Chapter 3

Design Methods for Naturally Commutated Static Converters.

1. Input and output sources

1.1. Modeling using current and voltage sources.

A power converter is placed between a generator and a load called “input sources” and “output sources” respectively. The interest of this name will appear when we consider the reversibility of the converter, the output source can then provide power to the input source in certain operating phases (during braking of a motor for example).

The input/output of a converter can be characterized as sources (generators or receivers) of voltage or current, unidirectional or bidirectional in voltage and/or current. Any electric dipole connected to the input or output of a static converter therefore belongs to one of the eight categories represented in Figure 1. The arrows designate the reversibility of the current and the signs (+ -) the reversibility of the voltage.

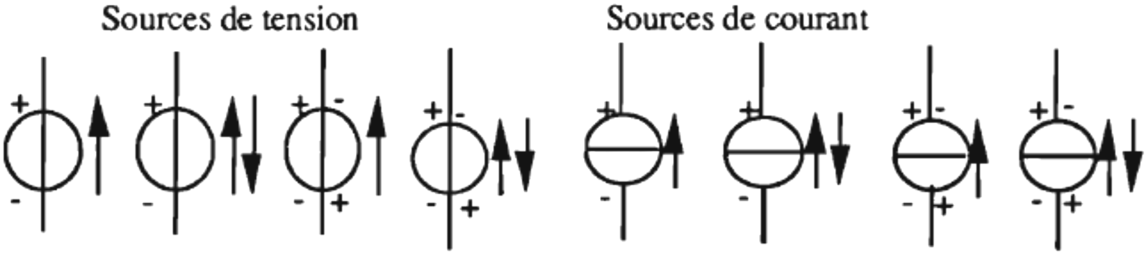


Figure 1. Sources Reversibility.

1.1.1. Reversibility of input and output sources

Determining the reversibility of the input and output sources is fundamental because it allows the static characteristics of the switches to be deduced. A source is said to be voltage reversible if the voltage across its terminals can change sign. A source is said to be current reversible if the current passing through it can be reversed.

Examples:

- The armature circuit of a direct current machine is equivalent to a current source because of the inductance due to the windings. If we have speed inversion and electric braking (armature current inversion), the source will be reversible in voltage and current.

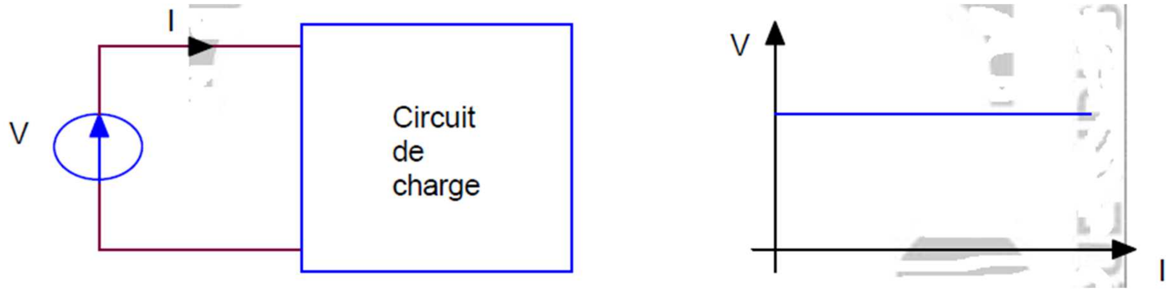
- A battery is a voltage source that is non-reversible in voltage and reversible in current (charging and discharging).

In electronics, we encounter “classic” voltage and current sources whose ideal characteristics are recalled.

1.2.Voltage and current sources

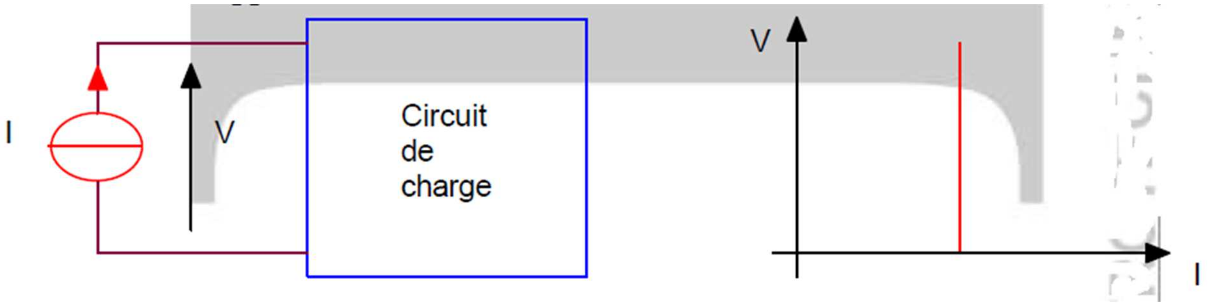
1.2.1. Perfect voltage source

A perfect voltage source is an active dipole which has at its terminals a voltage U independent of the current supplied.



1.2.2. Perfect current source

A perfect current source is an active dipole delivering an electric current I independent of the voltage V appearing at its terminals.



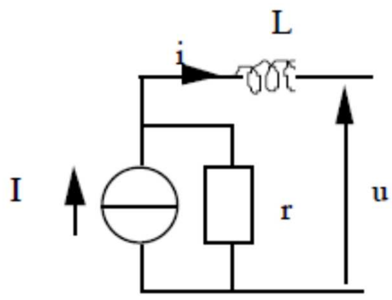
1.3.Improved sources

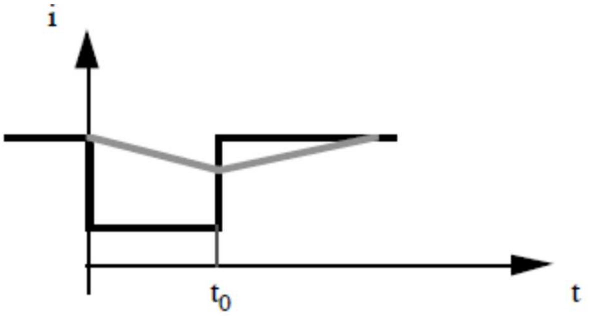
This involves improving sources by ensuring that accidental over-voltages or over-currents are mitigated.

1.3.1. Improvement of a real current source

Let us imagine the case of a real current source at the terminals of which an overvoltage Δu appears between 0 and t0.

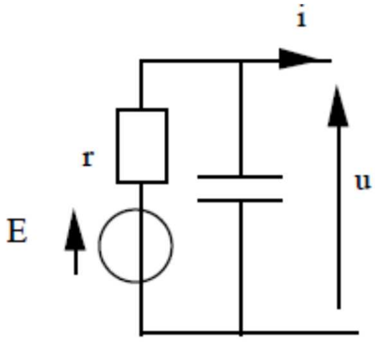
Without the coil, this produces a proportional jump in the intensity delivered by the source. The coil makes it possible to reduce the ripple of the current: this comes from the property of continuity of the current passing through this component. Also, the larger the inductance, the lower the ripple.

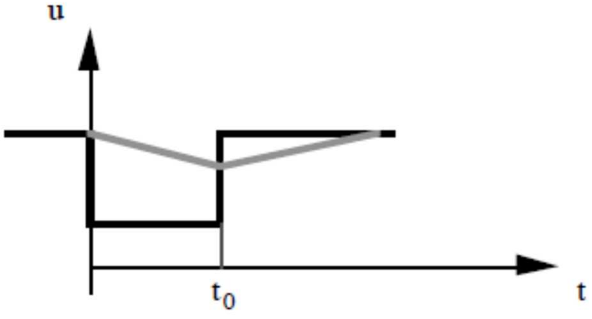




1.3.2. Improvement of a real voltage source

Analogously, we will place a capacitor in parallel on a voltage source in order to minimize the voltage ripple that can appear under the effect of an overcurrent. In this case we use the property of continuity of the charge and therefore of the voltage across a capacitor.

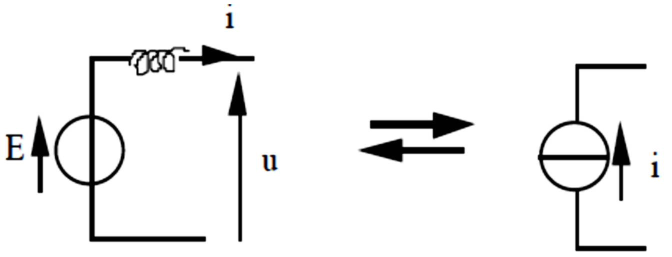




1.4. Change in nature of sources in the presence of switching

- A voltage source sees its nature modified if it is placed in series with a coil: in the presence of switching, the whole is equivalent to a current source. Indeed, we know that a coil opposes rapid variations in the current flowing through it. Here we have:

$$L\frac{di}{dt} = -u + E \text{ d'où } \frac{di}{dt} = \frac{1}{L}(E - u)$$

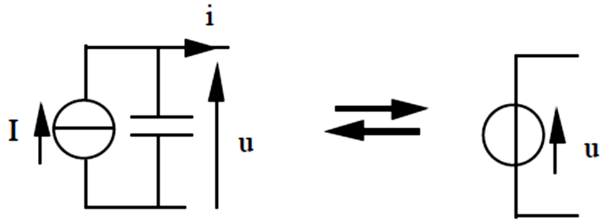


If L is large enough, the variations of i with u are small, which therefore corresponds to the definition we have given of a current source.

- A current source sees its nature modified if it is placed in parallel on a capacitor: in the presence of switching, the whole is equivalent to a voltage source.

Indeed, we know that a capacitor opposes rapid variations in the voltage at its terminals. Here we have:

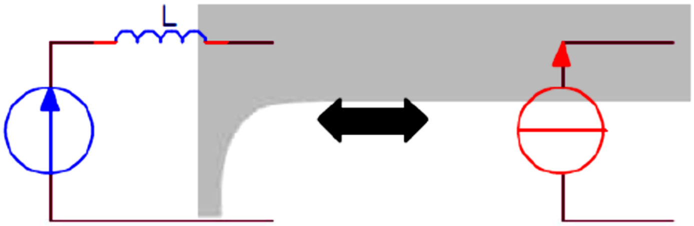
$$\frac{du}{dt} = \frac{1}{C}(I - i)$$



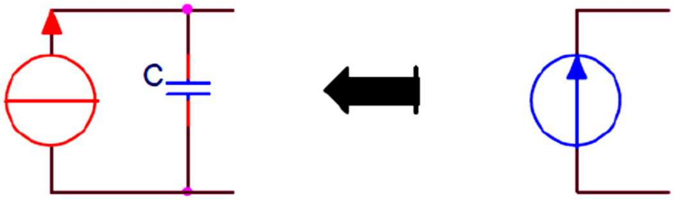
If C is large enough, the variations of u with i are small, which therefore corresponds to the definition we gave of a voltage source.

Reminder

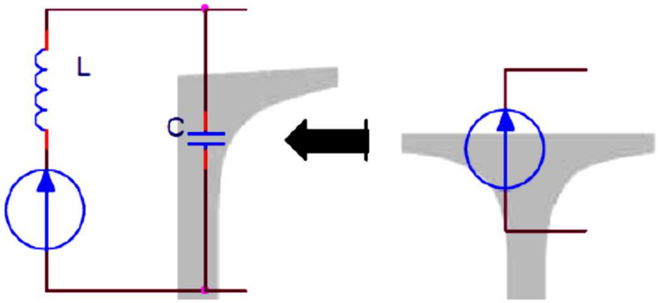
Une source de tension en série avec une inductance est équivalente à une source de courant.



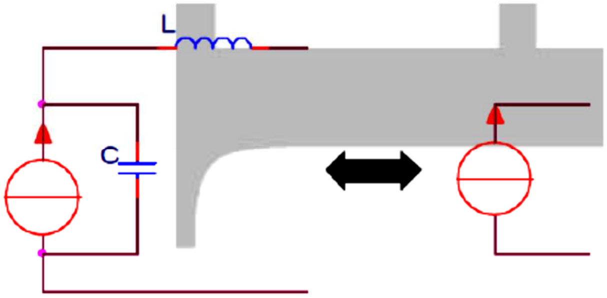
Une source de courant en parallèle avec un condensateur est équivalent à une source de tension.



Pour affirmer une source de tension, on disposera d'un condensateur en parallèle.



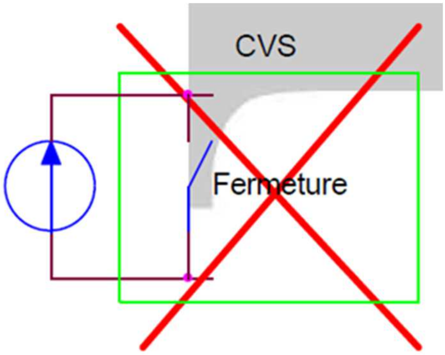
Pour affirmer une source de courant, on disposera d'une inductance en série.



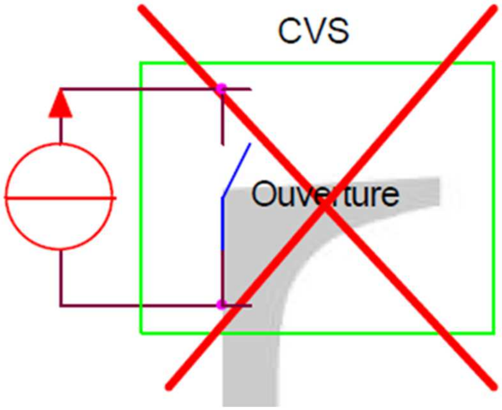
N.B : En électronique de puissance, il faudra être vigilant au câblage qui introduit des inductances parasites. La présence d'inductances parasites conduit à ajouter un condensateur en parallèle avec la source de tension.

2. Source interconnection rules

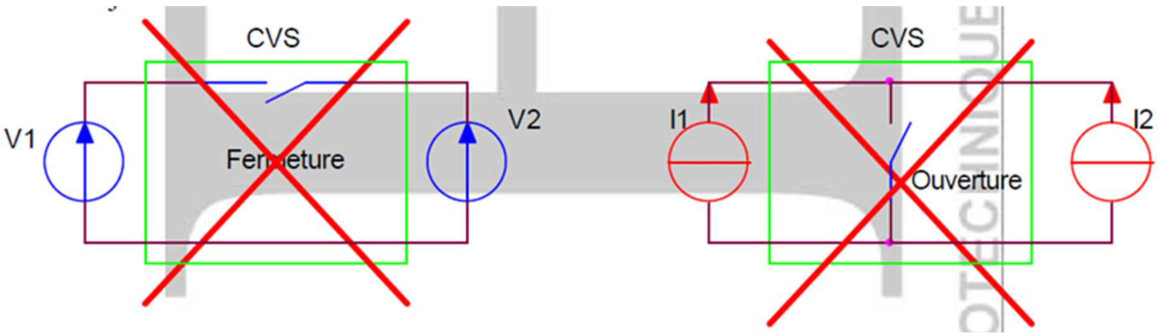
Rule Nr. 1: A voltage source must never be short-circuited but it can be opened. Otherwise the current would be destructive



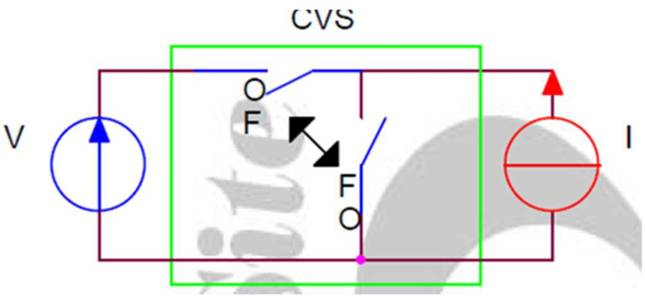
Rule Nr. 2: The circuit of a current source must never be open but it can be short-circuited. Otherwise opening causes an overvoltage.



Rule Nr. 3: You should never (and must not) interconnect two sources of the same nature. For two voltage sources: The voltage at their terminals would then become very high and this would lead to destruction. For two current sources: The current exchanged would then become very large and this would lead to destruction.



Rule Nr. 4: You can only connect between a current source and a voltage source. The two switches must be strictly complementary.



Conclusion

- If the static converter only has switches, then you must connect sources of different types.

- The smallest converter has at least two switches.

- The operation of these two switches must be strictly complementary.

- We can then speak of an elementary switching cell.

3. Structure of static converters

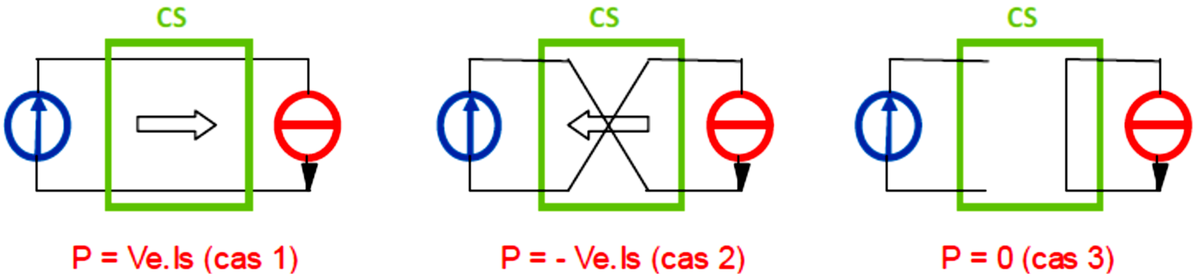
The structures of the converters follow logically from the nature of the generators and the receivers associated with them. They also depend on the desired energy reversibility and the mode of adjustment of these energy transfers. A conversion of electrical energy can be carried out by one or more structures. With one or more intermediate conversion stages. When this conversion is done without an intermediate stage capable of temporarily storing energy. This conversion is called direct and it is carried out by a direct converter. On the contrary, when this conversion is carried out with one or more stages capable of temporarily storing energy. This conversion is called indirect and it is carried out by an indirect converter.

3.1.Structure of direct static converters

In such a converter. The energy transfer takes place directly between the input and output and. If the losses in the converter are neglected, the power at the input of the converter is at all times equal to the power at its output. Under these conditions, if the input source of a direct converter is a voltage source (respectively current), the output of the converter behaves like a voltage source (respectively current) and can only be closed on a current source (respectively voltage). The input (respectively the output) of a direct converter is of the same nature as the output source (respectively the input source) as it is shown in the figure below:

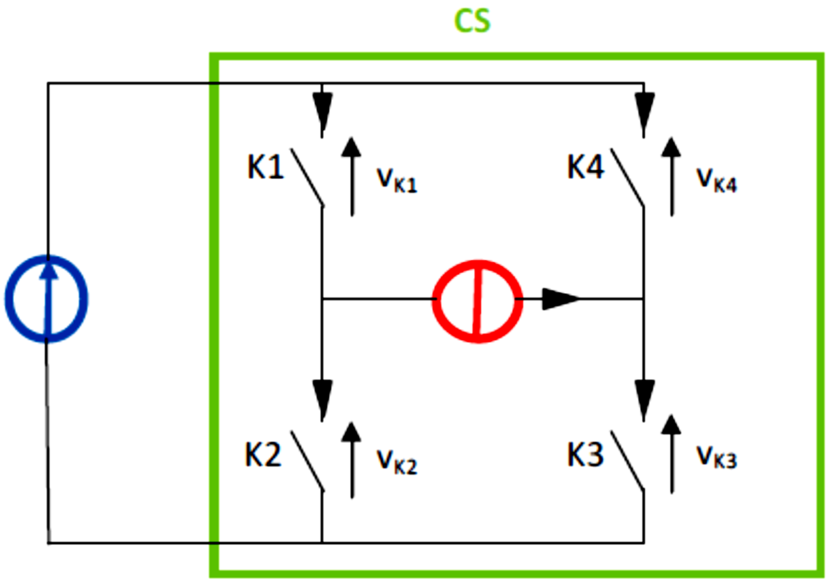
3.1.1. Direct voltage-current converter

We consider a conversion associating a voltage source with a current source. There are three types of possible connections between these two sources:



Note that these three types of interconnections are necessary to allow all energy exchanges and adjustments between the voltage source and the current source.

The most flexible solution is to use an assembly made up of 4 switches:



- When K1 and K3 are closed, we find case no. 1.

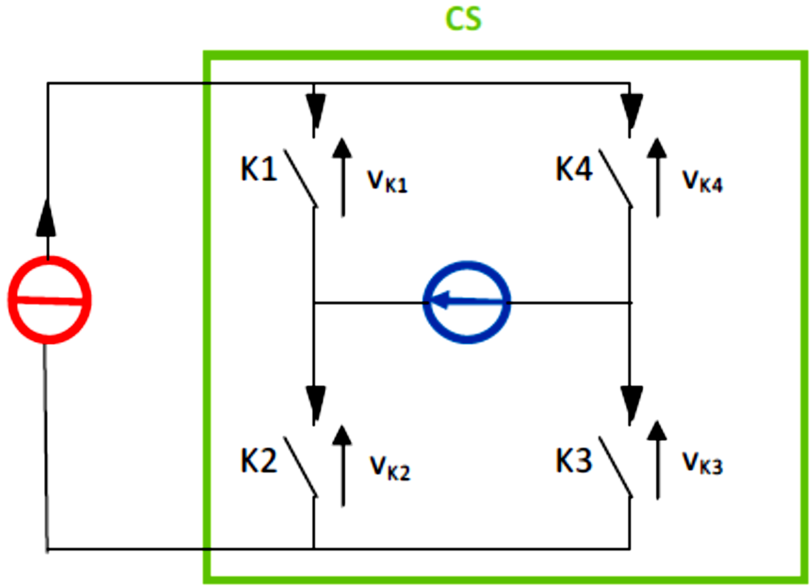
- When K2 and K4 are closed, we find case no. 2.

- When K1 and K4 are closed or K2 and K3 are closed, we find case no. 3.

This basic structure is found in choppers and partly in inverters.

3.1.2. Direct current-voltage converter

This type of converter corresponds to the rectifier or current switch assembly according to the authors. We find the same structure as for the direct voltage-current converter. It is usual in a rectifier assembly to arrange the current source at the output and the voltage source at the input.



3.2.Indirect static converters

An indirect converter is generally made up of a combination of direct converters and reactive elements (inductors and capacitors).

Indirect energy conversion is mainly used when the two sources to be interconnected by the converter are of the same nature.

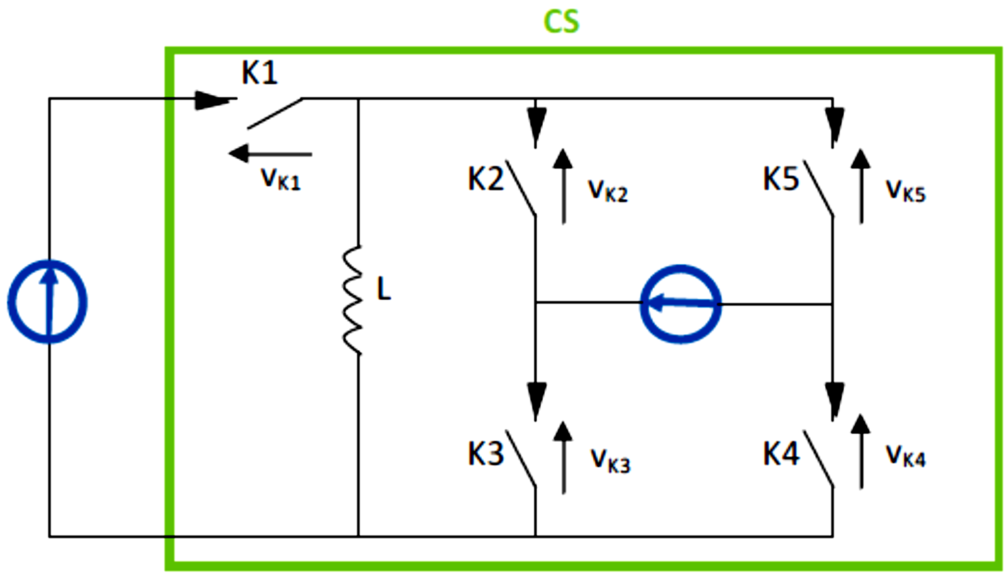
An intermediate stage (buffer stage) of a nature different from that of the sources present is essential. This buffer stage is a current source if the transfer of energy must take place between two voltage sources (Indirect voltage-voltage converter) or a voltage source if the transfer must take place between two current sources (Indirect current converter -fluent).

3.2.1. Indirect voltage-voltage converter

We cannot connect two sources of the same nature to each other, we must therefore convert one of the sources into a current source or use an inductive storage element which provides a dynamic current source as shown in the figure below . In this type of converter, the two voltage sources are never connected simultaneously to the storage element but successively.

- The inductor stores the energy supplied by the voltage source (K1 ON, K2 K3 K4 K5 OFF)

- The inductor returns its energy to the other voltage source (K1 OFF, K2 K4 ON or K3 K5 ON).

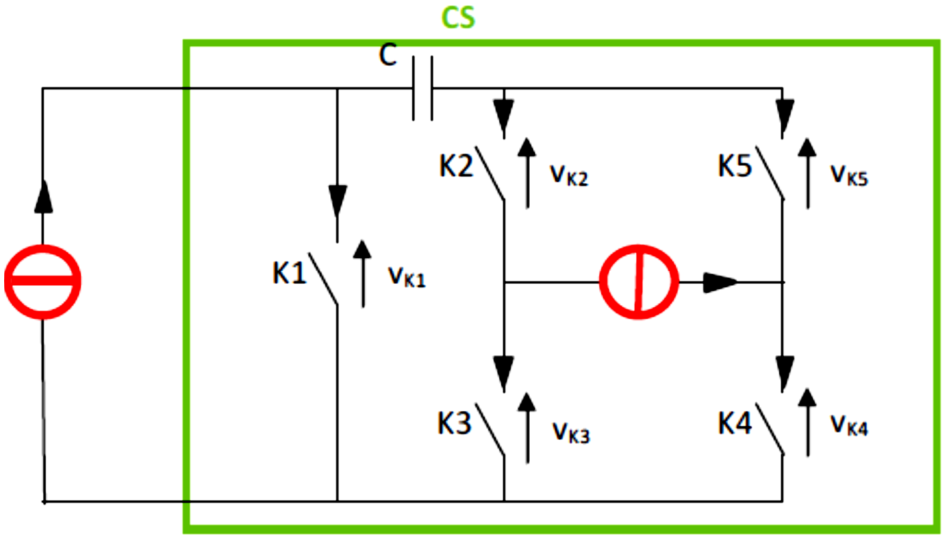


3.2.2. Indirect current-current converter

In this type of converter, the two current sources are never connected simultaneously to the capacitive storage element but successively.

- The capacitor stores the energy supplied by a current source (K2 K3 ON, K1 K4 K5 OFF);

- The capacitor returns its energy to the other current source either in one direction (K1 K2 K4 ON, K3 K5 OFF) or in the other (K1 K5 K3 ON, K2 K4 OFF).

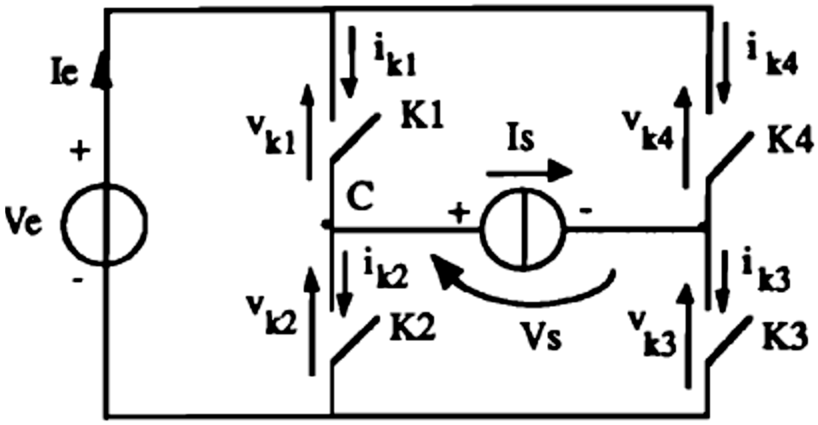


If the voltage source is bidirectional, the switches will need to support bidirectional voltage. Likewise, if the current source is bidirectional, the switches must support a bidirectional current.

La réversibilité des interrupteurs est liée à la réversibilité des sources en tension pour une source de tension et en courant pour une source de courant.

4. Switching rules

In all that follows, the sign conventions adopted for voltages (input and output voltages and those across the switches) and currents (input and output currents and those passing through the switches) are as shown in the following figure:



The basic structure of Direct Static Voltage-Current Converters (DSVCC) is the four-switch bridge structure.

1- The reversibility of sources implies the reversibility of switches.

1-1- Current reversibility of the current source involves current reversible switches.

1-2- The voltage reversibility of the voltage source involves voltage reversible switches.

2- In a direct converter we can only connect two sources of different natures.

2-1- A voltage source must never be short-circuited, but it can be open.

2-2- The circuit of a current source must never be open, but it can be short-circuited.

3- Four operating sequences are possible.

3-1- KI and K3 are closed (sequence A). The output voltage Vs has the same sign as the input source voltage Ve.

3-2- K2 and K3 are closed (sequence B), the voltage Vs is zero.

3-3- K2 and K4 are closed (sequence C), the output voltage Vs has the opposite sign to the input voltage Ve.

3-4- K1 and K4 are closed (sequence D), the voltage Vs is zero.

4- The research into the static characteristics of switches is based on chapter 1.

5- If the operating point located on a half-axis passes to a new operating point located on a perpendicular half-axis of the same sign, switching is ordered.

6- If the operating point located on a half-axis passes to a new operating point located on a perpendicular half-axis of opposite sign, the switching is spontaneous.

7- If the static characteristics of a two-segment switch are:

7-1- of the same signs then the two switches are controlled (transistor or “T” type switch).

7-2- of opposite signs then the two switching are spontaneous (diode or "D" type switch).

8- A three-segment switch is used with:

8-1- a unidirectional input voltage source in voltage and a bidirectional output current source in current the switch is then reversible in current and unidirectional in voltage.

8-2- an input voltage source reversible in voltage and a unidirectional output current source in current the switch is then reversible in voltage and unidirectional in current.

9- For a three-segment switch if:

9-1- the frequency of sign changes of the bidirectional source is equal to the switching frequency of the output voltage Vs (or the voltage Vc in a switching cell), then one of the two switching of the switch is spontaneous. This is called soft switching.

9-1-1- if the current source (output) is bidirectional in current, we have:

- a blocking command (dual thyristor type switch), the current of the output is lags behind the voltage of the output v s (or the voltage Vc).

- a start-up command (thyristor type switch) otherwise.

9-2- the switching frequency is different from the frequency of sign changes of the bidirectional source, the switching is hard (modulation). The switch is either:

9-2-1- a type T switch in series with another type D (unidirectional current and bidirectional voltage switch).

9-2-2- a type T switch in parallel with another type D (unidirectional voltage switch and bidirectional current switch).

10- A four-segment switch is:

- reversible voltage and current switch.
- Used with a voltage reversible voltage source and a bidirectional current source.
- The series or parallel association of two switches having two-segment (chapter 2).

11- Within an elementary switching cell:

11-1- only one switch is on at a time and a switching results in a simultaneous and complementary change of state of the two switches.

11-2- a positive switching leads to an increase in the potential of point C (previous figure).

11-3- negative switching leads to a reduction in the potential of point C.

11-4- a controlled switching of one of the switches leads to a spontaneous switching of the other.

11-5- if the switching and the current of the output source have the same signs, there is switching by command when the blocked switch is triggered.

11-6- if the switching and the current of the output source are of opposite signs, there is switching by command when the on-switch is blocked.

12- The structure of a direct static bridge converter with four switches contains two switching cells: K1, K2 and K3, K4.

13- In a four-switch bridge converter:

13-1- the controlled switching of a switch leads to the spontaneous switching of the other switch in the same cell.

13-2- if the switching of the output voltage Vs and the output current have the same signs, there is controlled ignition of the blocked switches.

13-3- if the switching of the output voltage and the output current are of opposite signs, there is controlled blocking of the on-off switches.

14- Transition from one operating sequence to another. Assuming the voltage source has a positive voltage:

14-1- If the output voltage vs, does not change sign during a change of operating sequences, we speak of zero switching (switching = 0).

When switching causes an increase in the potential of the output voltage, Vs, we speak of positive switching (switching >0).

Otherwise, it is a negative switching (switching <0).

If we go from a sequence where K1 and K3 were on to another sequence where K2 and K3 are closed, we must open K1 and close K2 and the switching is in this case negative.

To simplify the writing, we write:

K1, K3 ---> K2, K3, opening of K1 and closing of K2, switching < 0.

14-2- (K1, K3 ---> K2, K4) simultaneous opening of K1, K3 and simultaneous closing of K2, K4, switching < 0.

14-3- (KI, K3 ---> K1, K4) opening of K3 and closing of K4, switching < 0. 14-4- (K2, K3 ---> K1, K3) opening of K2 and closing of K1, switching > 0.

14-5- (K2, K3 ---> K2, K4) opening of K3 and closing of K4, switching < 0.

14-6- (K2, K3 -> K1, K4) simultaneous opening of K2, K3 and simultaneous closing of KI, K4, switching=0.

14-7- (K2, K4 --> K1, K4) opening of K2 and closing of K1, switching > 0.

14- 8- (K2, K4 --> K1, K3) simultaneous opening of K2, K4 and simultaneous closing of KI, K3, switching > 0.

14-9- (K2, K4 ---> K2, K3) opening of K4 and closing of K3, switching > 0.

14-10- (K1, K4 ---> K1, K3) opening of K4 and closing of K3, switching > 0.

14-11- (K1, K4 ---> K2, K4) opening of K1 and closing of K2, switching < 0.

14-12- (K1, K4 ---> K2, K3) simultaneous opening of K1, K4 and simultaneous closing of K2, K3, switching = 0.

5. Static converters

In electricity, four types of energy conversions are possible:

	Continuous source	Alternative load
Continuous load	Chopper	Rectifier
Alternative load	Inverter	Dimmer / Cyclo converter

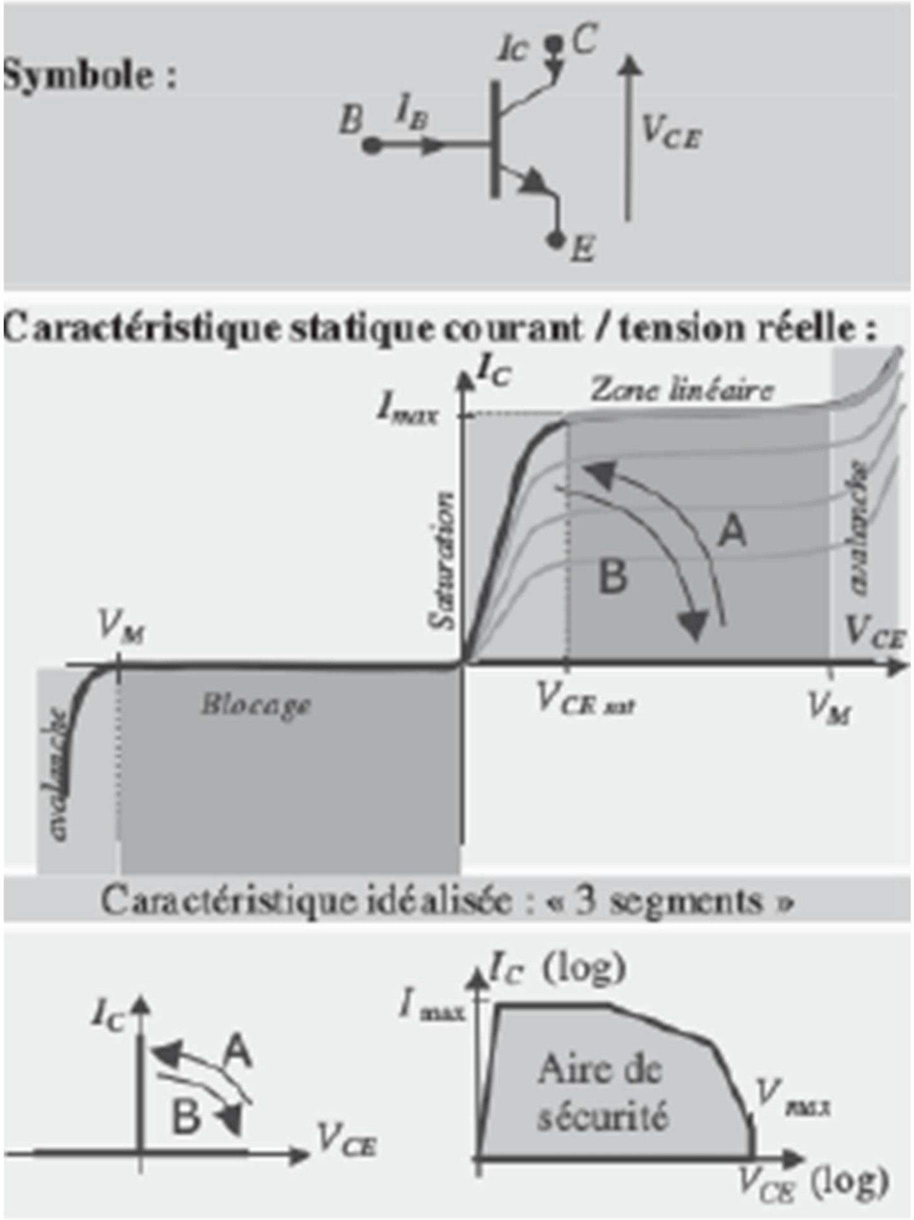
5.1. Components controlled for priming and blocking.

5.1.1. The bipolar transistor (of power)

Component controlled when opening and closing. Composed of 3 “Base” electrodes (B), serves to control the current between the two other “Collector” (C) and “Emitter” (E) electrodes.

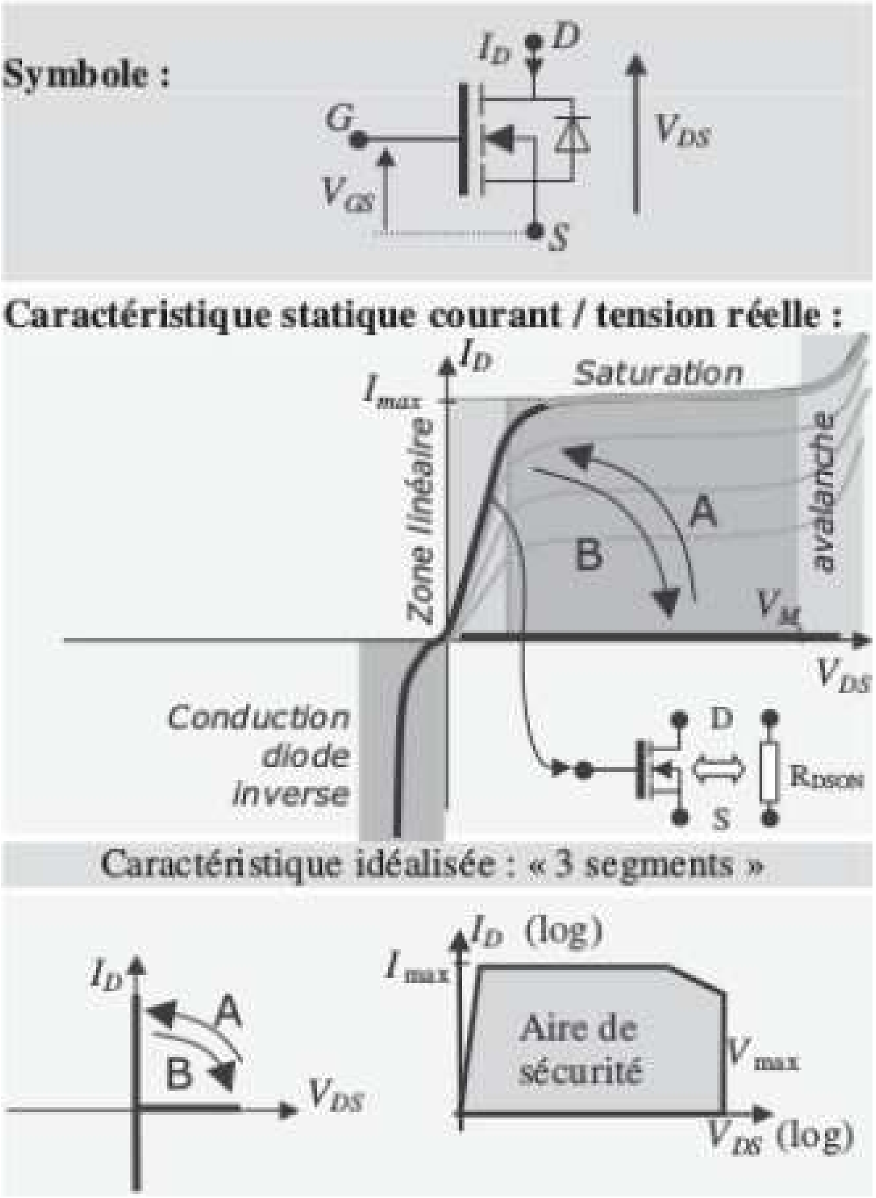
The current passing through the base IB: Permanently conditions the collector current, it allows both the conduction or blocking of the transistor. Just like the thyristor and the diode, the transistor has a maximum current, a forward voltage and a reverse voltage. However, there are several types of direct voltage breakdowns which leads manufacturers to specify a static safety zone in the operating point (intersection between linear line between Imax and VM with one of the lines of the linear zone) of the transistor.

Note: The bipolar transistor contains a fairly small safety area, because its maximum operating frequencies are quite low and the control current is quite high, which penalizes the efficiency of the system and makes the electronics of the close control heavier.



5.1.2. The MOS transistor (of power) “Metal Oxyde Semi-Conductor Field Effect Transistor ”

It is a field effect transistor, it was developed to allow the control of the main current which passes through it by the voltage applied between 2 of its legs. It is controlled in opening and closing. Featuring 3 electrodes “Grid” (G), “Drain” (D) and “Source” (S). A particularity exists in this component, it is the existence of the so-called “structural” diode allowing the conduction of negative current in an uncontrolled manner.

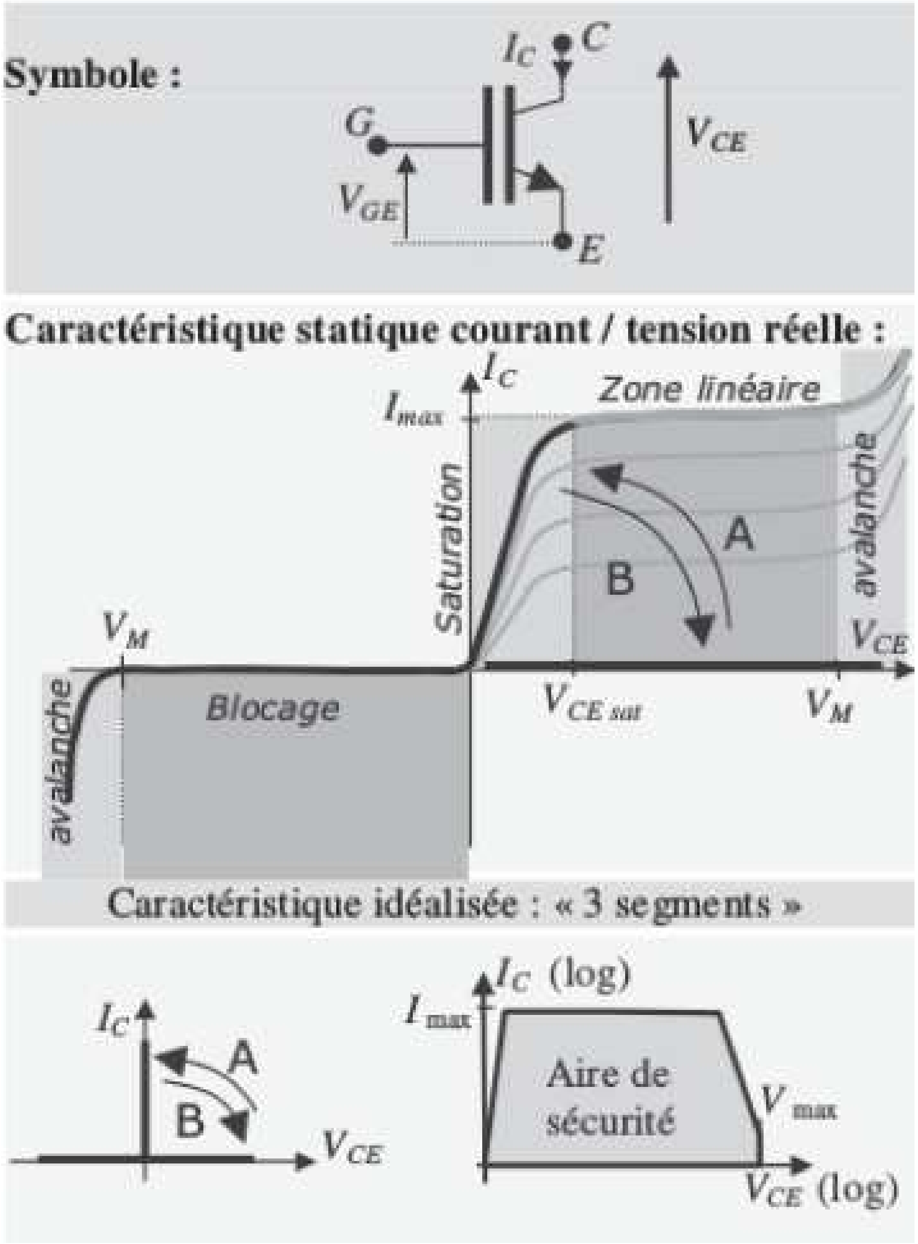


In this type of transistor, the VGS voltage permanently conditions the Drain ID current, it makes it possible to impose the conduction and blocking of the component. VGS=0 (case of blocking), VGS>0 (case of conduction). In the linear zone the component is in a conduction state, in this part the MOS is equivalent to an RDS resistance. When the conduction is optimal, the resistance is minimal and it is called “RDS ON”. The MOS contains IMAX and VMAX as well as a static safety zone from which the operating point can only exceptionally be exited in a transient manner.

Note: This type of transistor has much better ease of use and safety than bipolar transistors. But their uses are limited between small and medium powers.

5.1.3. The IGBT transistor "Insulate Gate Bipolar Transistor"

It is a hybrid transistor, combining the gate and field effect control of a MOS with the Collector/Emitter junctions of a bipolar. This type of component was developed to combine the advantages of the two structures (MOS and Bipolar) in the same element intended for switching work, particularly in the field of high powers (high voltages and high currents). It is a component controlled by opening and blocking, presenting a "Grid" (G), "Emitter" (E) and "Collector" (C). VGE continuously conditions the collector current IC. VGE=0 (Block), VGE>0 (Conduction).



Note: IGBTs replace thyristors in high power applications, they are present in applications linked to traction (electric vehicles) and the conversion of high voltages and high currents.

5.2. Convert continuous to continuous (Chopper)

Converting direct current to direct current may seem surprising. In reality it is one of the most useful functions of power electronics. This generally involves transforming a direct voltage having a given value into another voltage, also direct, but of a different value. However, it is impossible to use a transformer directly (reserved for alternative quantities) and any linear conversion of the "voltage divider bridge" type would prove unprofitable, with typically very poor efficiency (we have already seen this in the chapter 2 “Linear converter”). There are several types of choppers:

1st case (non-unsulated choppers): there are choppers with: 1-quadrant , 2-quadrant and 4-quadrant. In other hands, it exists: Direct choppers connect a generator and a receiver which behave one as a voltage source, the other as a current source. They only include switches which allow to act on the connections between the generator and the receiver. And indirect chopper connect a generator and a receiver of the same nature. They comprise switches and an energy storage element which acts as an intermediate source of current or voltage depending on whether the generator and receiver are sources of voltage or current. The storage element receives energy from the generator and then transmits it to the receiver based on the connections made by the switches.

2nd case: isolated choppers.

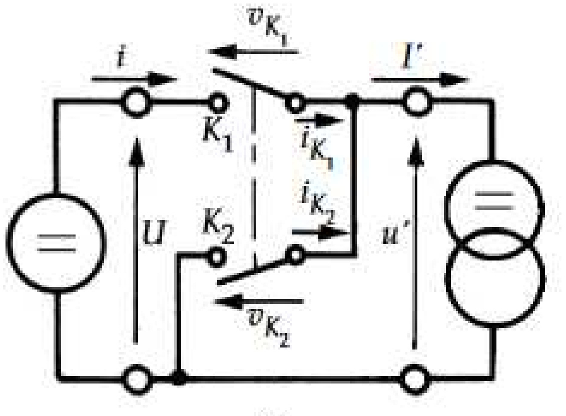
5.2.1. Non-insulated and non-reversible choppers assemblies:

This type of chopper is divided into 3 main types:

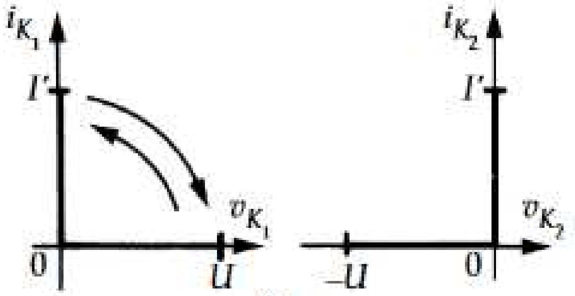
a. Non-reversible Buck chopper (step-down):

It is a step-down chopper. It is also called the series chopper. We will retain the following characteristics from this type of converter:

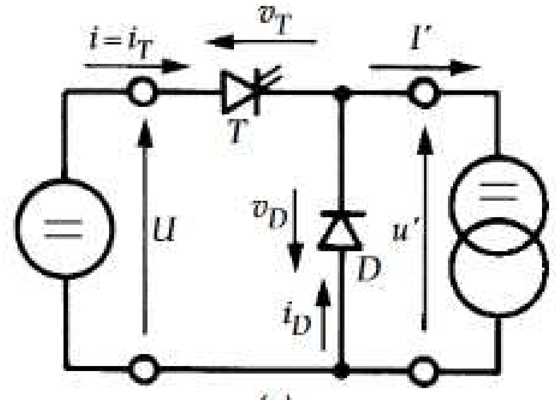
- Switches K1 and K2 are controlled in a complementary manner. When one of them drives, the other is blocked.
  When K1 is closed, iK1 is equal to I′, iK2 zero, vK1 zero and vK2 equal to −U.
  When K2 is closed, iK1 is zero, iK2 equal to I′, vK1 equal to +U and vK2 zero.
- The switchings are periodic, at the so-called “cutting” period T (is therefore at the frequency f=1/T).
- The switching conduction phases give rise to a switching “duty cycle” $\alpha\epsilon[0,1]$. It must then be remembered that operation is imposed by the control through the fact that K1 is conductive on the interval $[0, \alpha T]$ and K2 on $[\alpha T, T]$. The appearance of the voltage applied to the output source is therefore represented in the following figure.



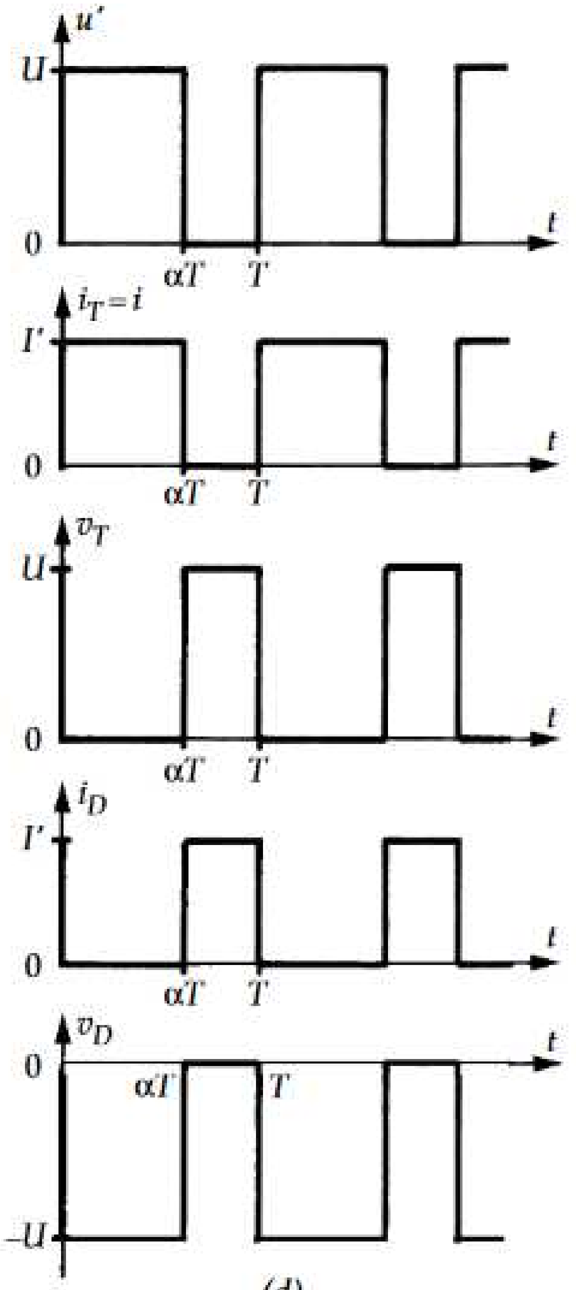
(a)



(b)



(c)



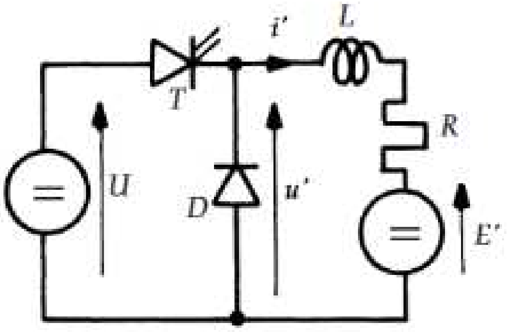
(d)

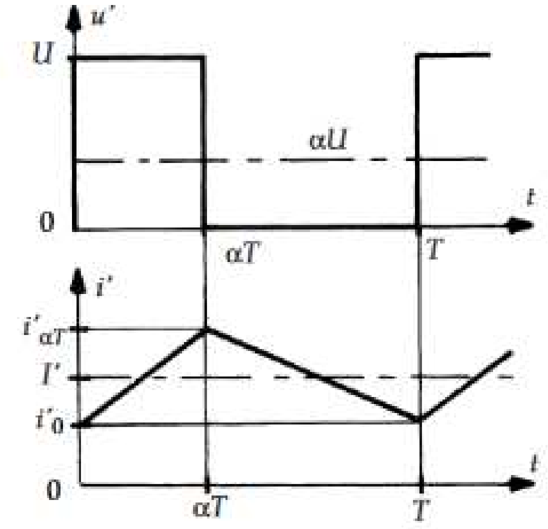
$$<V_s> = \frac{1}{T}\int_0^T v_{K2}(t)\cdot \mathrm{d}t$$

$$= \frac{1}{T}\int_0^{\alpha T} V_e \cdot \mathrm{d}t = \alpha \cdot V_e$$

It is necessary to understand that, if the assembly and its filtering work correctly, the current passing through the resistor must be almost continuous as well as the output voltage. We will therefore remember:

$$V_s \approx <V_s> = \alpha \cdot V_e \text{ et } I = \frac{\alpha \cdot V_e}{R}$$





It is then simply to deduce the current circulating in the inductance, in fact:

- When K1 is conductive:

$$v_L(t) = L \cdot \frac{di_L}{dt} = V_e - V_s > 0 \quad \text{Where} \quad i_L(t) = \frac{V_e - V_s}{L} \cdot t + cte$$

- When K2 is conductive:

$$v_L(t) = L \cdot \frac{di_L}{dt} = -V_s < 0 \quad \text{Where} \quad i_L(t) = -\frac{V_s}{L} \cdot t + cte$$

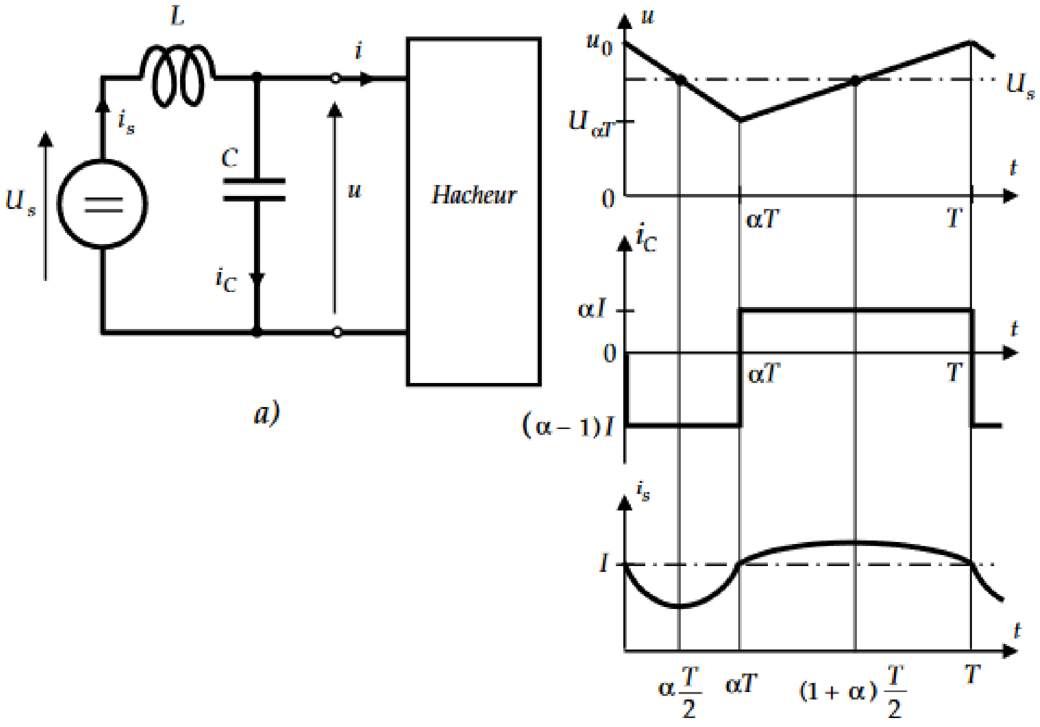
- The average value of the current iL (I‘) is precisely the direct component of this current which passes through the load

$$<i_L> = I = \frac{\alpha \cdot V_e}{R}$$

- Calculation of undulations

$$v_L(t) = L \cdot \frac{di_L}{dt} = L \cdot \frac{\Delta i_L}{\alpha \cdot T} \Rightarrow \Delta_{iL} = \frac{(V_e - V_s) \cdot \alpha T}{L}$$

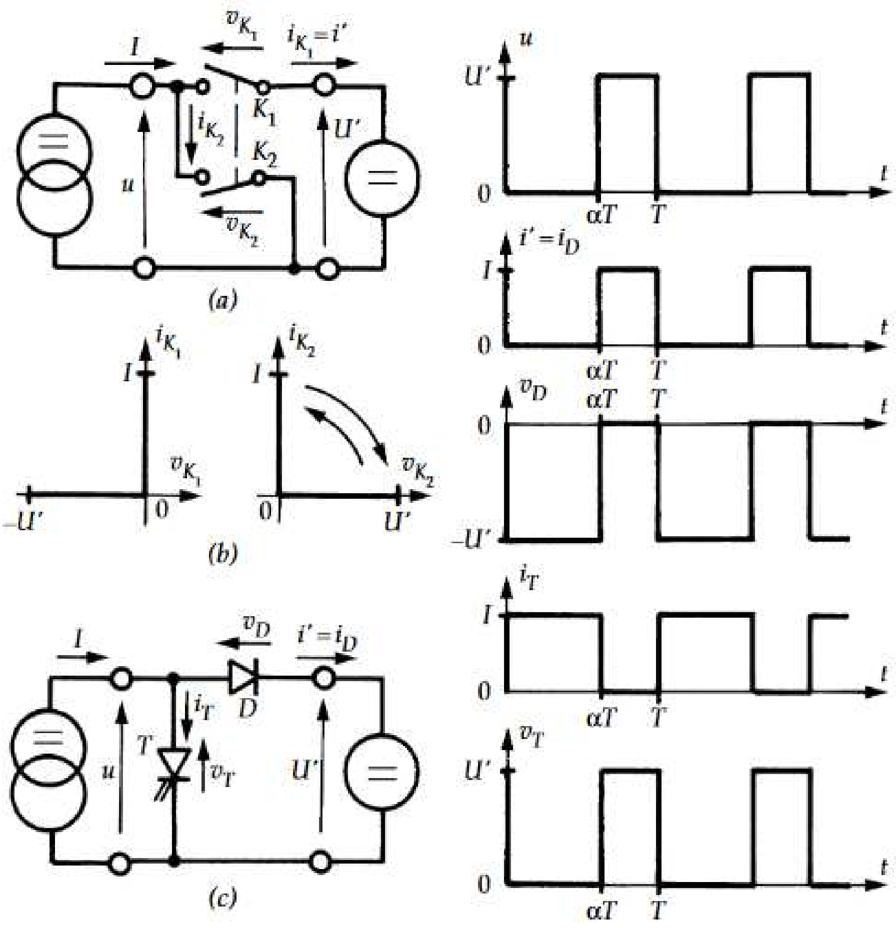
$$\Delta i_L = \frac{V_e \cdot T \cdot \alpha \cdot (1-\alpha)}{L} = \frac{V_e \cdot \alpha \cdot (1-\alpha)}{L \cdot f}$$



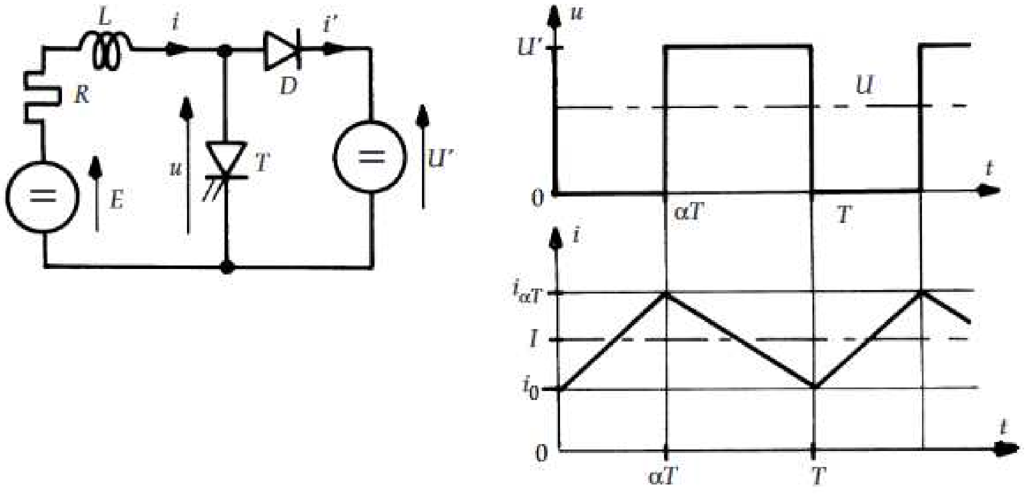
a) *b)*

b. Non-reversible Boost chopper (elevator)

It is a booster chopper. It is also called the parallel chopper. For this chopper we will retain the following characteristics: Switches K1 and K2 are controlled in a complementary manner. When one of them is driving, the other is blocked and vice versa. The switching are periodic, at the switching period T. The conduction phases of the switches give rise to “a cyclical ratio” of switching α϶[0,1].



It is then possible to determine the current/voltage combination associated with the inductance, in fact:



- When K1 is conductive:

$v_L(t) = L \cdot \frac{di_L}{dt} = V_e > 0$ and $i_L(t) = \frac{V_e}{L} \cdot t + cte$

iL is increasing

- When K2 is conductive:

$v_L(t) = L \cdot \frac{di_L}{dt} = V_e - V_s < 0$ and $i_L(t) = \frac{V_e - V_s}{L} \cdot t + cte$

iL is decreasing

An important and essential concept in this circuit lies in the fact that, the current being periodic, the average value at the edge of the inductance is zero.

$$<v_L> = \frac{1}{T}\int_0^T v_L(t) \cdot dt = \frac{1}{T} \cdot (\alpha \cdot V_e + (1-\alpha) \cdot (V_e - V_s)) = 0$$

We deduce that: Or

$V_e - (1-\alpha) \cdot V_s = 0$ $V_s = \frac{V_e}{(1-\alpha)}$ et $I = \frac{V_e}{R \cdot (1-\alpha)}$

Remember the fact that, the duty cycle being smaller than 1, therefore Vs > Ve

• Calculation of undulations

When K1 is conductive, the associated ripple is as follows:

$$v_L(t) = L \cdot \frac{di_L}{dt} = L \cdot \frac{\Delta i_L}{\alpha \cdot T} \Rightarrow \Delta i_L = \frac{V_e \cdot \alpha T}{L}$$

$$\Delta i_L = \frac{V_e \cdot T \cdot \alpha}{L} = \frac{V_e \cdot \alpha}{L \cdot f}$$

When K2 is blocked the capacitor discharges into the output resistor, the corresponding voltage ripple is as follows:

$$I = -C \cdot \frac{dV_s}{dt} = -C\frac{\Delta V_s}{\alpha \cdot T}$$

That's to say :

$$|\Delta V_s| = \frac{I \cdot \alpha T}{C} = \frac{V_s \cdot \alpha T}{R \cdot C}$$

Or again:

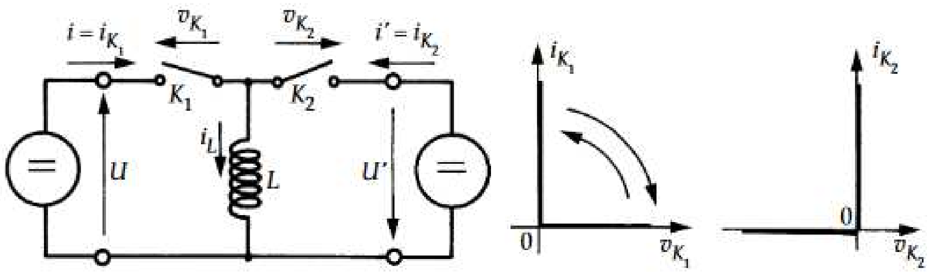
$$\Delta V_s = \frac{\alpha \cdot V_e \cdot T}{(1-\alpha) \cdot RC} = \frac{\alpha \cdot V_e}{(1-\alpha) \cdot RC \cdot f}$$

5.2.2. Isolated and non-reversible choppers assemblies:

a. Inductive storage chopper (Non-reversible Buck-Boost chopper)

It is a chopper also called “storage” and works substantially on the same principle as a step-up chopper, but also allows a lowering of the voltage.

it is an indirect connection chopper because when the chopper is mounted between a voltage generator and a voltage receiver, the storage element must be an inductor.



For this chopper we will retain the following characteristics:

- The two switches K1 and K2 must be complementary so that the two voltage sources are never directly connected and so that the inductance L is never in open circuit.
- The switchings are periodic, at the switching period T.
- The conduction phases of the switches give rise to “a cyclical ratio” of switching α϶[0,1].

It is then possible to determine the current/voltage combination associated with the inductance, in fact:

When K1 is conductive

$$v_L(t) = L \cdot \frac{di_L}{dt} = V_e > 0$$

And

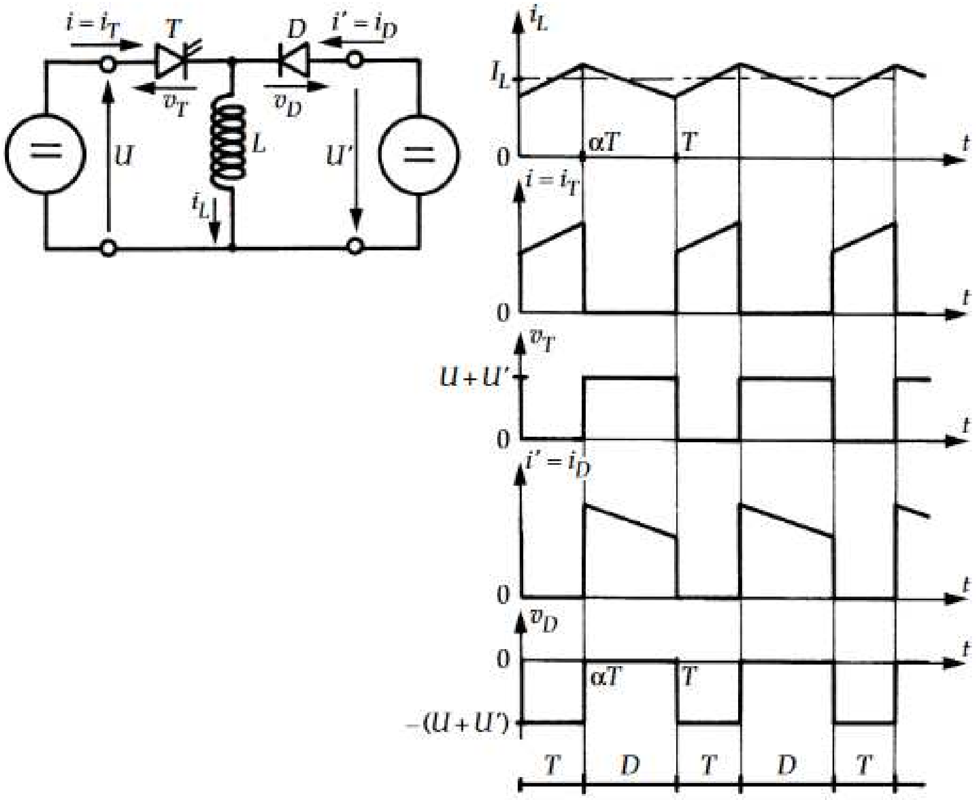
$$i_L(t) = \frac{V_e}{L} \cdot t + cte$$

iL is increasing

When K2 is conductive

$$v_L(t) = L \cdot \frac{di_L}{dt} = V_s \qquad \text{And} \qquad i_L(t) = \frac{V_s}{L} \cdot t + cte$$

iL is decreasing



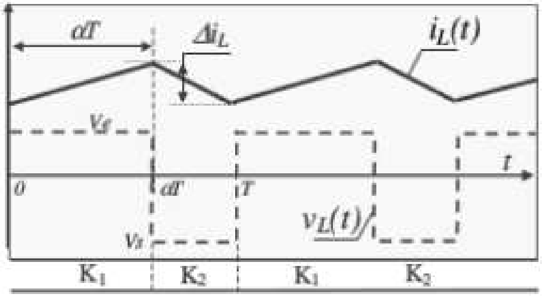
- The average value of the current iL is non-zero since the power supply must provide an average power at the output.
- The current iL being periodic, the average value at the edge of the inductance is zero.

$$<v_L> = \frac{1}{T}\int_0^T v_L(t)\cdot dt = \frac{1}{T}\cdot(\alpha \cdot V_e + (1-\alpha)\cdot V_s) = 0.$$

We deduced that

$$\alpha \cdot V_e + (1-\alpha) \cdot V_s = 0$$

Or $V_s = -\dfrac{\alpha \cdot V_e}{(1-\alpha)}$ et $I = -\dfrac{\alpha \cdot V_e}{R \cdot (1-\alpha)}$



Noticed : This relationship reveals the mixed behavior of this chopper. Indeed, we will check that if $\alpha < 1/2$ alors $|V_s| < V_e$ and on the other hand if $\alpha > 1/2$ alors $|V_s| > V_e$.

Calculation of undulations:

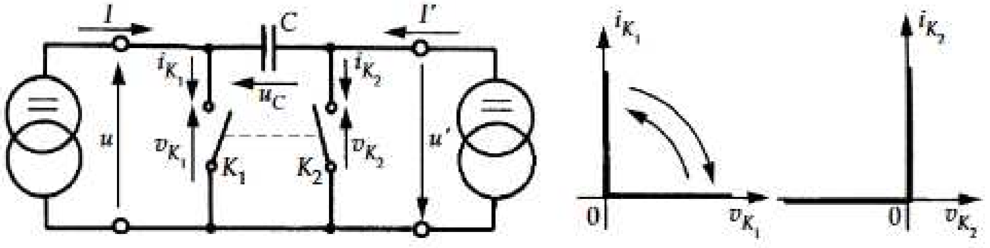
Calculating the ripples of this chopper reveals the same characteristics of the BOOST chopper, therefore:

$$\Delta i_L = \frac{V_e \cdot T \cdot \alpha}{\mathrm{L}} = \frac{V_e \cdot \alpha}{L \cdot f} \qquad \Delta V_s = \frac{V_s \cdot \alpha T}{R \cdot C} \qquad \Delta V_s = \frac{\alpha^2 \cdot V_e \cdot T}{(1-\alpha) \cdot RC} = \frac{\alpha^2 \cdot V_e}{(1-\alpha) \cdot RC \cdot f}$$

b. Capacitive storage chopper

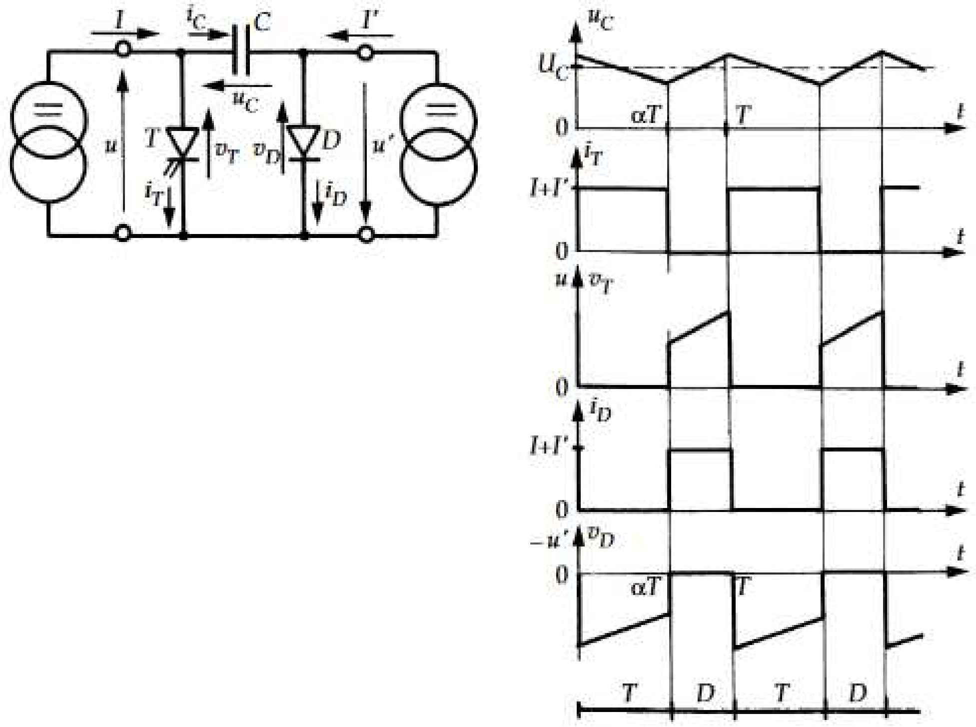
If the chopper must connect two current sources, the accumulation element must be a capacitor;

this plays the role of an intermediate source of tension. This converter is known as Cùk chopper or Cùk converter.



it is a diagram with two switches K1 and K2. These must be complementary. From the branches of characteristics used we deduce that K1 must be replaced by a semiconductor with controlled closing and opening T, and that K2 must be replaced by a diode D.

We thus arrive at the principal scheme of figure below; this also gives the waveforms of the main variables.



- For 0 < t < αT, the controlled semiconductor conducts; the capacitor supplies the receiver with constant current I′, the voltage u_C decreases linearly:

$$u = 0, \qquad u' = u_C$$

$$i_C = -I', \qquad \frac{du_C}{dt} = \frac{-I'}{C}$$

$$i_T = I + I', \qquad v_T = 0, \qquad i_D = 0, \qquad v_D = -u'.$$

- For αT < 0 < T, the diode conducts; the generator charges the capacitor at constant current I, the voltage uC increases linearly:

$$u = u_C, \qquad u' = 0$$

$$i_C = I, \qquad \frac{du_C}{dt} = \frac{I}{C}$$

$$i_T = 0, \qquad v_T = u_C, \qquad i_D = I + I', \qquad v_D = 0.$$

In steady state, the average value UC of the voltage across C is the same during its discharge and during its charge. Hence the average values U and U′ of the input and output voltages:

$$U' = \alpha U_C, \qquad U = (1 - \alpha)U_C.$$

If we neglect the losses in the chopper, the average powers at the input and output are the same:

$$\boxed{\frac{U'}{U} = \frac{I}{I'} = \frac{\alpha}{1 - \alpha}}$$

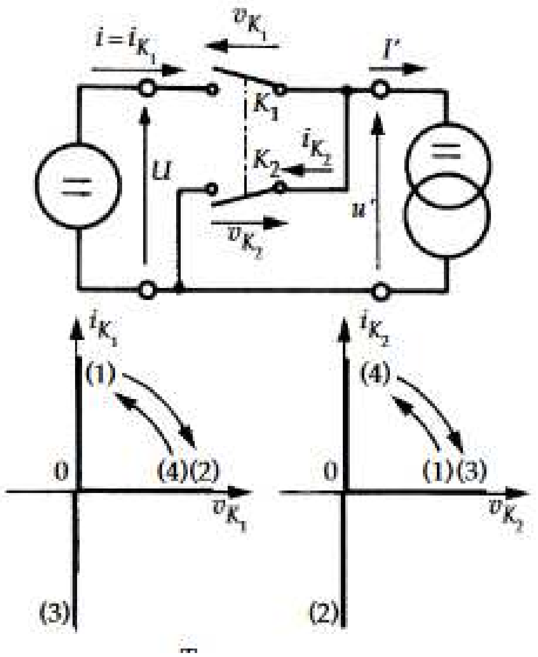
Usually, the generator is an RLE circuit, of negligible resistance R, which imposes in steady state U = E and the receiver is characterized by a relation U′ = U′(I′). In this case, by acting on α, we impose the value of the voltage applied to the receiver U′ = αE/(1 − α); the receiver reacts by then imposing I′.

5.2.3. Non-insulated two-quadrant chopper assemblies

These types of choppers make it possible to control the transfer of energy in both directions.

a. Current reversible chopper

It is obtained from reverse parallel placement of unidirectional switches.



The scheme with switches is always the same: K1 connects the input and the output, K2 short-circuits the current source when K1 is open.

When I′ is positive :

if K1 is closed (state 1) :	if K1 is open (state 2) :
vK1 = 0 , iK1 = I′ > 0	vK1 = +U , iK1 = 0
vK2 = +U , iK2 = 0	vK2 = 0 , iK2 = –I′ < 0 .

When I′ is negative :

if K1 is closed (state 3) :	if K1 is open (state 4) :
vK1 = 0 , iK1 = I′ < 0	vK1 = +U , iK1 = 0
vK2 = +U , iK2 = 0	vK2 = 0 , iK2 = –I′ > 0

We deduce from this the branches of characteristics used and the semiconductors to be substituted for mechanical switches:

– K1 must be replaced by a transistor T1 with a diode D1 in reverse parallel.

– similarly K2 must be replaced by transistor T2 with diode D2 in reverse parallel.

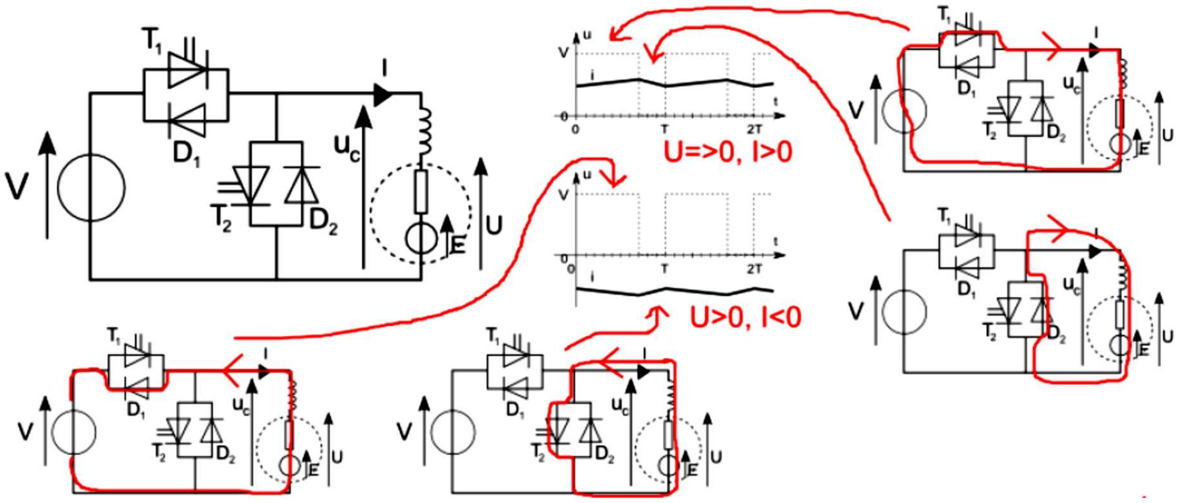
We see that this converter results from the association of a series chopper, formed by T1 and D2, and a parallel chopper, formed by T2 and D1.

• For positive I′, it operates as a series chopper; the current I′ passing sometimes through T1, sometimes through D2. If α1 is the relative duration of the closure of T1 during each period, u′ has the average value:

$$U' = \alpha 1 U.$$

• For negative I′, it operates as a parallel chopper: the current I′ passing sometimes through T2, sometimes through D1. If α2 is the relative duration of the closing intervals of T2, u′ has the average value:

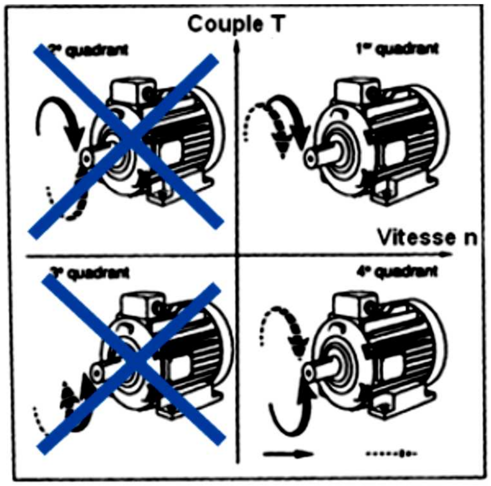
$$U' = (1 - \alpha 2)U.$$



- In discontinuous control, for positive I′, transistor T2 is permanently open, T1 is closed for α1T at each period: U′ equal to α1U goes from U to 0 when α1 goes from 1 to 0.

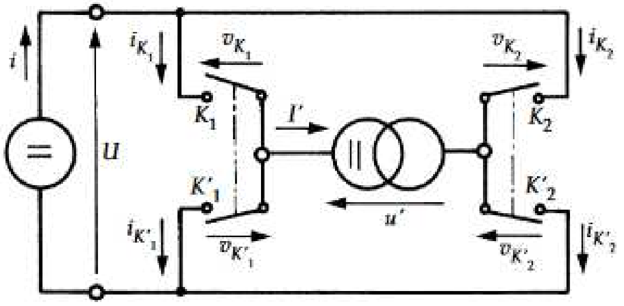
  For negative I′, T1 is permanently open, T2 closed for α2T: the voltage U′ goes from U to 0 when α2 goes from 0 to 1.

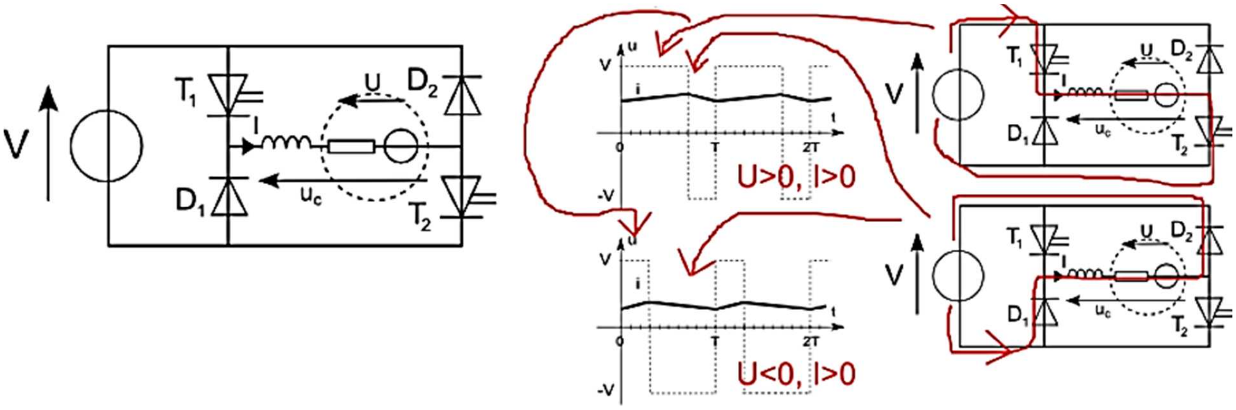
- In continuous control, we order the closing of T1 from 0 to $\alpha1T$ and the closing of T2 throughout the rest of the period. This amounts to imposing $\alpha1 + \alpha2 = 1$, the voltage U' is equal to $\alpha1U$ whatever the sign of the current I'.

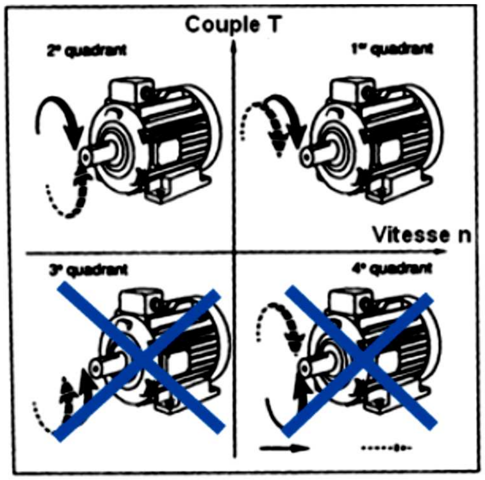


b. Voltage reversible chopper

It is obtained by creating a bridge structure.







$$<V_s> = V_e \cdot (2\alpha - 1)$$

5.2.4. Non-insulated four-quadrants chopper assemblies

This montage is obtained from the combination of the two previous montages.

The closing of the “switches”, K1 and K′1 on the one hand, K2 and K′2 on the other hand, must be complementary so that the voltage source is never in short circuit and the current source never in circuit open. Among the many possibilities offered by the bridge structure, one of the most used corresponds to the chopper connecting:

– a voltage source reversible into current: $U > 0$, $i > 0$ or $i < 0$

– and a current source reversible in current and voltage: $I' > 0$ or $I' < 0$, $u' > 0$ or $u' < 0$.

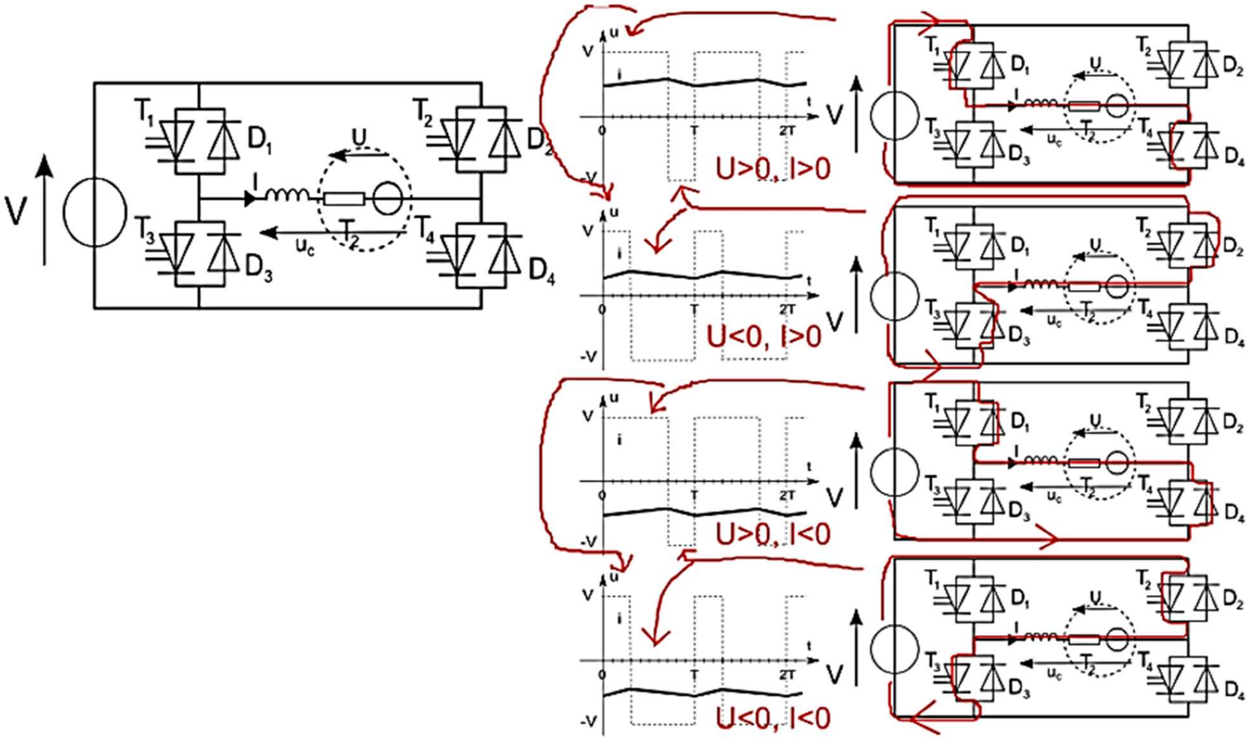
We will limit ourselves to the study of this case.

For positive U’, we permanently close K′2 and for α1T the switch K1. So $U' = \alpha 1U$

- If I′ is positive, for $0 < t < \alpha 1T$, I′ passes through T1 and T′2 for $\alpha 1T < t < T$, I′ passes through T′2 and D′1. • If I′ is negative, for $0 < t < \alpha 1T$, I′ passes through D′2 and D1 for $\alpha 1T < t < T$, I′ passes through T′1 and D′2. For negative U’, we permanently close K2 and, during the interval α1T, K1. SO : $U' = -(1 - \alpha 1)U$

- If I′ is positive, I′ passes through D2 and T1, then through D′1 and D2.

- If I′ is negative, I′ passes through T2 and D1, then through T′1 and T2.



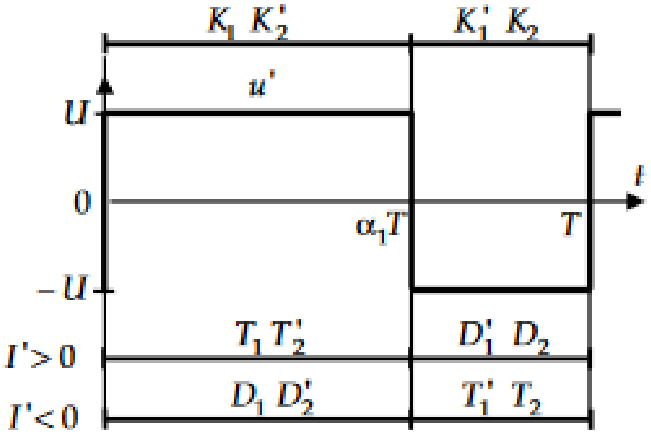
Several control laws are possible. The one which makes it possible to minimize the number of switching instants is the following figure:

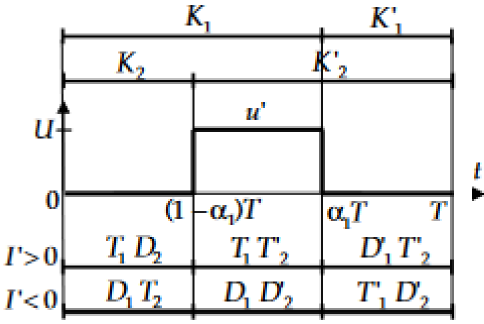
- For $0 < t < \alpha 1T$, we order the closing of K1 and K′2: the voltage u′ equals U. The current I′ passes through T1 and T′2 if it is positive; by D1 and D′2 if it is negative.
- For $\alpha 1T < t < T$, we order the closing of K2 and K′1: the voltage u′ equals −U. Current I′ passes through D′1 and D2 if it is positive; by T′1 and T2 if it is negative.

Whatever the sign of U′ and that of I′, we always have

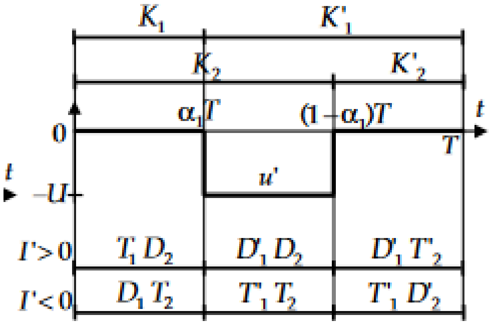
$$U' = \alpha 1\, U - (1 - \alpha 1\,)U = (2\alpha 1 - 1)U$$

The voltage U’ goes from +U to −U when α1 goes from 1 to zero.





$\alpha_1 > 0{,}5$



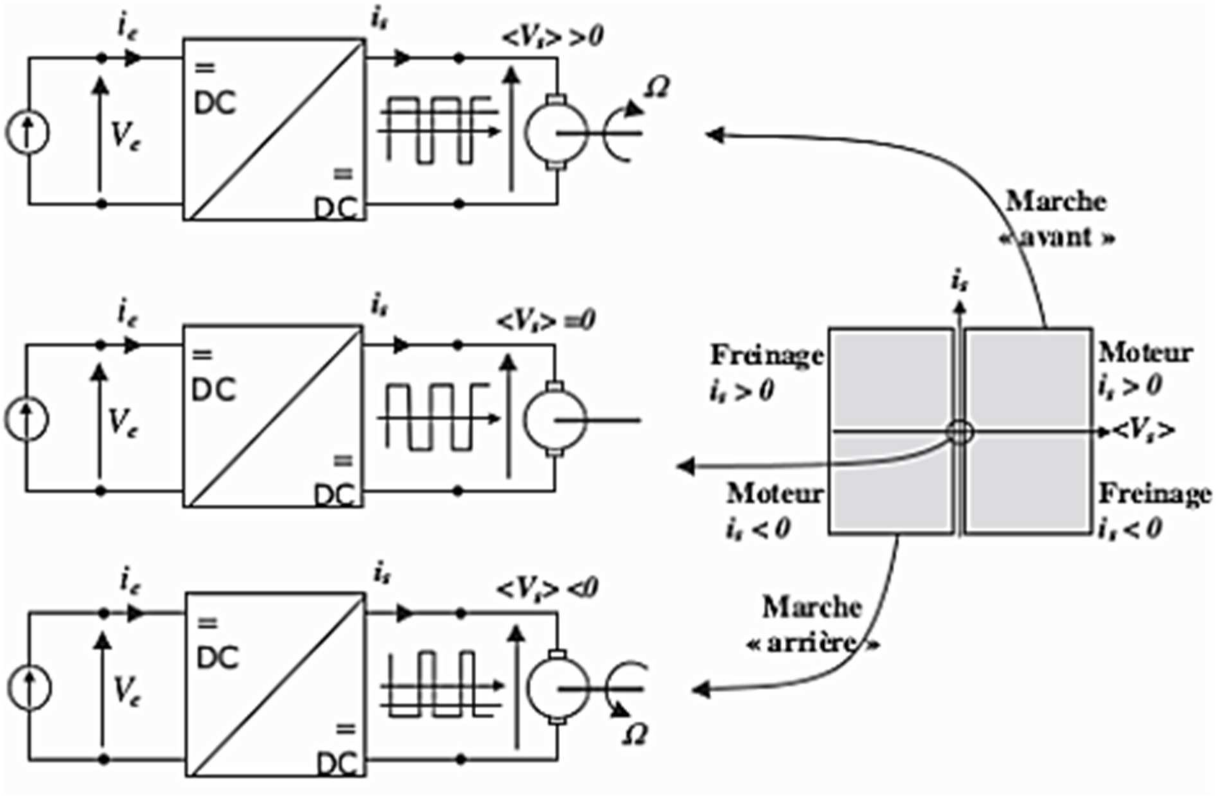
$\alpha_1 < 0{,}5$

For $0 < t < \alpha 1T$, we order the closure of K1, for $0 < t < (1 - \alpha 1)T$, that of K2.

We see that if α1 is greater than 0.5, from $t = (1 - \alpha 1)T$ to $\alpha 1T$, the voltage u′ equals U and is zero during the rest of the period. If α1 is less than 0.5, u′ equals −U for $\alpha 1T < t < (1 - \alpha 1)T$ and is zero for the rest of the period.

We therefore always have: $U' = (2\alpha 1 - 1)U$

In the context of powering a direct current machine, the different possible operating phases are illustrated in the following figure:



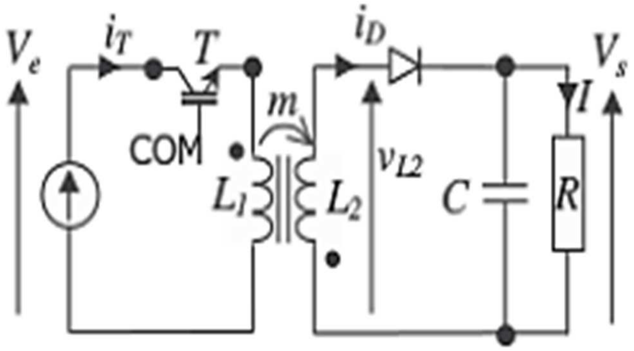
5.2.5. Insulated choppers

It is often important that the power supply of an electrical device is “isolated” from the electrical network. On the other hand, the association of a “galvanic isolation” function with a chopper type structure requires interposing a transformer between the energy source and the transformer.

a. Flyback structure

It is necessary to note the following elements in order to understand how this assembly works:

- The transformer appearing in this diagram works in a very particular way. In practice, there is never simultaneous conduction in the two windings. L1 and L2 are two coupled inductors (their “transformation ratio” m=n2 / n1, where n1 and n2 represents the number of turns of the windings.
- The convention of the points which appears on the diagram reveals that the secondary voltage is chosen in phase opposition to the primary voltage.



- The transistor is controlled periodically, at the switching frequency f and with the duty cycle α.
- When the transistor closes, the current iT= iL increases linearly according to the following equation:

$$i_T(t) = \frac{V_e}{L_1} \cdot t + cte$$

The energy stored in the primary inductance also increases:

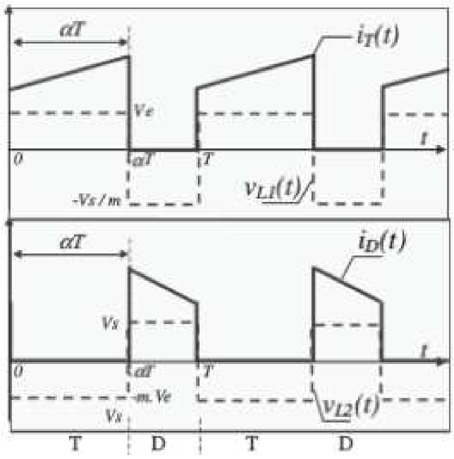
$$W_{L_1} = 1/2 \cdot L \cdot i_L^2(t)$$

“Transformer magnetization” phase.

- When the transistor is blocked (by control), the diode becomes conductive, which allows current to flow in the secondary.
- The energy stored during the first phase and therefore in whole or in part transmitted to the load and to the output capacitor. This leads to a decrease in secondary current.

$$i_D(t) = i_{L2}(t) = \frac{-V_s}{L_2} \cdot t + cte.$$

- This second phase corresponds to “demagnetization of the transformer”.
- The figure below represents the appearance of currents and voltages across the inductors in the context of supposedly interrupted conduction.



- The assembly works in two differentiated stages. In the first step, the primary current increases the energy stored in the inductor. In the 2nd stage this energy is delivered to the secondary and supplies the load.
- In interrupted conduction, the average value of the voltage across the primary inductance being zero, we write:

$$<v_{L1}> = \frac{1}{T}\int_0^T v_{L1}(t)\cdot \mathrm{d}t = \frac{1}{T}\cdot\left(\alpha\cdot V_e-(1-\alpha)\cdot\frac{V_s}{m}\right) = 0.$$

We deduce that:

$$m\cdot\alpha\cdot V_e-(1-\alpha)\cdot V_s = 0$$

So :

$$V_s = \frac{m\cdot\alpha\cdot V_e}{(1-\alpha)} \quad \text{et} \quad I = \frac{m\cdot\alpha\cdot V_e}{R\cdot(1-\alpha)}$$

b. Forward structure

The operating principle of this chopper is as follows:

- The transistor in this diagram is interposed between the transistor T and the freewheeling diode D2 of the BUCK chopper. It has three superimposed windings, n1, n2 and n3 representing these number of turns.
- The points appearing next to the windings make it possible to identify the direction of the corresponding voltages.
- Closing T allows the voltage to be applied to the primary winding (n1), and the appearance of voltage to the secondary (n2). The compatible direction of the secondary winding and the diode D1 allow the circulation of a direct current supplying the load through the inductance L. this transformer operates in a conventional way by simultaneously conveying the current in its

primary n1 and its secondary n2 . ¬ The position of the point on winding n3 reveals that diode D3 is reverse biased. Thus, the branch containing winding n3 is therefore open and useless in this first phase.

- the current iT represents:

$$i_T = i_m + \frac{n_2}{n_1} \cdot i_D \cdot$$

Where :
Im : magnetizing current from the transformer.

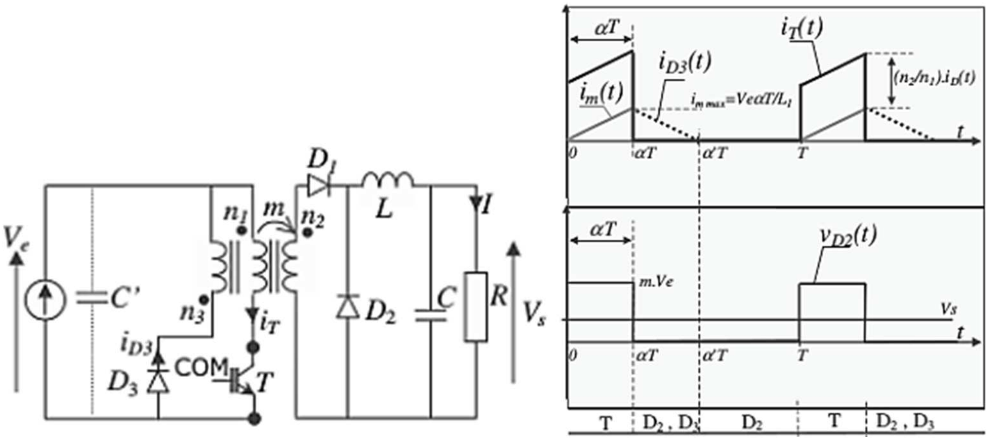
- The maximum value reached by the magnetizing current is written:

$$i_{m\ \max} = \frac{\alpha T \cdot V_e}{L_1}$$

Where :
L1 is the inductance of the primary winding.

- When T opens, diode D2 comes into conduction and ensures the “freewheeling” phase necessary for the continuity of the current circulating in the inductor L. the output stage is completely decoupled from the input, and diode D1 is also blocked.

- The simultaneous opening of the transistor and the diode D1 do not allow the transformer to evacuate the magnetic energy that it had stored.



5.3. Convert alternative to continuous (Rectifier)

5.4.

6.