Comparative Analysis of the Techniques of Current Commutation in Matrix Converters

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Abstract—The devices of power used in Matrix Converters (M.C.) need some operation sequences to commute the current in a safe way. These operation sequences are what we denominate strategies of current commutation, being these more complex than in other converters. In this article a comparative analysis of the different strategies of current commutation will be carried out by means of simulation and they will be implemented in an experimental matrix converter to analyze its behaviour. As comparison criterion of the different strategies that have been used, the Total Harmonic Distortion (THD), the efficiency of the converter, the maximum commutation frequency and the necessary hardware requirements for the implementation of the strategies.

I. INTRODUCTION

A M.C. is an Unrestricted Frequency Changer (UFC) that allows the conversion CA/CA in a single stage, thanks to this characteristic, presents a relationship volume/power inferior to which the traditional converters show. Moreover, due to its capacity of bidirectional flow of power, to its structure theoretically "all Silicon", and to its high integration density, it turns into a system with a strong future potential. However, since Gyugyi [1] presented the theory on the matrix conversion, until some years ago when the industrial interest was renewed by this type of converters, a significant time has passed. The main reasons of this long period of time are the problems associated to the poles of power used in the converter:
- Problems in the implementation of poles of power that work in four quadrants.
- Problems in the commutation processes of the current among the devices of power.

At the moment, the problem of the implementation has decreased substantially on incorporating gradually in the market cheaper and cheaper integrated modules of power and with more integration capacity. Among these integrated modules we highlight. Firstly, DYNEX that markets two poles of power with IGBT’s in common emitter configuration that allow to operate with currents of 200A or 400 A and voltages of 1700V or 1200V. Secondly, SIEMENS together with EUPEC that presented the EconoPack3 that is a module 3x3 of 7.5Kw. This way, the biggest problem as for the implementation of M.C., is to achieve a safe commutation of the current among the devices of power. To guarantee this safe commutation, the poles of power should be controlled so that two basic rules are verified the whole time. The first one is that two poles of power of the same phase should be never at the same time in ON, this will avoid short circuits among the input phases. Secondly, all the poles of the same phase should never be in OFF, this guarantees that a way for the inductive current of load exists.

These two rules generate conflicts on carrying out the commutations since the poles of power cannot commute in an instantaneous way due to the propagation retards and to the times of commutation. To solve this problem, we can take different procedures that allow us to fulfill these rules and therefore to guarantee a safe commutation.

These methods can be classified into those that are based on the knowledge of the sign of the current, those that are based on the knowledge of the sign of the input voltage and the mixed ones that require the knowledge of the two parameters. In the sections II, III and IV these commutation techniques will be analyzed.

II. COMMUTATION TECHNIQUES BASED ON THE SIGN OF THE CURRENT

These techniques can only be applied to poles of power that can work in 2 or 4 quadrants being able to be classified in:

Four Steps Strategy of Commutation: This strategy is characterized because it has the two IGBT’s in ON when the pole of power is conductive [2-3]. In the Fig. 1 the diagram of state of this strategy is shown. The commutation sequence depends on the sign of the current of output phase that will have to be acquired by the commutation logic.

Two Steps Strategy of Commutation: It is characterized because only the IGBT that drives the current in the pole of power is put in ON. In this strategy a threshold is settled down to small current, just as it is represented in to the Fig. 2.

When the current for the device of power is bigger than a defaulted value (+δ), the transistor T1 is put in ON. When the current is inside a band (±δ), both transistors (T1 & T2) are put in ON, until the current falls below (-δ)
where only T2 remains in ON. This commutation type, that is
denominated "Inter-Switches Commutation", only happens
when the pole of power is in ON and a sign change takes place
in the current circulation through it. When a commutation
among phases is required, the “Inter-Switches Commutation”
should be disabled to avoid conflicts.

In the Fig.4 the diagram of state of the commutation strategy
is shown applied to an output phase of a M.C. 3x1. The
commutation sequence not only depends on the sign of the
current of the phase, but also on the value of this one.

III. Commutation Techniques Based on the Sign of the Voltage

These techniques are based on the input voltages to obtain
the necessary information that allows to carry out a safe
commutation. The same as the techniques based on the sign of
the current, these ones require poles of power with capacity to
work in 2 or 4 quadrants. Although there are different
strategies in these techniques, we will analyze the method
"Metzi" [13] in this work, since we consider that it is the
technique that shows a better behaviour. This method is
another technique of commutation of two steps, but now based
on the input voltage lines that allow the determination of six
intervals of 60º, as it is represented in the Fig. 5a. In each one
of these intervals we have a positive input (V_p), an input with
intermediate voltage (V_m) and an input with negative voltage
(V_n). To carry out the analysis of this commutation process we
will consider the representation of states of each pole of power
indicated in the Fig. 5b.

The main idea of this commutation is to put in ON the
maximum of IGBT’s without causing short circuits in the input
voltages, this assures a way for the load current. Taking into
account this, we can establish three stable states (P,M,N) and
three transitory states (PM,MN,PN), as it is represented in the
Fig. 6, for a matrix converter 3x1. Each stable state guarantees
a bidirectional way to the load current, so this way, for
example, the state P presents a bidirectional way to the phase
V_p. Only two of the six IGBT’s are put to ON in each stable
state.

Let us analyze a commutation process, so we will suppose
that V_a(t) is the positive voltage (V_p), V_b(t) is the intermediate
voltage (V_m) and V_c(t) is the negative voltage (V_n), that is to
say, when we are in the interval 2. We consider a matrix converter 3x1, as the one represented in the Fig. 7 where a commutation of the pole S11 to the S31 takes place. Initially the pole S11 is active in the converter, that is to say it is the phase “a” the one that is connected to the output “u”, when the commutation toward the pole S31 is required. Then we will have to go toward the state N, through the transitory state NP. This transitory state NP assures a way to the load current avoiding short circuits in the input phases in the commutations among states.

IV. MIXED COMMUTATION TECHNIQUE

This technique is based on the use of the input voltages and the output currents to obtain the necessary information that allows to carry out a safe commutation [14]. The same as in the previous cases, it requires poles of power with capacity to work in two or four quadrants. We can establish three stable states \((P_F, M_F, N_F)\) when the output current is positive and other three stable states \((P_R, M_R, N_R)\) when the output current is negative, as it is represented in the Fig. 8, for a matrix converter of 3x1.

Each stable state provides an unidirectional way to the output current from an input phase to the output phase. The pole that drives in each one of the stable states depends on the interval where the input voltages are (Fig. 5(a)).

V. SIMULATION OF THE CURRENT COMMUTATION STRATEGIES

To simulate the behaviour of the different commutation strategies, a matrix converter of 3x1 has been implemented in DesignLab V8.0, where it is only commuted between the poles of power S11 and S21, to a frequency commutation of 4KHz. In the Fig. 9 the Schematics of the test circuit are represented. The devices of power are IGBT’s in anti-paralleled in common emitter configuration. The gate drivers of the IGBT’s are simulated by means of a gate resistance and a voltage-controlled voltage source, so that the IGBT’s are put in ON by means of the digital signals T1 to T6. The load applied to the convertor is a resistance of 25\( \Omega \) and an inductance of 100mH.

The commutation strategies based on the sign of the current, require to know characteristics of the output current phase, such as, if this is positive or negative, what is settled down with the “I” signal, or to know its position inside a band that is settled down with the “POS” and “NEG” signals. The circuit that we use to know these characteristics, is the block “Meter of Current” of the Fig.9.
Fig. 7. *METZI* commutation in the interval 2 between the poles S11 and S31.

Fig. 8. Stable states in the strategy of mixed commutation: (a) $i_{u}(t)>0$; (b) $i_{u}(t)<0$.

Fig. 9. Schematics in DesignLab V8.0 to check the commutation strategies.
In the commutation strategies based on the sign of the tension, the knowledge of the interval is required where the input voltages phases are, in order to be able to make a safe commutation. The block "Detector of Sector" of the Fig. 9 is in charge of it. The block "Control S11 and S21" take charge of putting S11 ("A/B" = 1) or S21 ("A/B" = 0) in ON, in a synchronous way with the signal "CLK A/B", from a signal "Disp" generated by a clock of 4KHz “DSTM28”. The block “Division of Frequency” is in charge of generating three signals, from the signal “CLK” (1MHz), that is applied to the FPGA. These clock signals are “CLK I” (500KHz), “CLK V” (250KHz) and “CLK A/B” (125KHz), the generation of these signals assures that in the descending flank of the signal “CLK”, the signals that are applied to the FPGA are stable.

The block “Control of Current Commutation” establishes the strategy commutation which is going to be used, this way for example in the commutation strategy of four steps, the state diagram that is implemented in the FPGA is the one represented in the Fig. 1.

After carrying out different simulations of each one of the commutation strategies, we can obtain the different signals that will allow us to analyze the parameters that were established like comparative approaches. This way for example in the Fig. 10, the forms of wave of output voltage and current is represented in the case of the commutation strategy of four steps.

The Fig. 11 represents the Total Harmonic Distortion (THD) of the output tension and current for the different analyzed strategies of current commutation. The Fig. 12 represents the THD of the input currents as for the "a" phase and the "b" phase, for the different analyzed strategies of current commutation. The Fig. 13 represents the efficiency that has been obtained in each one of the control strategies. The Table I indicates the necessary hardware to implement each one of the strategies. The Fig. 14 represents the maximum frequency to which we could commute the devices of power of a matrix converter with every commutation strategies.

VI. PRACTICAL IMPLEMENTATION OF THE STRATEGY OF COMMUTATION

Once we have analyzed and compared the different strategies of current commutation by means of simulation, we have implemented the strategy of commutation of four steps on a prototype matrix converter 2x1, with the same structure as the one used in simulation. As stage of power we have used the module FM35R12KE3 of Eupec. In order to implement the
commutation strategy we have used the FPGA Spartan XC2S300E of Xilinx on the development platform B5-X300 of Burched. As control system the TMS320F2812 has been used. The prototype is represented in the Fig. 15 and the Fig. 16 represents the shape of wave of output voltage and current that we have obtained.

![Fig.14. Maximum frequency of commutation of devices for a control signal “CLK” of 100KHz.](image)

![Fig.15. Representation of the matrix converter prototype.](image)

![Fig.16. Output voltage (channel 1) and output current (channel 2).](image)

VII. CONCLUSIONS

The basic rules that allow a commutation of safe current, in a matrix converter are: firstly to avoid short circuits in the input phases and secondly to avoid interruptions of the current in the output lines. In this article different solutions that allow to make this safe commutation of current have been compared. The first comparison approach is the THD represented in the Fig. 11 and 12. After analyzing the figures you can conclude that the quality of the input and output signals do not differ in a substantial way in the analyzed commutation strategies, then from this point of view, none of the strategies highlights on another.

From the efficiency point of view, Fig. 13, the strategy of commutation of four steps is highlighted, almost two units over the other ones. As for the necessary hardware to implement each one of the strategies, Table I, we see again that it is the strategy of commutation of four steps the one that presents less requirements. From the point of view of the maximum frequency to the one that we could commute the devices of power, Fig. 14, we can see as any of the strategies of current commutation covers the current range of commutation of the devices of power used in matrix converters. In view of the previous results, we have decided to implement the algorithm of control of four steps in the FPGA, in the prototype of matrix converter that is being implemented at the moment.

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