Power converters: definitions, classification and converter topologies

F. Bordry
CERN, Geneva, Switzerland

Abstract
This paper introduces power conversion principles and defines the terminology. The concepts of sources and switches are defined and classified. From the basic laws of source interconnections, a generic method of power converter synthesis is presented. Some examples illustrate this systematic method. Finally, the notions of commutation cell and soft commutation are introduced and discussed.

1 Introduction
The task of a power converter is to process and control the flow of electric energy by supplying voltages and currents in a form that is optimally suited for the user loads.

Energy was initially converted in electromechanical converters (mostly rotating machines). Today, with the development and the mass production of power semiconductors, static power converters find applications in numerous domains and especially in particle accelerators. They are smaller and lighter and their static and dynamic performances are better.

A static converter is a meshed network of electrical components that acts as a linking, adapting or transforming stage between two sources, generally between a generator and a load (Fig. 1).

An ideal static converter controls the flow of power between the two sources with 100% efficiency. Power converter design aims at improving the efficiency. But in a first approach and to define basic topologies, it is interesting to assume that no loss occurs in the converter process of a power converter. With this hypothesis, the basic elements are of two types:

- non-linear elements, mainly electronic switches: semiconductors used in commutation mode [1];
- linear reactive elements: capacitors, inductances and mutual inductances or transformers. These reactive components are used for intermediate energy storage but also for voltage and current...
This introductory paper reviews and gives a precise definition of basic concepts essential for the understanding and the design of power converter topologies. First of all the sources and the switches are defined. Then, the fundamental connection rules between these basic elements are reviewed. From there, converter topologies are derived. Some examples of topology synthesis are given.

Finally, the concept of hard and soft commutation is introduced.

2 Sources

As mentioned in the introduction, a power converter processes the flow of energy between two sources. To synthesize a power converter topology, the first step is to characterize these sources. We shall see later that the converter structure can be directly deduced as soon as the sources are defined: voltage or current sources and their reversibilities.

In the energy conversion process, a source is mainly a generator (called often input source) or a load (called output source). However, in the case of a change of direction of the energy flow, i.e., a change in the sign of the power, the sources (generators and loads) can exchange their functions (i.e., restitution of energy of a magnet towards the grid).

2.1 Nature of sources

2.1.1 Definitions

There are two types of sources: voltage and current sources. As mentioned earlier, any of these sources could be a generator or a receptor (load).

A source is called a **voltage** source if it is able to impose a voltage regardless of the current flowing through it. This implies that the series impedance of the source is zero (or negligible in comparison with the load impedance)

A source is called a **current** source if it is able to impose a current regardless of the voltage at its terminals. This implies that the series impedance of the source is infinite (or very large in comparison with the load impedance).

These definitions correspond to permanent properties. The principle of operation of a converter is based on the switch mode action of its switches. Commutations of the switches generate very fast current and/or voltage transients so that the transient behaviour of the sources is fundamental for converter design. The transient behaviour of a source is characterized by its ability or inability to withstand steps generated by the external circuit in the voltage across its terminals or in the current flowing through it. Then new definitions could be stated:

- a source is a **voltage source** if the voltage across its terminals can not undergo a discontinuity due to the external circuit variation. The most representative example is the capacitor since an instantaneous change of voltage across its terminals would mean an instantaneous change of its charge which would require an infinite current;

- a source is a **current source** if the current flowing through it can not undergo a discontinuity due to the external circuit variation. The most representative example is the inductance since an instantaneous change in current would correspond to an instantaneous change in its flux which would require an infinite voltage.
This is shown in Fig. 2.

It should be noted that a square wave voltage generator (respectively a current generator) is indeed a voltage source (respectively a current source) as defined above since the voltage steps (respectively current steps) are not caused by the external circuit.

With these definitions, it is interesting to define the notion of instantaneous impedance of a source as the limit of the source impedance when the Laplace operator tends towards infinity. Theoretically this instantaneous impedance can be zero, finite or infinite.

A source is referred to as a voltage source when its instantaneous impedance is zero, while a source is called a current source if its instantaneous impedance is infinite.

For example:

Capacitor: \( Z(s) = 1/(Cs) \), \( \lim_{s \to \infty} Z(s) = 0 \Rightarrow \) voltage source.

Inductance: \( Z(s) = Ls \), \( \lim_{s \to \infty} Z(s) = \infty \Rightarrow \) current source.

The determination of the source reversibilities is fundamental. We shall see that the static characteristics of the switches can be derived from the reversibility analysis.

The voltage (or the current) that characterizes a source is called DC if it is unidirectional. As a first approximation, it can be taken as constant. The voltage (or the current) is called AC if it is periodic and has an average value equal to zero. As a first approximation, it can be taken as sinusoidal.

A source is voltage-reversible if the voltage across its terminals can change sign. In the same way, a source is current-reversible if the current flowing through it can reverse.

In summary, the input/output of a converter can be characterized as voltage or current sources (generator or loads), either DC or AC, current-reversible and/or voltage-reversible. There are only eight possibilities, as shown in Fig. 3.
2.1.2 Source nature modification

Connecting in series an inductance with an appropriate value to a voltage source (that is a dipole with zero instantaneous impedance) turns the voltage source into a current source. In the same way, connecting in parallel a capacitor of appropriate value to a current source (dipole with infinite instantaneous impedance) turns the current source into a voltage source (Fig. 4).

These inductive or capacitive elements connected in parallel or in series with the source can temporarily store energy. Consequently, if an inductance connected to a voltage source turns it into a current source, it is important to determine the current reversibility of this source.

In practice, the identification of a real generator or of a real load with a voltage or current source is not obvious. This is why the nature of the source is often reinforced by the addition of a parallel capacitor in the case of voltage sources and by the addition of a series inductor in the case of current sources.

Obviously, the current source obtained by connecting an inductance in series with a voltage source keeps the same current reversibility as the voltage source. The inductance acts as a buffer absorbing the voltage differences. Consequently, the current source obtained by connecting a series inductance to a voltage source is reversible in voltage. When the voltage source itself is reversible in voltage there is no particular problem. But, if the voltage source is not reversible in voltage, the
current source obtained by connecting a series inductance to the voltage source is only instantaneously reversible with respect to voltage.

The former result can easily be transposed to the voltage source obtained by connecting a capacitor in parallel with a current source. The voltage source thus obtained keeps the same voltage reversibility as the current source and is reversible in current. However, this reversibility is only instantaneous if the current source is not reversible in current.

2.1.3 Example

The set of ideal batteries shown in Fig. 5 behaves as a load during charging and as a generator during discharging; such a source is called a DC voltage source, current-reversible but not voltage-reversible. Nevertheless, because of the inductance of the connecting cables, this battery can sometimes be taken as a current source instantaneously voltage-reversible and permanently current-reversible. If a capacitor bank is added at the terminals of the cables, it becomes again a voltage source.

3 Switches characteristics

Static converters are electrical networks mainly composed of semiconductor devices operating in the switch mode (switches); through proper sequential operation of these components, they transfer energy between two sources with different electrical properties.

Minimizing the losses in the switches maximizes the efficiency of the converter. These switches must have a voltage drop (or an ON resistance) as low as possible in the ON-state, and a negligible leakage current (or an OFF resistance) in the OFF-state. These two states are defined as static states.

The change from one state to the other (switch commutation) implies a transient behaviour of the switch. This behaviour is complex because it depends on the control of the switch (through a gate control) and on the conditions imposed by the external circuit.
3.1 Static characteristics

In the static domain, a switch has the same behaviour as a non-linear resistance: very low in the ON-state and very high in the OFF-state.

Taken as a dipole with the load sign convention (Fig. 6), the static characteristics $I_k(V_k)$, which represents the operating points of a switch, are made up of two branches totally located in quadrants 1 and 3 such that $V_k \times I_k > 0$. One of these branches is very close to the $I_k$ axis (ON-state) and the other is very close to the $V_k$ axis (OFF-state). Each of these branches can be located in one or two quadrants. In the case of an ideal switch, the static characteristics are the half-axis to which they are close.

![Fig. 6: Static characteristics of a switch](image)

In this representation, any switch which behaves really as a switch (commutation: ON $\leftrightarrow$ OFF), has a static characteristic consisting of at least two orthogonal half-axes (or segments) except for the obvious cases of the short circuit and of the open circuit which correspond, respectively, to a switch always ON and to a switch always OFF.

The static characteristics, an intrinsic feature of a switch, are reduced to a certain number of segments in the $I_k(V_k)$ plane:

- **two-segment characteristics**: the switch is unidirectional in current and in voltage. Two two-segment characteristics can be distinguished: in the first case, current $I_k$ and voltage $V_k$ are of the same sign; in the second case, current $I_k$ and voltage $V_k$ are of opposite sign. The switches having such characteristics are respectively called T and D switches (Fig. 7);

![Fig. 7: Static characteristics of a two-segment switch](image)
three-segment characteristics: the switch is bidirectional in current and unidirectional in voltage, or vice versa. Therefore there are two types of three-segment static characteristics (Fig. 8). Note that these two types of switches could be synthesized with the association in parallel or in series of two-segment switches (T and D).

![Fig. 8: Static characteristics of a three-segment switch](image)

four-segment characteristics: the switch is bidirectional in voltage and in current. There is only one such type of static characteristic (Fig. 9). A four-segment characteristic could be obtained by a connection in series or in parallel of switches with three-segment characteristics.

![Fig. 9: Static characteristics of a four-segment switch](image)
3.2 Dynamic characteristics

The dynamic characteristics is the trajectory described by the point of operation of the switch during its commutation, going from one half-axis to the perpendicular half-axis. A switch being either ON or OFF, there are two commutation dynamic characteristics corresponding to the turn-ON and to the turn-OFF, which will be grouped under the global term of dynamic characteristics.

Unlike the static characteristics, the dynamic characteristics is not an intrinsic property of the switch but depends also on the constraints imposed by the external circuit. Neglecting second-order phenomena and taking into account the dissipative nature of the switch, the dynamic characteristics can only be located in those quadrants where $V_k \times I_k > 0$ (generator quadrants). For the two commutations (turn-ON and turn-OFF), two modes are possible: controlled commutation and spontaneous commutation.

3.2.1 Controlled commutation

In addition to its two main terminals, the switch has a control terminal on which it is possible to act in order to provoke a quasi-instantaneous change of state (case of T switch). The internal resistance of this switch can change from a very low value to a very high value at turn-OFF (and inversely at turn-ON). These changes are independent of the evolution of the electrical quantities imposed on the switch by the external circuit.

It should be noted that in a controlled commutation, the switch imposes its state on the external circuit. Under such circumstances, the element can undergo severe stresses that depend on its dynamic characteristics. If the switching time is long and the operating frequency is high, the commutation losses can be important.

3.2.2 Spontaneous commutation

The spontaneous commutations correspond to the turn-OFF when the current flowing through the switch reaches zero and to the turn-ON when the voltage applied across its terminals reaches zero. The spontaneous commutation is the commutation of a simple PN junction (D switch). It only depends on the evolution of the electrical variables in the external circuit. Spontaneous commutations could be achieved with any controlled semiconductor if the gate control is synchronized with the electrical variables of the external circuit. A spontaneous commutation is achieved with minimum losses since the operating point moves along the axes.

It is important to point out that a controlled commutation can happen only in the first or third quadrants while a spontaneous commutation can happen only with a change of quadrant (Fig. 10).
3.3 Classification of switches

Finally, switches used in power converters can be classified by their static characteristics (two, three or four segments) and by the type of commutation (controlled or spontaneous) at turn-ON and at turn-OFF.

3.3.1 Two-segment switches

Two switches with two-segment characteristics can be distinguished (not counting the open circuit and the short circuit) (Fig. 11):

- The first of these switches has the static characteristics of a D switch and its turn-ON and turn-OFF commutations are spontaneous. This switch is typically a diode.

- The second of these switches has the static characteristics of a T switch and its turn-ON and turn-OFF commutations are controlled. It is a power semiconductor: MOSFET, IGBT, GTO, IGCT, etc.

This switch will be symbolized by separating the turn-ON and turn-OFF control gates as shown on Fig. 11.

A switch with two-segment characteristics similar to the T type (both segments in the same quadrant), must have controlled turn-ON and turn-OFF commutations. Should it have only one controlled commutation, it would then be necessary to put in series or in parallel a D switch (a diode) to get the spontaneous commutation. In this case, it is no longer a two-segment switch but a three-segment one. Therefore, only two two-segment switches can be used directly.

![Fig. 11: Dynamic characteristics of two-segment switches](image)

3.3.2 Three-segment switches

These switches can be divided into two groups depending on whether they are

- unidirectional in current and bidirectional in voltage (Fig. 12);

- bidirectional in current and unidirectional in voltage (Fig. 13).
Except for the thyristor, all these switches are synthesized switches, realized by connecting a diode in parallel or in series with a two-segment switch. A special driver is needed to obtain the spontaneous commutation. The ‘dual-thyristor’ (unidirectional in voltage, bidirectional in current, controlled turn-OFF and spontaneous turn-ON) is a good example of a useful three-segment switch [3], [4].

In each of these two groups, all switches have the same static characteristics but differ by their commutation mechanisms. It is important to remark that if a three-segment switch has both commutations controlled (turn-ON and turn-OFF) or both spontaneous, it would never use the three segments of its static characteristics. Therefore, a three-segment switch must necessarily have one controlled commutation and one spontaneous commutation.

The cycle of operation, which represents the locus described by the point of operation of these switches, is then fully determined. They can only be used in converter topologies which impose a single cycle of operation on the switches.
3.3.3 Four-segment switches

All four-segment switches have the same static characteristics. They differ only by their commutation modes that can, \textit{a priori}, differ in quadrants 1 and 3. So, six four-segment switches can be distinguished.

These switches are used mainly in direct frequency changers and in matrix converters; in practice they are made up of two three-segment switches connected in series or in parallel.

4 Interconnection of sources: commutation rules

To control the power flow between two sources, the principle of operation of a static power converter is based on the control of switches (turn-ON and turn-OFF) with particular cycles creating periodic modifications of the interconnection between these two sources.

The source interconnection laws can be expressed in a very simple way:

- a voltage source should never be short-circuited but it can be open-circuited;
- a current source should never be open-circuited but it can be short-circuited.

From these two general laws, it can be deduced that a direct connection between two voltage sources or between two current sources can not be established by means of switches, as shown in Fig. 14.

![Fig. 14: Basic interdictions of source interconnection](image)

In the case of two voltage sources, the switch turn-ON can only happen when the two sources have the same values, that is to say at the zero crossing of the voltage across the switch. The turn-ON must then be spontaneous (since it depends on the external circuit) and the turn-OFF can be controlled at any time. In the case of two current sources, the switch turn-OFF can only happen when the two current sources reach the same value, that is to say when the current in the switch reaches zero. In this case, the turn-OFF is spontaneous and the turn-ON can be controlled at any time.

Thus it is obvious that capacitors can be connected in parallel and inductances in series but with zero voltage, respectively, zero current, as is routinely done.

The previous laws forbid the commutation of switches between two sources of the same nature.
5 Structure of power converters

A power converter can be designed with different topologies and with one or several intermediate conversion stages. When this conversion is achieved without an intermediate energy storage stage, the conversion is called direct conversion and is achieved by a direct converter. On the other hand, when this conversion makes use of one or more stages storing energy temporarily, the conversion is called indirect and is achieved by an indirect converter.

The prohibition on connecting two sources of the same nature gives relevance to the following two classes of basic conversion topologies:

- direct link topology: when the two sources have different natures;
- indirect link topology: when the two sources have the same nature.

5.1 Direct link topology converters

A direct converter is an electrical network composed of switches only and is unable to store energy. In such a converter, the energy is directly transferred from the input to the output (assuming the losses can be neglected); the input power is equal to the output power at any time.

Taking into account the interconnection rules recalled above, the possible connections between a voltage source and a current source are shown in Fig. 15. The simplest structure allowing all these connections is the four-switches bridge (Fig. 16):

- with K1 and K3 closed, the connection of Fig. 15(a) is obtained;
- with K2 and K4 closed, the connection of Fig. 15(b) is obtained;
- with K1 and K2 closed (or with K3 and K4 closed), the connection of Fig. 15(c) is obtained.

When some of these connections are not necessary, it is possible to replace the bridge structure by simpler structures using fewer switches (i.e. buck converter).
The energy conversion between an input current source and an output voltage source poses the same problem. The basic configuration is the same but it is more usual to represent the input source on the left and the output source on the right (Fig. 17).

5.2 Indirect converters

It is not possible to directly interconnect two sources of the same nature with switches. It is necessary to add components to generate an intermediate buffer stage of a different type without active energy consumption (capacitor or inductance). This buffer stage is a voltage source (capacitor) if the energy transfer is between two current sources, and it is a current source (inductance) if the energy transfer is between two voltage sources.

5.2.1 Modification of the nature of the input or output source

In the case of the voltage–voltage conversion, one solution consists in adding an inductance in series with the input voltage source or with the output voltage source. With this change of the nature of the source, it is possible to use a direct converter: current–voltage or voltage–current converter according to where the inductance was added (Fig. 18).

The case of the current–current conversion is the opposite of the previous case. A capacitor is added in parallel or in series with the input or with the output current source.
5.2.2 Use of two direct converters

If it is not possible or too costly to modify the nature of one source, two direct converters can be connected with an intermediate buffer stage: an inductance for a voltage–voltage conversion and a capacitor for a current–current conversion (Fig. 19).

5.2.3 Voltage–voltage indirect converters

In the indirect converters, the two voltage sources are never connected directly (see the previous basic laws). Two sequences are then necessary. During the first sequence, the energy is transferred from the input voltage source to the inductance (voltage to current conversion). During the second sequence, the inductance gives back the energy to the output voltage source (current to voltage conversion; two directions are possible) (Fig. 20). An extra switch is necessary to get these sequences.
5.2.4 Current–current indirect converters

In the indirect converters, the two current sources are never connected directly. Two sequences are then necessary. During the first sequence, the energy is transferred from the input current source to the capacitor (current to voltage conversion). During the second sequence, the capacitor gives back the energy to the output current source (voltage to current conversion; two directions are possible) (Fig. 21).
5.3 Conclusion

Figure 22 represents the three basic configurations of all single-phase converters.

From these basic configurations, it is possible, according to the nature of the sources, to associate them or to add other components. For example, in the case where one of the sources is AC, it is possible to insert a transformer for adaptation or galvanic insulation (Fig. 23).

It is also possible to associate several basic topologies. One of the more usual applications is to have an intermediate stage at high frequency to reduce the size of the transformers and magnetic elements and to get a higher performance at the output (bandwidth, ripple, etc.) (Fig. 24).
Figure 25 illustrates the case of resonant converters [5], [6]. Note that the interconnection of the various intermediate sources must respect the interconnection laws. It is especially important when choosing the output filter.

6 Power converter classification

Figure 26 summarizes in tabular form the power conversion topologies.

- The crossed cells correspond to reversibility incompatibilities between the input and output sources.
– Two symmetric cells, with respect to the diagonal D, represent two reversible topologies.

– Two topologies corresponding to two cells symmetric with respect to the point O are dual.

![General power conversion table](image)

Fig. 26: General power conversion table

Figure 27 gives the different types of power converters and their usual names.

![Power converter classification](image)

Fig. 27: Power converter classification
7 Synthesis of power converters

7.1 Synthesis method

A general and systematic method to design power converter topologies goes as follows:

a) determine the nature of input and output sources. Next choose the basic structure (Fig. 22);

b) from the specifications, define the voltage and current reversibilities of the input and output sources corresponding to one configuration of the general table (Fig. 26);

c) from the basic structure, identify the different phases of operation according to the reversibilities and to the energy transfer control. If necessary, simplify the configuration (short-circuit or open switches);

d) for the various phases, check the sign of the current through the ON switches and the sign of the voltage across the OFF switches: the static characteristics $I_k(V_k)$ of each switch are thus defined;

e) from the specifications (desired output current or voltage functions or both), derive the sequential order of the different phases. For every commutation, plot the working point of each switch before and after the commutation;

f) from static and dynamic characteristics, choose the type of each switch (semiconductor type).

7.2 Examples

7.2.1 Non-reversible current chopper

Hypothesis:

- power conversion between a voltage source and a current source;
- these two sources are unidirectional in voltage and in current.

Following the steps of the synthesis method:

a) a direct converter topology can be used;

b) select cell (1,8) of the general table according to the source reversibilities;

c) select sequence 1 (active phase) and 2 (free-wheel phase) of Fig. 28;

d) and

e) the plots of the four switches can be found in Fig. 28 for the two sequences;

f) from the previous plots, it is found that:

K1 is a controlled two-segment switch (T switch) (Fig. 11)

K2 is an inverse D switch

K3 is a short-circuit

K4 is an open-circuit.

The topology of the converter is thus fully determined.
7.2.2 Reversible current chopper

Hypothesis:
- power conversion between a voltage source and a current source;
- the input voltage source is bidirectional in current;
- the output current source is unidirectional in voltage and bidirectional in current.

Following the steps of the synthesis method:
  a) a direct converter topology can be used;
  b) select cell (2,6) of the general table according to the source reversibilities;
  c) select sequence 1 (active phase) and 2 (free-wheel phase) of Figs. 28 and 29;
  d) and
  e) the different plots for the four switches are represented in Fig. 28 for the two sequences of energy transfer from the input source to the output source. Figure 29 represents the analysis of the brake phase: transfer of energy from the output source to the input source.
  f) the analysis of the two phases results in the structure presented in Fig. 30.

Fig. 28: Study of a non-reversible current chopper
Fig. 29: Study of a reversible current chopper: brake phase

Active phase

Brake phase

Fig. 30: Structure of a reversible current chopper
7.2.3 Voltage inverter

Hypothesis:

– power conversion between a voltage source and a current source;

– the input voltage source is unidirectional in voltage and bidirectional in current; it is a DC source of value $E$.

– the output current source is bidirectional in voltage and bidirectional in current; it is an AC source. A $+E, -E$ voltage at the output of the converter is specified.

Following the steps of the synthesis method:

a) a direct converter topology can be used;

b) select cell (2,5) of the general table according to the source reversibilities;

c) the two sequences are shown in Fig. 31;

d) from the analysis of the two sequences, it is found that the switches must be bidirectional in current and unidirectional in voltage. They correspond to three-segment switches (D and T in parallel; Fig. 8);

e) to represent the working point of each switch, it is necessary to give more detailed specifications. Two cases are defined according to whether the output voltage is ahead of the output current or not.

![Fig. 31: Sequences of a voltage inverter](image)

7.2.3.1 Case 1: the output voltage is ahead of the output current

Figure 32 shows the dynamic characteristics based on the analysis of the commutation between the two sequences with the hypothesis that the output voltage is ahead of the output current.

It is clear that the four switches (K1, K2, K3 and K4) are controlled turn-off and spontaneous turn-on switches (dual thyristor; Fig. 13).
The topology of the converter is fully determined and shown in Fig. 33. It is a zero-voltage-switching topology (see Section 9).

7.2.3.2 Case 2: the output current is ahead of the output voltage

An identical approach can be used if the output current is ahead of the output voltage. Figures 34 and 35 represent the dynamic characteristics of the switches and the derived topology. It is a zero-current-switching topology using thyristor with reverse diode in parallel (Fig. 13).
Commutation cell

As discussed in the previous sections, the operation of a static converter can be split into sequences. Distinct electrical networks characterize each sequence. The modification of the sources interconnections by switches define the electrical networks. In general, the modifications are made by switches connecting \( n \) branches to one. Figure 36 shows an example of a three-way switch.
The network branches connected to these switches must respect the connection laws of the sources. Therefore it can be deduced that:

- each switch is connected to a voltage source (otherwise opening a switch would result in open-circuiting a current source);

- the node at the centre of the star is connected to a current source since a voltage source can be connected only to a current source through a controlled switch;

- at a given time one and only one switch must be ON to avoid connecting two voltage sources and open-circuiting the current source.

Thus each commutation mechanism is a sequence of commutations involving two switches only. Thus an elementary commutation cell, represented in Fig. 37, is defined. The reversibilities of the voltage and current sources determine the static characteristics of the two switches. The switches need to have static characteristics with the same number of current and voltage segments. The two switches must be complementary, that is to say if one switch is ON the other one is OFF; furthermore if the turn-ON (turn-OFF) commutation of a switch is controlled, the turn-OFF (turn-ON) commutation of the other must be spontaneous.

To study a power converter topology, it is essential to isolate all the elementary commutation cells and to check the complementarities of the switches. Figure 38 represents several examples of power converter topologies for which the elementary cells were highlighted.

Detailed information on commutation cells and on local and system commutation mechanisms can be found in Refs. [6] and [7].
9 Hard and soft commutation

In the field of power conversion, the only available active components were once the diode and the thyristor. The topologies had to respect the commutation of these two components: spontaneous turn-OFF of the thyristors. The commutation mechanism was called ‘natural commutation’.

If the spontaneous turn-OFF was not directly obtained (especially in the case of DC sources), it was necessary to add auxiliary circuits with reactive components (inductance and capacitors) and auxiliary semiconductors. The purpose of these circuits was to make the thyristor turn-OFF possible. This commutation mechanism was called ‘forced commutation’.

Power specialists were dreaming of a power semiconductor with a controlled turn-OFF and limited to the grid frequency to replace complex and costly auxiliary circuits. With the development of the power transistor and the GTO, a new spectrum of topologies was opened. Specialists then pushed to get faster components with simple and light drivers. These components are available on the market since 1985. Power converters with higher power and frequency have been designed and built since then. This resulted in (very) high $dV/dt$ and $dI/dt$ putting stress on semiconductors and on all the other components. EMC became a constant concern of power electronics designers. Hard commutation was born! In a first approach components (snubbers) were added to slow down the commutation (series inductance for a controlled turn-ON and a parallel capacitor for a controlled turn-OFF) and to avoid as much as possible the commutation losses close to the axes: aided-commutation. To avoid discharging the energy stored by the snubber in the semiconductor at the following commutation (inductance energy at turn-OFF and capacitor energy at turn-ON), an auxiliary circuit has been added to discharge the snubber energy and then to generate losses.
Having only one controlled command per switch avoids these problems and makes it possible to use these new fast semiconductors with lossless snubbers. One commutation is spontaneous and the other one is controlled. Two types of commutation are possible: zero-voltage switching (ZVS; Fig. 39) and zero-current switching (ZCS; Fig. 40).

Fig. 39: Zero-voltage switching principle

Fig. 40: Zero-current switching principle

The spontaneous commutation is lossless and it is easy to limit the losses of the controlled commutation with an inductance series for ZCS and a capacitor in parallel for ZVS. These reactive components are naturally discharged prior to the next commutation which is a spontaneous commutation. This commutation mechanism is called soft commutation.
In order to get the conditions of soft-commutation, for a power converter topology, the following conditions must be fulfilled:

- the switches must have three-segment characteristics;
- the characteristics must be entirely described at each period;
- the converter must include reversible source(s) creating the conditions for the spontaneous commutation of the switches at the right instant.

The attractive properties of soft-switching are [6], [8]:

- a significant reduction of switching losses
- an improved reliability due to reduced stress on the components
- a limited frequency spectrum, advantageous with respect to EMI and losses in passive components
- a reduction of weight and volume of the components resulting from the higher switching frequency
- a higher bandwidth resulting from the high internal switching frequency
- integration of parasitic elements in the commutation mechanism (e.g., leakage inductance of the transformer in the resonant circuit).

Soft commutation has been a key research domain in power electronics in the last two decades. Numerous papers and conferences can be consulted for more information.

It should be noted that all LHC power converters were designed with soft-commutation topologies [9–11].

10 Conclusion

This paper has introduced and classified the basic power converter components: sources and switches. The direct and indirect power converter topologies were derived from the interconnection rules of the sources. A general and systematic method of synthesis was described and illustrated by some examples.

With the fast development of turn-off controllable power semiconductors, the commutation mechanism becomes more and more important. To improve the performance of the converters, the frequencies are increased with a reduction of the losses and EMI perturbations. The local treatment of the commutation is no longer possible and it is thus essential to design a suitable topology for the commutation of high-frequency and high-power semiconductors. The right turn-on and turn-off conditions for the switches have to be enabled by the circuit topology. Soft commutation is certainly the most appropriate way to reach these goals.

Acknowledgements

References in the domain of power electronics have been cited, in particular and especially from publications of the LEEI (Laboratoire d'Electricité et d'Électronique Industrielle, Toulouse, France). The author would like to express his deep gratitude and admiration to Professor Foch who initiated the research about the systematic synthesis of power converter topologies. It was an opportunity and an honour to work with him for more than 10 years.
References


Bibliography

