Chapter 2

Switching mechanism in static converters.

1- Introduction

Power electronics uses semiconductors working in "switches". A switch can be formed by only one semiconductor or by a series or parallel grouping of several semiconductors.

Before tackling the study of the main power electronics assemblies, it is necessary:

- To recall the characteristics of power semiconductors and to indicate how they can be combined to obtain switches with given characteristics.
- To precise how the switches can switch from one state (open or close) to another (close or open) when inserted into an assembly.

2- Reminder on semiconductors switches

To show the role that a "switch" can fulfill, we indicate it (figure 2.1a) in the plane [voltage *v* at the terminals - current *i* passing through the switch]:

• the characteristic branches where it can work,

• the branch changes that it can ensure.

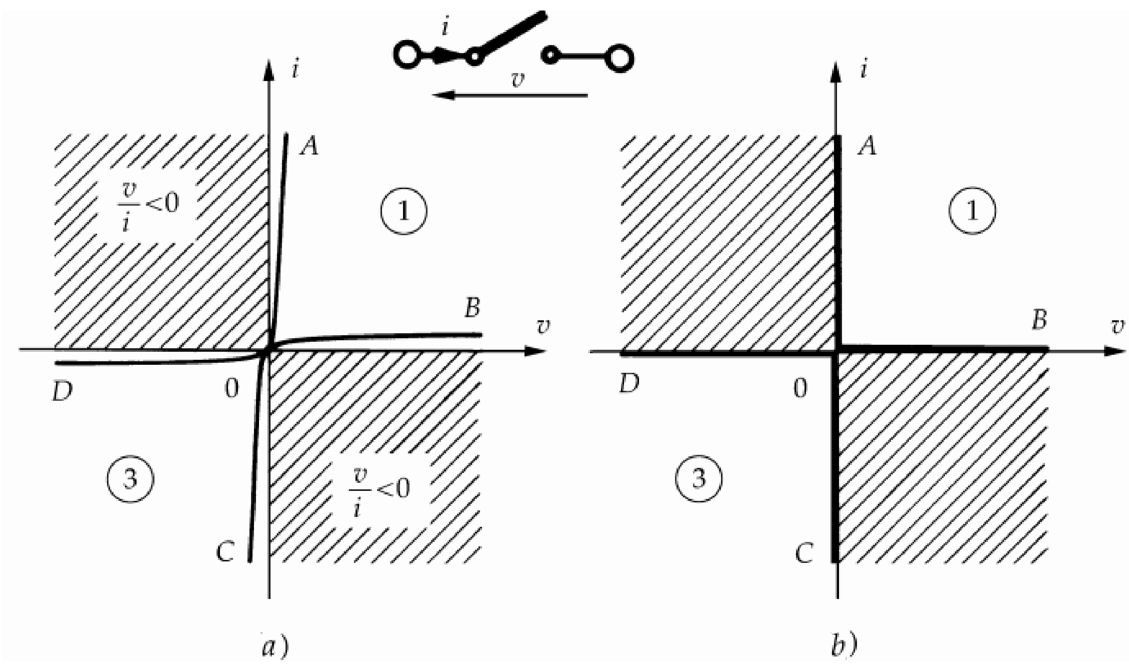


Figure 2.1

A semiconductor switch, like a mechanical switch, is equivalent to a resistor:

• very weak when closed,

• very strong when open, but always positive.

Its operating point can only be located in quadrants 1 and 3 of the plane [v, i] where v/i is positive. The transition from one of these quadrants to the other can only be done by passing through point O. The low voltage found across its terminals when closed is called direct voltage drop. The small current that flows through it when it is blocked is called leakage current.

Since a static switch operates on an all or nothing basis, apart from switching, its operating point can only move on the following branches or segments:

- OA, closed with a direct current ($i > 0$, $v > 0$ very weak),
- OB, open with direct polarization ($v > 0$, $i > 0$ very weak),
- OC, closed with a reverse current ($i < 0$, $v < 0$ very weak),
- OD, open with reverse polarization ($v < 0$, $i < 0$ very weak).

A static switch is characterized by:

- The set of segments that comprises its characteristic $v - i$; we thus distinguish between two-segment, three-segment and four-segment switches,
- the way(s) in which transitions from the closed state to the open state or the reverse transition take place. Switching is spontaneous or natural if the change results from the natural evolution of the current and the voltage at the terminals under the action of the circuit in which the switch is inserted. Switching is forced if the transition results from a control action on the switch.

As a first approximation, during a simplified study of circuits, we assume perfect switches:

• zero direct voltage drop,

• zero leakage current,

• zero switching duration.

The branches of the static characteristics become straight line segments merging with the axes (figure 2.1b).

2-1- Two-segment switches

When the characteristic $v - i$ of a switch has only two segments, one corresponds to the closed state (branch OA or OC) and the other to the open state (OB or OD), these segments belonging to or not in the same quadrant.

2-1-1- Diode

A switch whose two segments are in different quadrants of the $v - i$ plane is an uncontrolled switch. It performs the diode function.

The diode is a component with two electrodes, the anode A and the cathode K, without a control electrode. Its operation is totally imposed by the circuit in which it is inserted.

When this circuit tends to pass a current in the direct or permeable direction, that is to say from A to K, the diode is conducting or passer-by.

When this circuit applies a negative or reverse voltage across its terminals, the diode is blocked or insulating.

Figure 2.2 shows the representative symbol of the diode and the two segments of its simplified static characteristic. The transition from one segment to another, in one direction or the other, is necessarily carried out through point O; switching is spontaneous.

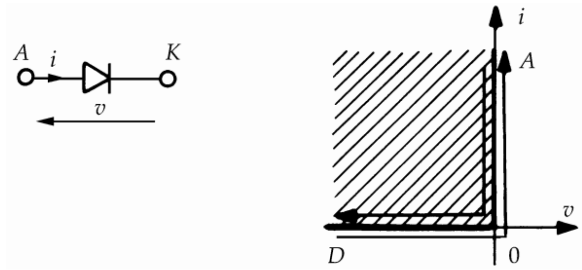


Figure 2.2

2-1-2- Power transistor

Figure 2.3 represents the $v - i$ characteristic of a transistor. Figure 2.4 shows the symbols used to represent different types of transistors.

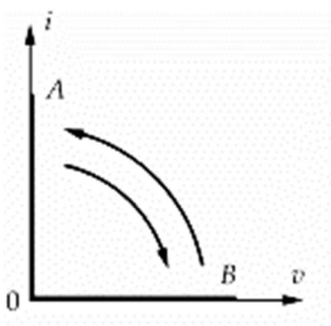


Figure 2.3

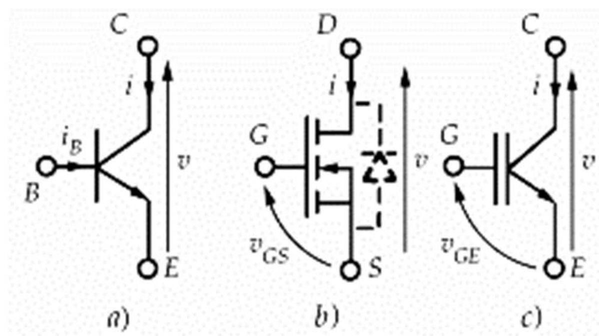


Figure 2.4

a) Bipolar transistor

It is represented in Figure 2.4 (a). It is a fully controlled component when closing and opening. it is not reversible in current, only allowing Ic > 0 to pass. it is not reversible in voltage, only accepts VCE > 0 when it is blocked.

Principal of functioning

Blocked transistor (OFF): Ib = 0 ⇒ Ic = 0, VCE (source voltage)equivalent to open switch.

Saturated transistor (ON): VCE = 0 imposed by Ib, Ic saturated transistor reaches a limit value called saturation, Isat equivalent to a closed switch.

Mode of functioning of a transistor

Ib = 0, Ic = 0 (open switch)

Ib > 0, Ic = β.Ib (amplifier)

IB = Ibsat, Ic = Icmax (close switch)

b) Power MOS (Metal Oxide Semiconductor) transistor

It is represented in Figure 2.4 (b). It is a fully controlled component when closing and opening. he is passing thanks to VGS it is isolated from the rest of the transistor, which provides a very high gate-source impedance. the grid therefore does not absorb any current in steady (permanent) state. the drain-source junction can then be compared to a very low resistance (closed switch). We block it with VGS=0.

Principal of functioning

Blocked transistor (OFF): the equivalent of an open switch VGS= 0, ID=0

Saturated transistor (ON): the equivalent of a close switch VGS > 0, ID > 0.

c) Power IGBT (Insulate Gate Bipolar Transistor)

It is represented in Figure 2.4 (c). It is a bipolar transistor with an insulated gate resulting from a mixture between bipolar and MOS (hybrid transistor). It is totally controlled. The bipolar transistor ensures a better on-state VCE drop than the MOS. MOS is more advantageous due to its voltage control.

2-2- Three-segment switches in voltage reversible case

The characteristic $v - i$ of a three-segment voltage reversible switch includes:

• the OA branch in the on state,

• the OB and OD branches in the blocking state.

It makes it possible to combine controlled switching between segments OB and OA and spontaneous switching between segments OA and OD.

2-2-1- Thyristor

Figure 2.5 gives the representative symbol of the thyristor and shows the three segments of its characteristic. A thyristor has three terminals: the anode A and the cathode K, between which it plays the role of switch, and the trigger G which forms the control port with the cathode.

it is unidirectional (current passes in only one direction), controlled on closing, reversible in voltage (VAK > 0, VAK < 0) and not reversible in current (IAK > 0).

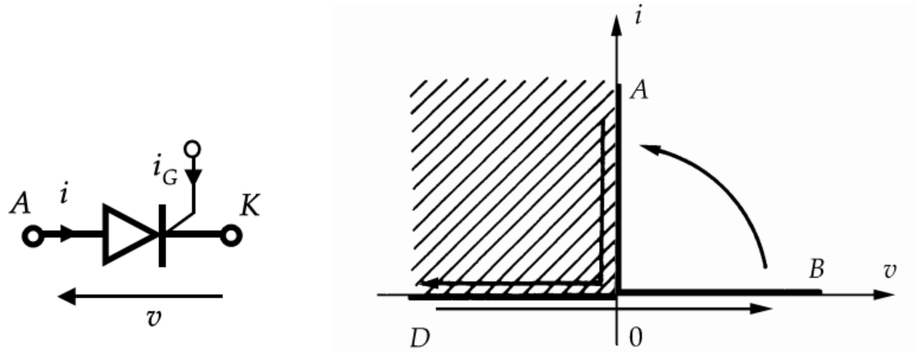


Figure 2.5

Principal of functioning

In the OFF state: the Ig= 0, IAK = 0. Blocked when the voltage is negative (branch OD), the reminder if *v* is positive (branch OB)

We distinguish two types of blockages: - Natural blockage IAK = 0

- Forced blockage by the inversion of VAK.

In the ON state: priming is obtained by a trigger current Ig > 0 of sufficient amplitude while Vak > 0, here it can be possible to move from OB to OA. But, as soon as the current *i* exceeds a certain value called “latching current” (courant d’accrochage), the component locks in the on state and the command can be removed without causing a return to the OB branch.

The return to the blocking state can only occur spontaneously by passing from the OA branch to the OD branch. The operating point must then remain on this branch for a sufficient time, called defusing time (temps de désamorçage), so that the thyristor remains blocked when the voltage *v* becomes positive again.

2-2-2- Thyristor (GTO) (Gate Turn Off)

Its property is that it can be blocked using the trigger. it is used for high power switching. Its representative symbol (Figure 2.6) is the same as that of the ordinary thyristor, except that a dash perpendicular to the gate connection means that the current injected into the trigger-cathode circuit can be positive or negative.

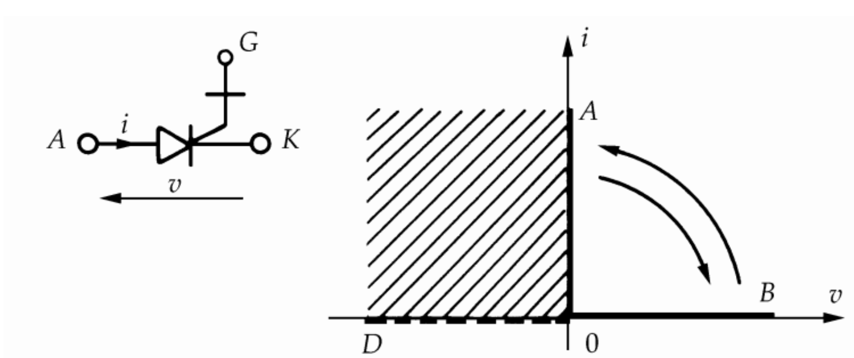


Figure 2.6

Principal of functioning

In the ON state (passage from OB to OA): priming is done by the trigger, the trigger current can be a few A. once conduction has started, it is necessary to maintain the trigger current at a slightly positive value to ensure a good current distribution within the component.

In the blocked state: this type of thyristor consists of diverting almost all of the anode current into the trigger. spontaneous blocking by passing from the OA branch to the OD branch operates as for the classic thyristor.

In practice, a negative voltage is applied to the trigger (G) where VGK < 0 to divert the current. the operation must have a minimum duration in order to ensure reliable blocking.

2-2-3- Transistor and diode association

We can also make a three-segment voltage-reversible switch by combining a diode and a transistor in series (figure 2.7). The control (ON-OFF) of the transistor ensures the transition from OB to OA and the reverse transition when *v* and *i* are positive.

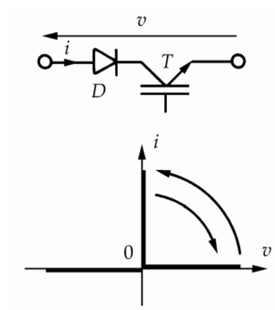


Figure 2.7

• When an ON command is applied to the transistor, it is the diode which sets the state of the switch: it is on if *v* is positive, it remains blocked if *v* is negative.

• When an OFF command is applied to the transistor, the component is or remains blocked regardless of the sign of *v*.

2-3- Three-segment switches in current reversible case

2-3-1- Reverse Conducting Thyristor

The RCT (Reverse Conducting Thyristor) thyristor results from the reverse paralleling of a diode and an asymmetrical thyristor (figure 2.8). We can control the closing of the switch when it is blocked with a positive voltage *v* across its terminals by controlling the priming of the thyristor. This conducts as long as the current *i* is positive. When *i* becomes negative, the diode conducts and the thyristor blocks by canceling the current passing through it.

When the current in the diode is zero, the switch is open with a positive voltage *v* at its terminals.

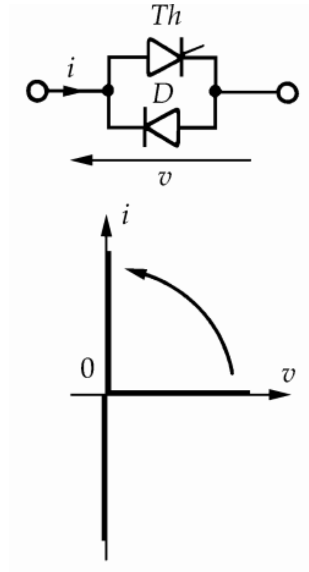


Figure 2.8

2-3-2- Association of a transistor and a diode

By associating in inverse parallel a transistor and a diode (figure 2.9), we obtain a switch which can carry out controlled switching between OA and OB when *v* and *i* are positive, spontaneous switching between OB and OC if the control of the transistor is at the OFF state. We naturally move from segment OA to segment OC and vice versa, if the control of the transistor is in the ON state at the time of the polarity change of *i*.

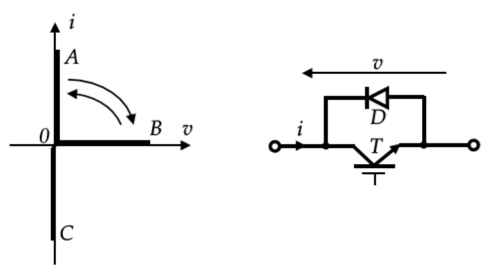


Figure 2.9

The dual thyristor corresponds to a particular operation of this switch. Spontaneous closing is obtained by switching on the diode (passage from OB to OC) and the return to the off state is controlled by the transistor when *i* has become positive (passage from OA to OB) (figure 2.10b). This implies that the control of the transistor is switched from OFF to ON as soon as the diode has activated to allow the transition from OC to OA when *i* changes polarity.

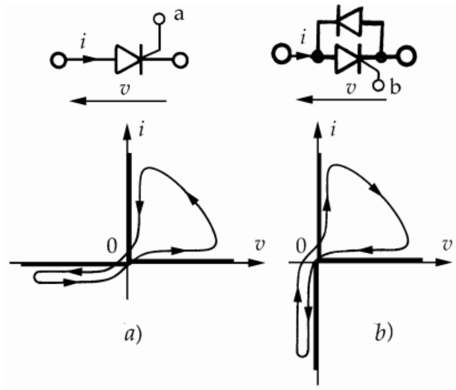


Figure 2.10

The name "dual thyristor" comes from the fact that the trajectory of the operating point thus obtained is deduced from that of the classic thyristor (figure 2.10a) provided that *i* is replaced by *v*, *v* by *i*, controlled firing by controlled blocking.

2-4- Four-segment switches

We obtain a four-segment switch of which only the primings are controlled by associating two symmetrical thyristors in anti-parallel (figure 2.11). At weak power, the two thyristors can be replaced by a single component, the triac, whose single trigger allows firing in both directions.

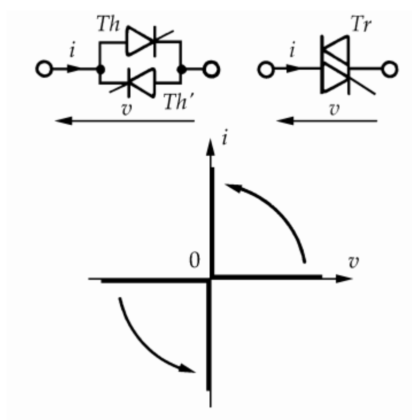


Figure 2.11

We obtain a four-quadrant switch controllable on opening and closing (figure 2.12):

• either by connecting in series two 3-segment switches at current reversible mounted in opposite directions,

• either by connecting two 3-segment switches at voltage reversible in reverse parallel.

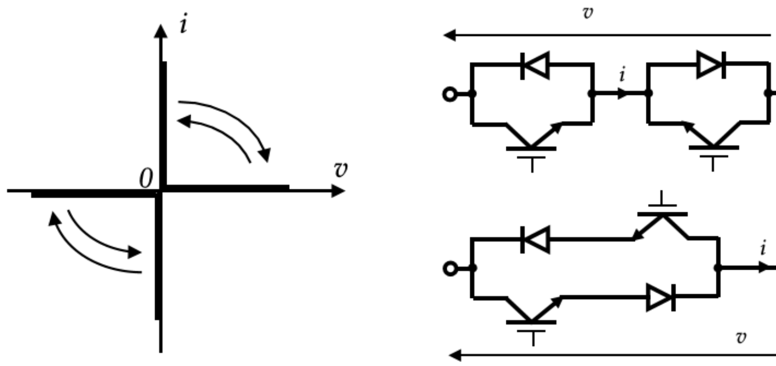


Figure 2.12

The arrays of two transistors and two diodes can be replaced by an array of one transistor and four diodes mounted in a bridge (figure 2.13).

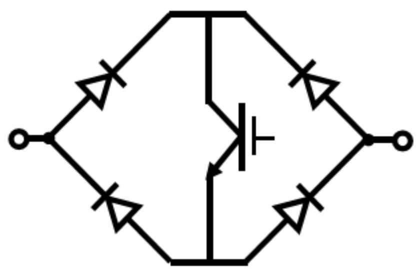


Figure 2.13

3- Converter and reliability

As any energy transfer is accompanied by losses (see below in Figure 2.14), this results for each converter in a non-unitary efficiency (less than 1) and given by:

$$\eta = \frac{W_{useful}}{W_{total}} = \frac{W_{useful}}{W_{useful} + W_{losses}}$$

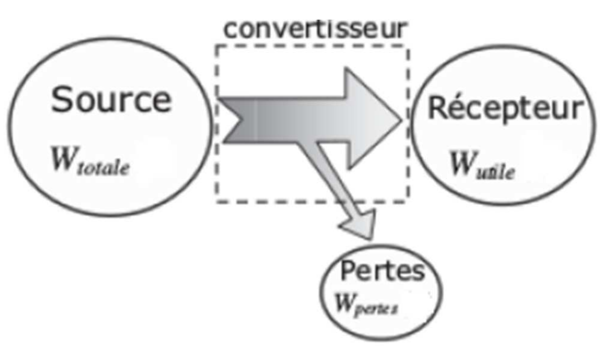


Figure 2.14

A circuit with poor efficiency (i.e. significant losses compared to the useful power) heats up unnecessarily, requires an oversized power supply, and therefore rhymes with an inflated weight and price. The efficiency of an energy conversion system is therefore a fundamental and determining quantity in technological choices.

3-1- Linear converter

A "linear" converter is any energy conversion circuit based on the use of linear components (resistors, inductors, capacitors). Whether in continuous or sinusoidal mode, it is possible to model such a circuit using the Thévenin equivalent diagrams shown in the figure below (Figure 2.15).

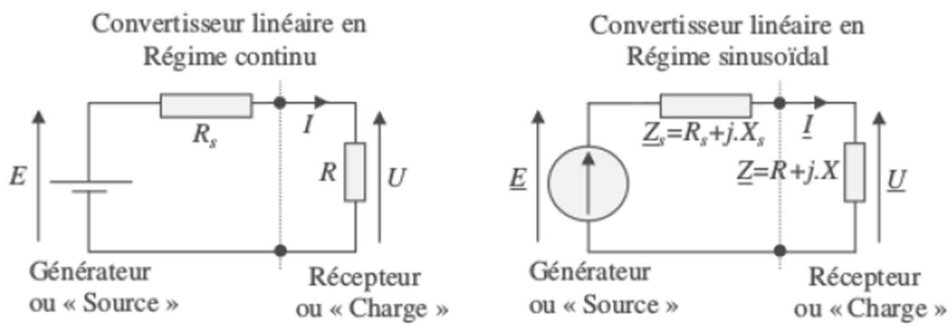


Figure 2.15

3-2- Cutting converter

We call "cutting converter" any electrical energy conversion circuit based on the use of non-linear components of the "switch" type intended to work in "all or nothing", i.e. diodes, transistors, thyristors, etc. (See figure below Figure 2.16).

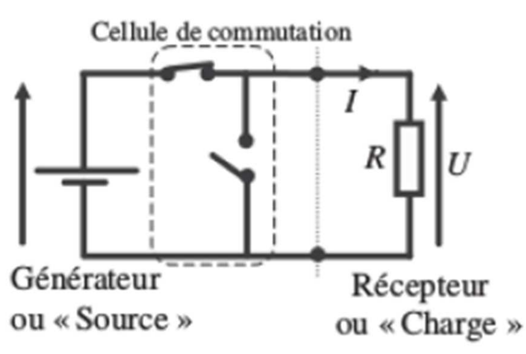


Figure 2.16

The main characteristic of cutting converters is that they require very low power dissipation. This dissipated power is due to the low impedance of the switches in conduction and switching mode.

4- Forced switching and natural switching

The semiconductors used in power electronics converters can be compared to switches, alternately closed or open.

4-1- Forced switching

A switch at forced switching must receive a control signal to cause opening or closing. applied to direct current circuits:

-We obtain it when we have a reverse bias or the current is below the maintaining current.

-Capacitor and inductor are used.

- Forced switching is applied to choppers and inverters.

4-2- Natural switching

On the other hand, we call a natural switching, if the opening or closing of the switch leads to changes in external operating conditions and therefore occurs triggers any control signal.

This phenomenon exists in:

- phase controlled rectifier.
- voltage controllers.
- cyclo converters.

4-3- components used in natural and forced switching

- Transistor (forced opening – forced closing).
- Thyristor in direct bias (forced opening – forced closing).
- Thyristor in reverse bias (natural opening).
- Diode in direct polarization (natural closure).
- Diode in reverse polarization (natural opening).

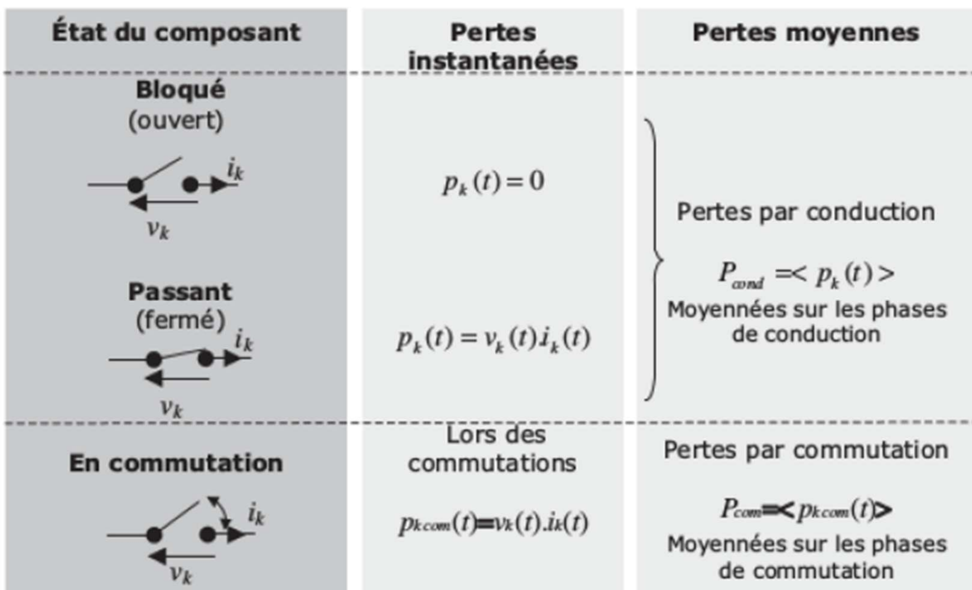
5- Calculation of the energy losses

Static cutting converters are generally high efficiency circuits. Even if they are relatively weak compared to the powers transmitted, the losses associated with switches (diodes, transistors, etc.) are often non-negligible and it is important to know how to calculate or estimate their values. In other words, these components are the source of losses which require the presence of thermal evacuation (cooling) devices.

There are two basic types of losses:

- Conduction losses, due to the fact that the passage of current is accompanied by a slight drop in voltage across the component.

- Switching losses, due to the fact that each blocking or each controlled priming is accompanied by a certain quantity of energy lost.



Noticed: In all cases, the term “losses” designates the average power consumed by the component during a complete period of operation.

5-1- General expressions for conduction and switching losses:

To better understand the meaning and writing of losses, the figure below represents the reading of the voltage and current associated with an IGBT transistor working in controlled switching within a BUCK chopper.

The following points can be seen in figure 2.17:

- When current passes through the transistor, that is to say during the conduction phase, the voltage Vk is not zero. This on-state voltage is classically worth a few tenths of a volt to a few volts, it is denoted Vk_on, on the graph. This voltage being almost constant in this example, the conduction losses will be written as follows:

$$P_{k_{on}} =< V_{k_{on}}.I_k \geq V_{k_{on}}.< I_k >$$

- By observing the zooms carried out on the switchings (priming and blocking), zones of "overlap" of the current and voltage of the component appear (mainly at the blocking level in this example). This means that the instantaneous power consumed by the component, equal to the product, is not zero during these phases, which are periodic, and that thus an average power is consumed by the component. This power represents the switching losses.

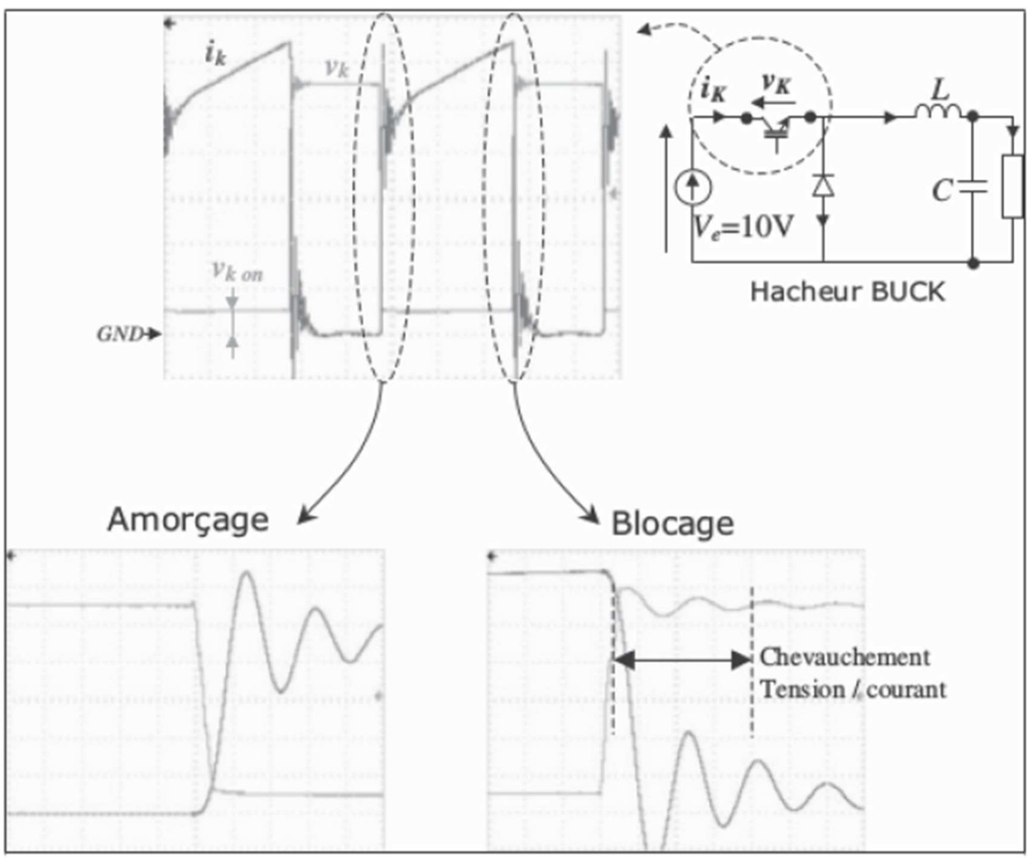


Figure 2.17

The figure below (Figure 2.18) thus represents, over a period, the appearance of the product, that is to say the instantaneous power consumed by the transistor; the area under the curve presented here corresponding to the energy consumed by this transistor.

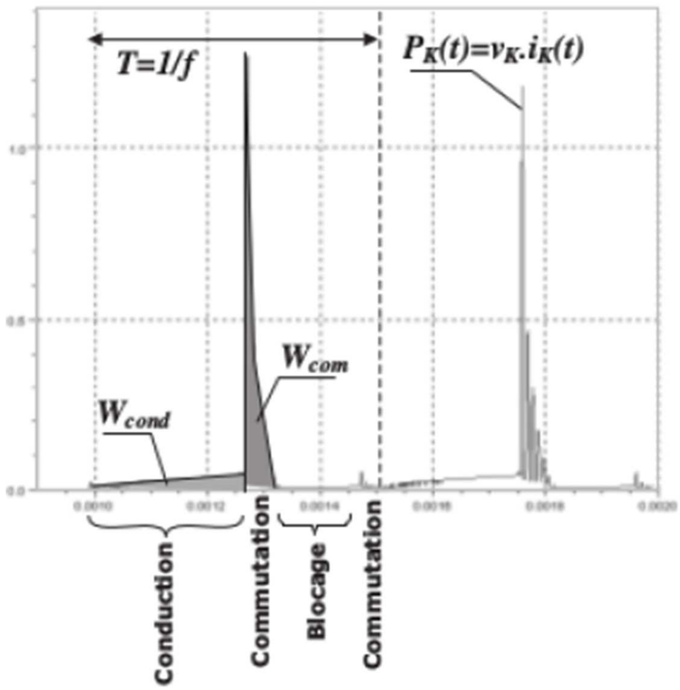


Figure 2.18

Two particular areas are dissociated so as to show the energy consumed by conduction and that consumed during switching:

As the losses correspond to the average values of the associated powers, we will write:

$$P_{cond} = \frac{1}{T}.\int_T P_{kcond}\,(t).dt = \frac{1}{T}.W_{cond}$$

In the same way:

$$P_{com} = \frac{1}{T}.\int_T P_{kcom}\,(t).dt = \frac{1}{T}.W_{com}$$

Noticed: The power lost by switching is directly proportional to the frequency of use. (In practice, this “energy linked to switching” is even sometimes specified in certain technical documentation. Under the name of switching losses.

5-2- Special expressions of losses linked to components.

5-2-1- Losses associated to diodes.

The current and voltage developments associated to the diodes always show the cancellation of the current before the appearance of the voltage and vice versa. As a result, the diodes have minimal switching losses, almost negligible. On the other hand, the existence of a systematic voltage in the on state leads to inevitable conduction losses. The figure below (Figure 2.19) shows the equivalent diagram of a diode.

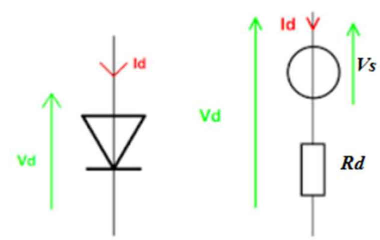


Figure 2.19

In the passing state, we can write:

$$v_d = V_s + r_d.i_d$$

In this specific context, the conduction losses are written as:

$$P_{dcond} = V_s. < i_d > + r_d. < {i_d}^2 >$$

Such that $< {i_d}^2 > = {I_{eff}}^2$the square of the effective value of the diode current.

So :

$$P_{dcond} = V_s.i_{d\,average} + r_d.{i_{d\,eff}}^2$$

This academic expression is interesting. But suffers from the fact that the precise values of the threshold voltage Vs and Rd are sometimes not informed by the documentation and are quite variable depending on the temperature of the component. Consequently, it is often simpler and more "technological" to use the voltage Vf in the on state (corresponding to the maximum voltage drop), to write:

$P_{dcond} = < V_d.i_d > \approx < V_d.i_d > = V_f . < i_d >$ Or: $P_{dcond} \approx V_f . i_{d\,average}$

Noticed:

In the documentation, the term AV (Average) designates an average value ($I_{f\_AV} = I_{d\_moy}$) and the term RMS (Root Mean Square) an effective value ($I_{f\_RMS} = I_{d\_RMS}$).

5-2-2- Losses associated with MOS transistors.

MOS transistors are widely used in the field of small and medium powers. Regarding their losses, a MOS transistor is simply equivalent to a resistance between its drain and its source when it is RDS_ON.

The value of this resistance is one of the major technical data of the component since it makes it possible to directly write the expression of the losses associated with conduction.

$$P_{MOS\,cond} = R_{DS\,on}.I_{d\,eff}^{2}$$

Switching losses in this type of transistor are linked to the overlaps of current and voltage and especially to the time this overlap lasts. We will then remember that the predominant parameters which condition the formulation of the losses are two durations, two “times”: Ton and Toff, the values of which are specified by the technical documentation of the components. However, knowing these times alone is not enough since the voltage and current overlaps depend on the components associated with the MOS within the switching cell. The principle of calculation is detailed in the following pages (“losses associated with a switching cell”).

5-2-3- Losses associated to IGBT transistors.

IGBT transistors are widely used in the field of medium and high powers, and we also encounter in this component the two types of losses mentioned above. When it comes to conduction losses, the important thing to know is that an IGBT transistor is analogous to a bipolar transistor with respect to its collector/emitter (CE) junction. It is thus, like the bipolar transistor, used in switching in “saturated/blocked” mode, which means that it only conducts current in the saturation state. Consequently, the collector/emitter junction is the seat of a minimal, but not negligible, on-state voltage called VCE. The value of this voltage, given by the technical documentation, makes it possible to easily write the conduction losses :

$$P_{IGBT\,cond} = V_{CE\,sat}.I_{c\,average}$$

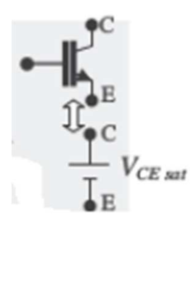


Figure 2.20

5-2-4- losses associated to a switching cell

a) Switching cell

In power electronics circuits, switches are actually not used in a huge variety. Concretely, as they directly connect, by switching, energy sources to receivers that often behave in a particular way, they must ensure the rules for interconnecting these sources. As a voltage source can only be connected to a current source, we will notice throughout the chapters that the circuits will always revolve around a structure called a "switching cell", shown in the figure below (Figure 2.21).

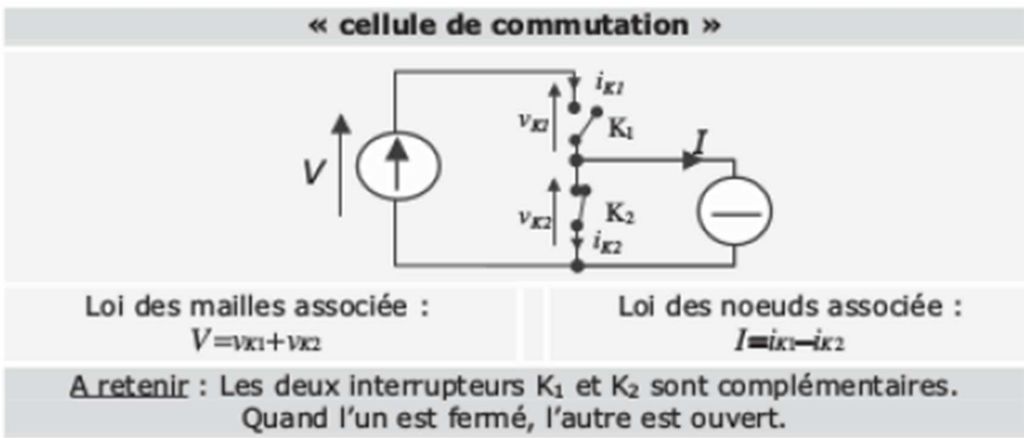


Figure 2.21

In this structure, the two switches must also never "short-circuit" the voltage source nor "open" the current source; consequently, they must always be opened and closed in an absolutely complementary manner to each other. When it comes to controlled components, they are controlled by a signal forcing one to drive, the other to be permanently blocked; we then speak of “additional control”.

b) Losses

As an illustration, the figure below (Figure 2.22) represents a “Transistor/Diode” type switching cell, naturally placed between a voltage source and a current source. The shapes of the currents and voltages associated with the switches are represented during switching.

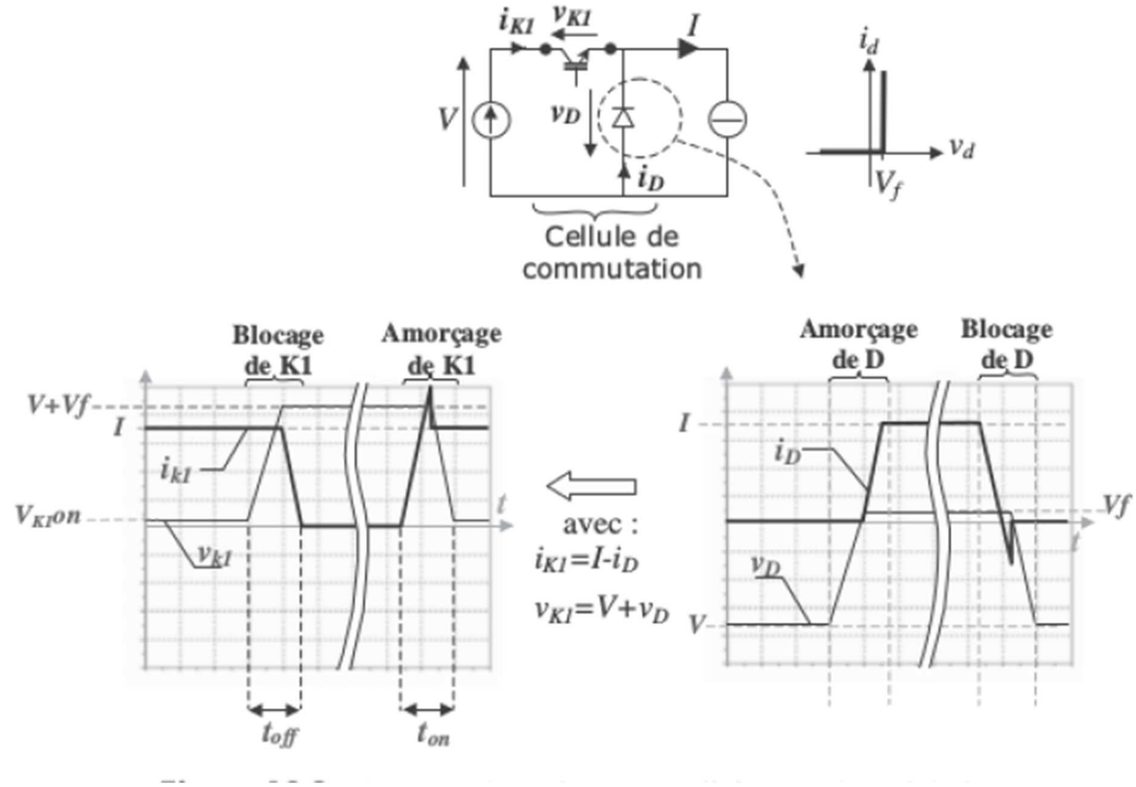


Figure 2.22

This figure shows many points that must be identified correctly: - The characteristic developments of its natural switching appear on the chronogram. Indeed, we see that the voltage is canceled before the establishment of the current and that the current is also canceled before the establishment of the voltage (no losses by switching). - The changes in the quantities are not, moreover, instantaneous and the curves show slopes during switching which correspond to overall durations linked to switching called ton and toff (named thus with respect to the transistor). - The diode also produces a small reverse current peak when it is blocked. This inevitable phenomenon is called "reverse recovery peak" and is linked to the reorganization of the carriers in the semiconductor structure of the diode. This particular current is all the more obvious as the operating frequency is high and the duration of the peak, which must be small compared to the period, even imposes a limit on the frequency of use of the diode. - The current ik1 which passes through the transistor is deduced from the evolution of the current in the diode, knowing that the law of nodes imposes: ik1=I-iD. It will thus be noted that the reverse recovery peak of the diode is reflected in the transistor current. - The voltage across the transistor is

Vk1, also deduced from the voltage across the diode according to Ohm's law: Vk1=V+VD.

- The construction of the current/voltage couple of the transistor is thus revealing: the quantities "overlap" during switching and the presence of losses linked to these phases is obvious. To illustrate this, the figure below (Figure 2.23) represents the evolution of the product (ik1 X Vk1) which is none other than the evolution of the power consumed by the transistor: Pk1 (t).

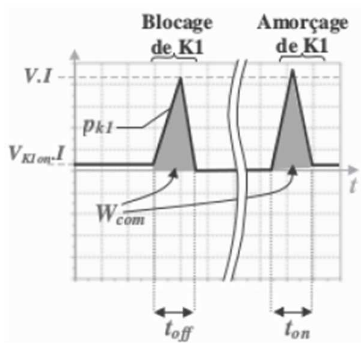


Figure 2.23

- The simplified curves thus reveal a direct writing of the energy involved in the switching, which is represented by the area under the power curve. This energy is written (neglecting the presence of the overlap peak and the on-state voltage):

$$W_{com} = \frac{1}{2}.V.I.t_{on} + \frac{1}{2}.V.I.t_{off}$$

- We will thus retain in a simplified way the expression of this energy and the corresponding average power (knowing that f switchings occur per second):

$$W_{com} = \frac{1}{2}.V.I.(t_{on} + t_{off}) \quad \text{and} \quad P_{com} = f.W_{com}$$

Conduction losses can also be formalized. As the on-state voltage of the transistor is assumed to be constant (or assimilated to its maximum value by default):

$$P_{K1\,cond} = < V_{K1}(t)\,.\ i_{K1}(t) >$$

In the same way for the diode:

$$P_{Dcond} = V_f. < i_D >$$

and we will therefore retain:

$$P_{cond} = < V_{K1}.i_{K1} > + V_f . < i_D >$$

Noticed: Use the formulations established previously for the calculation of conduction losses (IGBT / MOS).