# Railway Train Main Power Converter: Model Predictive Current Control of a Modular Multilevel Converter

Vitor Monteiro[1], Jose Cunha[1], and Joao L. Afonso[1]

[1] University of Minho, Centro ALGORITMI / LASI, Campus de Azurem, Portugal
vmonteiro@dei.uminho.pt

**Abstract.** In electric railway trains two main power systems can be distinguished: the system of the power propulsion and the system of the auxiliary power services. Consequently, since the train is supplied from the catenary in AC, the use of an AC to DC power converter is indispensable. This paper proposes the application of a modular multilevel converter (MMC) as main power converter (i.e., interfacing the AC catenary and the DC link inside the train). The operation of the MMC is ensured by a model predictive current controller, which controls its input AC current according to specific power requirements. The MMC and the model predictive current control are validated recurring to computer simulations. Based on the developed simulation models, the presented results permit to verify the advantages associated with the modularity of the converter and with the performance of the model predictive current control.

**Keywords:** Railway Power Systems, Auxiliary Power, Power Converters, Modular Multilevel Converter, Model Predictive Current Control.

## 1 Introduction

Power electronics systems have always been extremely important in a modern society, but the fact is that they have increasingly become indispensable for a very wide range of applications [1][2]. Consequently, more and more, new technologies for power electronics are emerging for several purposes, which is easily verifiable from electrical energy production systems, transport and distribution systems, and also in railway systems [3][4]. In fact, power electronics is pivotal in any kind of modern railway system, allowing several tasks, including the interface of the catenary and the motor drivers, managing key electrical variables like voltages and currents [5][6]. Obviously, despite power electronics systems starting from the same principle of converting voltage and current levels into other voltage and current levels, it is easy to see that the power electronics converters that perform the various operations are not all based on same topology [7]. The main power converter of a railway train is a critical component in modern railway systems [8], since it is responsible for connecting the catenary to the electrical system inside the railway [9]. This paper proposes the application of a modular multilevel converter (MMC) as main power converter for interfacing the AC catenary and the DC-link inside the train. The operation of the MMC is ensured by a model predictive current control, operating, in real-time, to guarantee that its input AC current in accordance to the specific power requirements of the diverse appliances inside the train.

The MMC under study in the scope of this paper is based on submodules with half-bridge structure, which one permitting the operation with two distinct voltage levels [10][11]. As main contributions, it can be identified the following points: (i) MMC utilization for interfacing the AC catenary and the internal power system of the train; (ii) application of the model predictive current control for the MMC in railway systems; (iii) computer simulation, both with stable and unstable input AC voltages to fully validate the MMC and the control technique. Fig. 1 contextualizes the application of power electronics in a railway system, specifically highlighting the framework of the main converter (in this case, where is applied the MMC).

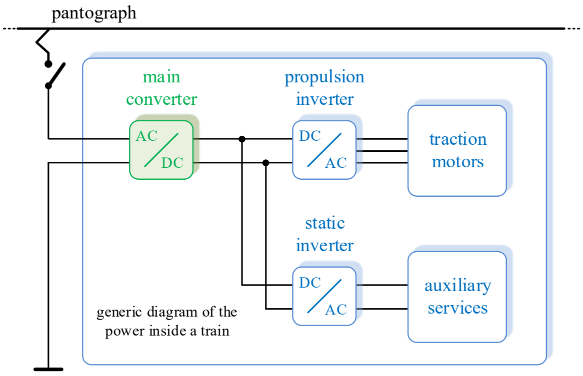


Fig. 1. Contextualization about the application of power electronics in an electric railway system.

## 2 Modular Multilevel Converter: Application and Topology

The MMC has appeared as a radical topology in power electronics since it is very versatile for several applications, and it a prominent actor in high-voltage and high-power applications such as railway systems [4]. The MMC stands out from usual power converters since it has a modular and scalable design, containing various sub-modules. With the objective of creating a multilevel structure, multiple sub-modules are connected in series, providing a wide range of voltage levels [6]. With a precise control by selectively switching the state of each submodule, it is possible to synthesize an output voltage with high-quality waveform, making it ideal for various applications, such as railway applications. The structure of the MMC under the scope of this paper is presented in Fig. 2. A shown, inductive filter are considered in the interface with the catenary, ensuring the possibility of controlling the waveform of the current. By increasing the number of sub-modules, it is possible to increase the operating voltage levels and the value of the DC-link voltage and reducing the voltage rating of the power semiconductors (cheaper and better in terms of reduced switching losses) and lower stress. Although the application requires the control in unidirectional mode, if properly controlled, the MMC permits the bidirectional power operation.

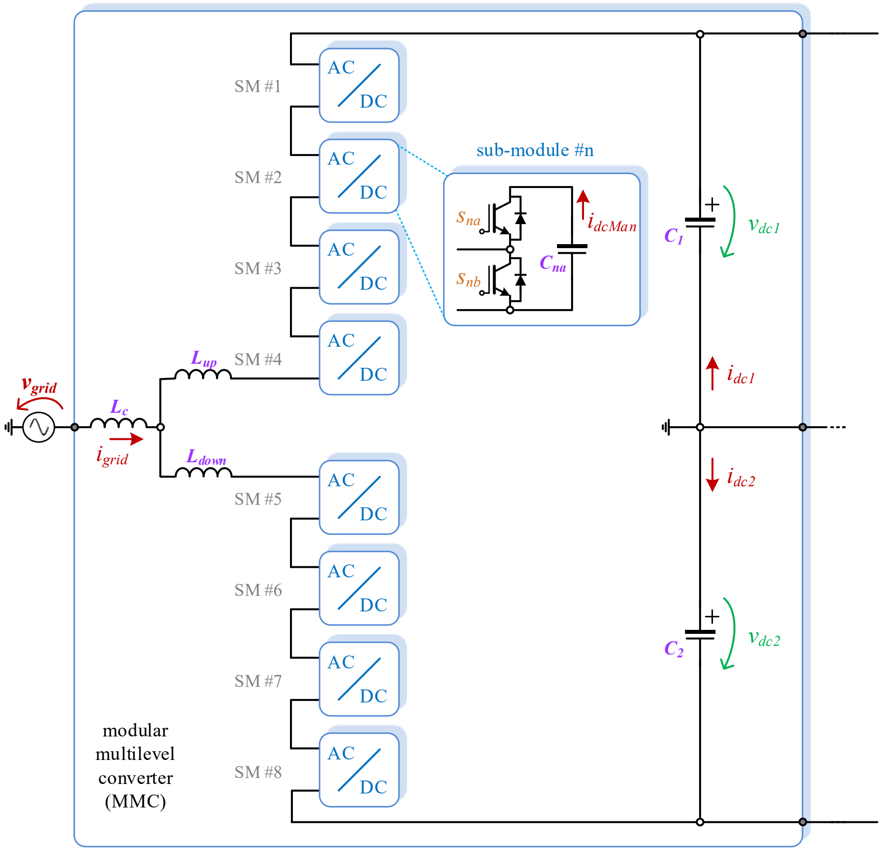


Fig. 2. Structure of the MMC used as main power converter of the electric railway train.

## 3 Modular Multilevel Converter: Control and Operation

The key point of the MMC control lies on the control of the individual sub-modules, which is critical for synthesizing the desired output voltage. Regarding the voltage balancing across the sub-modules, several voltage balancing algorithms can be implemented, but such analysis is out of the scope of this paper. Typically, each sub-module is controlled using pulse-width modulation (PWM), where control techniques based on phase-shifted PWM strategies are used. The establishment of a precise control of the phase shift for each sub-module is crucial for ensuring that the MMC produce the multiple voltage levels. In the AC side, it synthesizes a nearly sinusoidal waveform with minimal harmonic distortion. In terms of control, several strategies can be considered to regulate the power flow between the MMC and the power grid. In railway power systems, the MMC must be synchronize with the frequency of the power grid voltage, enabling to match its output voltage with the power grid voltage, preventing the operation with undesired reactive power. Due to its fast-switching capability, the MMC exhibits excellent dynamic response, establishing a quick response to changes in the operating conditions, making it suitable for applications where prompt modifications are required. The block diagram of the control is presented in Fig. 3.

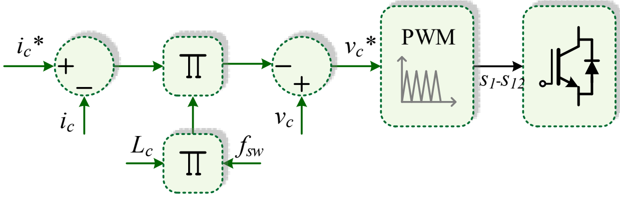


Fig. 3. Principle of the predictive current control applied to the MMC.

## 4 Modular Multilevel Converter: Computer Validation

This section exhibits the main results that permit verifying the applicability of the predictive current control to the MMC converter and in railway applications. The results that allow to evaluate the current waveform obtained on the catenary side, as well as the respective voltage, are shown in Fig. 4. It is noted that the current assumes a waveform that corresponds to the voltage waveform, i.e., without harmonic content. The operation only happens with active power (i.e., voltage and current in phase).

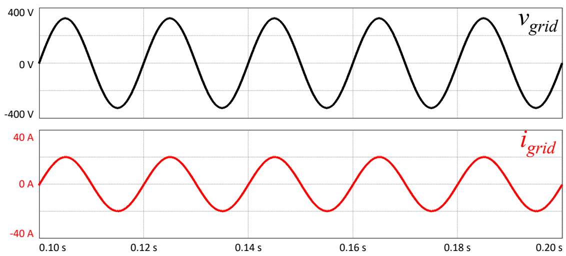


Fig. 4. Validation of the MMC: voltage ($v_{grid}$) and current ($i_{grid}$) on the power grid side.

Fig. 5 shows the currents in the main DC-link and on the DC-link of two of the submodules (the behavior being the same for the remaining). Each of the currents in the main DC link presents a sinusoidal waveform, and they are in phase opposition due to the positioning of the current sensor. Each current in the DC-link presents a waveform due to the high switching frequency (10 kHz) of the power semiconductors.

After the previous validations, Fig. 6 shows, again, the voltage and current signals in the catenary, however, verifying a more realistic situation from the point of view of voltage operation. Thus, the voltage has harmonic content, but the current remains as before. This situation is only feasible due to the use of a PLL algorithm, in which the output signal is used as input for the algorithm that allows taking the reference signal. Furthermore, it can also be seen that the current is correctly controlled even under these voltage controlling conditions, which proves the correct application of predictive control in this converter. In this situation, it was reflected a power quality problem that affects the RMS value of the voltage. However, the current stays to be properly controlled, always presenting the same amplitude and the same waveform, not being interfered by voltage fluctuations. It is important to note that the objective was just to control the current and not adjust the operating power.

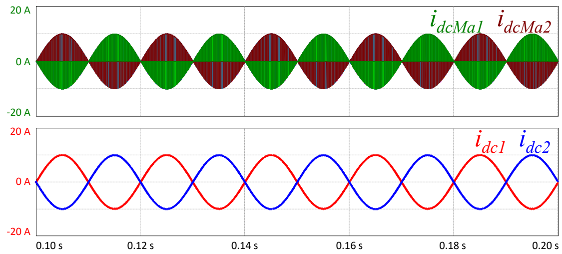


Fig. 5. Validation of the MMC: currents in the DC-link of the two exemplificative sub-modules ($i_{dcMa1}$ and $i_{dcMa2}$) and currents in the main DC-link ($i_{dc1}$ and $i_{dc2}$).

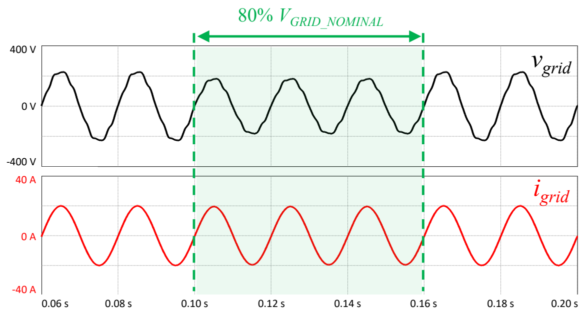


Fig. 6. Validation of the MMC under operation with a voltage sag on the power grid side: voltage ($v_{grid}$) and current ($i_{grid}$) on the power grid side.

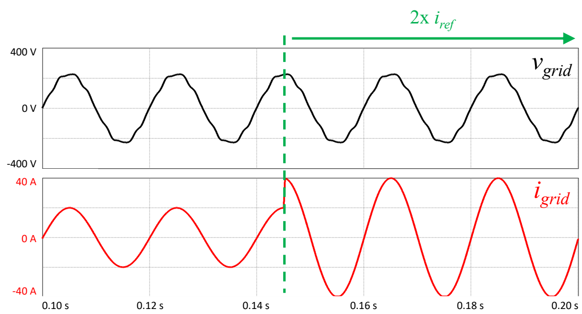


Fig. 7. Validation of the MMC under operation with a sudden variation of the current on the power grid side: voltage ($v_{grid}$) and current ($i_{grid}$) on the power grid side.

Fig. 7 presents a result that validates the behavior of a variation in operating power, due to the increase in current. Specifically, this result was obtained for a condition in which the current changes abruptly by double, i.e., resulting in an increase in operating power by double. Once again, the correct application of this control to this converter and this specific application is verified.

## 5 Conclusions

In the context of electric railway trains, it can be distinguished two main power systems, namely for the power propulsion and for the auxiliary power services. This paper proposes the application of a modular multilevel converter (MMC) for the railway train main power converter, where the application of model predictive current control is a key distinguished feature. The application of the model predictive current control for the MMC in railway systems is presented, highlighting the main principle of operation and functionalities. The validation was carried out with simulations, both with stable and unstable input AC voltages, and with sudden variations of operating power.

## Acknowledgment

This work has been supported by FCT – Fundação para a Ciência e Tecnologia within the R&D Units Project Scope: UIDB/00319/2020.

## References

1. K. Przybyła, et al., "Educational Platform for Remote Power Electronics Laboratory Classes," IEEE Power Electronics and Motion Control Conference, Romania, pp.311-314, 2022.
2. F. Guo, et al., "Hybrid Virtual Coordinate-Driven CBPWM Strategy of Three-Level T-Type NPC Converters for Electric Aircraft Propulsion Applications," IEEE Trans. Ind. Electron., vol.71, no.3, pp.2309-2319, Mar. 2024.
3. J. Zhang et al., "An Embedded DC Power Flow Controller Based on Full-Bridge Modular Multilevel Converter," IEEE Trans. Ind. Electron., vol.71, no.3, pp.2556-2566, Mar. 2024.
4. M. Tanta, J. Cunha, L. Barros, V. Monteiro, J. Pinto, A. Martins, J. Afonso, "Experimental Validation of a Reduced Scale Rail Power Conditioner Based on Modular Multilevel Converter for AC Railway Power Grids," MDPI Energies, vol.14, no.2, pp.1-27, Jan. 2021.
5. M. Tanta, et al., "Topologies and Operation Modes of Rail Power Conditioners in AC Traction Grids: Review and Comprehensive Comparison," MDPI Energies, vol.13, May 2020.
6. X. He, J. Peng, P. Han, Z. Liu, S. Gao, P. Wang, "A Novel Advanced Traction Power Supply System Based on Modular Multilevel Converter," IEEE Access, pp.165018-165028, 2019.
7. L. Liu, Z. Zhou, N. Dai, K. -W. Lao, Y. Song, "Interpolated Phase-Shifted PWM for Harmonics Suppression of Multilevel Hybrid Railway Power Conditioner in Traction Power Supply System," IEEE Trans. Trans. Electrification, vol.8, no.1, pp.898-908, Mar. 2022.
8. M. Tanta, J. Cunha, V. Monteiro, A. Martins, A. Carvalho, J. Afonso, "A Novel Hardware Protection Scheme for a Modular Multilevel Converter Half-Bridge Submodule," IEEE IECON Industrial Electronics Society, Portugal, Oct.2019, pp.6043-6048, 2019.
9. S. Wu, M. Wu, L. Li, S. Wang, K. Song, Y. Wang, "Analysis and Comparison of MMC-Based Co-Phase Traction Power Supply Topology for Auto-Transformer Power Supply System," IEEE Trans. Power Delivery, vol.37, no.5, pp.4053-4063, Oct. 2022.
10. F. Ma et al., "A Railway Traction Power Conditioner Using Modular Multilevel Converter and Its Control Strategy for High-Speed Railway System," IEEE Trans. Trans. Electrification, vol.2, no.1, pp.96-109, Mar. 2016.
11. Q. Xu et al., "Analysis and Comparison of Modular Railway Power Conditioner for High-Speed Railway Traction System," IEEE Trans. Power Electron., vol.32, Aug. 2017.