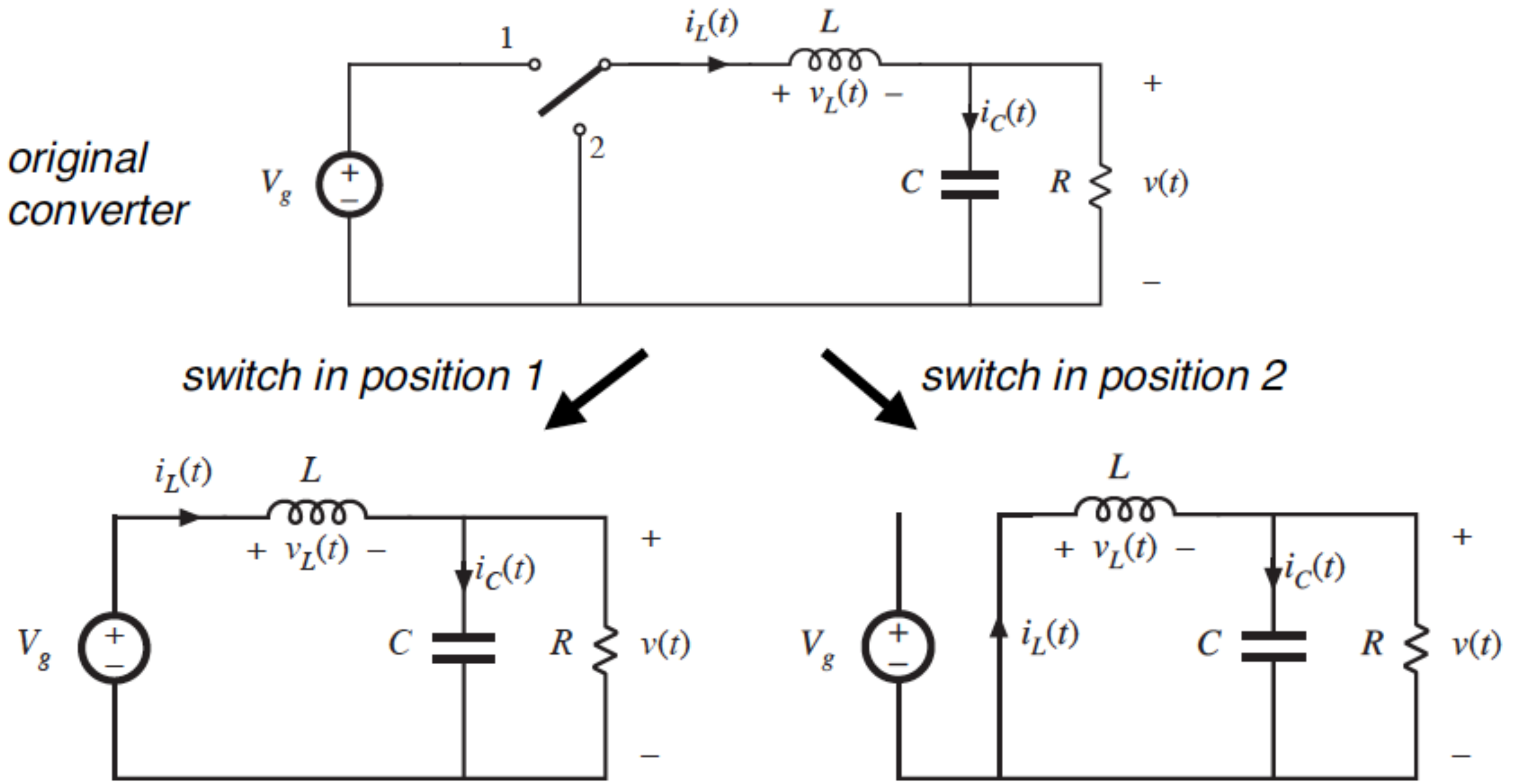
Approximation de **faibles ondulations** (small-ripple approximation) **est valable pour**:

- Des ondulations faibles
- Forme d'ondes continue
- **N'est pas valable pour des signaux discontinus** (provenus des commutations, par exemple v_L)
- Cette approximation est appliquée pour: **courant sur les inducteurs** ou **tension sur les condensateurs**
- La période T_S est petite comparée aux constants de temps du circuit.

Cette approximation simplifie la solution, spécialement sur les filtres:

Il n'y pas besoin de résoudre des équations différentielles

Méthode: volt-second balance et capacitor charge balance
Application: convertisseur "buck"



Méthode: volt-second balance et capacitor charge balance
Application: convertisseur "buck"

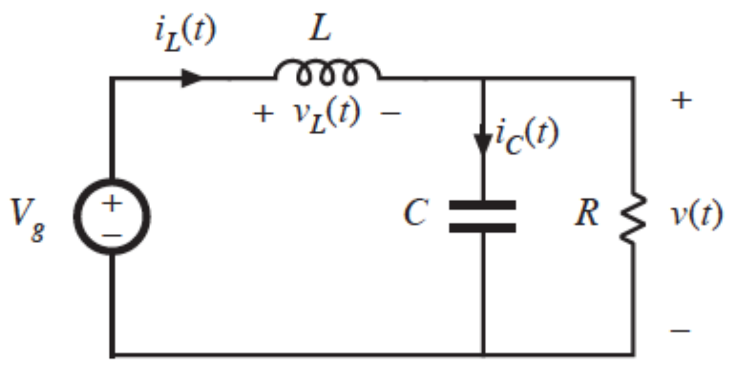
Position 1

Inductor voltage

$$v_L = V_g - v(t)$$

Small ripple approximation:

$$v_L \approx V_g - V$$



Knowing the inductor voltage, we can now find the inductor current via

$$v_L(t) = L\frac{di_L(t)}{dt}$$

Solve for the slope:

$$\frac{di_L(t)}{dt} = \frac{v_L(t)}{L} \approx \frac{V_g - V}{L}$$

$\Rightarrow$ *The inductor current changes with an essentially constant slope*

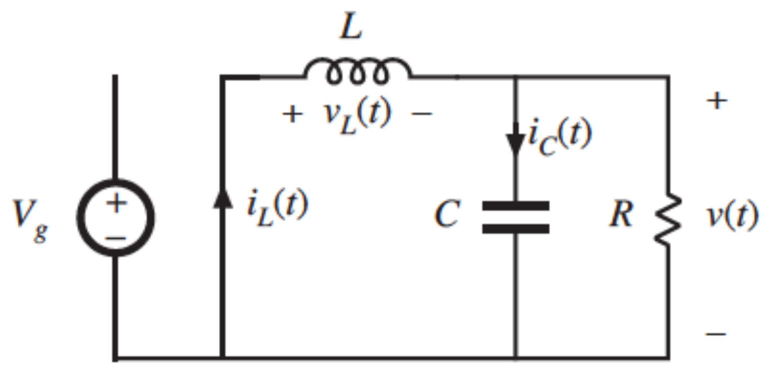
Méthode: volt-second balance et capacitor charge balance
Application: convertisseur "buck"

Position 2

Inductor voltage

$$v_L(t) = -\,v(t)$$

Small ripple approximation:



$$v_L(t) \approx -\,V$$

Knowing the inductor voltage, we can again find the inductor current via

$$v_L(t) = L\,\frac{di_L(t)}{dt}$$

Solve for the slope:

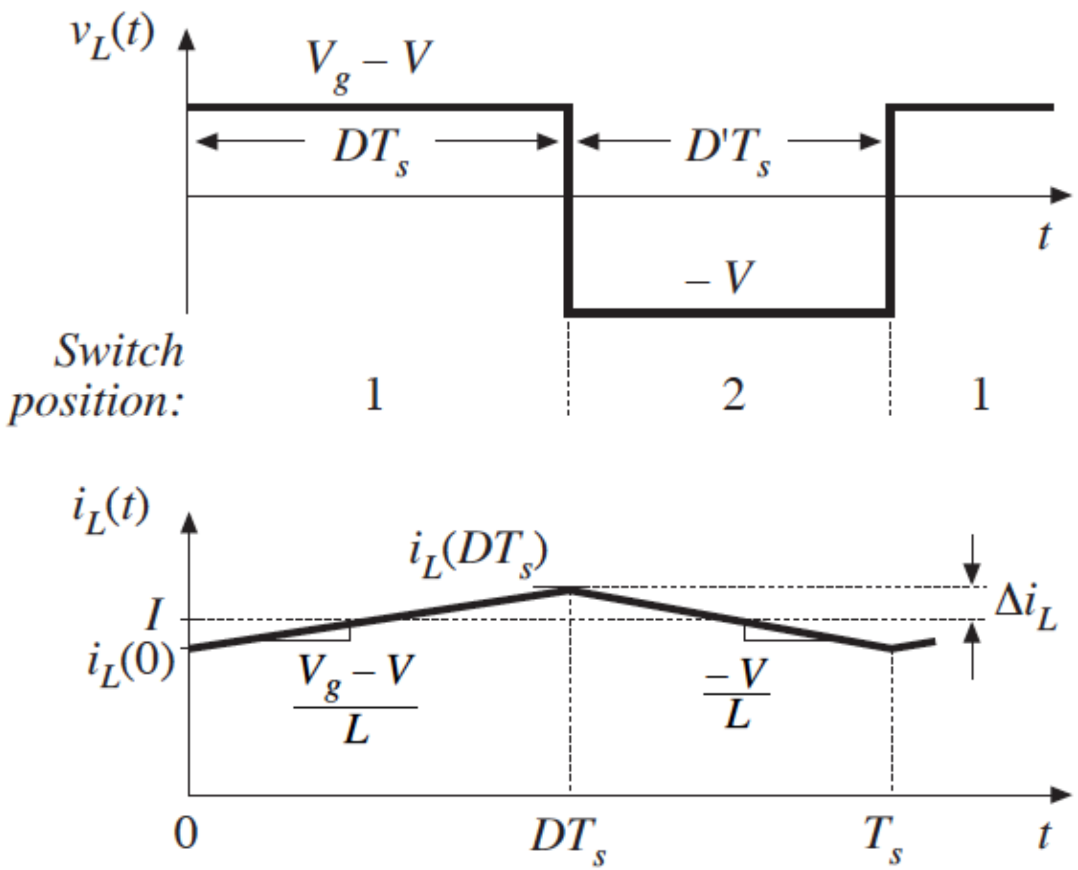
$$\frac{di_L(t)}{dt} \approx -\,\frac{V}{L}$$

$\Rightarrow$ *The inductor current changes with an essentially constant slope*

Negative slope

Méthode: volt-second balance et capacitor charge balance
Application: convertisseur "buck"

Plots de courant et tension

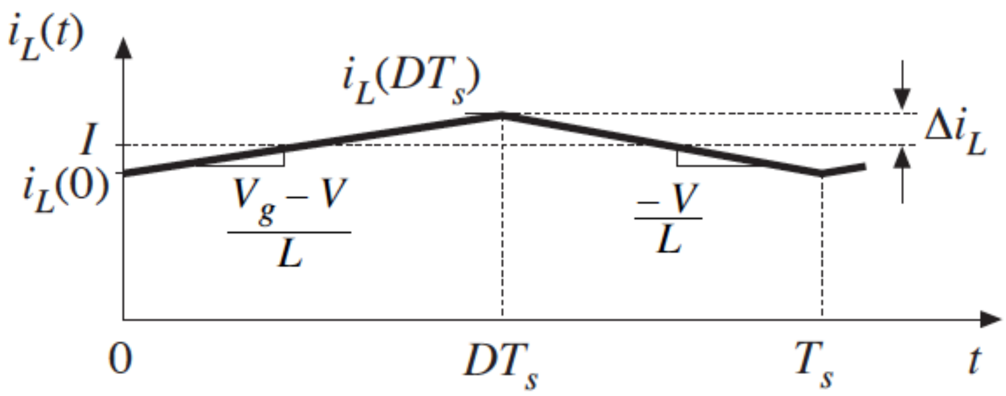


$$v_L(t) = L\,\frac{di_L(t)}{dt}$$

inductor current slope is constant

Méthode: volt-second balance et capacitor charge balance
Application: convertisseur "buck"

Ripple



$$(change\ in\ i_L) = (slope)(length\ of\ subinterval)$$

$$(2\Delta i_L) = \left(\frac{V_g - V}{L}\right)(DT_s)$$

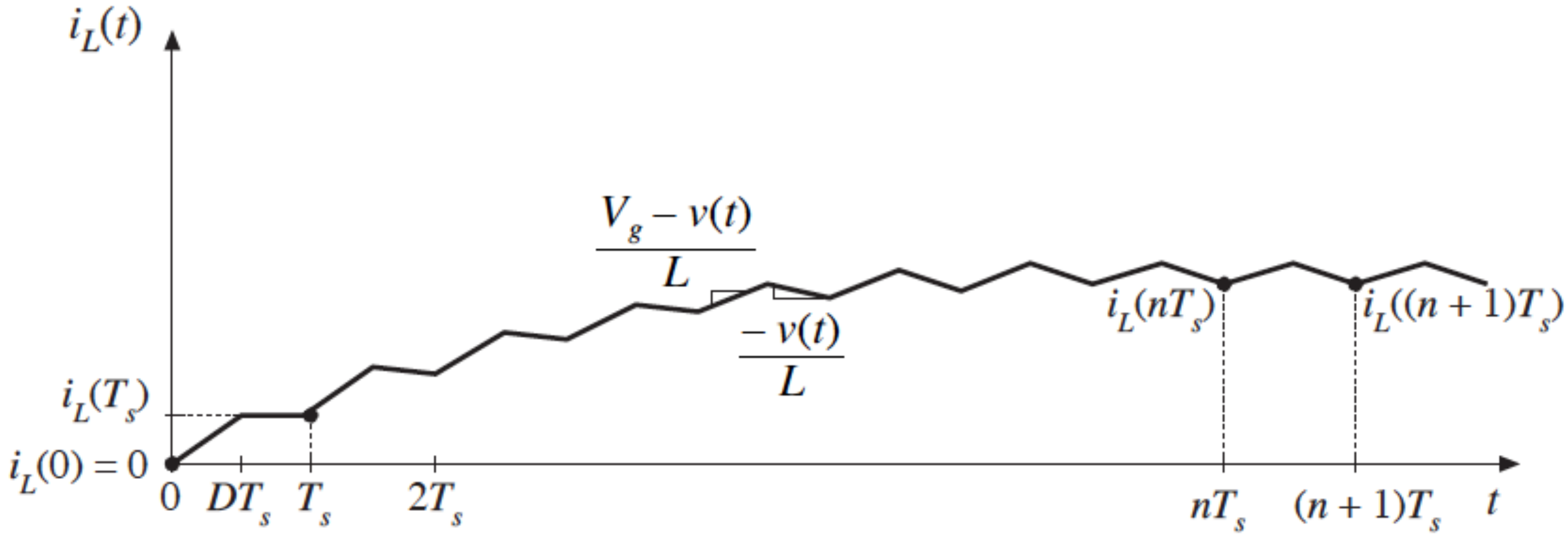
$$\Rightarrow \qquad \Delta i_L = \frac{V_g - V}{2L} DT_s \qquad\qquad L = \frac{V_g - V}{2\Delta i_L} DT_s$$

value of inductance in the buck converter

- Knowledge of the **peak current** is necessary when specifying the ratings of these devices
- Typical values of Δi_L lie in the **range of 10% to 20%** of the full-load value of the dc component I
- It is undesirable to allow Δi_L to become too large:
  - increase the peak currents of the inductor and of the semiconductor switching devices
  - increase the size and cost of the inductors
- The small-ripple approximation $I_L = I$ is usually justified for the inductor current
  - The problem could be solved exactly but results are typically very close to this approximation.

Méthode: volt-second balance et capacitor charge balance
Application: convertisseur "buck"

Régime de transitoire (turn on)



When the converter operates in equilibrium:

$$i_L((n+1)T_s) = i_L(nT_s)$$

Principe "volt-second balance"

Inductor defining relation:

$$v_L(t) = L\,\frac{di_L(t)}{dt}$$

Integrate over one complete switching period:

$$i_L(T_s) - i_L(0) = \frac{1}{L}\int_0^{T_s} v_L(t)\,dt$$

In periodic steady state, the net change in inductor current is zero:

$$0 = \int_0^{T_s} v_L(t)\,dt$$

Hence, the total area (or volt-seconds) under the inductor voltage waveform is zero whenever the converter operates in steady state.

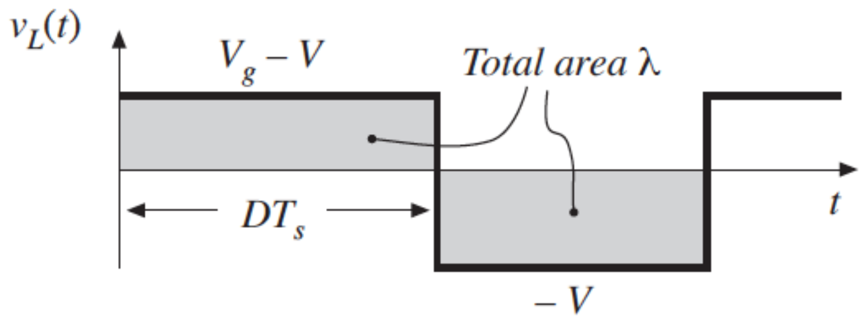
An equivalent form:

$$0 = \frac{1}{T_s}\int_0^{T_s} v_L(t)\,dt = \langle v_L \rangle$$

The average inductor voltage is zero in steady state.

Principe "volt-second balance": convertisseur "buck"

Inductor voltage waveform, previously derived:



Integral of voltage waveform is area of rectangles:

$$\lambda = \int_0^{T_s} v_L(t)\, dt = (V_g - V)(DT_s) + (-V)(D'T_s)$$

Average voltage is

$$\langle v_L \rangle = \frac{\lambda}{T_s} = D(V_g - V) + D'(-V)$$

Equate to zero and solve for *V*:

$$0 = DV_g - (D + D')V = DV_g - V \qquad \Rightarrow \qquad V = DV_g$$

Principe inducteur volt-second balance:

- Nous permet de dériver facilement l'expression DC de la tension de sortie
- Le même résultat, sans utiliser l'argument de transformé de Fourier pour la composante DC
- C'est un principe général pour tous les types de convertisseurs

Principe "capacitor-charge balance": convertisseur "buck"

Capacitor defining relation:

$$i_C(t) = C\,\frac{dv_C(t)}{dt}$$

Integrate over one complete switching period:

$$v_C(T_s) - v_C(0) = \frac{1}{C}\int_0^{T_s} i_C(t)\,dt$$

In periodic steady state, the net change in capacitor voltage is zero:

$$0 = \frac{1}{T_s}\int_0^{T_s} i_C(t)\,dt = \langle i_C \rangle$$

Hence, the total area (or charge) under the capacitor current waveform is zero whenever the converter operates in steady state. The average capacitor current is then zero.

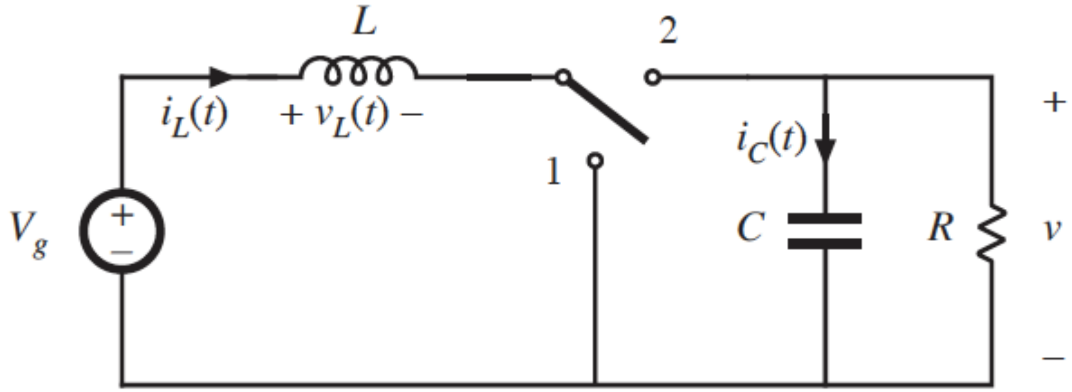
Intuitive result:

- If a dc current is applied to a capacitor:
  then the capacitor will charge continually and its voltage will increase without bound
- if a dc voltage is applied to an inductor:
  then the flux will increase continually and the inductor current will increase without bound

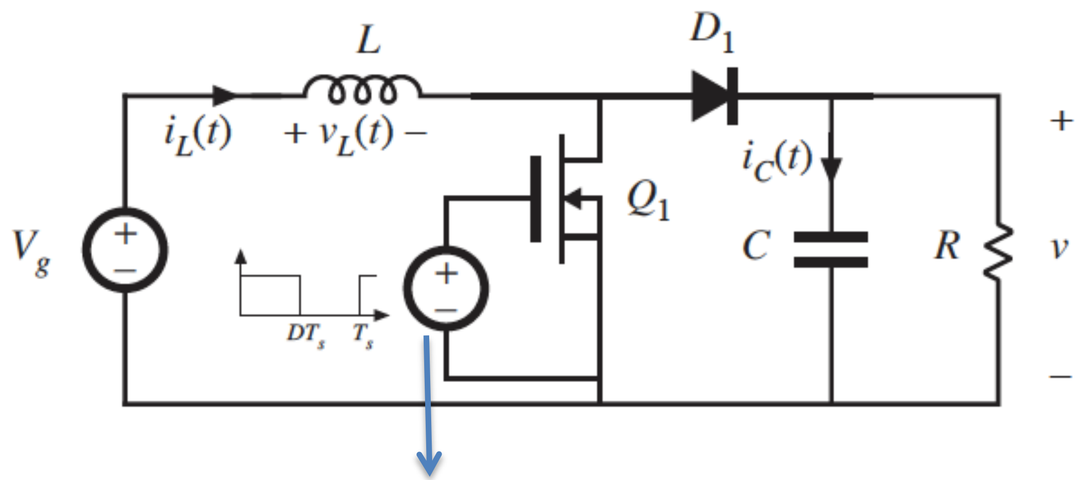
Principle of capacitor charge balance: steady-state currents in a switching converter

Exercise: convertisseur boost

Boost converter with ideal switch

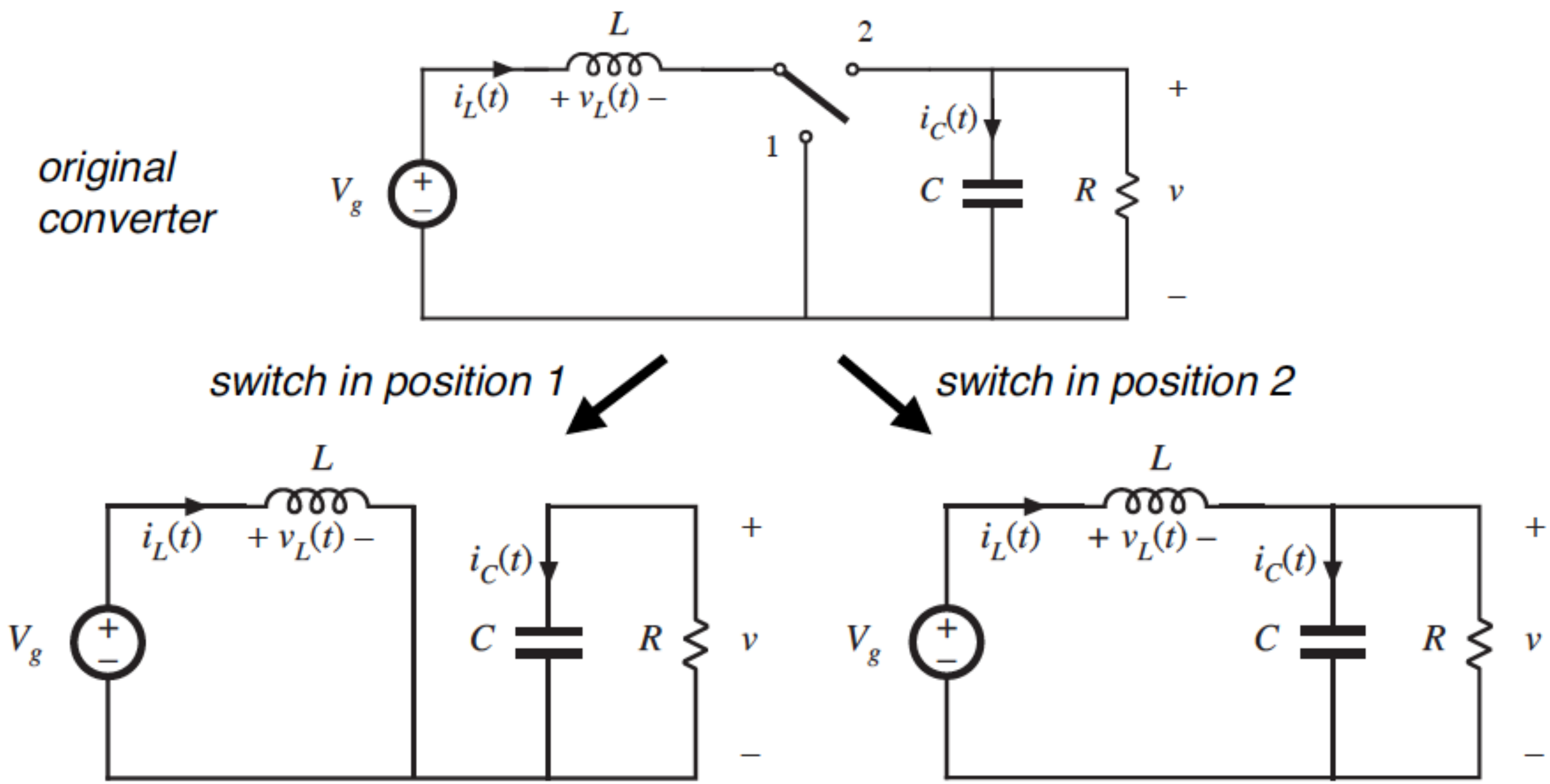


Realization using power MOSFET and diode



Gate driver:
Position1: driver turns on the MOSFET
Position2: driver turns off the MOSFET

Exercise: convertisseur boost



Ecrivez l'orientation des tensions et courants avant de commencer la résolution

Exercise: convertisseur boost

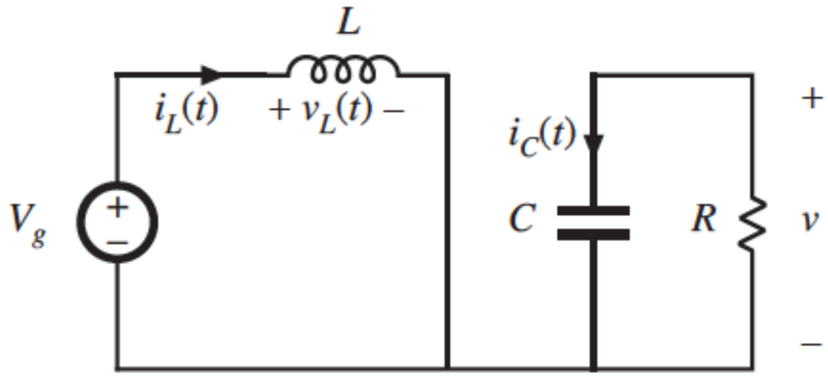
Position 1

Inductor voltage and capacitor current

$$v_L = V_g$$
$$i_C = -v / R$$

Small ripple approximation:

$$v_L = V_g$$
$$i_C = -V / R$$



Exercise: convertisseur boost

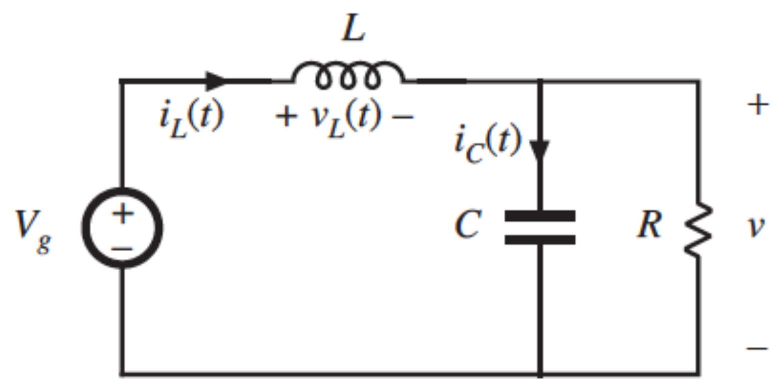
Position 2

Inductor voltage and capacitor current

$$v_L = V_g - v$$
$$i_C = i_L - v / R$$

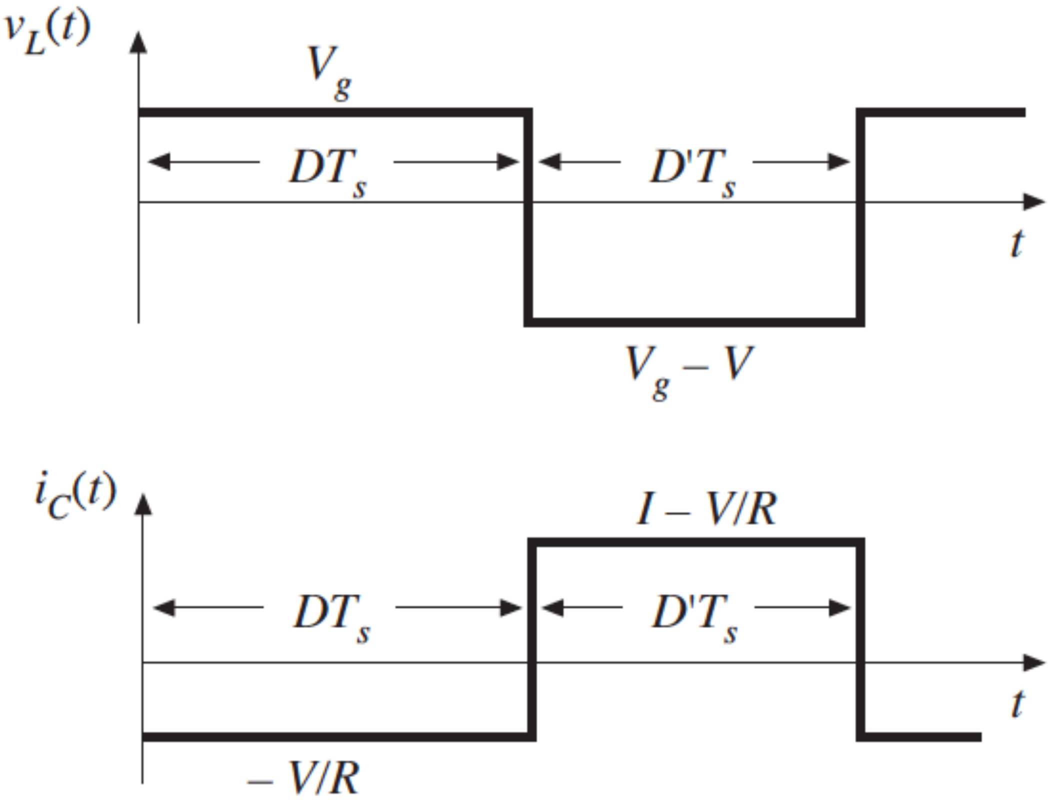
Small ripple approximation:

$$v_L = V_g - V$$
$$i_C = I - V / R$$



Exercise: convertisseur boost

Tension et courant

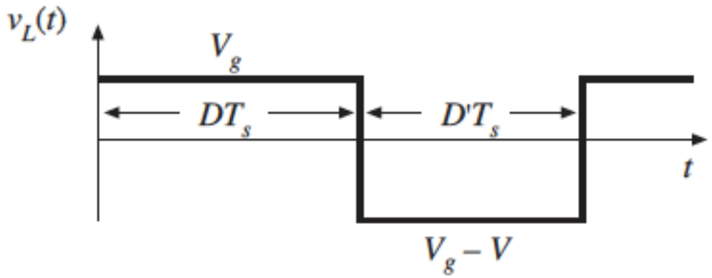


Exercise: convertisseur boost

Calcul de la tension DC de sortie V:

Net volt-seconds applied to inductor over one switching period:

$$\int_0^{T_s} v_L(t)\, dt = (V_g)\, DT_s + (V_g - V)\, D'T_s$$



Equate to zero and collect terms:

$$V_g\,(D + D') - V\,D' = 0$$

Solve for V:

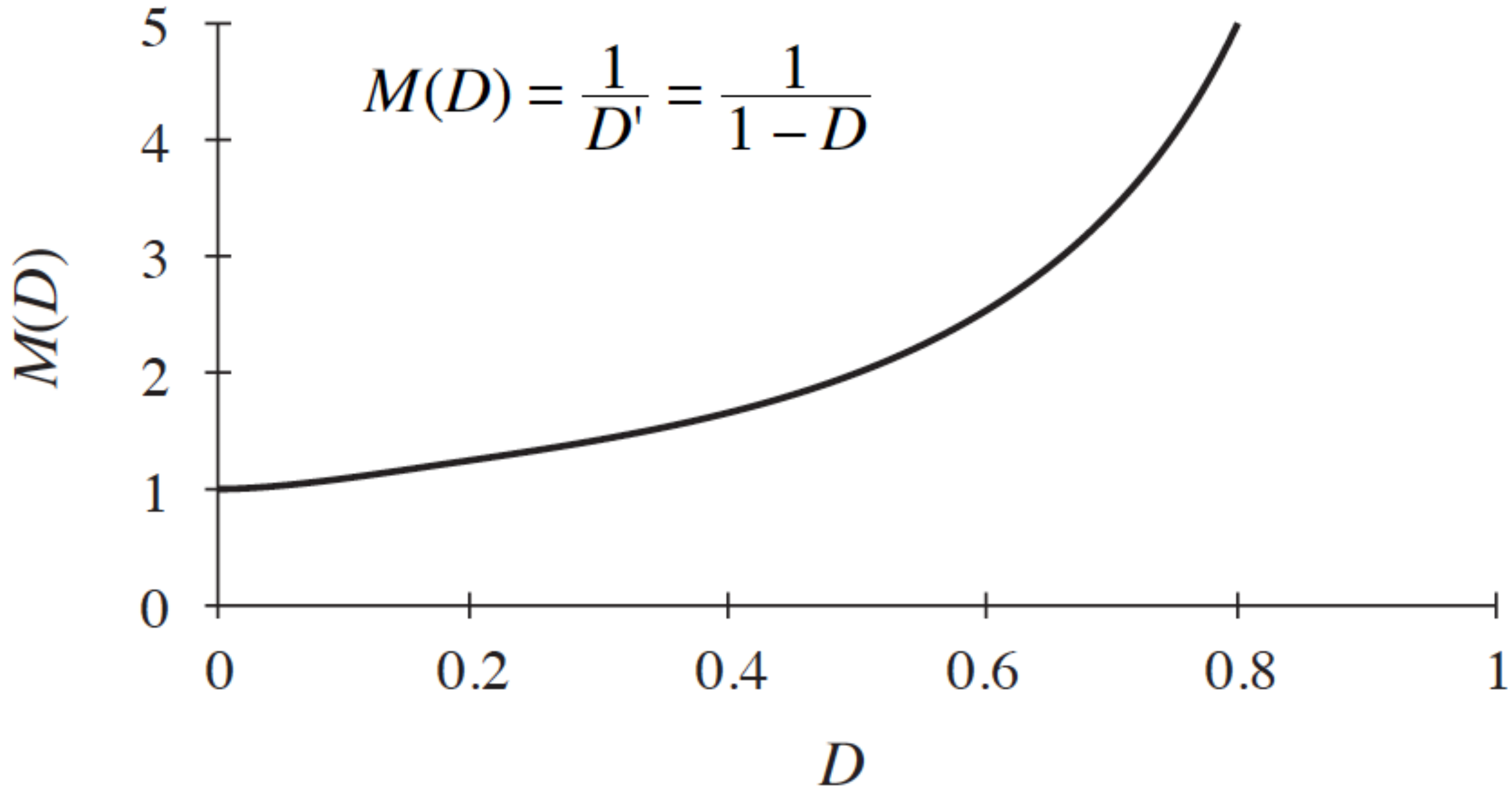
$$V = \frac{V_g}{D'}$$

The voltage conversion ratio is therefore

$$M(D) = \frac{V}{V_g} = \frac{1}{D'} = \frac{1}{1 - D}$$

Exercise: convertisseur boost

Conversion ratio M(D)

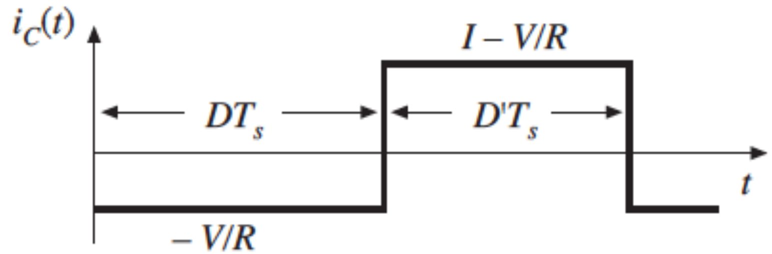


Exercise: convertisseur boost

Calcul du courant DC sur l'inductance L

Capacitor charge balance:

$$\int_0^{T_s} i_C(t)\, dt = \left(-\frac{V}{R}\right) DT_s + \left(I - \frac{V}{R}\right) D'T_s$$



Collect terms and equate to zero:

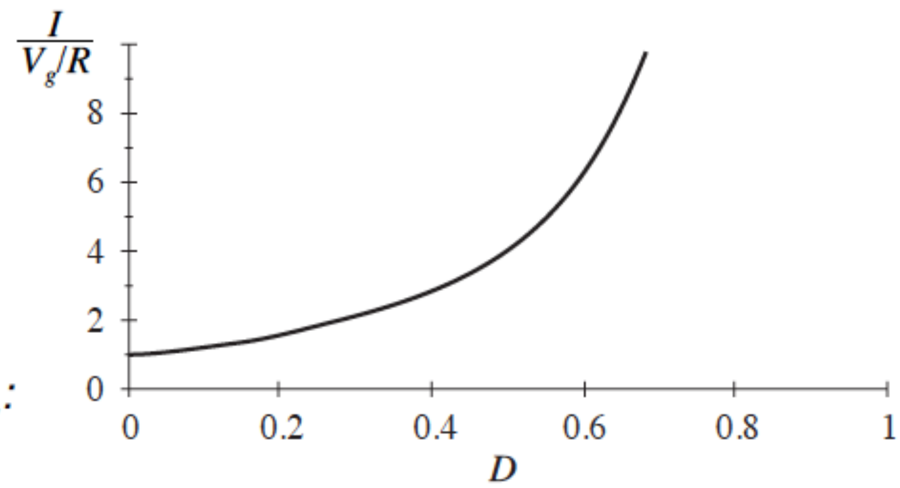
$$-\frac{V}{R}(D + D') + I\, D' = 0$$

Solve for I:

$$I = \frac{V}{D'\, R}$$

Eliminate V to express in terms of V_g:

$$I = \frac{V_g}{D'^2\, R}$$



Exercise: convertisseur boost

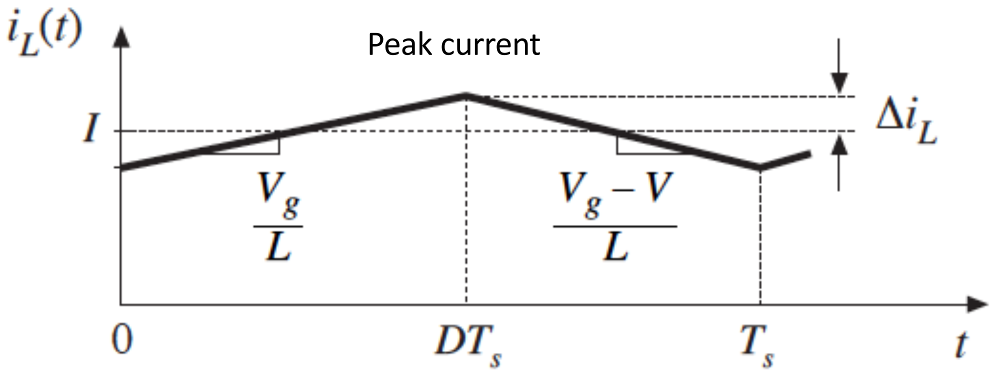
Calcul du courant "ripple" de l'inducteur

Inductor current slope during subinterval 1:

$$\frac{di_L(t)}{dt} = \frac{v_L(t)}{L} = \frac{V_g}{L}$$

Inductor current slope during subinterval 2:

$$\frac{di_L(t)}{dt} = \frac{v_L(t)}{L} = \frac{V_g - V}{L}$$



Change in inductor current during subinterval 1 is *(slope) (length of subinterval):*

$$2\Delta i_L = \frac{V_g}{L} DT_s$$

Solve for peak ripple:

$$\Delta i_L = \frac{V_g}{2L} DT_s$$

- Choose L such that desired ripple magnitude is obtained

Exercise: convertisseur boost

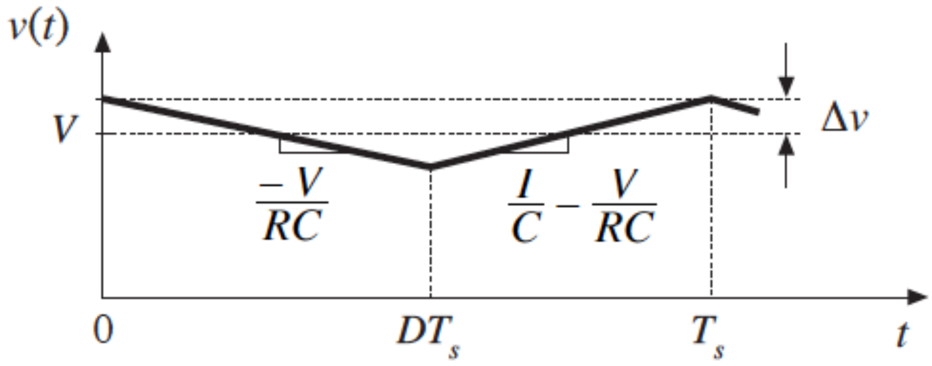
Calcul de la tension "ripple" du condensateur

Capacitor voltage slope during subinterval 1:

$$\frac{dv_C(t)}{dt} = \frac{i_C(t)}{C} = \frac{-V}{RC}$$

Capacitor voltage slope during subinterval 2:

$$\frac{dv_C(t)}{dt} = \frac{i_C(t)}{C} = \frac{I}{C} - \frac{V}{RC}$$



Change in capacitor voltage during subinterval 1 is *(slope) (length of subinterval)*:

$$-2\Delta v = \frac{-V}{RC} DT_s$$

Solve for peak ripple:

$$\Delta v = \frac{V}{2RC} DT_s$$

- Choose C such that desired voltage ripple magnitude is obtained
- In practice, capacitor *equivalent series resistance* (esr) leads to increased voltage ripple