Chapter 3

The Bi-directional Switch Commutation Issues

By definition a bi-directional switch, in literature also named bilateral switch or AC-switch or 4Q-switch (Q stands for quadrant), has to be capable of conducting currents and blocking voltages of both polarities, depending on control actual signal [1]. Even though the research activity on the design and fabrication of a true bi-directional switch is keep going either in the academy or in the power semiconductor industry [2]-[4], so far no true bi-directional switches are available on the power electronics market. Consequently, bi-directional switches have to be realized with discrete unidirectional semiconductor devices variously arranged.

Industry Issue

The practical problems related to the implementation of the bi-directional switch and the relevant commutation issues have represented one of the main obstacle to the industrial success of forced commutated direct AC-AC power converters.

This chapter, after a brief description of the different possible configurations for the bi-directional switch implementation, focuses the attention on the commutation problem in bi-directional switches realized with two discrete antiparallel connected unidirectional IGBTs with series diode. Most of the existing commutation strategies are reviewed. A new commutation strategy, named "three-step", is proposed. Some details on its implementation on a complex programmable logic device are given.

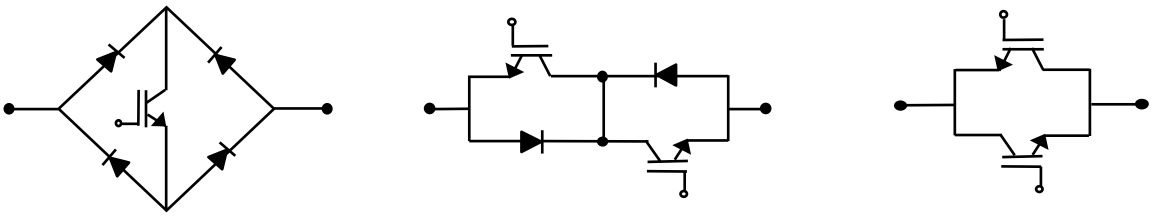
For the sake of clarity, throughout this chapter even the simple term switch will be used for the bi-directional switch whereas the term device will be used to indicate the single unidirectional switch, as an IGBT.

3.1 The implementation of a Bi-directional Switch

As already explained, bi-directional switches have to be realized by discrete unidirectional devices. These realizations require much more chip area and they produce higher switching losses compared to a completely integrated solution. In Fig.3.1 the different bi-directional switch configurations which have been used in prototype and proposed in literature for matrix converters [1], [5], [8] are shown.

The diode bridge switch has been the first configuration used for a matrix converter prototype [5]. This configuration has the advantage of requiring only one active device per switch with its associated driver circuitry. But it has the relevant disadvantage that three devices are conducting whenever the switch conducts, giving rise to relatively high conduction losses [9].

The IGBT provides the path for both current polarities and therefore it is not possible to separately control the current direction. When the current changes sign, it is automatically commutated to the opposite conducting diodes.



a) Diode bridge with a single IGBT b) Two anti-paralleled IGBT with series diodes. c) Two anti-paralleled NPT-IGBT's with reverse blocking capability.

Fig.3.1 Possible discrete implementations of a bi-directional switch.

As far as the commutation problem is concerned, it is not possible to define a timing which allows to carry out a safe commutation of the load current between two diode bridge switches. However, the commutation process cannot be based on a switching method other than the "make-before-break" or "break-before-make" one [10].

switching commutation issue

With respect to the circuit scheme of Fig.3.2, if a make-before-break switching method is used, the on-coming switch is turned on before the off-going switch is turned off. In this way the switches S1 and S2 establish a short circuit path between the two voltage sources V_1 and V_2. The consequent generated current spikes, if not limited somehow, would destroy the switches.

In the case a break-before-make switching method is employed, the dual situation occurs: the off-going switch is turned off before the on-coming is turned on and in this way a path for the conduction of the inductive load current is no longer provided. Destructive voltage spikes are induced on the opened switches [1].

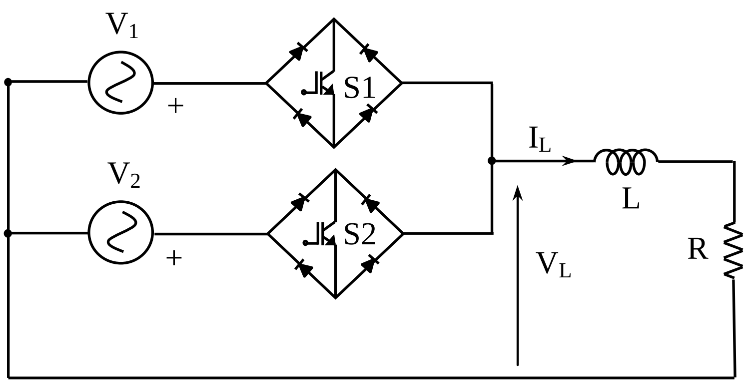


Fig.3.2 Simple circuit where commutation problem exists.

In both cases additional protection circuits and snubber networks are needed. Where the make-before-break method was used [5], [6], in order to limit the short circuit current due to the conduction overlap of the switches, inductances were added between the input filter capacitors and the switches, which then required a snubber circuit for protection against overvoltages. Where a break-before-make method was used [7], small local snubbers plus a single voltage clamp circuit were added to prevent harmful voltage spikes.

The second proposed configuration of bi-directional switch was the antiparallel arrangement of two active device, IGBTs in Fig.3.1.b, with series diode [1], [9]-[11]. The two diodes are used to provide the reverse voltage blocking capability. In this switch arrangement separated internal conduction paths exist for the two load current polarities and these paths can be independently controlled. This is a basic feature, which allows, by means of proper commutation strategies, to safely commutate the load current between different bi-directional switches, reducing the switching losses and eliminating any local snubber network requirements. Furthermore, compared to the diode bridge switch, this solution has also the advantage of lower conduction losses, since only two devices are conducting at any given time.

Depending on how the two IGBTs are connected a common emitter and a common collector arrangement is possible. The connection mode does only affect some technological aspects of the converter realization, as the number of isolated power supply needed for the gate drive circuits. With common emitter switches an isolated power supply per switch is needed, for a total of 9. With common collector switches, as in Fig.3.1.b, since the emitter of each device is connected to an input or an output line of the matrix converter, the number of isolated gate drive supplies is reduced to six [12].

The last proposed configuration of bi-directional switch is shown in Fig.3.1.c and consists of two NPT-IGBTs with reverse blocking capability in antiparallel connection [8]. The basic advantages of this solution are the reduction of the number of semiconductors device in the matrix converter by half and the reduction of the conducting losses, since only one device is conducting at any given time. Six is the number of isolated gate drive supplies.

Unfortunately, the switching losses of these devices are rather high. The higher or lower efficiency of this NPT-IGBTs switch with respect to the antiparallel arrangement with series diode depends on the voltage level of the AC mains and the converter switching frequency. In Fig.3.3 the simulated matrix converter efficiency as function of the AC mains voltage level and the converter switching frequency is shown. RB-NPT-IGBT stands for reverse blocking NPT-IGBTs switches. CCC stands for the antiparallel common collector arrangement with series diode switches.

But, for a given rated power of the load, whatever is the AC mains voltage level, the NPT-IGBTs switch imposes a lower switching frequency which consequently will lead to the design of a larger input filter.

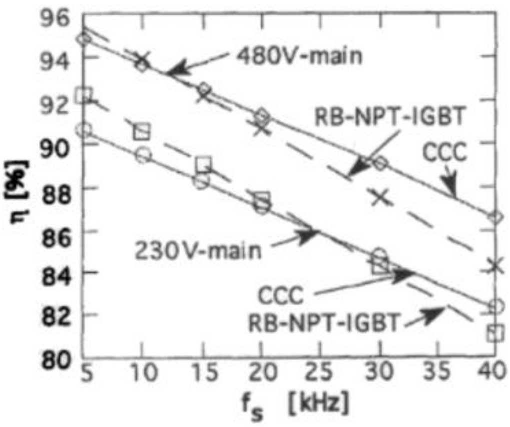


Fig.3.3 Simulated matrix converter efficiency. (reprinted from [8], pp. 111).

3.2 Commutation strategies for antiparallel bi-directional switches

Overcoming the undeniable greater realization and control complexity, the antiparallel arrangement of two unidirectional active devices with series diode has established in the 1990s as the most used bi-directional switch configuration [9]-[17]. This has been mainly due to the implementation of several commutation strategies that using such bi-directional switch, which provides the capability to selectively enable the conduction of the negative and positive current polarity, allow to carry out safe load current commutation and to eliminate the need of any snubber network.

Hereinafter, the bi-directional switches will be considered in the antiparallel arrangement of Fig.3.1.b. Then, for the three phase to three phase matrix converter the topology to refer to in order to deal with the commutation problem and the related proposed commutation strategies is the one shown in Fig.3.4.

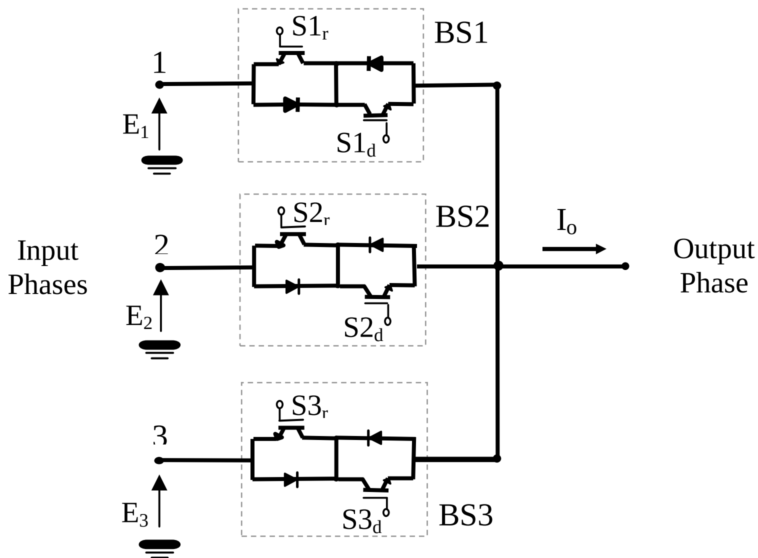


Fig.3.4 Three phase (input) to single phase (output) basic connection scheme for a matrix converter.

In Fig.3.4 subscripts d and r in the IGBTs label stand for direct and reverse respectively and they refer to the output current flow direction, which is assumed to be direct or positive when it is from the input to the output.

With reference to Fig.3.4, when the output phase, accordingly to the main control algorithm, has to be commutated from one input phase to another, two rules must be respected by any commutation strategy:

i) the commutation does not have to cause a short circuit between the two input phases, because the consequent high circulating current might destroy the switches;

ii) the commutation does not have to cause an interruption of the output current because the consequent overvoltage might likely destroy the switches.

To fulfill these requirements some knowledge of the commutation conditions is mandatory. In order to carry out a safe commutation, the voltage between the involved bi-directional switches or the output current must be measured.

These information are required in order to determine the proper sequence of the devices switching states combinations that does not lead to the hazard either of a short circuit or of an overvoltage and provides the safe commutation of the output current. This is the common operating principle of all the commutation strategies that have been proposed in literature.

3.3 Four-step commutation strategy based on the current sign measurement

This strategy was firstly proposed in [1]. It has a general validity, in a sense that it does not depend on the matrix converter control algorithm employed. In order to explain the strategy it is helpful to refer to the simplified commutation circuit shown in Fig. 3.5.

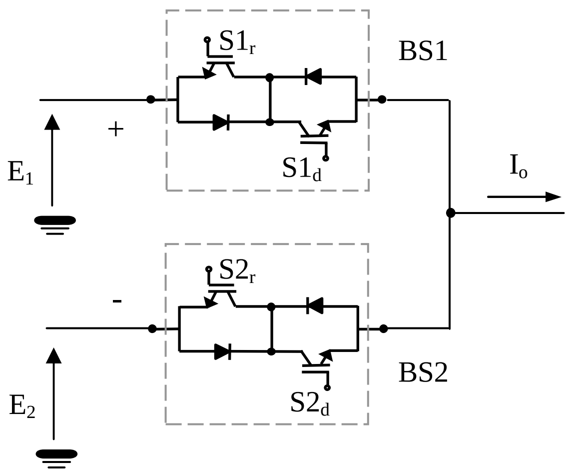


Fig.3.5 General commutation circuit of two bi-directional switches.

The strategy assumes that when the output phase is connected to an input phase both the IGBTs of the bi-directional switch, BS1 for instance, have to be turned on. Due to the finite turn-off and turn-on time of the IGBTs as well as the different propagation time delay of their gating signals, when the commutation of the output phase between the two input lines is required it is not possible to simultaneously switching off BS1 and switching on BS2.

For instance, assuming that $E_1 > E_2$, if the device $S2_r$, because of the aforementioned time delays, turns on before the device $S1_d$ turns off, a short circuit current starts to flow between the two input phases. In a dual way, assuming that $I_o > 0$, if the device $S1_d$ turns off before the device $S2_d$ turns on, the output current is interrupted and a voltage spike is induced on the opened switches.

The way to solve the problem consist in a careful control of the switching instants and in performing the commutation using only non-hazardous switch state combinations [1]. In Table I a group of non-hazardous combinations, accordingly to the output current sign, is given.

Table I.
Non-hazardous combinations of devices state.

State	$S1_d$	$S1_r$	$S2_d$	$S2_r$	Sign I_o
1	1	1	0	0	+ -
2	0	0	1	1	+ -
3	1	0	0	0	+
4	0	1	0	0	-
5	0	0	1	0	+
6	0	0	0	1	-
7	1	0	1	0	+
8	0	1	0	1	-

The ON state of a device is indicated by 1 and the OFF state by 0. It has to be noted that the switch states 1 and 2, are unconditional states, since they may exist independently by the current sign; but switch states 3 to 8 are conditional states, since they are legal till the current sign is the one dictated by the most right hand-side column. Now, a commutation process always starts from and terminates to an unconditional state. This transition cannot be made directly in one step but it has to be made through a sequence of several conditional states.

In the case a 1 to 2 commutation is required and the output current I_o is positive, the switching state sequence to perform consists of the following four steps:

1. turning off $S1_r$;
2. turning on $S2_d$;
3. turning off $S1_d$;
4. turning on $S2_r$;

Accordingly to the sign of the output current that must be measured, in general:

STEP 1 consists in turning off the IGBT which is not conducting the output current within the off-going bi-directional switch, BS1 in the case;

STEP 2 consists in turning on the IGBT which will conduct the output current within the on-coming bi-directional switch, BS2 in the case;

STEP 3 consists in turning off the IGBT which is conducting the output current within the off-going bi-directional switch;

STEP 4 consists in turning on the IGBT which will not conduct the output current within the on-coming bi-directional switch.

In the same way, if the output current I_o is negative, the switching state sequence to follow is:

1. turning off S1d;
2. turning on S2r;
3. turning off S1r;
4. turning on S2d;

Symmetrical switching state sequences have to be used when the output current has to be commutated from BS2 to BS1. In order to ensure that the actual sequence of the IGBT gating signals is that required, a short time delay is inserted between consecutive steps. The time delay has to be set to a value higher than the maximum propagation time delay difference of the IGBT gating signals.

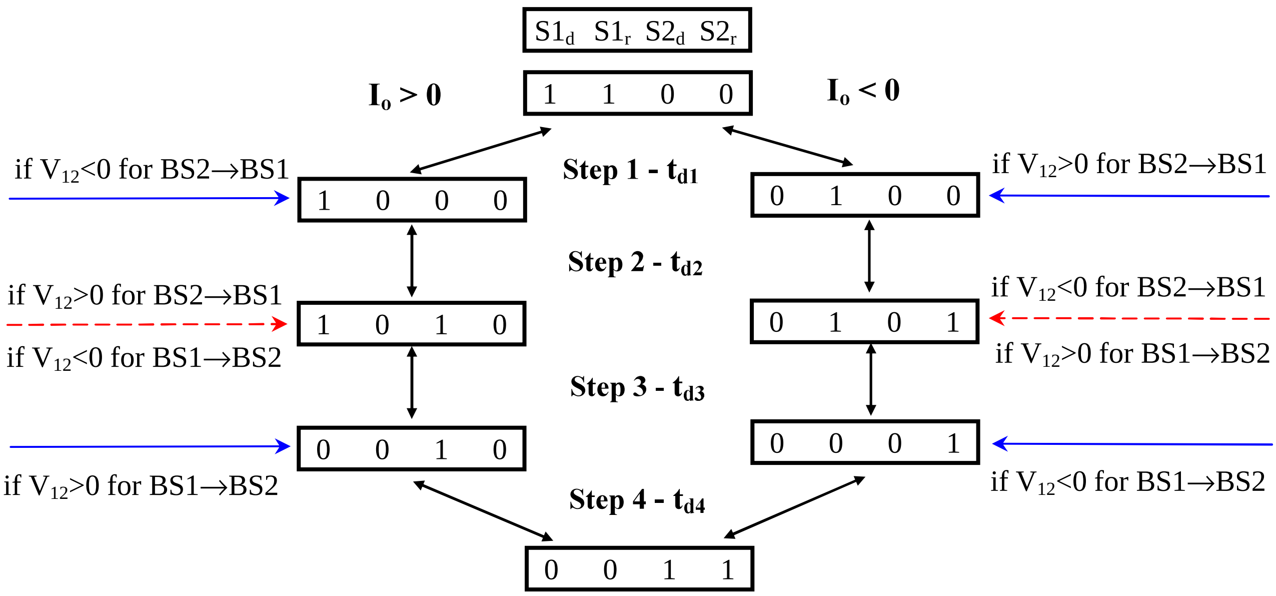


Fig.3.6 Four-step switching diagram for two bi-directional switches.

In Fig.3.6 the four-step switching diagram for two bi-directional switches is shown and the output current commutation instant is highlighted. The numeration of the steps refers to a commutation from BS1 to BS2.

It has to be noted that the output current commutation takes always place after step 2 or 3, depending on the polarity of the voltage across the two switches. In an unconditional state, whenever the output current is dictated to reverse by the source and the load, it is able to do it automatically. Looking at the switching diagram in Fig.3.6 and to Fig.3.5, it can be also noted that during a commutation sequence it is impossible for the output current to change sign. This is the main potential drawback of the strategy. But it becomes a minor problem when an output current sensor with good resolution is used, since breaking a current, even an inductive one, at the zero crossing does not cause significant overvoltages.

It is worth noting that the extension of this commutation strategy to a power converter with a higher number of input phases, as the matrix converter is, does not imply significant complications because the commutation always takes place between two bi-directional switches and the other are idle during the process. With reference to the topology shown in Fig.3.4 the switching diagram for three bi-directional switches is given in Fig.3.7 and the list of the legal switch state combinations is quoted in Table II. The numeration of the steps refers to a commutation from BS1 to BS2.

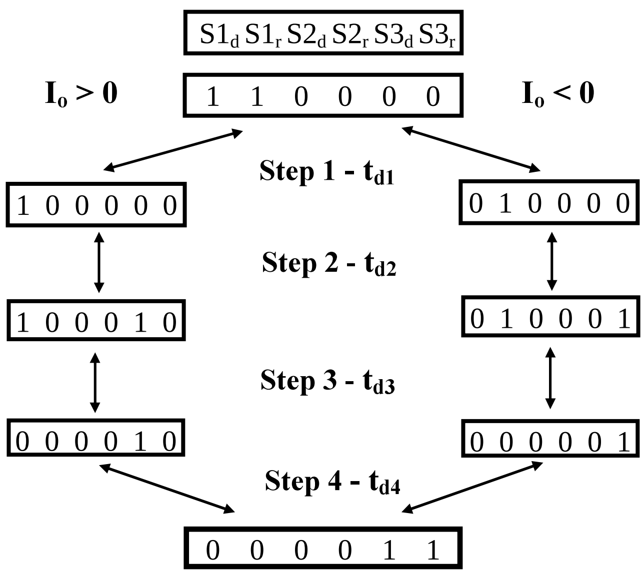


Fig.3.7 Switching diagram for three bi-directional switches.
BS1 ↔ BS3 commutation.

The four-step commutation strategy does not have significant hardware requirements apart from some sort of output current sign circuit measurement. It carries out safe commutation of the output current and no snubber networks are needed. The time step delays can be set to the same constant value [16], [18] or to different constant values [19] or to different variable values [20]. As a matter of fact, it is important to point out that the sum of the time step delays settles the minimum duty cycle that the converter modulation control is able to apply to the output and hence it settles the width of the control discontinuity in the linear modulation region of the converter. In other words the sum of the time step delays settles the theoretical minimum time for which an output phase can be connected to an input phase. The strategy can be quite easily implemented into programmable logic devices like CPLD.

Table II.
List of legal device state combinations for three-input to one-output direct AC-AC converter.

State	$S1_d$	$S1_r$	$S2_d$	$S2_r$	$S3_d$	$S3_r$	Sign I_o
1	1	1	0	0	0	0	+ -
2	0	0	1	1	0	0	+ -
3	0	0	0	0	1	1	+ -
4	1	0	0	0	0	0	+
5	0	1	0	0	0	0	-
6	0	0	1	0	0	0	+
7	0	0	0	1	0	0	-
8	0	0	0	0	1	0	+
9	0	0	0	0	0	1	-
10	1	0	1	0	0	0	+
11	0	1	0	1	0	0	-
12	1	0	0	0	1	0	+
13	0	1	0	0	0	1	-
14	0	0	1	0	1	0	+
15	0	0	0	1	0	1	-

3.4 Two-step commutation strategy based on the current sign measurement

This commutation strategy was firstly proposed in [10] and [14] and more recently improved in [21], [22]. With reference to the commutation circuit of Fig.3.5, the key idea of this strategy in order to safely commutate the output current is to keep the non-conducting IGBTs turned off during the commutation process. In steady-state condition the non-conducting IGBT of the switched on bi-directional switch is also turned off.

When the output current is larger then a small predefined positive threshold value $+I_{thre}$ only the positive current conducting IGBTs, $S1_d$ and $S2_d$ in this case, can be gated. When a commutation is required the overlap method is used: the on-coming IGBT is gated before the off-going IGBT is turned off. Likewise when the output current is lower then a predefined negative threshold value $-I_{thre}$ only the negative current conducting IGBTs, $S1_r$ and $S2_r$, can be gated.

When the output current falls within the threshold band $\pm I_{thre}$, which means that the current is close to zero and about to reverse, the non-conducting IGBT of the switched on bi-directional switch is turned on in order to allow the current to reverse. As soon as the current has overcome the opposite signed threshold value, normal operation are resumed. Since during this commutation the output phase is connected to the same input phase and the current only commutates from one IGBT of the bi-directional switch to another, it is referred as “Inter-Switch Commutation” [10].

With respect to the four-step, this strategy has the advantage of a reduced number of steps and consequently a faster commutation process which improves the output modulation control. But the presence of the inter-switch commutation causes some drawbacks. First of all, if a phase commutation is required during an inter-switch commutation a special procedure has to be followed, otherwise a short or open circuit may occur.

A first possibility is to disable the phase commutation and hence the output modulation until the end of the inter-switch commutation [14]. Obviously the modulation of the output current and voltage are to some extent negatively affected by this solution, which might also give poor performance when the current measurement is not accurate and the desired output current is small.

A second possibility [23] is to use a dead time commutation if a phase commutation is required when the output current is within the threshold band. The two devices of the off-going switch are turned off and the devices in the on-coming switch are turned on a short time later.

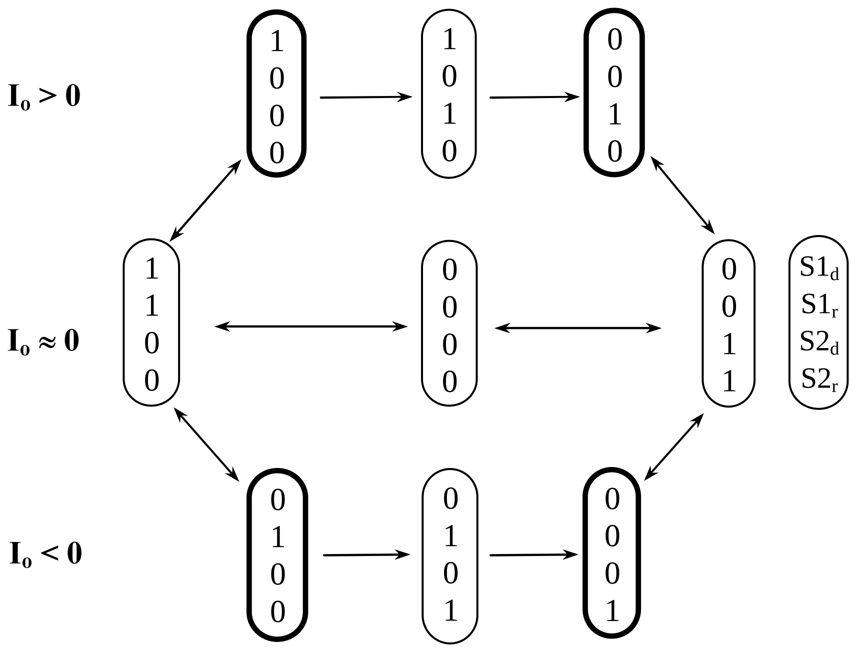


Fig.3.8 Switching diagram of the two-step strategy for two bi-directional switches.

This is not an ideal solution because the output current is interrupted. Whether a snubber network may be needed or not depends on the output current threshold value.

Fig.3.8 shows the switching diagram of the two-step commutation strategy related to the circuit of Fig.3.5. In bold are the steady states switches configurations. As for the four-step, the extension of the strategy to a three phase matrix converter is a straightforward task.

In [21], [22] the inter-switch commutation as defined before is eliminated. This is done by a significant improvement of the current sign detection and the implementation of an intelligent gate drive circuit. The current sign is detected monitoring the collector-emitter voltage of the IGBTs within the bi-directional switch and this information is continuously provided to all the gate drivers of the IGBTs on the same output phase through a communication ring. In this way the reliability of the current sign detection is increased, so when the output current has to reverse a simple dead time commutation is carried out. The dead time is so short (≈ 250 ns) that it does not unduly distort the output current waveform [22]. In Fig.3.9 the modified switching diagram with respect to Fig.3.8 is shown.

This improved two-step commutation strategy performs fast and safe commutations but it needs to monitor the collector-emitter voltages, which set some constraints on the technological realization (i.e. the insulated power supply are 9) and it is implemented on FPGA controllers.

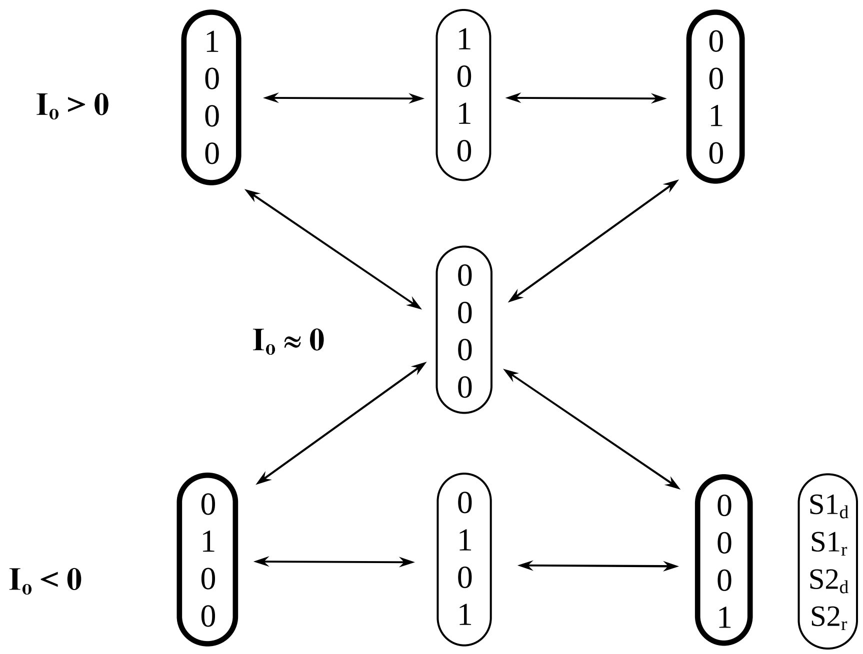


Fig.3.9 Switching diagram of the two-step strategy without inter-switch commutation for two bi-directional switches.

3.5 Four-step commutation strategy based on the input voltage sign measurement

In the previous sections some commutation strategies based on the output current sign measurements have been explained. But as aforementioned, commutation techniques relying on the input voltages measurement have been also proposed [1] and effectively implemented in [11], [13], [24].

The basic idea of the strategy proposed in [11], referred as “staggered commutation”, is to reproduce the same operating conditions of a commutation process as in a traditional DC-link converter, where the dead time commutation method can be easily used because of the automatic timing action of the freewheeling diodes.

To achieve this aim, the input phase voltages have to be measured in order to detect the sign of the voltage across the two bi-directional switches involved in the commutation process. The strategy assumes that when the output phase has to stay connected to an input phase, both the active devices of the correspondent bi-directional switch are turned on.

When a commutation of the output phase between two input lines is required it is firstly determined whether the switch turning off is at lower or higher voltage than that of the next switch turning on. This is needed to identify within the two commutating bi-directional switches the active devices which will operate as “freewheeling” devices.

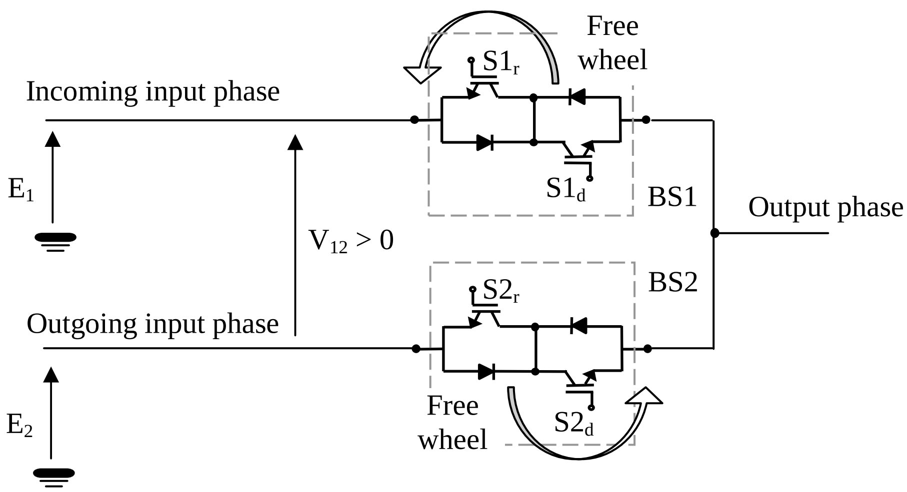


Fig.3.10 Staggered commutation. V_{12} is the “commutation voltage” across the incoming and the outgoing input phases. For $V_{12} < 0$ the freewheeling devices are reversed.

In general, within the commutating bi-directional switches, the two freewheeling devices are those that allow the current to flow outward from the lower input phase voltage switch ($S2_d$ in Fig.3.10) and inward to the higher input phase voltage switch ($S1_r$).

Once the freewheeling devices have been identified, the commutation strategy staggers in the following sequential steps:

STEP 1. it is turned on the freewheeling device of the incoming switch ($S1_r$ in Fig.3.10);

STEP 2. it is turned off the non-freewheeling device of the outgoing switch ($S2_r$);

STEP 3. it is turned on the non-freewheeling devices of the incoming switch ($S1_d$);

STEP 4. it is turned off the freewheeling device of the outgoing switch ($S2_d$).

In order to guarantee the above desired four-step switching sequence a short time delay has to be inserted between the steps. With reference to the commutation circuit shown in Fig.3.10, the switching diagram of the strategy is shown in Fig.3.11 and the relevant list of legal combinations of devices state is quoted in Table III. Using this commutation strategy it is possible to safely commutate the output current and additional snubber networks are not required.

However, it has to be noted that the hazard of a short circuit, differently from the open circuit one, during a commutation process is not completely removed. As a matter of fact, if the measurement of the commutation voltage sign is not correct a short circuit path becomes available. Therefore, a reliable measurement of the input voltages is required by the commutation strategy to be effective. From a practical point of view, this constraint can affect either the matrix converter output modulation strategy, by choosing a safe but non-optimal switching sequence, or the input filter parameter design, in order to reduce the ripple of the matrix converter input voltages.

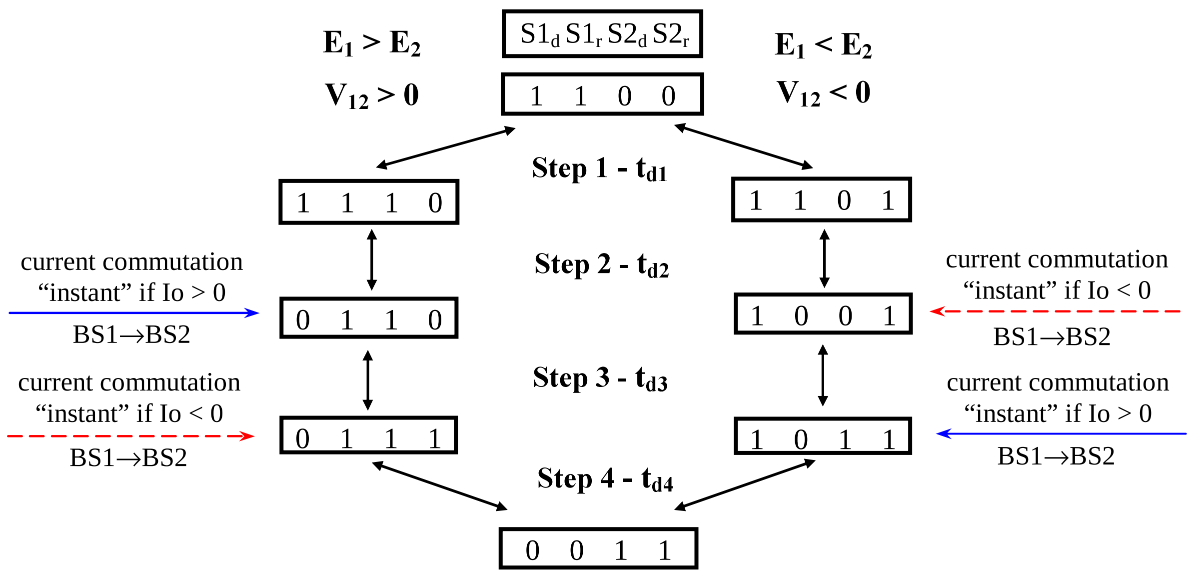


Fig.3.11 Switching diagram of the four-step voltage based commutation strategy for two bi-directional switches.

It has also to be pointed out that as for the current based four-step commutation strategy, but in a dual way, the actual output current commutation instant during the switching sequence is variable depending on the output current sign. In this case the current can commutate after the second step or after the third. For an optimised modulation of the output quantities such variability has to be taken into account and compensated.

As for the previous current based commutation strategies, the extension of this strategy to a power converter with a higher number of input phases does not imply significant problems because the commutation always takes place between two bi-directional switches and the others are idle during the process.

Table III.
Legal combinations of devices state for the four step voltage based commutation strategy.

State	$S1_d$	$S1_r$	$S2_d$	$S2_r$	Sign V_{12}
I	1	1	0	0	+ -
II	0	0	1	1	+ -
III	1	1	1	0	+
IV	1	1	0	1	-
V	0	1	1	1	+
VI	1	0	1	1	-
VII	0	1	1	0	+
VIII	1	0	0	1	-

3.6 Two-step commutation strategy based on the input voltage sign measurement

A two-step commutation strategy, the so called METZI commutation, based on the input voltages measurement has been recently proposed and implemented in [13]. It is based on the basic operating principle to provide a freewheeling path for both output current polarities at any time, either for steady or for transient devices state combinations.

It is specifically defined for a three phase to three phase matrix converter and it applies to the basic converter topology shown in Fig.3.4.

With respect to the four-step staggered commutation strategy the number of steps required in the switching sequence is halved with a consequent positive effect on the modulation performance of the converter. Unfortunately the reduction of the steps number is obtained at the expense of the commutation strategy simplicity. In fact, in order to reduce the steps number more devices have to be switched on either in steady or transitient states: from a minimum of two to a maximum of four. As a whole, the strategy consists of 30 different device state combinations [25].

Since the switching sequence during a commutation process is defined accordingly to the commutation voltage sign, the reliability of the input line-to-line voltages zero-crossing point detection is a important issue even for the METZI strategy. The voltage sign detection circuit proposed in [25] and patented in [26] relies on the detection of the zero-crossing instant of the filtered and unfiltered line-to-line voltages.

However, despite of a very reliable commutation voltage sign detection the hazard of a short circuit cannot be eliminated because the voltage difference can change sign during the commutation process. In order to completely remove the risk of a short circuit it is necessary to modify the switching sequence requested by the modulation algorithm.

In Fig.3.12 a fundamental period of the matrix converter input line-to-neutral voltages is shown and the regions where the detection of the line-to-line voltages sign becomes critical are highlighted.

Now, let us assume that in the region marked as "uncritical" in Fig.3.12 the switching sequence required by the main control algorithm in order to minimize the converter switching losses is $b \rightarrow c \rightarrow a$. In the region marked as "uncritical" this switching sequence can be carried out safely. A critical situation appears when the voltage Eb becomes nearly equal to Ec : if the sign detection of the line-to-line voltage Vbc is wrong or if the sign changes when the switching sequence is already in progress a freewheeling path becomes a short circuit path.

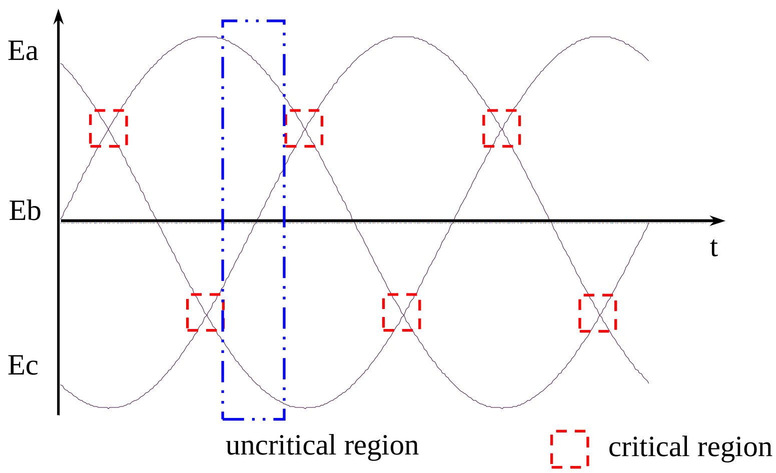


Fig.3.12 Critical regions for commutation strategies based on the commutation voltage sign detection.

There are several possibilities to manage commutations within a critical region [27].

A first solution might be to interdict the critical phase commutation $b \rightarrow c$ till the voltages differ enough from each other. But in this way the connection time of the output phase to the input phases b and c would be unduly modified. Such variation may have little effect on the output voltage because the input voltages are nearly equal but would distort the input currents.

A second solution, proposed in [25], is to change the switching sequence adding uncritical commutations: the critical phase commutation is carried out passing through the remaining third input line-to-neutral voltage. With reference to the previous example the modified switching sequence would be $b \rightarrow a \rightarrow c \rightarrow a$. This solution is easy to be implemented in the commutation logic and requires only an information about the critical region but it has the disadvantage of inserting additional commutations that increase the converter switching losses.

A better solution is proposed in [27]. The basic simple idea is to reshuffle, within a critical region, the switching sequence in order to avoid any critical commutation. This solution still need to detect the critical area but no additional commutations are inserted. With reference to the previous example the reshuffled safe switching sequence would be b → a → c. In this way the input-output modulation performance of the converter are not affected. The unique side effect of such solution is an increase of the switching losses with respect to the optimized switching sequence. The amount of this extra losses depends on the width of the critical region which depends on the disturbances existing on the AC mains, the power delivered to the load and the value of the input filter capacitance.

It is worth noting that the previous proposed solutions for eliminating the short circuit hazard inherent to commutation strategies based on the input voltage sign detection can be applied to the four-step staggered commutation strategy too.

It is also worth noting that in METZI commutation, as in the previous staggered commutation, the actual output current commutation instant during a two-step switching sequence is variable depending on the output current sign. As for the current based four-step commutation strategy the time difference is equal to one step delay.

3.7 A New Three-step commutation strategy based on current & voltage measurement

In all the above surveyed commutation strategies, the commutation instant of the output current between two bi-directional switches is inherently variable. For commutation strategies based on the output current measurement the instant depends on the sign of the voltage across the switches involved in the commutation process. In a dual manner, for commutation strategies based on the input voltage sign detection the instant depends on the output current direction.

This variability has to be taken into account and compensated when an optimum modulation of the matrix converter output voltages and input currents is desired.

A first basic advantage of the proposed three-step commutation strategy is that the output current commutates between the off-going and the on-going bi-directional switches always at the same instant with respect to the beginning of the commutation process. In this way no compensation of the output-phase-to-input-phase connection times calculated by the main control algorithm is needed.

Analyzing the above commutation strategies it has been also pointed out that the time needed to a commutation process, that is the sum of the time step delays, sets the limit to the minimum time interval for which an output phase can be connected to an input phase and hence sets the width of the control discontinuity within the linear operating region of the matrix converter. From a modulation performance point of view, assuming equal time step delays, two-step commutation strategies have been deemed preferable to four-step commutation strategies.

The proposed three-step commutation strategy allows the minimum connection time to be decreased with respect to the four-step commutation strategies. Moreover, by choosing different time delays for different steps the value is further reduced.

It is important to point out that these improvements are achieved without negatively affecting the safety and the effectiveness of the current commutation. It can be also pointed out that the strategy has the same hardware requirements of the current based four-step commutation strategy. Actually, the three step commutation strategy requires the knowledge of the input voltages too, but in vector controlled matrix converter adjustable speed drives input voltages are already measured because needed by the main control algorithm.

The three-step commutation strategy is hereinafter explained with reference to the converter topology shown in Fig.3.4 but it could also be referred to the basic commutation circuit of Fig.3.5 and then easily extended to the topology with three input phases.

The three-step commutation strategy assumes that in steady state both the active devices of the turned on bi-directional switch are gated, allowing an automatic output current reversal when dictated by the source and the load. In order to operate the three-step commutation strategy necessarily requires:

i) the detection of the output current sign;

ii) the detection of the commutation voltage sign, where the commutation voltage is the line-to-line voltage defined as difference of the incoming and outgoing input line-to-neutral voltages, E_{incom} - E_{outgo} .

When the output phase is required to commutate from one input phase to another, then two different three-step switching sequences are available.

If the output current is positive, then the following two switching sequence are used accordingly to the commutation voltage sign:

a) if the voltage E_{incom}-E_{outgo} is positive: the active device that is not carrying the current in the off-going bi-directional switch is firstly turned off; then the active device that will carry the current in the on-coming bi-directional switch is turned on; last the active device still gated in the off-going bi-directional switch and the active device that will not carry the current in the on-coming bi-directional switch are simultaneously and respectively turned off and turned on;

b) if the voltage E_{incom}-E_{outgo} is negative: the active device that is not carrying the current in the off-going bi-directional switch and the active device that will carry the current in the on-coming bi-directional switch are simultaneously and respectively turned off and turned on; then the active device still gated in the off-going bi-directional switch is turned off; last the active device that will not carry the current in the on-coming bi-directional switch is turned on.

If the output current is negative, the switching sequences have to exchanged with respect to the commutation voltage sign, it follows that :

a) if the voltage E_{incom}-E_{outgo} is positive: the active device that is not carrying the current in the off-going bi-directional switch and the active device that will carry the current in the on-coming bi-directional switch are simultaneously and respectively turned off and turned on; then the active device still gated in the off-going bi-directional switch is turned off; last the active device that will not carry the current in the on-coming bi-directional switch is turned on.

b) if the voltage E_{incom}-E_{outgo} is negative: the active device that is not carrying the current in the off-going bi-directional switch is firstly turned off; then the active device that will carry the current in the on-coming bi-directional switch is turned on; last the active device still gated in the off-going bi-directional switch and the active device that will not carry the current in the on-coming bi-directional switch are simultaneously and respectively turned off and turned on;

In Fig.3.13 the three-step switching diagram relevant to the commutation of the output phase from input phase 1 to 3 is shown as an example. The different branches relate to different sign of the output current I_o and of the input line-to-line voltage V_{31}, which represents the commutation voltage between the on-coming bi-directional switch BS3 and the off-going bi-directional switch BS1.

Let us consider the most left hand side branch of Fig.3.13. The output phase is initially connected to the input phase 1 and finally connected to the input phase 3. The output current sign is positive (I_o >0) as well as the sign of the input voltage V_{31}, which means $E_{incom}=E_3 > E_1=E_{outgo}$. When the commutation command is given, the strategy performs the following sequence:

STEP 1. the IGBT of the off-going switch BS1 that is not carrying the output current ($S1_r$) is turned off;

STEP 2. the IGBT of the on-coming switch BS3 that will carry the output current in the final steady state ($S3_d$.) is turned on. Due to the input voltage sign, at this stage the output current commutates from BS1 to BS3, which means that the output current is now carried by the IGBT $S3_d$.

STEP 3. AT THE SAME TIME, the IGBT still gated ($S1_d$) of the off-going switch BS1 is turned off and the IGBT that is not carrying the current ($S2_r$) in the on-coming switch BS3 is turned on.

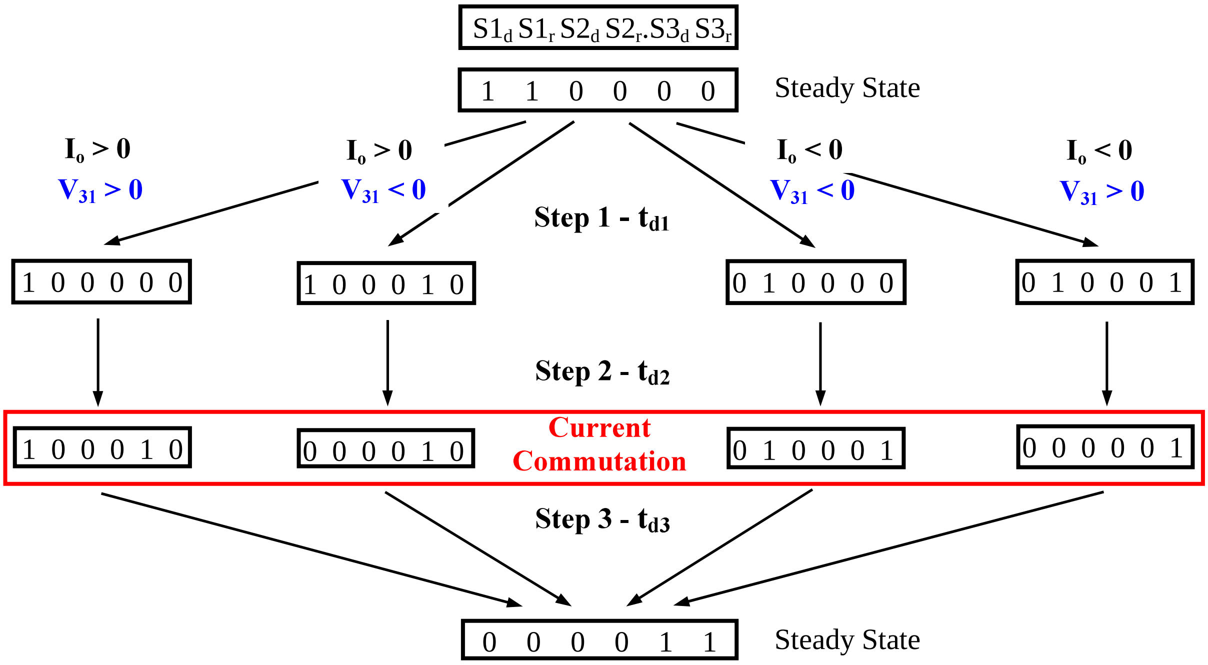


Fig.3.13 Three-step switching diagram based on output current and input voltage sign detection. BS1 → BS3 case. $V_{31} = E_3 - E_1$ is the line-to-line commutation voltage. I_o is the output current.

In Fig.3.14 the switching sequence is shown. For each device state combination, the turned on IGBTs are dashed circled.

The key point worth noting is the contemporaneity of two switching commands which basically allows to cancel one step with respect to a conventional current based four-step

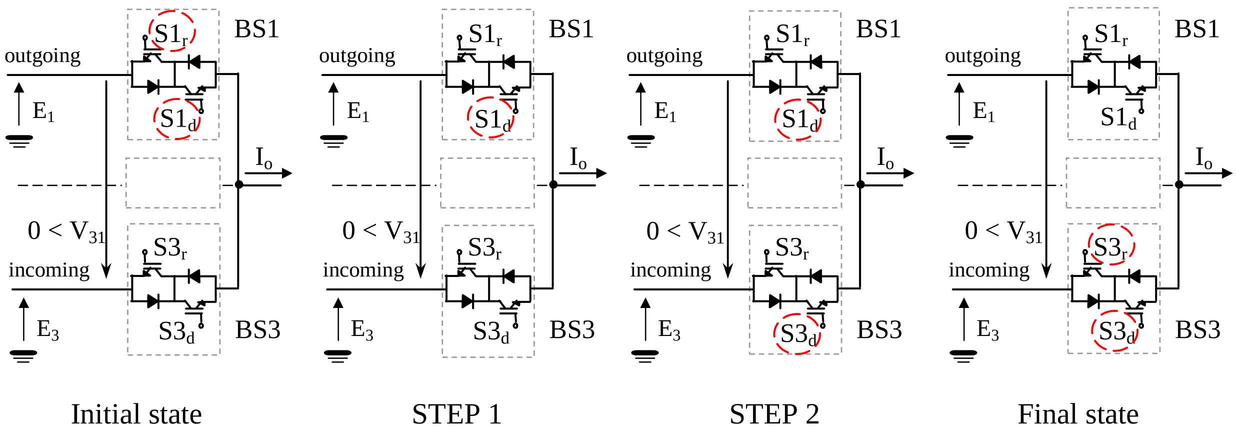


Fig.3.14 Three-step switching sequence for BS1 → BS3 commutation. $V_{31} = E_3 - E_1 > 0$. $I_o > 0$.

commutation strategy. It is important to highlight that such contemporaneity does not imply any short circuit hazard. Although a short circuit current path might become available ($S1_d$ and $S3_r$ gated at the same time for a short period) because of the different propagation time delays of the respective gating signals, the short circuit current is prevented from flowing by the input line-to-line voltage across the two switches, which opposes the short circuit current path.

It can be verified that for the other branches of Fig.3.13 the switching sequence changes accordingly to the output current and input line-to-line voltage signs, but it holds the basic idea to simultaneously turn on/off the two IGBTs for which a consequent possible short circuit current is prevented from circulating by the input line-to-line voltage across the commutating switches.

It has to be noted that, in the same way as for the current based four-step commutation strategy, during a commutation process the output current cannot reverse. This means that there is the possibility of an open circuit if the output current is dictated to reverse during a commutation process. However, as already said, the overvoltages that may rise by stopping a current at the zero crossing are not cause for concern. Moreover, due to the faster commutation process, with the three-step strategy the problem is somehow further limited.

With regard to the commutation voltage sign detection the three-step commutation strategy needs a reliable signal. But if the commutation voltage reverses during the commutation a short circuit path may become available whenever two devices are switched at the same time. In the following section it will explained how, on the basis of some practical thoughts, this problem can be considered of minor concern.

3.7.1 Implementation of the Three-step commutation strategy

The three-step commutation strategy can be effectively implemented on a programmable logic device. In this case a XC9572TQ100 CPLD (Complex Programmable Logic Device) from Xilinx has been used. A brief and simplified description of the strategy implementation will be given in this section.

In Fig.3.15 a block diagram of the matrix converter control system is shown. There are three CPLD, one for each output phase. The three-step commutation strategy is implemented on each CPLD.

In Fig.3.16 the input signals fed to the CPLD and the output signals are shown.

The two input signals A0 and A1 are fed to the CPLD by the PWM generator of the DSP control board. They encode the input phase (a, b, c) the output phase must be connected to and they set how long for.

The three input signals V_{ab}, V_{bc} and V_{ca} are fed to the CPLD directly by the voltage transducers. They encode the sign of the three input line-to-line voltages accordingly to Table IV, where Ea, Eb, Ec are the input line-to-neutral voltages, $V_{ik} = 1$ means that the voltage V_{ik} is positive and $V_{ik} = 0$ means that the voltage V_{ik} is negative.

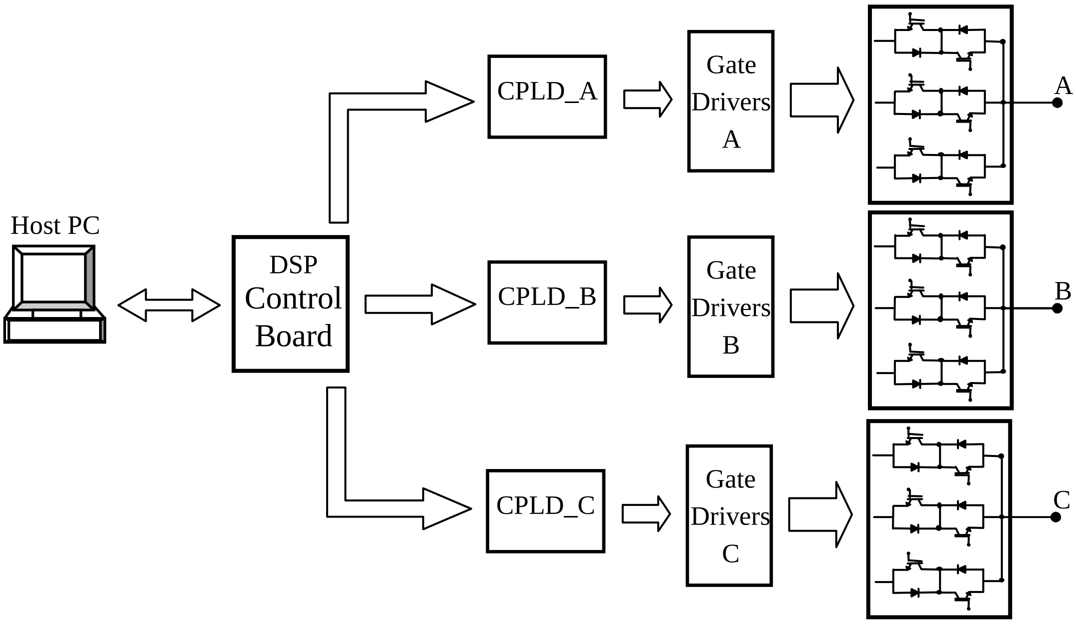


Fig.3.15 Block diagram of matrix converter control system.

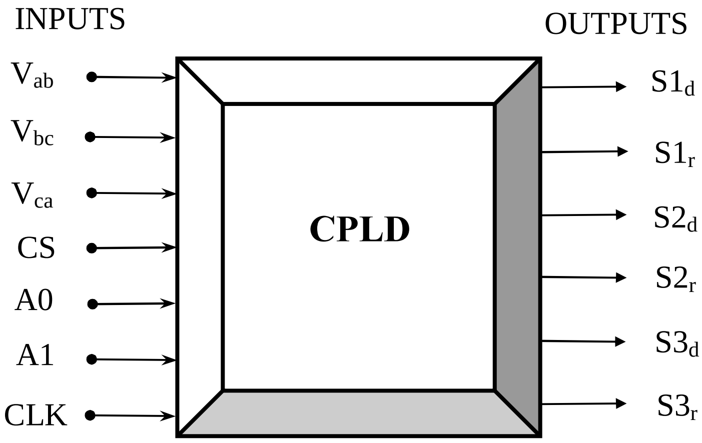


Fig.3.16 Input and output signals of a single CPLD implementing the three-step commutation strategy.

The feature that the input voltages signals are directly fed to the CPLD by the transducers plays an important role in reducing the dangerousness of a possible short circuit, because the actual sign of the input line-to-line voltages is continuously available to the CPLD. If it is assumed that the measurement of the input voltages is reliable, the actual sign availability means that in the worst case, the input line-to-line voltage that might sustain the short circuit current is that generated by a variation within a one microseconds time interval. Consequently few volts, whose effect would be further limited by the forward voltage of the semiconductor devices in the short circuit path.

Last but not least point that should be noted is that in the three-step commutation strategy a short circuit due to a wrong detection of the commutation voltage would always last for a time interval shorter than a time step delay, that is less than 1 μs. Accordingly to the thermal behaviour of IGBTs such eventual short circuit do not cause any harm to the device.

The input signal CS is fed to the CPLD directly by the current transducers and it encodes the sign of the relevant output phase current.

The input signal CLK is the clock, which can be directly fed to the CPLD by an oscillator or by the DSP. The CPLD requires a clock for synchronized timing operations and to generate the step time delays. A clock with a frequency of 20 MHz has been used.

With regard to the time step delays, it has to be pointed out that in order to reduce the overall time of the commutation process different time delays are used for the sequence steps.

In detail, the first step time delay t_{d1} is shorter than the other two and it depends on the clock frequency only. For a 20 MHz clock the time delay t_{d1} is equal to 100 ns.

The second and third step time delays are equal and their value has to be set accordingly to the maximum propagation time delay difference of the devices' gating circuit and to the IGBTs turn on and turn off time. A value of 600 ns has been chosen.

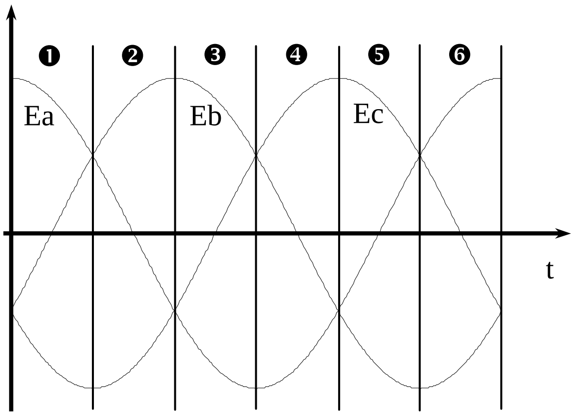


Table IV

Sector	E_{MIN}	E_{MID}	E_{MAX}	V_{ab}	V_{bc}	V_{ca}
❶	E_c	E_b	E_a	1	1	0
❷	E_c	E_a	E_b	0	1	0
❸	E_a	E_c	E_b	0	1	1
❹	E_a	E_b	E_c	0	0	1
❺	E_b	E_a	E_c	1	0	1
❻	E_b	E_c	E_a	1	0	0

The output signals $S1_d$, $S1_r$, $S2_d$, $S2_r$, $S3_d$, $S3_r$ are the gating signals of the 6 IGBTs, three bi-directional switches, that are connected to the same output phase. These signals are provided by the CPLD to the output phase relevant gate drivers board.

The three-step commutation strategy make use of the same devices state combinations listed in Table II. This is due to the fact that the switching policy of the strategy relies on the detection of the current sign and the detection of the commutation voltage sign is simply used to jump one step of the four-step switching sequence shown in Fig.3.6.

In Fig.3.17 and Fig.3.18 the strategy state diagrams for positive and negative output current direction are respectively shown.

In the diagrams the voltage signals V_{ab}, V_{bc} and V_{ca} have been replaced by AB, BC, CA respectively.

It has also to be noted that with respect to each state the actual input signals have been indicated. For any state, the input signals inside the green box are actual signals, which means that these signals are currently read within the state while the input signals inside the red box are “freezed”, that is they are not currently read within the relevant state.

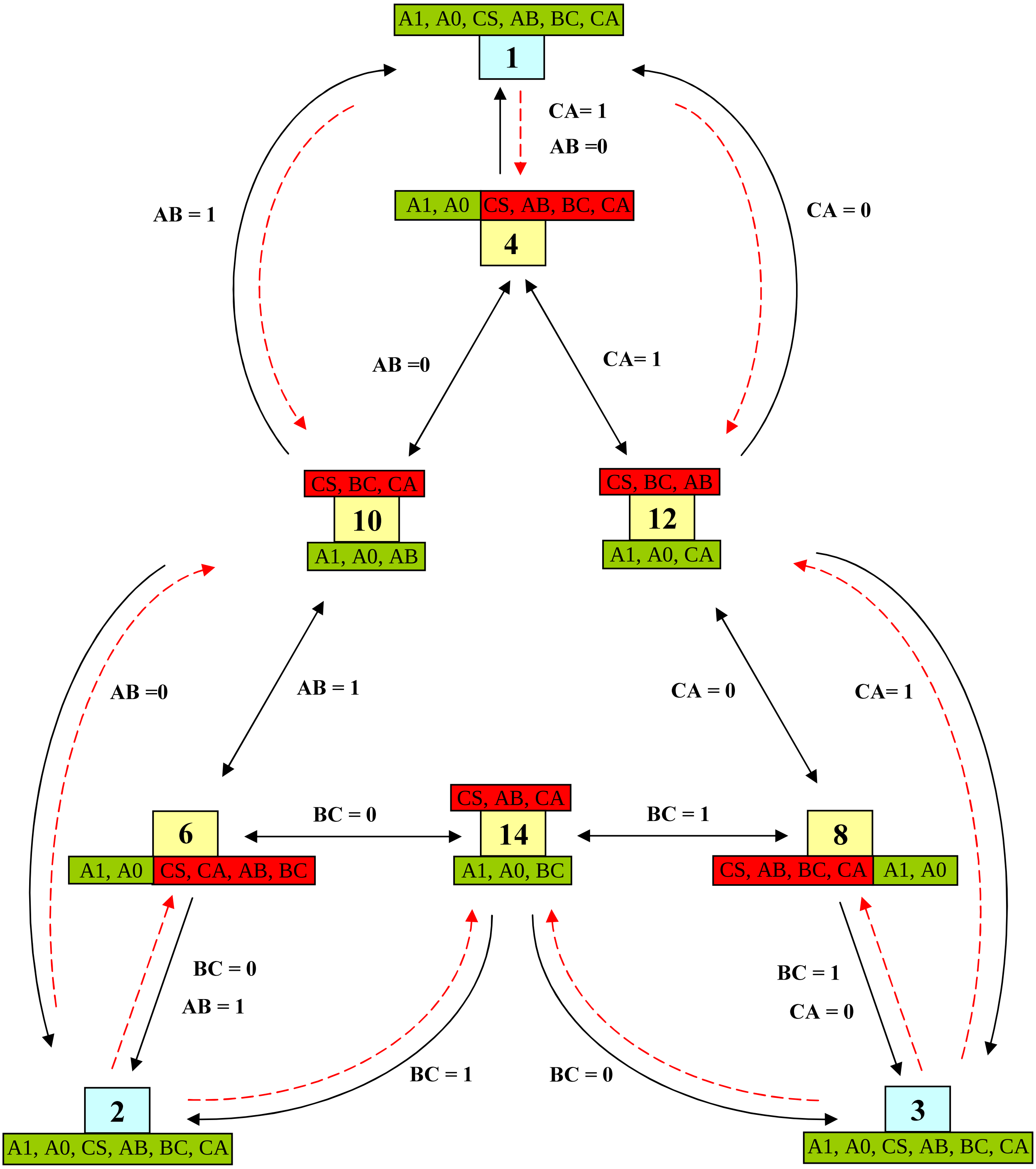


Fig.3.17 Three-step commutation strategy state diagram for positive output current direction.

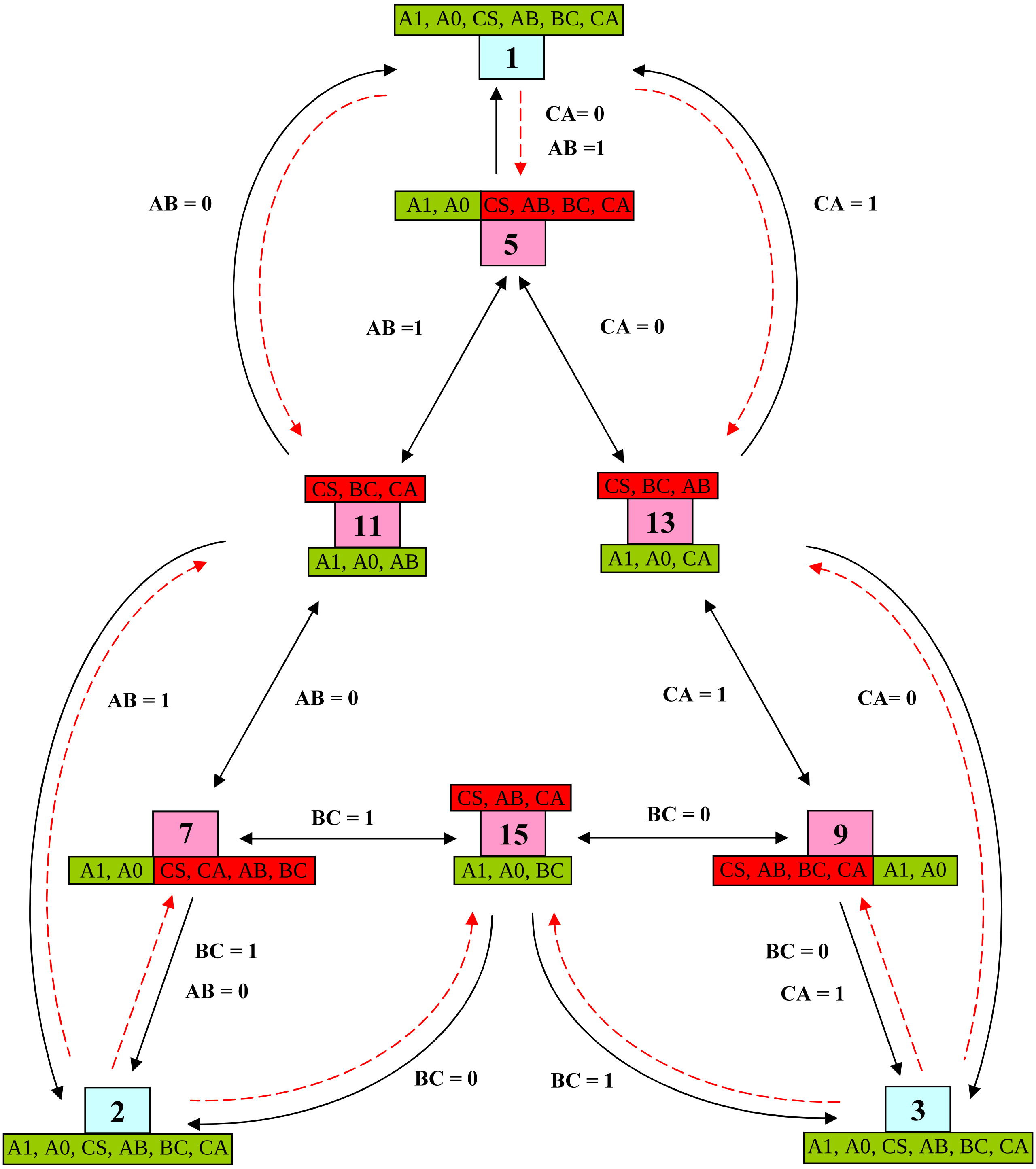


Fig.3.18 Three-step commutation strategy state diagram for negative output current direction.

Legend :
- represents a steady state;
- represents a transient state for positive output current direction;
- represents a transient state for negative output current direction;
- means that the relevant time step delay is the short one;
- means that the relevant time step delay is the standard one;

3.8 Conclusions

The practical realization of a matrix converter requires the use of bi-directional switches. Since a true bi-directional switch does not exist yet, this is generally provided by the use of an antiparallel arrangement of discrete power semiconductor devices plus series diode to provide reverse blocking capability.

This implementation implies a higher complexity of the matrix converter as 18 active devices have to be controlled in a three phase to three phase matrix converter but most of all it establishes the commutation problem. In matrix converters, the problem of safely commutate the load current from one bi-directional switch to another basically arises by the absence of natural freewheeling paths.

In order to carry out a safe commutation of the load current the voltage between the involved bi-directional switches or the output load current must be measured. These information are required in order to determine the proper sequence of the switching states combinations that does not lead to the hazard either of a short circuit or of an open circuit.

In this chapter several commutation strategies, based either on the detection of the input commutation voltage or the ouput current measurement have been reviewed and discussed.

A new three-step commutation strategy has been presented. This strategy relies on the measurement of both commutation voltage and output current sign. The advantage of the proposed new strategy compared to the others is that the commutation of the load current occurs always at the same instant with respect to the beginning of a switching commutation sequence. As a consequence, no compensation is required to the control DSP in order to get an optimum modulation of the input/output quantities. Furthermore, with respect to the four-step strategies, a faster commutation process is achieved. Some details on the implementation of the three-step commutation strategy on a complex programmable logic device have been also given.

It is worth noting that all the commutation strategies presented in the chapter intrinsically need to independently control the conduction path of the negative and positive current polarity. In the case this capability was no longer available, as it might be, for instance, in a future true bi-directional switch, these strategies would become ineffective.

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