Electromagnetic Energy Conversion ELEC0431

Exercise session 10: Electronic control systems

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Reminders

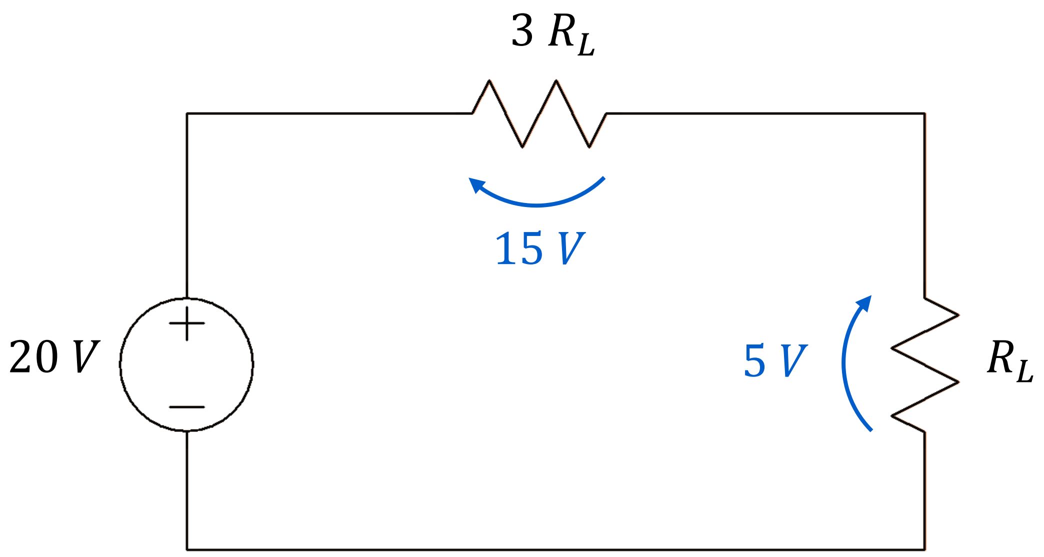
The DC converters

The DC converters – problematic

You want to build a drone. For this, you use DC motors running at 20 V and a 20 V battery. However, the camera and the control part work at 5 V. When the drone is waiting to take off, the control part is in standby and takes only 3 V. How to obtain 5 or 3 V from the 20 V battery to supply the control part?

The DC converters – resistive voltage divider

How to obtain 5 or 3 V from the 20 V battery ?



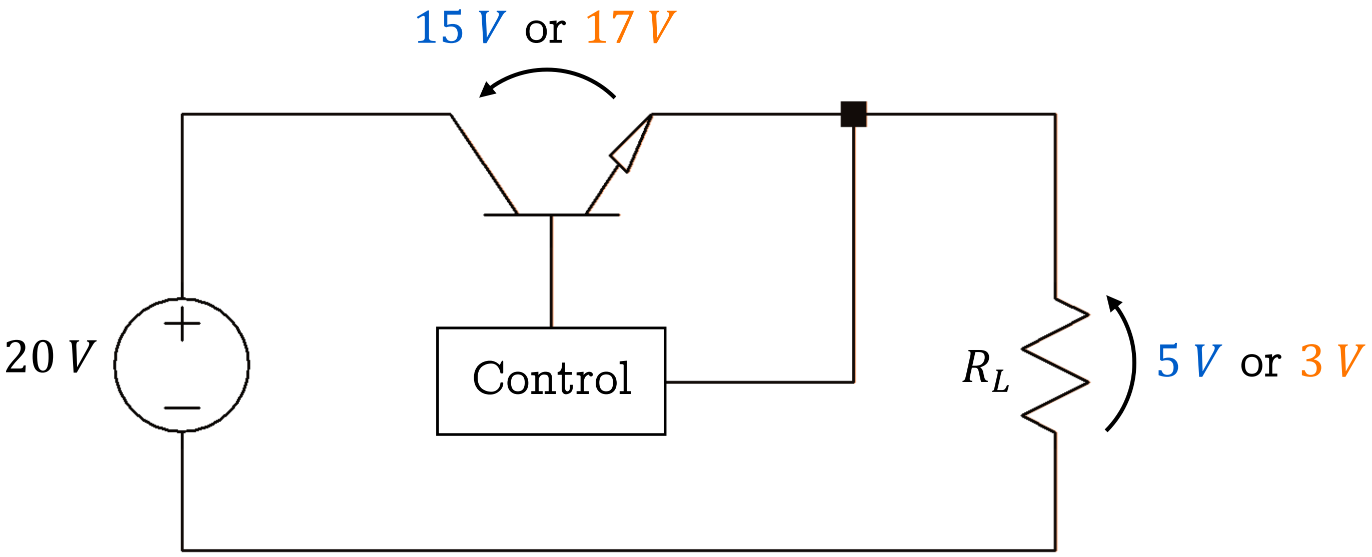
☺ We have the $5\ V$ to power the control part.

☹ No possible to get the $3\ V$.

☹ Huge power losses

The DC converters – series pass regulator

How to obtain 5 or 3 V from the 20 V battery ?



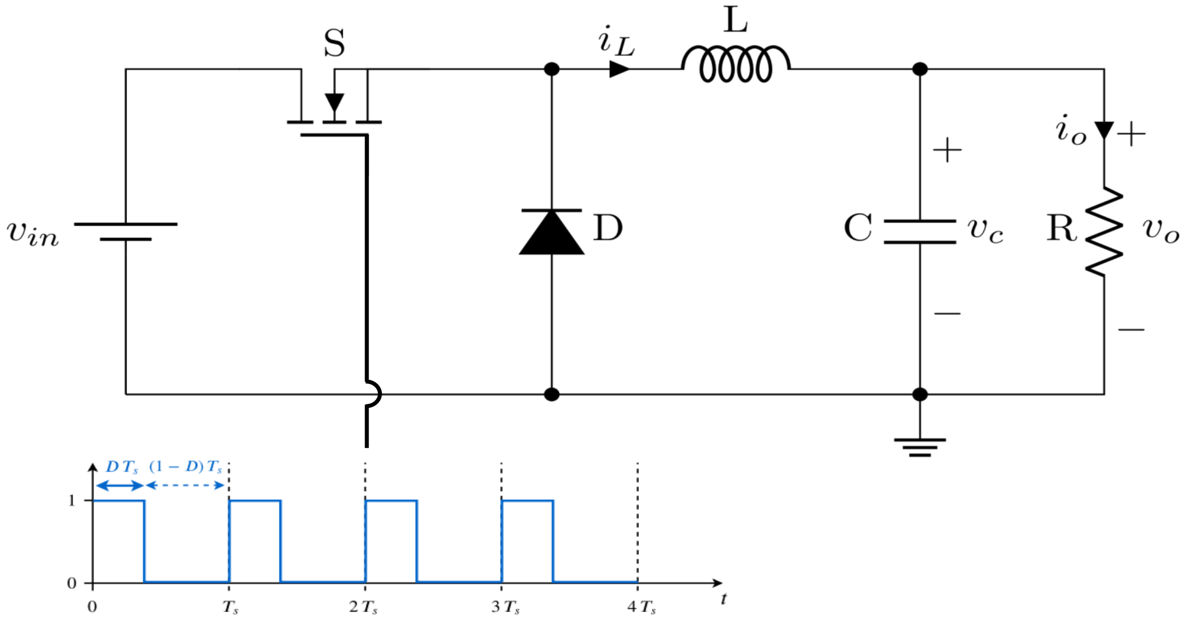
☺ We have the 5 V to power the control part.

☺ Possible to get the 3 V.

☹ Huge power losses

The DC converters – buck converter

How to obtain 5 or 3 V from the 20 V battery ?



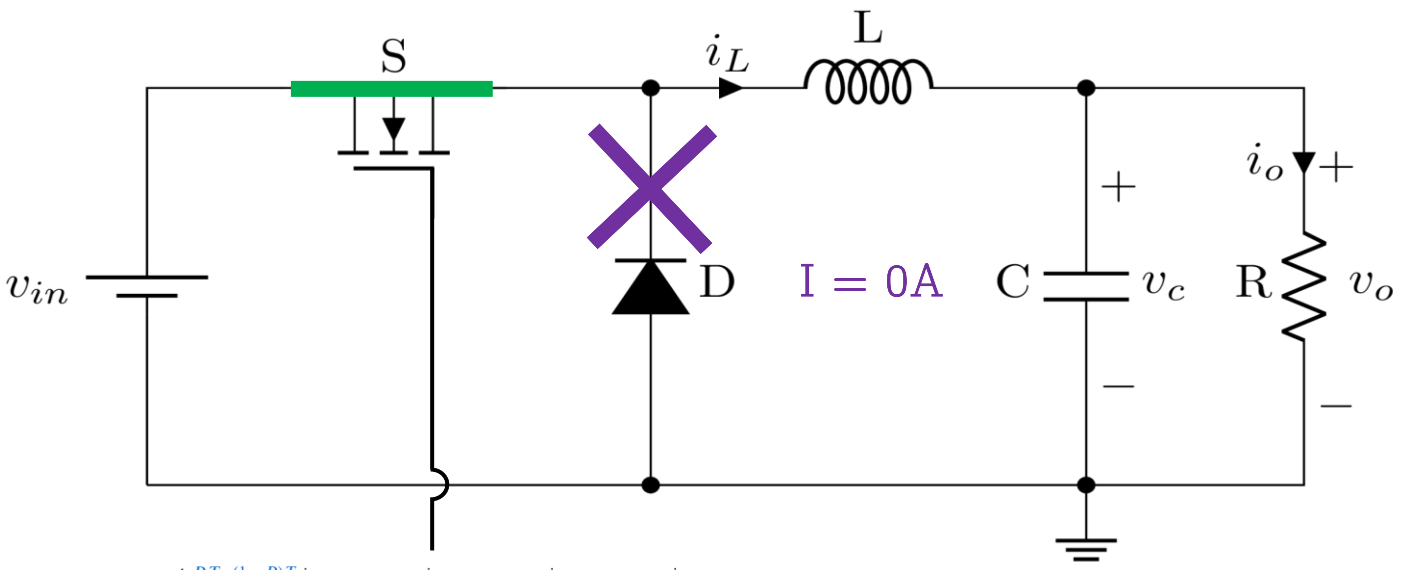
☺ We have the 5 V to power the control part.

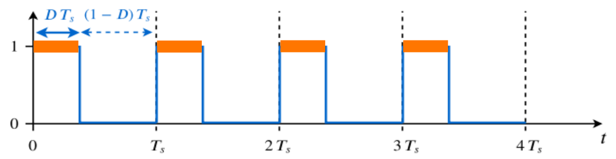
☺ Possible to get the 3 V.

☺ Good efficiency

The DC converters – buck converter analysis

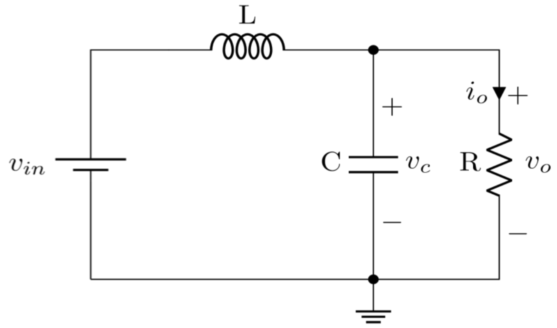
First case: There is a high voltage on the mosfet grid.





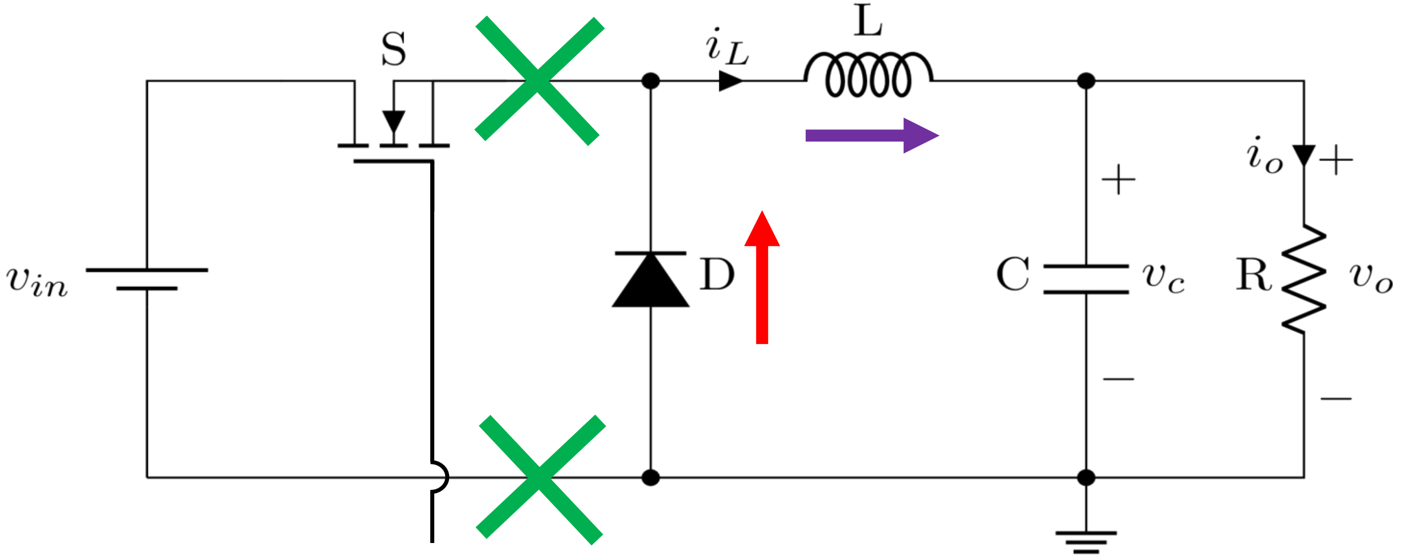
- The mosfet conducts.
- The diode blocks.

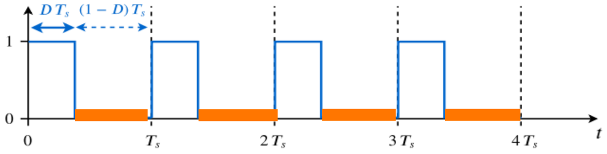
Equivalent circuit



The DC converters – buck converter analysis

Second case: There is a low voltage on the mosfet grid.



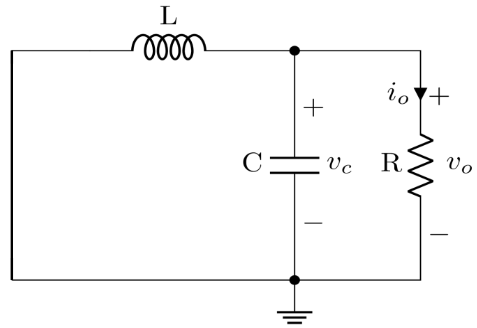


- ➢ The mosfet blocks
- ➔ The battery is disconnected.

- ➢ The Inductance forces current to keep flowing.

- ➢ The diode conducts.

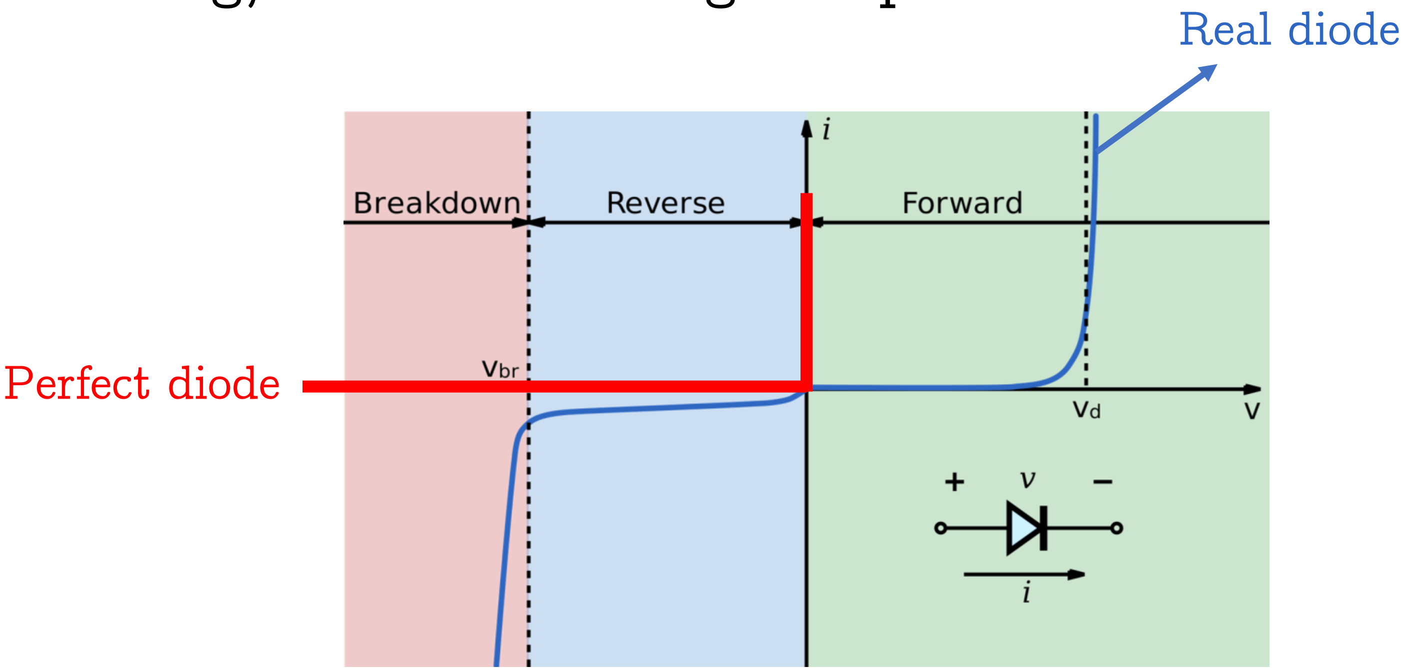
Equivalent circuit



The DC converters – perfect components hypothesis

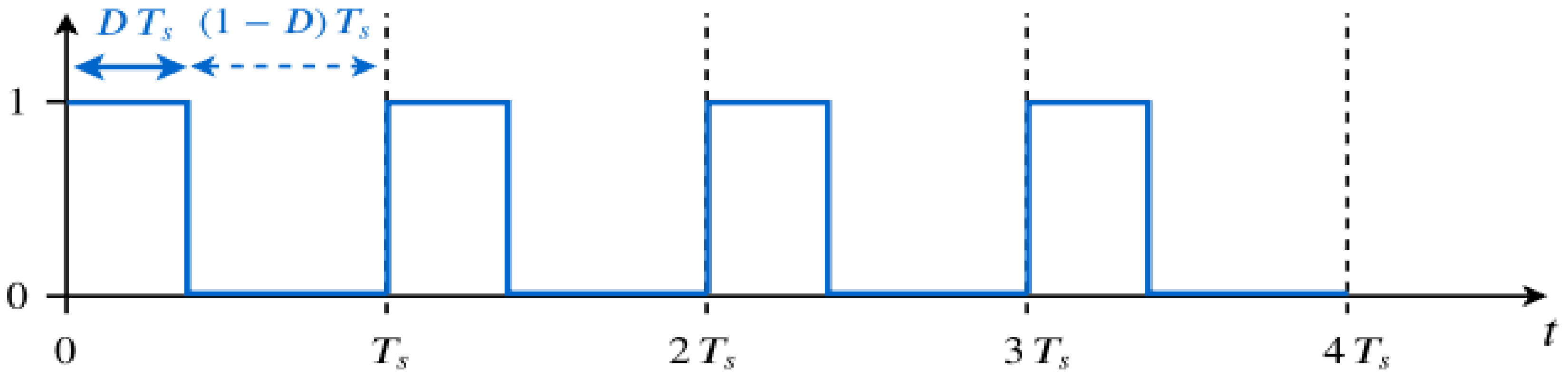
The equivalent circuits are obtained with the assumption that components are perfect (mosfet and diode), which is not the case in practice:

- Mosfets have a resistance.
- When blocking, diodes let pass a small current and, when conducting, there is a voltage drop:



The DC converters – duty cycle

The mosfet is all the time turned OFF and ON again using the control signal:



Each period of time T_s (the switching period) is divided in two:

- During a time $D\,.T_s$, the mosfet conducts.
- During a time $(1 - D).T_s$, the mosfet blocks.

D is the "duty cycle". It is the proportion of time during which the switch is closed. $(0 < D < 1)$

The DC converters – The inductor volt-second balance

Governing equation for inductors:

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

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

In periodic steady state, the net change in the inductor current is zero ➔ $i_L(T_s) = i_L(0)$

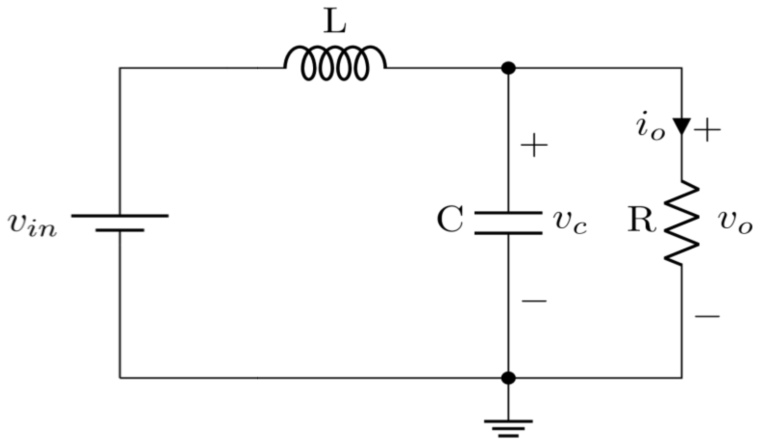
$$\Rightarrow \int_0^{T_s} v_L(t)\,dt$$

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

➔ The average inductor voltage is zero in steady state !

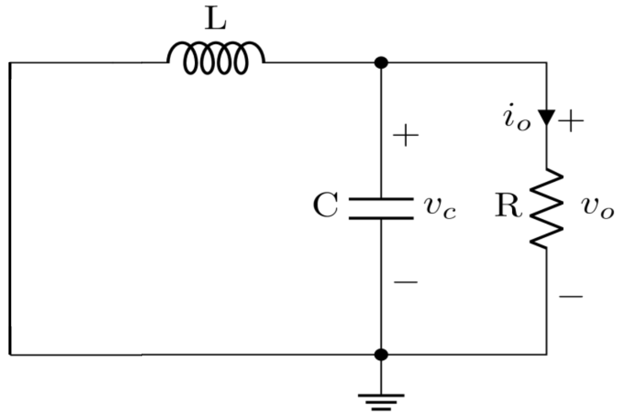
The DC converters – buck converter analysis

During D % of the time:



$$v_{in} = v_L(t) + v_o(t)$$
$$\approx V_L + V_o$$

During (1-D) % of the time:



$$0 = v_L(t) + v_o(t)$$
$$\approx V_L + V_0$$

Volt second balance: ⟨v_L⟩ = 0

➔ $D\ (V_{in}\ -\ V_o) + (1 - D)\ (-V_o) = 0$
➔ $D\ V_{in}\ - D\ V_o\ - V_o + D\ V_o = 0$
➔ $V_o = D\ V_{in}$

Exercises

Exercise 24: Regenerative braking

Exercise 26: DC-DC buck converter

Exercise 27: DC-DC boost converter

Exercise 24: Regenerative braking

Hybrid electric vehicles are generally provided with regenerative braking, allowing to load onboard battery when the vehicle is braking or when the vehicle acts as a driving load. In this exercise, the DC motor, having an electromotive force E and internal resistance $R = 0.5\,\Omega$ is connected (when the regenerative breaking is active) to a battery delivering a current I under the voltage $V = 100\,\text{V}$ using a chopper DC-DC converter (Fig. 64).

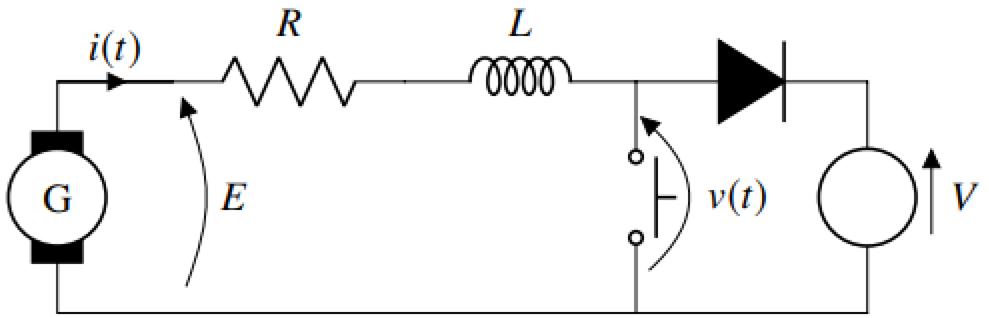
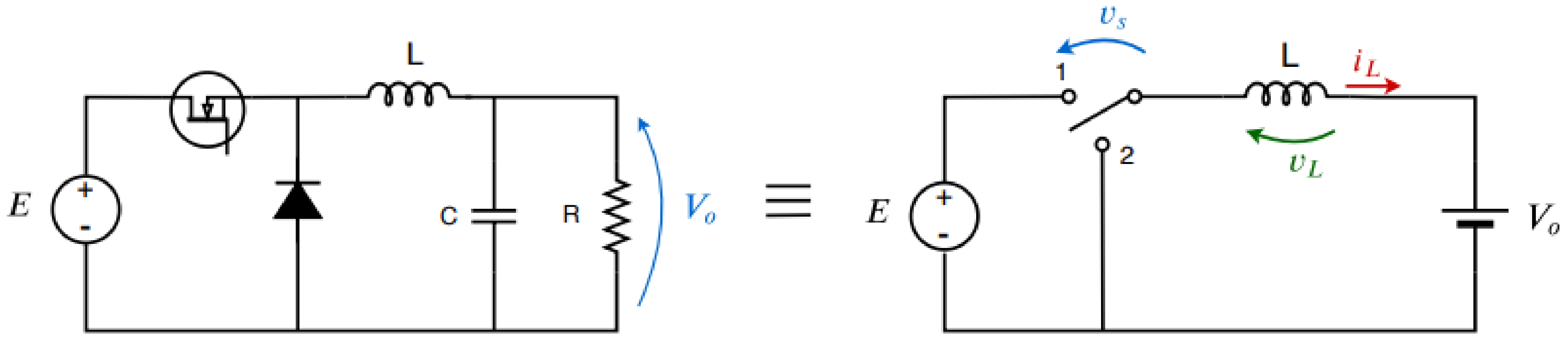


Figure 64: DC-DC converter for regenerative braking.

1. Find the mean value of $v(t)$: V_m;
2. Find the link between the mean input current I_m and the mean output current I;
3. Express the voltage V with respect to I_m, E, R and D, the duty cycle;
4. Compute the duty cycle allowing to obtain $V_m = 60\,\text{V}$;
5. Compute the mean braking current I_m when the motor delivers an electromotive force $E = 70\,\text{V}$ for $V_m = 60\,\text{V}$;
6. Calculate the braking power $E I_m$ and the braking torque C_m if the motor speed of rotation is $\dot{\theta} = 955\,\text{RPM}$.

Exercise 26: DC-DC buck converter

DC-DC converters are used to adapt two different voltage levels. For instance, in particular model of an electric car, the battery voltage is set to $E = 302$ V, whereas the auxiliaries (lights, cigar lighter, window and wiper motors, ...) are working with $V_o = 12$ V. A DC-DC buck converter is used to reduce the battery high voltage to the lower value (12 V) ensuring high efficiency. The DC-DC buck converter can be modelled by the following circuit.



1. Find the waveforms of the voltage across the ideal switch (v_s) and the voltage across the inductance (v_L).

2. Deduce the inductance current waveform from it.

Exercise 26: DC-DC buck converter

Now, suppose that the average voltage across the inductance is 0 during a switching period (corresponding to a steady-state condition).

3. Express the ratio $\frac{V_o}{E}$ in terms of the duty cycle D.

4. Give the value of D in this situation.

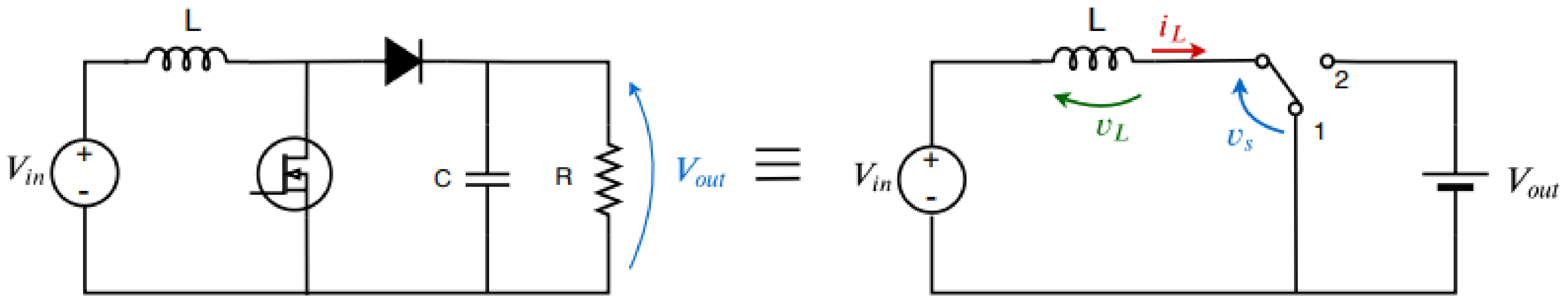
The current ripple Δi is defined as the absolute difference between the maximum of current (during a switching period) and the average current I (over the same switching period).

5. Find the expression of the inductor current ripple Δi_L in terms of V_o, E, D, T_s and L.

6. Estimate the inductor current ripple Δi_L for a switching frequency $f_s = 1000$ Hz and an inductance of 50 mH. Compare the value of the current ripple to the value of the output current if the auxiliaries draw 12 W.

Exercise 27: DC-DC boost converter

DC-DC converters are used to adapt two different voltage levels. In some electronic calculator, the battery voltage is set as V_{in} = 3 V, whereas the electronic parts work under V_{out} = 9 V. A DC-DC boost converter is used to increase the battery low voltage to the higher value (9 V) ensuring high efficiency. The DC-DC boost converter can be modelled by the following circuit.



1. Find the waveforms of the voltage across the ideal switch (v_s) and the voltage across the inductance (v_L).
2. Deduce the inductance current waveform from it.

Exercise 27: DC-DC boost converter

Now, suppose that the average voltage across the inductance is 0 during a switching period (corresponding to a steady-state condition).

3. Express the ratio $\frac{V_{out}}{V_{in}}$ in terms of the duty cycle D.
4. Give the value of D in this situation.

The current ripple Δi is defined as the absolute difference between the maximum of current (during a switching period) and the average current I (over the same switching period).

5. Find the expression of the inductor current ripple Δi_L in terms of V_{out}, V_{in}, D, T_s and L.
6. Estimate the inductor current ripple Δi_L for a switching frequency $f_s = 30$ kHz and an inductance of 75 mH. Compare the value of the current ripple to the value of the output current if the system draws 15 mW.