

New fault tolerant matrix converter

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ABSTRACT

The matrix converter (MC) presents a promising topology that will have to overcome certain barriers (protection systems, durability, the development of converters for real applications, etc.) in order to gain a foothold in the industry. In some applications, where continuous operation must be insured in the case of a system failure, improved reliability of the converter is of particular importance. In this sense, this article focuses on the study of a fault tolerant MC. The fault tolerance of a converter is characterized by its total or partial response in the case of a breakage of any of its components. Taking into consideration that virtually no work has been done on fault tolerant MCs, this paper describes the most important studies in this area. Moreover, a new method is proposed for detecting the breakage of MC semiconductors. Likewise, a new variation of SVM modulation with failure tolerance capacity is presented. This guarantees the continuous operation of the converter and the pseudo-optimum control of a PMSM. This paper also proposes a novel MC topology, which allows the flexible reconfiguration of this converter, when one or several of its semiconductors are damaged. In this way, the MC can continue operating at 100% of its performance without having to double its resources. In this way, it can be said that the solution described in this article represents a step forward towards the development of reliable matrix converters for real applications.

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1. Introduction

The clear intent of the power electronics market is to attain the following objectives: improve interaction with the grid, flow of bidirectional power, high efficiency and operation at high switching frequencies, small size and, lastly, integration of complex and intelligent solutions within the same power module. In principle, the matrix converter [1] (MC) meets all of these targets. Fig. 1 shows a PMSM with a three phase MC. The MC is composed of 9 common collector bidirectional switches. It contains an input filter and a clamp circuit with two diode bridges, a C_{clamp} capacitor, a crowbar and a R_{ntc} resistor. The MC feeds the rotor of a PMSM.

The main advantages of the MC are as follows: it is an *all-silicon* AC/AC converter, with no dc-link requirement, low volume and compact design. It presents bidirectional power flow, sinusoidal input and output waveforms and unity power factor. In addition, the converter has a long lifetime with high-temperature and high and low pressure surroundings due to the absence of the electrolytic capacitors.

The MC is a very promising technology, but its industrial acceptance has been held back due to some challenges which must be overcome; some of these are set out below:

- The MC has a limited voltage transfer ratio of $\sqrt{3}/2$.
- The MC uses a high number of switches and nowadays, there is an absence of natural bidirectional switches.
- The MC is very sensitive to voltage dips and distortions in the grid and has a poor “ride-through capability”.
- The modulation and control techniques are very complex.
- Protecting the converter is a complex task, because there is no way to store energy.

Considering the overall characteristics of the MC, it could provide solutions for a wide range of applications: wind turbine applications [2], aerospace and military environments [3,4], deep-sea ROVs [5], aeronautic applications [6], elevators with energy recovery systems [7], etc. This converter is more competitive in applications where reduced space and weight as well as high-temperature operation are critical issues [8,9].

In the aforementioned applications, the reliability of the power converter is especially relevant due to the fact that it must guarantee the operation of the conversion system even when there is

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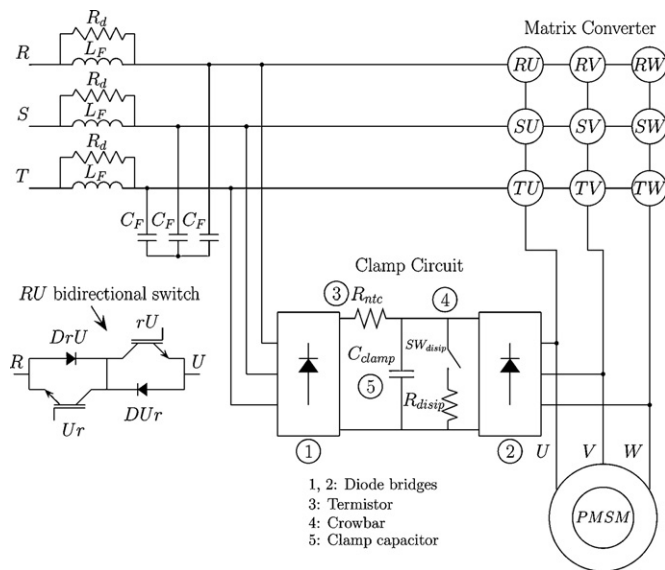


Fig. 1. Matrix converter, input filter and clamp circuit driving a *PMSM*.

a failure of one of its component parts. This is known as a fault tolerant system.

In the MC, the great majority of scientific studies is being focused on improving the control techniques (wind generation [2], distributed generation [10], loss reduction [11], predictive control [12,13,4], sensorless control [14–17], etc.), modulation (Space Vector Modulation [18] and other variants [19], direct torque control [16,20], etc.), waveform quality [21,22] stability analysis [23] and semi-soft commutation [24–26]. Likewise, there are several references in which the behavior of the MC in the presence of unbalanced networks is improved [27].

On the other hand, very few references study *MC* hardware and the problems this involves [28]. In this sense, it can be said that there are virtually no references that concentrate on the study of fault-tolerant *MCs* [3].

Taking all these considerations into account, this paper examines, on the one hand, the motives that might cause the *MC* to rupture. On the other hand, a number of strategies to protect the *MC* are presented. In view of the fact that virtually no work has been done on fault tolerant *MC*s this paper describes the most important studies in this area. Later, a new fault detection method and novel fault tolerant modulation technique for open switch faults is presented. Short circuit switch faults are not considered in this work. Finally, a series of topologies of innovating *MC*s that resolve partial ruptures of the converter are presented.

2. MC fault conditions and protection strategies

The MC performs a direct AC/AC conversion, without any storage element. So, it is a low ride-through capability converter and it is very difficult to control and protect the MC during fault conditions. In general, fault conditions can be classified as overvoltage and overcurrent, which are caused by applying forbidden switching states, starting up or shutting down the MC suddenly, disturbances in the input grid, parasitic inductances of switches and load faults.

Today, the most relevant protection strategies of an MC can be classified as follows.

2.1. Software protections

In the case of a fault, the *MC* control can activate a series of vectors (“software protection strategies”) in order to reduce voltage

and/or current surges. Thus, for example, in [29] a protection strategy is applied in situations in which an MC switch does not respond. In [30,31] the magnetic energy (W_L) stored in the load is controlled during the normal operation of the converter and in [32] W_L , as well as the load current, is controlled during fault situations.

Although *software* protection strategies can be beneficial for the MC, these are not enough to attain sufficient robustness. In fact, *software strategies* may not include the full range of protection strategies, or may even fail due, for example, to an incorrect application of the protection algorithm or an EMC failure. Moreover, it must be remembered that these strategies are based on programs, which when executed respond with certain latency. In overcurrent and/or overvoltage situations, this delay may be excessive. For this reason, in order to increase the robustness of the MC, it is necessary to protect it through *hardware* solutions (irrespective of the control *software*), which respond instantaneously and in a more robust manner.

2.2. Hardware protections

The most efficient *hardware solutions* [33] for protecting the MC are shown below:

1. Power-up resistor (R_{pu}) of the input filter [28,34], which can partially minimize the overvoltages and overcurrents generated in the filter capacitor.
2. Clamp circuit: this circuit reduces the *all-silicon* nature of the MC. However, it increases its robustness considerably, as it mitigates the overvoltage problems deriving from a lack of natural free-wheeling paths in the MC. These also arise due to the existence of parasitic inductances that, together with the switchings of the semiconductors, give rise to undesirable voltage surges. Moreover, thanks to the clamp circuit capacitor the input overvoltages and *inrush* currents are partially mitigated. There are certain alternatives (varistors and suppressors, use of MC switches to give way to W_L , etc.) to the clamp circuit [31]. However, these do not offer sufficient guarantees to warrant discarding the aforementioned clamp circuit.

On the other hand, in order to increase the robustness of the MC and leave the latency problems of the *software strategies* to one side, in [28] a number of new *hardware solutions* are proposed, such as a power-up resistor (R_{nrc}) placed in the clamp circuit.

3. Breakage of the MC: problems

Unfortunately, under certain circumstances, the protection strategies described in the previous section are incapable of protecting the converter. This situation may cause it to break. When one of the switches that make up the *MC* is damaged, the converter loses the capacity to deliver the nominal power for which it has been dimensioned. For example, if an *IGBT* (or its corresponding diode placed in series) stops working correctly and if the control technique of the converter is not modified, the maximum power drops to 94.4%; if there are two “damaged” *IGBTs* (or a bidirectional switch) power is reduced to 88.9%; without two bidirectional switches this would fall to 77.8% and so on.

In this sense, **Table 1** shows the results obtained when the *DS SVM (Double Sided Space Vector Modulation)* [18] is applied in a MC of 7.5 kW when one or more semiconductors are broken. In this situation, the MC can continue to operate while the inductive current of the load is provided with a free-wheeling path. The clamp circuit (**Fig. 1**) allows the aforementioned induction current to circulate. The results of **Table 1** refer to the loss of power delivered by the converter, to the *THD* of the input current and to the *rms*

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