New self-switching mechanisms for active bidirectional switches

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Abstract

The self-switching principle is a synthesis of synchronous type switching and switch inner protection mechanisms. Both switch ON and switch OFF are performed on the base of current and voltage measurement across the switch. Applied to an active bidirectional device, it may give complete autonomy to the switch. On the basis of those principles, the synthesis of an autonomous bidirectional free-wheeling path for an AC/AC buck converter is implemented with active switches. This paper introduces the current/voltage state representation in order to illustrate the experimental switching mechanisms. As a further application, the automatic triac is synthesized for a bipolar AC/DC half-bridge converter.

Introduction

A new self-switching principle based on switch protection circuits was recently introduced. By short-circuit and overvoltage detection, both turn-on and turn-off switching are performed automatically [1]. This self-switching process has been extended to zero crossing detection, for current and voltage. A new type of free-wheeling management using active switches has been recently published [2]. That work details the self-switching mechanisms of synthesized active diode and active thyristor where spontaneous commutations are performed by an active control based on measurement and logic circuits. One interesting issue of these principles is their application on bidirectional devices that may appear in the future [3].

The main goal of this paper is to go further and present the self-switching mechanisms applied to a bidirectional switch. A complete synthesis is made on the base of spontaneous devices switching mechanisms as well as protection circuits. This particular switching strategy is described to allow complete autonomy of active bidirectional switches by a detection circuit implemented close to the device. The switch gate control signal is a combination of an external modulator signal and local detection.

The first part of this paper is related to the principle of self-controlled switching. It describes the new mechanisms that allows a replacement of components like diodes and thyristors. The discussion is extended to the synthesis of bidirectional devices using both zero-crossing or protection based self-switching mechanisms. A second part details the implementation of the bidirectional switch with its self-switching circuits. In the final part, two test circuits that have been investigated are presented to validate some of the described mechanisms when applied to bidirectional switches.

The self-switching principle

The self-switching, or automatic switching, is a process based on current and voltage measurement across the switch. The switching mechanisms include two types of detection that induce a change of state for the switch. One of them, synthesized on the behavior of spontaneous components, is based on zero-crossing detection. The second, close to protection circuits, triggers on the base of gradient measurements.

Self-switching process

In the conventional switching process, two states are usually admitted for both switches of a switching cell. The switches obey some rules in order to always keep a conducting path for current sources and to avoid short-circuits in voltage sources. The self-switching mechanisms allow a third state for a short transient time where both switches of a cell are either ON or OFF. Between two states, the control is fast enough to avoid any damages for the switches or the sources.
The self-switching process begins with a first change of state, which is either controlled by an external modulator or by some other spontaneous or automatic mechanisms. This immediately induces a fast change of the electrical quantities of both switches in the cell. A variation of either current or voltage is detected and results on a change of state of the opposite switch.

Spontaneous switching synthesis

Devices like diodes and thyristors are naturally characterized by spontaneous switching mechanisms. Both of them switch off on zero-current and present reverse recovery phenomena in hard commutation mode. A simplified model of the diode is a device that conducts current on forward voltage and blocks on zero current.
A synthesis of these behaviors using active components is made with zero-crossing detection of the inner electrical values. The automatic switch is switched on when the voltage gets over a threshold value and switched off when the current crosses the zero value. The difference between diode and thyristor behaviors is made on the choice of the voltage threshold value, which would be either zero or another positive value. That threshold is not absolutely necessary for a thyristor if the trigger is made by an external modulator controlled by the user.
One interesting skill of the automatic thyristor is that on zero-current crossing, it switches off and does not retrigger if the voltage gets immediately positive. In a basic thyristor, the blocking voltage must be negative to allow a total reverse recovery of the carriers in the semiconductor. In the same point of view, an automatic diode may turn off quickly without any reverse current.

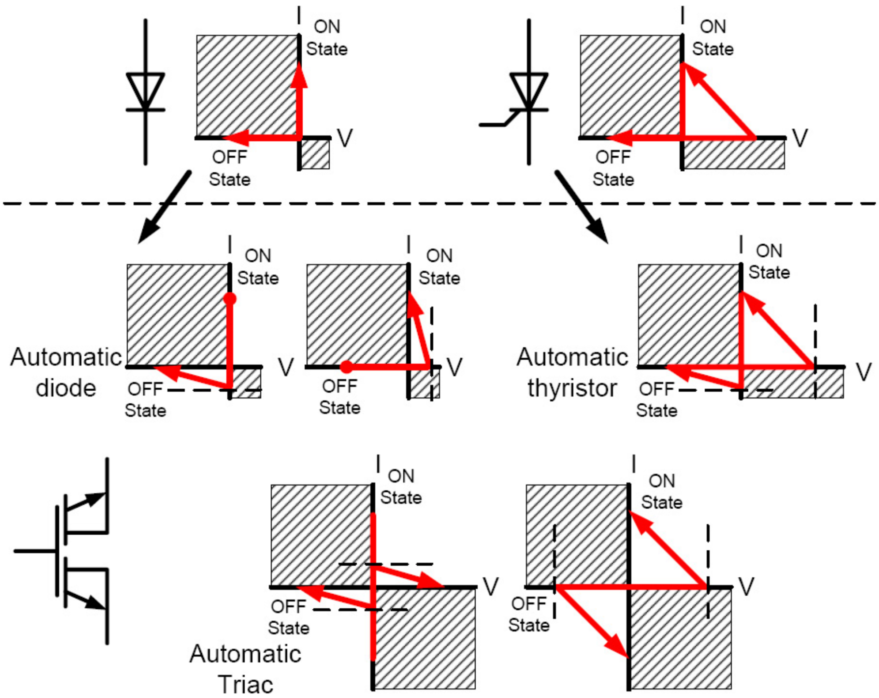


Figure 1: Switching mechanisms of synthesized spontaneous devices

To allow a fast detection in hard switching mode for example, not only threshold comparison is made by the detection system, but also a negative gradient measurement. In some cases, switching induces some fast variations in a cell. Threshold detection is then performed with some non negligible delay, which is avoided by a faster detection based on gradient measurements.
To go further, the automatic triac is synthesized on the base of the behavior of the thyristor. Both threshold turn on and zero crossing turn off are applied to a bidirectional switch. The implementation of a voltage threshold detection for closing instead of triggering by external modulator gives a complete autonomy to the switch. Figure 1 shows switching mechanisms of both automatic diodes and thyristors and the final automatic triac obtained by these principles. The dynamics are represented on a voltage/current diagram and thresholds detection levels. The switching mechanisms are shown by arrows connecting one state to the other.

Overvoltage and overcurrent protection based switching

Protection for switches are usually set for overvoltages or overcurrents and should not be activated in normal running but only in case of disfunction. A switching occurs to avoid any failure in both switches or sources. A self-switching principle has been described in [1] where these protection mechanisms take part in the normal switching process itself.
A synthesis of theses behaviors is made by high level threshold detection or better, by positive gradient measurement. Figure 2 shows the protection based switching mechanisms applied to a bidirectional switch. These mechanisms are applied to transistor type devices to allow more autonomy for the switch. On the other hand, an automatic transistor needs a short-circuit or an over voltage to turn on or off at each period. Detection circuit need to be fast for a minimal lose of efficiency.

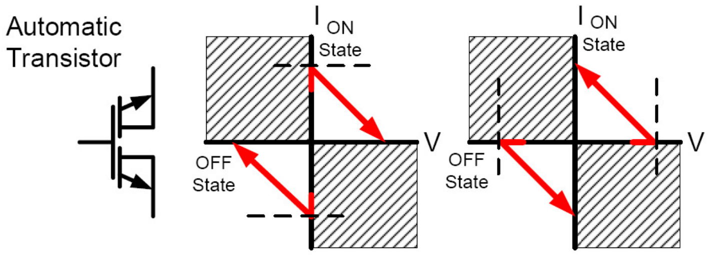


Figure 2: Protection circuit based switching mechanisms

Automatic switch implementation

For experimental validation, a switch is realized using a combination of devices with limited reverse recovery phenomena. The self-switching principle design is an analog and digital circuit implemented close to the switch gates. It is based on three stages including detection, decision and command. The measurement and detection procedure implemented on the prototype is detailed for all possible configurations.

Bidirectional power switch synthesis

The bidirectional switch is implemented using MOSFET devices. The gates are driven by one logic signal which is a function of an external user command modulator and the self switching circuit. The detection and decision stage is made out of analog and logic devices. The current goes trough a very low value shunt resistor which allows a fast measurement and detection. Voltage across the switch is directly measured at its both sides by a resistive divider.
The switch will be submitted to hard commutations. These provoke voltage instabilities due to parasitic inductances. To avoid voltage oscillations across the switches, simple RC snubber circuits are added in parallel to each device. The time constant is set in order to be similar to the period of the oscillations, namely in the few tens of nanoseconds domain.
First experimentations has shown that reverse recovery phenomena are not suppressed by using MOSFETs in reverse conduction. To improve the switch behavior, especially in hard commutation mode, a Silicon Carbide (SiC) Schottky diode, in which no reverse recovery occurs [4], is added in parallel to the MOSFET. In that configuration the reverse current flows through that diode and any reverse current in the MOSFET is avoided by a second one in serial connection. Figure 3 shows the complete switch implementation.

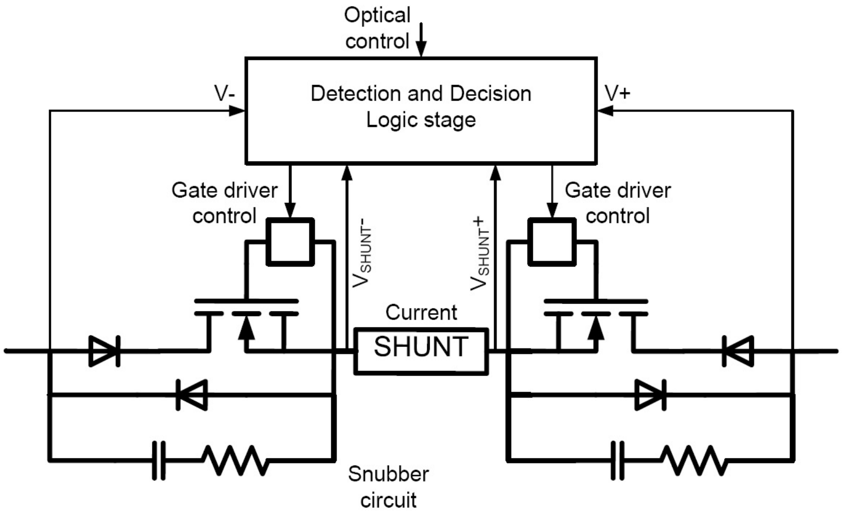


Figure 3: Bidirectional switch implementation

Automatic switching and control implementation

The detection stage, similar for both voltage and current measurements, is made out of differential amplifiers and comparators. The resulting signal is sent to the decision block. The final control signal is a function of the external modulation input and the result of the detection. Figure 4 shows a block diagram of the detection and decision stage. Two types of detection circuit, namely a threshold based detection and a gradient measurement, result on a logic stage which produces the final gate signal.

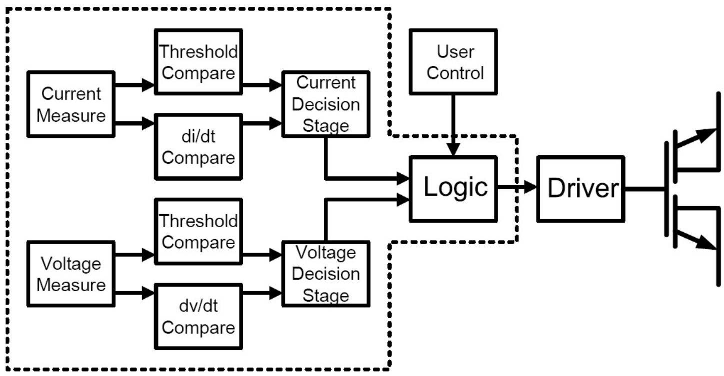


Figure 4: Detection stage implementation

Threshold detection

The direct instantaneous value is measured and compared to a fixed value. Gradients of any kind are detected by setting a high value which would be reached only by high voltage or current. In the active diode application, the threshold is set to a value close to zero to be able to detect the zero crossing.
This type of detection is very efficient when voltage and current vary slowly, namely if a thyristor is to be synthesized. In case of a fast gradient, the reaction time may not be fast enough to provide an efficient self-switching.

Gradient detection

The previous problem is solved by detecting fast variations of the electrical values. This detection is obtained by a derivation of the measured value, implemented by simple RC high-pass filters. Only fast variations are detected and induce an action on the switch.
A gradient of any electrical value is then detected before it reaches the threshold value. The much faster reaction of the system then permits a much better efficiency in the detection.

Logic block

The result of the detection is made by comparison between measurement and some variables. The resulting signals are combined and sent to a flip-flop logic circuit. Any voltage detection result on the closing of the switch where, on the other hand, any current detection result on its opening. The choice is given to combine a signal coming from an external modulator. This one may act as a master control for one part of the whole switching process, blocking or closing. This may also be combined to the detection signal as an external enabling signal which assures a self-switching process in safe conditions and to avoid any instabilities due to retriggering.

Prototyping

Two bidirectional switches are built using *IRFP21N60L* MOSFETs, *TC4421* drivers and *SDT10S30* SiC diodes. Powering is done by *TES2N-1221* and *TEN3-1222 TRACO* DC/DC converters that permit galvanic insulation between the devices. The self-switching control circuits are designed on an external layout that is directly mounted on the power board. The *LMH6624* operational amplifiers, *LMV7219* comparators and *MC74VHC1G08*, *MC74VHC1G32* and *NL17SZ74* logic circuits are chosen for their fastness skills. The picture on Fig. 5 shows the converter system. The load is a 12Ω resistor with a 35mH inductor.

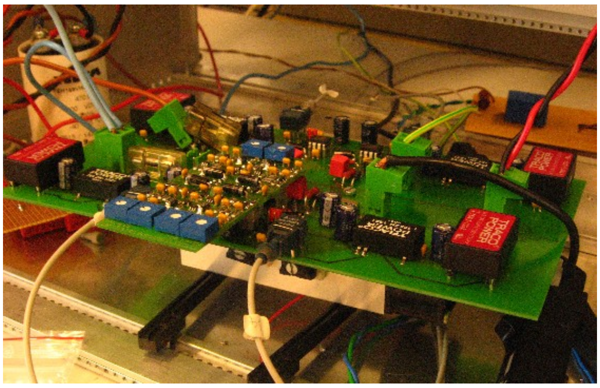


Figure 5: Picture of the whole converter system

Implementation of switching cells with synthesized switches

On the base of the presented results in [2], both buck and AC/DC converters are extended to bidirectionality. The automatic switches are implemented and tested for experimental validations. During OFF switching, a short circuit current appear which is added to the source constant current, in the scale of the microseconds. Similarly for ON switching, the over-voltage is punctual and independent of the source constant voltage.

Automatic free-wheeling AC/AC buck converter

A classical AC/AC buck converter is made out of two bidirectional switches operated in alternance with their functions of direct connecting and free-wheeling elements. They interface a voltage source and a load considered as a current source. Control is performed by an external modulator which provides a synchronous control for both switches as no spontaneous devices likes diodes can assume alone the free-wheeling functions. In the proposed scheme of Fig. 6 the automated bidirectional free-wheeling path is implemented as one independent intelligent switch.

Description of the converter

The modified self-switching cell includes an automatic switch for the free-wheeling path. Four different cases are to be considered depending on the polarity of the electrical quantities [5]. Figure 6 shows the converter and both switching mechanisms for one current direction, the two other cases with negative current are symmetric.
When the source current and the source voltage are both of the same polarity according the defined conventions, the switch works as an automatic diode. Mechanisms are then identical as already seen in

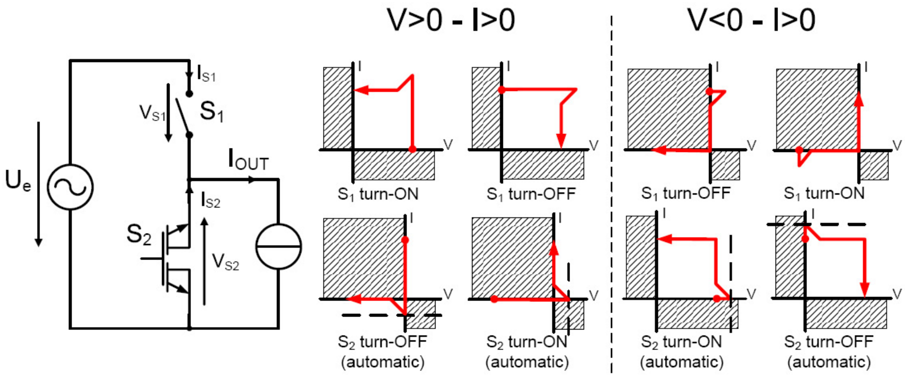


Figure 6: AC/AC buck converter and switching mechanisms

previous works [2]. Self-switching is performed by zero-crossing or negative gradient detection. For the other case, when the source electrical values are in opposite polarity, both short-circuits and over-voltages induce positive variations and no zero-crossing can be detected in the free-wheeling path. The free-wheeling switch works then as an automatic transistor and switching is triggered on high values thresholds or by positive gradient detections.
For implementation, the switch must deal with positive and negative gradient detection only. Because of the bidirectionality of the sources, threshold detection needs some additional logic to deal with negative values as well as positive values.

Experimental validation

The converter has been implemented and tested for a 100V AC source and 5A AC current. Fig. 7 shows a global representation of both current and voltages across the switches. The oscillations on the voltage are a direct consequence of the hard commutations applied to the source.

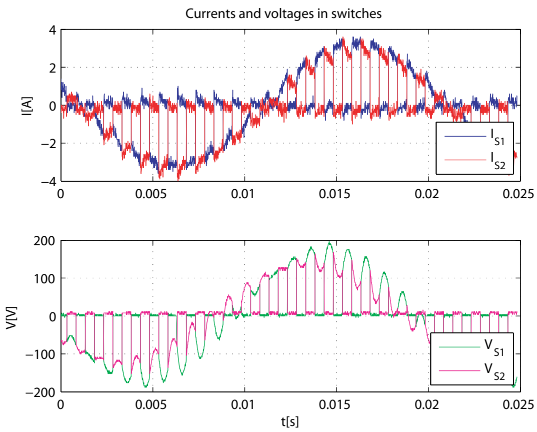
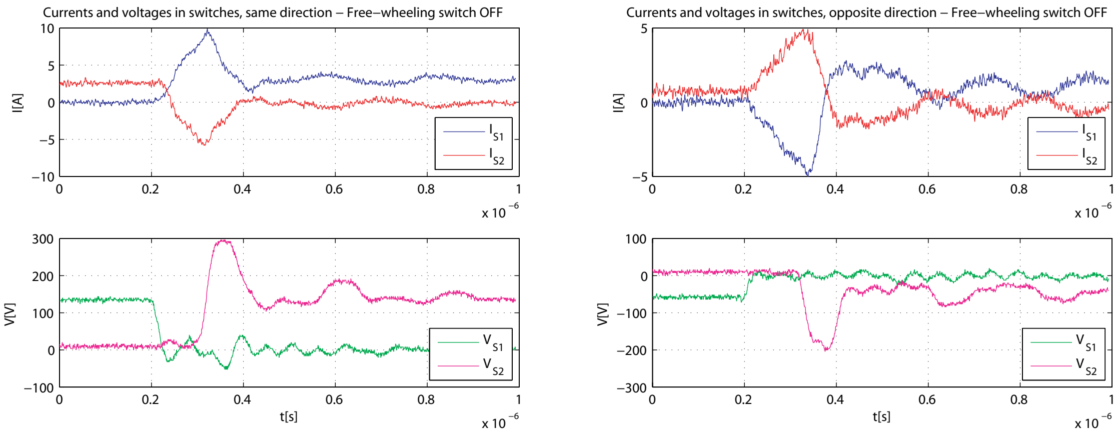


Figure 7: Currents and voltages across the switch

A closer look at the switching is reported on Fig. 8 and 9. The figures show the behavior of currents and voltages across the switches for two different detections during both free-wheeling switch OFF and ON. The total switching time is constant for all states of the electrical values during the conversion. The detection time is around 125ns witch is measured on both dead and overlap times between both switch gate signals.

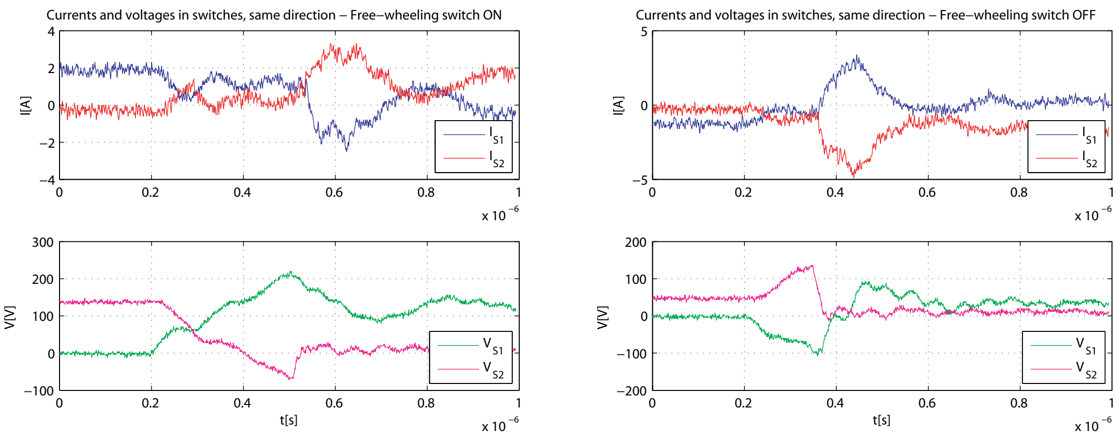
Figure 8a shows the switching process when the short-circuit current is opposite to the source current. Its zero-crossing in the switch is detected. Figure 8b shows the case where the source voltage and current are in an opposite polarity. In that case, the short-circuit current is in the same direction than the source current and does not cross the zero value in the free-wheeling switch. The short-circuit ramp magnitude is proportional to the voltage source value. An observation of the voltages during the switching process



(a) (b)

Figure 8: Free-wheeling turn OFF by zero current crossing (a) and by gradient detection (b)

makes clear that a short-circuit occurs and is detected. The area of the voltage pic after switching is similar to the area of the lost voltage during short-circuit. The behavior of both current and voltage show similarities with the reverse recovery phenomenon that occurs in a blocking diode.

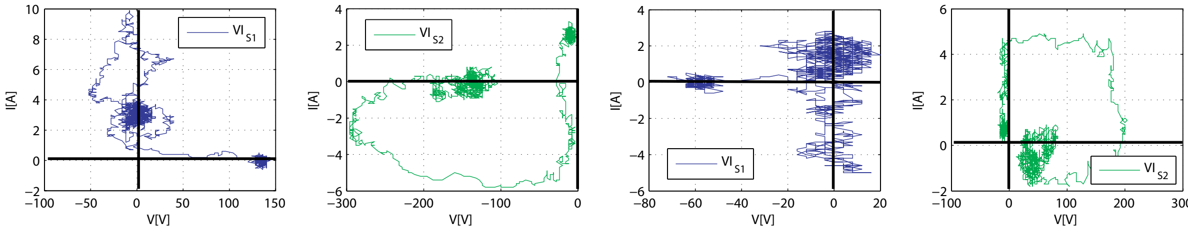


(a) (b)

Figure 9: Free-wheeling turn ON by zero current crossing (a) and by gradient detection (b)

Figure 9a shows the switching process when the overvoltage grows in the opposite direction of the source. Similarly to the previous observations, the detection is made by its zero-crossing. Again, Fig. 9b shows the opposite case, when the overvoltage is only detected by its gradient measurement.

The switches static and dynamic characteristics are deduced from the curves. The experimental switching mechanisms that occur in the conversion are represented by plotting the current over the voltage in the switch. The current/voltage state representation of each switching mechanism is compared to their theoretical description. These curves should not cross the quadrant where voltage and current have different polarity.
Figure 10a and 10b show the current extinction in the free-wheeling path in S_1 and S_2 respectively. The mechanism is obvious, by current zero crossing S_2 switches OFF. In S_1 the current stabilize after the short-circuit current path is closed. Figure 10c and 10d show an opposite behavior. The detection is made a positive current and the path drawn by the curve shows switching power losses.
The behavior reported on Fig. 10b is different from the theoretical predictions. The curve make a huge excursion in the state-space quadrant illustrating power losses. This behavior is identical to the theoretical



(a) (b) (c) (d)

Figure 10: Experimental static and dynamic characteristics : Free-wheeling switch OFF

curves given by [6] for the reverse recovery of a blocking diode. The switching mechanism and its state-space representation on Fig. 11 confirm that Fig. 10b is the dynamic behavior of a diode with its reverse recovery. It shows that this effect is not yet suppressed.

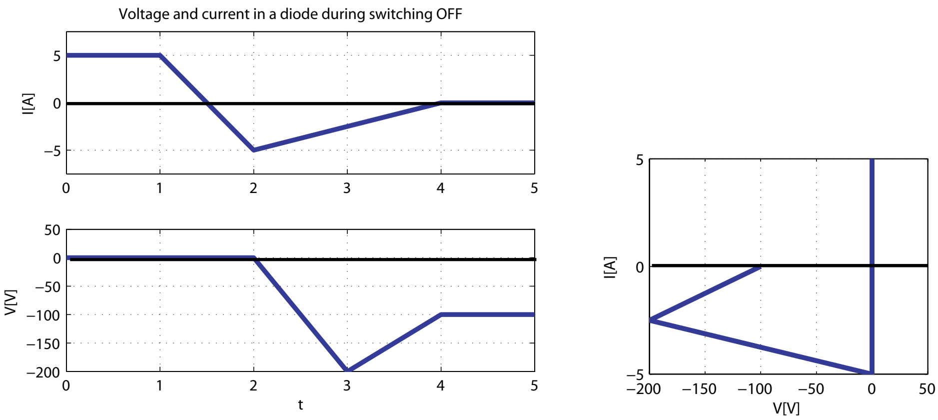
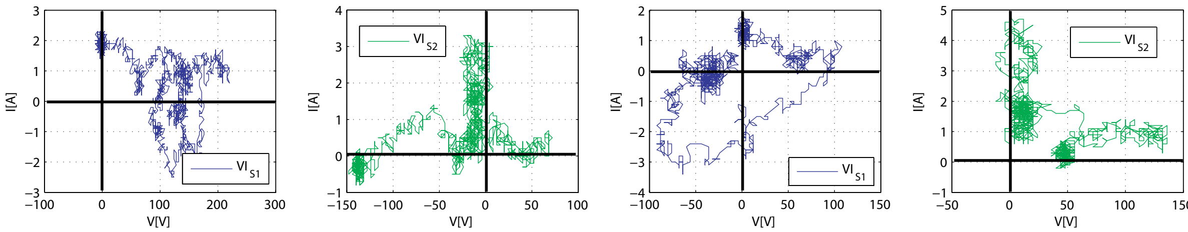


Figure 11: Diode turn OFF, current, voltage and state-space representation

Figure12a and 12b show the free-wheeling switch ON for zero-crossing detection. The switching mechanism for S_2 follows precisely the theoretical shape where the voltage is detected by zero crossing. For Fig.12d and 12c, the path followed by the switching show a detection on positive voltage. The same but complementary observation are made for switching losses.



(a) (b) (c) (d)

Figure 12: Experimental static and dynamic characteristics : Free-wheeling switch ON

Some curves like the one on Fig.12c go trough the quadrant where the instant power is negative. This clearly illustrates the recovery of the energy contained in the snubber circuits.

This representation is very interesting to have a good qualitative view on the power losses. Unfortunately some of these curves are not following the strict theoretical path. This is partly because of the oscillations caused by short-circuits and over-voltages. Two other explanations are mentioned above, considering snubber circuits and reverse recovery phenomena.

Perspectives

The results obtained by the previous converter lead naturally to the synthesis of the automatic AC/DC half bridge converter. Adding bidirectionality, the triac is synthesized in order to obtain a bipolar DC current source.
For further works, a complete autonomy for the bidirectional switch is to be reached by applying the self-switching principles.

Automatic bipolar AC/DC half-bridge converter

The classical switching cell for AC/DC conversion with thyristors interfaces two AC voltage sources to a current DC source. Depending on the firing angle of the switches, either hard-switching or soft-switching occurs in the conversion. In both cases the thyristor switches off at zero current and is triggered at the condition that its voltage is greater than opposite switch's.
With automatic triacs, the DC source becomes bipolar. Four cases, are to be considered regarding the current source polarity and the states of the voltage sources. Only two cases are described, the others are symmetric. Fig. 13 shows the converter with mechanisms for both switching cases. The off switching mechanisms are strictly the same than in the previous converter. On the other side, the triggering mechanisms are a consequence of two self-controlled based threshold detection which values decide on the polarity and the mean value of the current source.

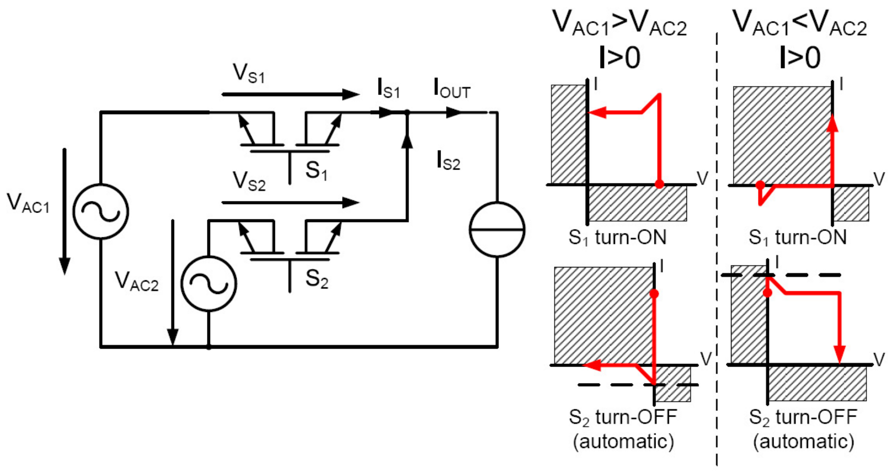


Figure 13: AC/DC half-bridge converter and switching mechanisms

For the case where the voltage across the conducting switch is greater than across the one that gets fired, a similar situation than in the last converter occurs. The short-circuit current doesn't cross the zero value as it grows positively. The gradient detection, as in an automatic transistor, performs the switching. This case is interesting because it never happens with normal thyristors as they will be retriggered.
This converter has not yet been implemented for experimental validations but similar results than for the previous converter are expected as it works as an extension of it.

Autonomous bidirectional active switch

The experimented converter was run by a signal which enables the automatic ON or OFF switching of the free-wheeling switch. This means that no over-shooting is up to occur as it is avoided by a signal coming from the external modulator. An autonomous bidirectional active switch will work with a strong logic stage in order to avoid a ON switching immediately after the OFF switching because of variation of both electrical values during the switching.

Conclusion

That paper presents an original way to describe switching mechanisms in a cell. The experimental results are presented using a current/voltage state graph to illustrate the real switching mechanisms. The self-switching principle is applied to a bidirectional switch in order to obtain an autonomous active switch for a bidirectional free-wheeling application as well as for the synthesis of a triac.

The main differences between theoretical and experimental curves come from the energy contained in snubbers and reverse recovery phenomena. Obviously the effect has not been suppressed by using SiC diodes, but only limited. The question on what is to be considered for a switch except the device still remains. The snubbers and control have an important effect on the behavior and switching mechanisms of a device.
These results could be reached within a research program funded by the Swiss National Science Foundation.

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