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Technical and Economical Evaluation of Modular Multilevel Converters for the Electrical Power Grid Interface

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Modular Multilevel Converter (MMC), Power Converters, Electrical Power Grid Interface

ABSTRACT

Over the past few years, it has been verified a raise in the demand, as well as the price of electricity, urging the need for the development of more efficient power converting systems. Two of the most used power converters are the AC-DC, commonly known as rectifier, and the DC-AC, commonly known as power inverter. There are many different topologies for both the referred converters, but one of the most common is the H-Bridge, which can operate as a bidirectional converter that enables the possibility of a single power converter working either as an active rectifier or a grid-tied power inverter, according to the application in use. In this paper, a Modular Multilevel Converter topology is presented and compared to the most conventional bidirectional power converter, discussing both technical and economical details recurring to simulations and a critic analysis of the results, which allows the understanding of the tied relation between economics and engineering, optimizing the functionality of the converter, as well as the costs associated with R&D and production in short term, and the efficiency in the long term.

INTRODUCTION

Power converters have been evolving in the last few decades, with the focus of the development of efficient power converting systems. For the most varied range of applications, from renewable energy interface (Alepuz et al., 2006) to battery integration (Monteiro et al., 2012), UPS (Racine et al., 2005), active power filters (Afonso et al., 2000), motor drives (Latt & Win, 2009) and many others, a DC-AC converter is necessary. Depending on the power at stake, there are many different topologies that can be used, being the H-bridge one of the most common. Another type of converters growing in popularity is the multilevel family, with special focus on the Modular Multilevel Converter (MMC) (Du et al., 2018), which possesses some unique qualities offered by its modularity feature.

Over the past few years, MMC has been a very common topic in research in the field of power electronics, with proposals of different applications, such as railway power conditioners (Tanta et al., 2021), static compensators (Pereira et al., 2011), solid-state transformers (Li et al., 2016), renewable energy interface (Serban et al., 2015), among others, being the most promising one High Voltage Direct Current (HVDC) distribution. There are many MMCs in use around the world in high power HVDC power lines (She et al., 2013), being the Dolwin1 project one of the most important (Wijk et al., 2013). Figure 1 presents a high-level block diagram of an DC-AC power converter interfacing a DC-link and the power grid.

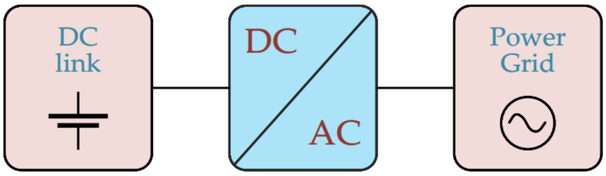

Figure 1: High-Level Block Diagram.

This paper intends to compare technically and economically the MMC with the H-bridge converter in the same conditions of operation and study its differences. To perform an economic analysis, it is first necessary to understand the technical differences between the power converters in study.

Even though the power converters studied in this paper are usually three-phase, the analysis will be made using single-phase ones, in order for an easier comprehension of the functioning and the differences between them.

The paper organization consists of the presentation of the analysis and results for the different topologies in study, followed by a detailed comparison, as well as a discussion of the results presented for each power converter. A conclusion is presented to conclude the paper.

H-BRIDGE

Regarding DC-AC bidirectional converters, the H-Bridge is the most used across a wide array of applications due to its versatility and simplicity, from active power filters, renewable energy interface with the electrical power grid, UPS, and many others. Figure 2 presents the electrical schematic of a single-phase H-Bridge.

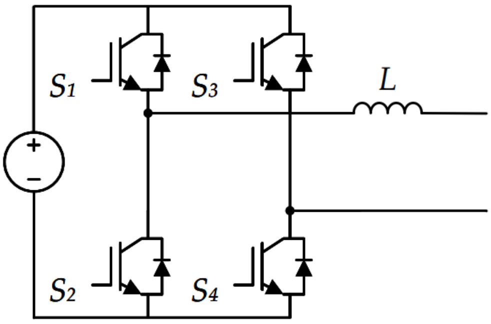

Figure 2: Schematic of a single-phase H-Bridge.

The H-Bridge power converter possesses a DC power source as input and 4 IGBTs as switching devices that are responsible for generating an AC output signal, which will be filtered by an inductance, resulting in a sinusoidal waveform.
In order to understand the functioning and evaluate the performance of the converter, a simulation was developed recurring to PSIM software. This simulation was designed for a rated power of 4 kW, and it was used a resistive load and an inductive filter. In order to simulate the power losses across the switching devices, the IKZA50N65RH5 IGBT (Infineon, 2020) characteristics were added to the simulation model (Infineon, 2009), aiming to simulate the real behaviour of the IGBTs and to obtain results as realistic as possible.

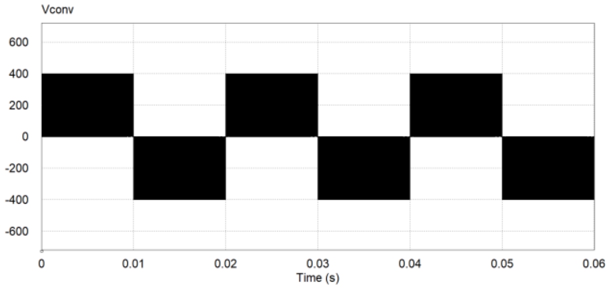

Figure 3a: H-Bridge Output voltage

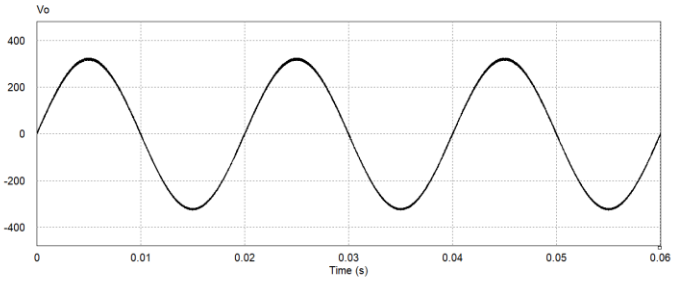

Figure 3b: H-Bridge Output voltage alter Filtering

Figure 3a presents the output voltage of the H-Bridge converter without load, while in Figure 3b is presented the output voltage of the converter in load, after filtering. The Total Harmonic Distortion (THD) of the referred signals is 75% and 1.2%, respectively. The control of the converter was implemented using unipolar Pulse Width Modulation (PWM), which results in even power losses across all the switching devices. Analyzing the obtained results in the simulations, it was observed that the power losses across each IGBT is about 27.5 W.

MODULAR MULTILEVEL CONVERTER

In the family of DC-AC multilevel converters, the MMC stands out due to its unique characteristics coming from the modularity (Martinez-Rodrigo et al., 2017), such as:

- Modular construction;
- Voltage, current and power scalability;
- Fault-tolerant operation.

On top of the above, the MMC also shares all the advantages of the other multilevel topologies:

- Low dv/dt;

- Near-sinusoidal currents;
- Necessity for smaller filters;
- Low voltage harmonic distortion;
- High efficiency;
- Low common-mode voltage.

However, there are also some disadvantages associated to MMC, such as:

- Need for monitoring the capacitor voltage of every submodule;
- Requires a controller for the capacitor voltage balancing;
- Circulating currents in the arms which increases device losses if not suppressed;

The referred disadvantages culminate in a more complex control system and the need for more sensors. (Martinez-Rodrigo et al., 2017). The MMC under study in this paper possesses a DC link composed by two DC power sources to have an accessible neutral point. The number of switching devices of the converter varies with the number of submodules, where each submodule is composed by a capacitor in the DC-link and two IGBTs as switching devices. This type of converter is composed by two arms that connect to each other and the load through coupling inductances, and each arm is responsible for the synthetization of a part of the output signal, the positive and the negative.

For the converter to be able to interface with the electrical power grid with a peak voltage value of 325 V, each DC power source of the converter must be higher than 325 V. As such, the value of each DC power source in the simulation is 400 V. With a raise of the number of submodules, the voltage across the DC-link capacitors of each one will decrease in proportion.

Modular Multilevel Converter With 2 Submodules Per Arm

In Figure 4 is presented the schematic for an MMC with 2 submodule per arm.

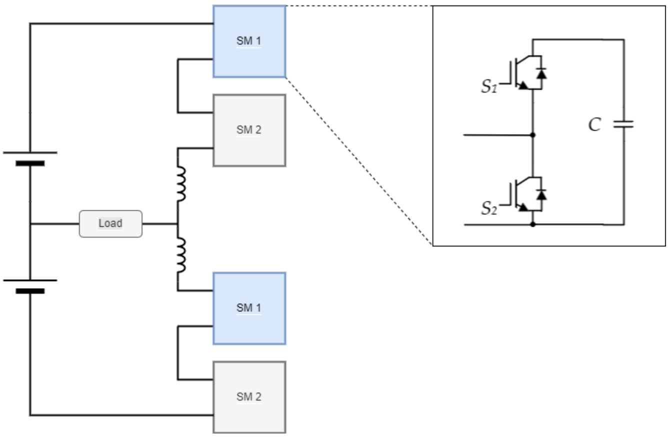

Figure 4: Modular multilevel converter with two submodules.

Using half-bridge submodules, the presented converters is constituted by a total of 8 IGBTs as switching devices, which are responsible for the synthesis of the output wave. Having 2 submodules in each arm, the voltage in the DC-link capacitors of each submodule is 400 V, which also means that each IGBT must withstand 400 V in its terminals.

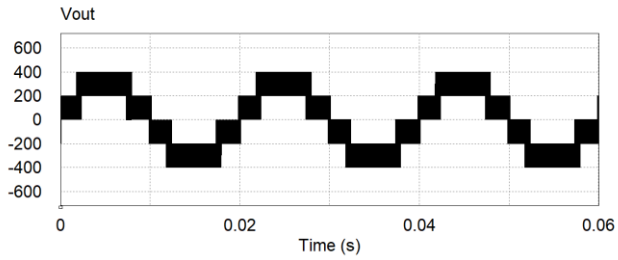

Figure 5: 2 SM MMC output voltage levels

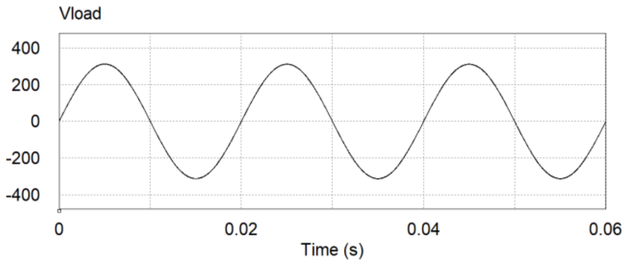

Figure 6: 2 SM MMC output voltage after filtering

In Figure 5 is presented the output voltage of the 2 submodules MMC without load, while in Figure 6 is presented the output voltage of the converter in load after filtering. The Total Harmonic Distortion (THD) of the referred signals is

42% and 0.7%, respectively. The control of the converter was implemented using phase-shift PWM, which results in even power losses across all the switching devices. Based on the obtained results, it was observed that the power loss across each IGBT is 11.4 W.

Modular Multilevel Converter With 4 Submodules Per Arm

In Figure 7 is presented the schematic for an MMC with 4 submodule per arm.

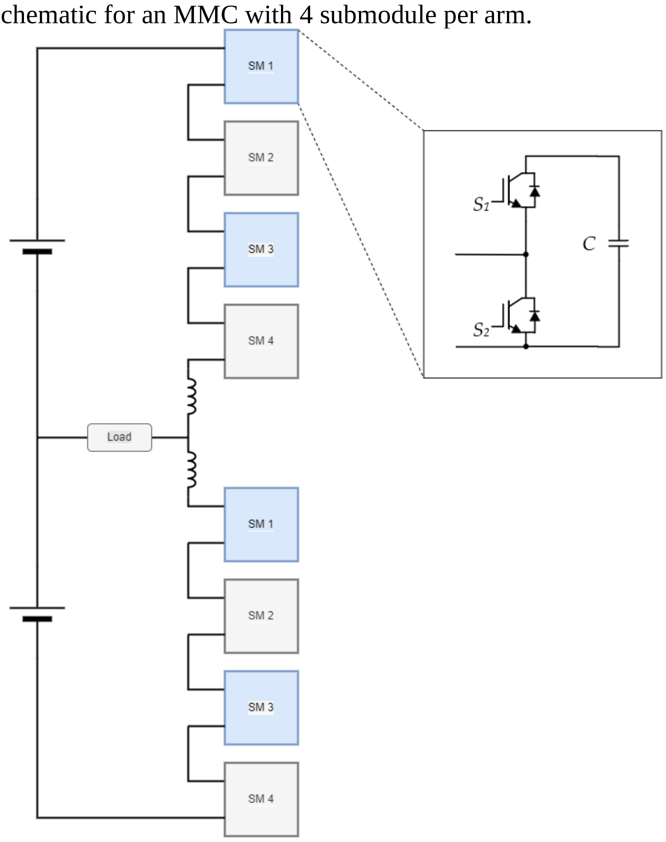

Figure 7: 4 SM Modular Multilevel Schematic

Using half-bridge submodules, the presented converters is constituted by a total of 16 IGBTs as switching devices, which are responsible for the synthesis of the output wave. Having 4 submodules in each arm, the voltage in the DC-link capacitors of each submodule is 200 V, which also means that each IGBT must withstand 200 V in its terminals.

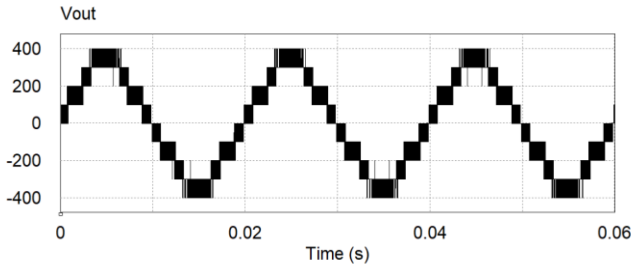

Figure 8: 4 SM MMC output voltage levels

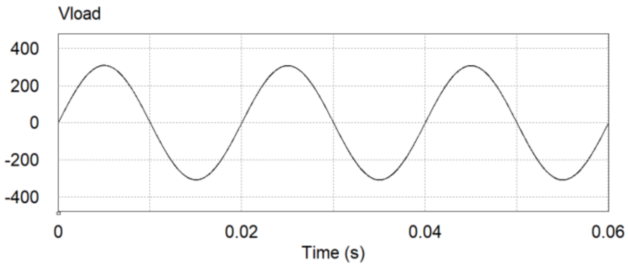

Figure 9: 4 SM MMC output voltage after filtering

In Figure 8 is presented the output voltage of the 2 submodules MMC without load, while in Figure 9 is presented the output voltage of the converter in load after filtering. The Total Harmonic Distortion (THD) of the referred signals is 21% and 0.2%, respectively. The control of the converter was implemented using phase-shift PWM which results in even power losses across all the switching devices. Based on the simulations, it was observed that the power loss across each IGBT is 11 W.

TECHNICAL AND ECONOMICAL ANALYSIS

The simulation results presented in Figure 3 to Figure 7 were obtained with a nominal power of 4 kW in every converter, with a power grid voltage of 230 V, aiming to simulate the behavior of the converters when injecting power into the electrical power grid, and to be able to compare them. Table 1 summarizes the results obtained.

Table 1: Electrical comparison of MMC with the H-Bridge.

	H-BRIDGE	2 SM MMC	4 SM MMC
Voltage levels	3	5	9
Number of IGBTs	4	8	16
DC-link voltage (V)	400	400	200
Individual IGBT losses (W)	27.5	11.4	11
Total IGBT losses (W)	78	64.5	126
Output Voltage THD (%)	75	42	21
Filtered Voltage THD (%)	1.2	0.7	0.2

From the obtained results, it is verified that with the raise of the number of components in use, the number of voltage levels on the output is increased, causing an improvement on the quality of the output signal, which can be observed by the decrease of the THD of the voltage signal. The raise of the number of submodules in the MMC allows the use of smaller and cheaper filters, due to the decrease of the DC-link voltage, which is the same voltage the IGBT must withstand, and the output level created by each submodule.

In the MMC, the power is distributed through the submodules, which leads to the notorious differences in the individual power losses in each IGBT, comparing to the H-Bridge. Such distribution causes less stress on the semiconductors leading to less heat, reducing the need for big and expensive heat-sinks (Nelson, 2016).

Looking at the MMC with 4 submodules in each arm, it is possible to see that the total losses on the IGBTs is higher than in the MMC with 2 arms and the H-bridge, however, the voltage that each IGBT needs to withstand is only 200 V instead of 400 V, which allows the selection of cheaper capacitors and semiconductors, rated for less voltage, thus reducing the production costs, as well as increasing the system overall efficiency.

Table 2: Quality comparison between the MMC and the H-Bridge power converter.

	H-BRIDGE	2 SM MMC	4 SM MMC
Modularity	-	+ +	+ +
Control Complexity	-	+	+ +
Initial Costs	-	0	+
Reliability	+	+ +	+ +
Fault-tolerant	-	-	+
EMC compliance	-	0	+

In Table 2 is presented a quality comparison between the referred power converters. The modularity allows scability in voltage and current, thus resulting in scalability in power. Furthermore, it allows the construction of the submodules to be independent from each other. This brings the possibility for mass production of submodules, reducing the cost of production.

With the addition of more submodules, the control complexity raises exponentially due to the amount of sensors and controllers necessary, however, it allows fault tolerance, with means that in case of a device malfunction, the submodule in which it belongs is shut down, and the converter can still operate at a lower power, or even at nominal power, depending on the application and the rated power of each submodule. This is not possible in the conventional converters such as H-Bridge, where a single component failure forces the shutdown of the entire converter, which can lead to major monetary losses, or energy failure, depending on the application in use.

Regarding the cost associated to each converter, the initial costs of the MMC are higher due to the quantity of components that it possesses, increasing significative with the number of submodules. However, the increase of the costs is not linear and proportional to the raise of the number of submodules, since it also allows the use of smaller, cheaper and more efficient components, rated for less voltage or power values, since the power is distributed by more submodules, as explained previously. Furthermore, as the components are subject to less stress, with fewer power losses and less heat, their lifetime will increase thus reducing the need for maintenance or replacement, reducing the long-term cost associated to the MMCs.

CONCLUSIONS AND FURTHER RESEARCH

This paper presents a technical comparison between different DC-AC power converters leading to an economic analysis based in simulation results. Engineering is focused on solving problems, and the cost of the solution is of paramount importance. However, the costs associated need to be looked at from different perspectives, short term and long term. In short term it is contemplated the initial cost of the prototype and the associated R&D, while in long term it is taken into account the lifetime of the solution, as well as the costs associated with potential maintenance which is directly connected to the reliability.

Whenever faced with a decision of which power converter to use, several parameters must be taken into account according to the project specifications, from the rated power of the application, to the budget available for the project since in lower power applications the migration to a modular topology may not be justified due to the cost associated, while in higher power applications the reliability of the modular topologies is much higher, justifying the investment in a more expensive initial solution that will most likely pay off in time. As both topologies have their own advantages and disadvantages, a tradeoff must be considered between functionality, reliability and costs.

Regarding future works, it passes through the implementation of a more complete simulation model to allow a better understanding of the different components in each power converter to be able to decide which topology is the most adequate and which components to use in the intended applications. Furthermore, it can be contemplated the implementation of a laboratorial prototype of each converter to validate the simulation results experimentally.

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