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Optimization-based Sizing of a Modular Multilevel Converter based on 650 V GaN Modules for New LVDC/MVDC Grids

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G06 Modular Multilevel Converters
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Abstract

This paper introduces a new co-design approach based on optimization for the modular multilevel converters (MMCs) using wide-bandgap (WBG) switches. This method takes into account several control strategies from the beginning and through the entire procedure. Gallium-Nitride (GaN) mature switches are attractive solutions to increase the compactness and efficiency in embedded applications. It could be a great opportunity for new grid-connected converters, thanks to their improved switching characteristics and lower on-resistance. Nevertheless, their 650 V rating requires the use of multilevel topologies to reach new 1.5 kV DC grids for eco-districts or, more generally, for MVDC grids. The proposed design method is validated using an experimental prototype involving GaN half-bridge submodules (SM-HB).

1 Introduction

Wide-bandgap (WBG) components have shown disruptive performance, particularly in terms of losses and therefore efficiency, ability to increase switching frequency, and power density [1]. The work presented here is part of a wider project aimed at developing, assessing, and revealing the potential of WBG components in multilevel converters. The first step in this direction was the development of a 3-level active neutral point clamped converter (ANPC) prototype based on GaN half-bridge modules [2]. The latter having shown interesting performances, work is now done to push further by dealing with the 5-level MMC.

The main novelty lies within the development of a sizing procedure for the MMC involving a fast and simple optimization algorithm where the user can specify a control strategy. An MMC optimization co-design concept that both integrates control and sizing constraints is thus proposed. In the paper, the control strategy selection focuses on the circulating current for which the control strategy is chosen from the very beginning of the sizing procedure. Compared to the recent work from [3], the proposed work implements a new step to the sizing process and considers a wider range of possibilities of the DC and AC grid.

First, section 2 introduces the model for the sizing procedure. The latter is then described in section 3 as well as the formulation of the associated optimization problem. The method is applied afterward to the case of an MVDC-grid to LVAC-grid connection that meets the European grid standards. Section 4 shows the first results in simulation and the corresponding test bench prototype that make it possible to validate the generic sizing approach.

2 Operational sizing-oriented model of the MMC

The approach is straitforward, based on models from [4], [5]. More details will be found in the full paper.

3 Optimization-based sizing of the MMC

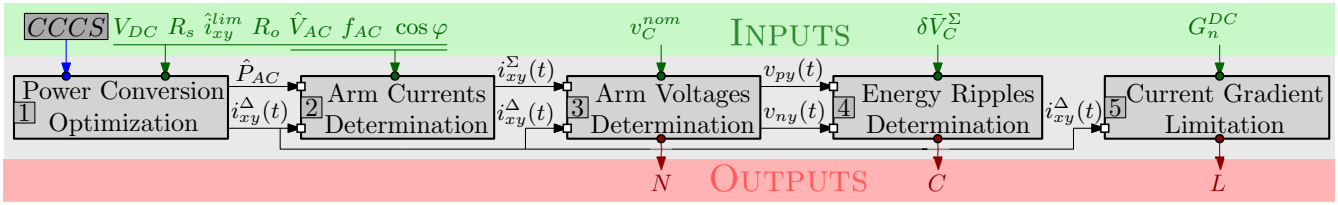


Fig. 1: MMC optimization-based sizing procedure (from left to right).

The sizing procedure proposed here is presented in Fig. 1. It consists of five steps, the first of which is where optimization takes place, to find the maximum power that can be converted by the MMC while minimizing losses in the converter arms:

$$
(OSP): \begin{cases}
\max_{\hat{P}_{AC}, i_{xy}^{\Delta}(t)} J = \hat{P}_{AC} - \sum_{y=y_1}^{y_m} i_{xy}^{\Delta}(t)^2 \\
subject\ to: \\
i_{xy}^{\Sigma}(t) := \frac{2\hat{P}_{AC}}{m\hat{V}_{AC}\cos\varphi}\sin(2\pi f_{AC}t - \varphi_y - \varphi) \quad \text{(AC-side grid current definition)} \\
v_y(t) := \hat{V}_{AC}\sin(2\pi f_{AC}t - \varphi_y) \quad \text{(AC-side grid voltage definition)} \\
\frac{V_{DC}}{2} i_{xy}^{\Delta}(t) - \frac{R_s}{2} i_{xy}^{\Delta}(t) \sum_{y=y_1}^{y_m} i_{xy}^{\Delta}(t) = v_y(t) i_{xy}^{\Sigma}(t) + R_o i_{xy}^{\Sigma}(t)^2 \quad \text{(Power balance constraint)} \\
i_{xy}^{\Sigma}(t) + i_{xy}^{\Delta}(t) \leq +2\,\hat{i}_{xy}^{lim} \quad \text{(Arm current upper boundary constraint)} \\
i_{xy}^{\Sigma}(t) + i_{xy}^{\Delta}(t) \geq -2\,\hat{i}_{xy}^{lim} \quad \text{(Arm current lower boundary constraint)}
\end{cases} \tag{1}
$$

In Eq. (1), the circulating current control strategy (CCCS) allows the determination of the optimum circulating current injection (CCI) to guarantee the energy balancing of the converter while minimizing the losses associated with this current. If the desired effect is to suppress the circulating current (CCS), the equation $i_{xy}^{\Delta}(t) - \frac{1}{m}\sum_{y=y_1}^{y_m} i_{xy}^{\Delta}(t) = 0$ must be included in the (OSP) as an equality constraint. An important concept to keep in mind is that this optimization also takes into account the maximum $\hat{i}_{xy}^{lim}$ constraint that the arms can withstand, to achieve sizing as close as possible to actual realization capabilities. Details about the four remaining steps will be found in the full paper.

4 Validation of the sizing procedure

The proposed procedure is applied to the case of a typical PV-to-grid power supply, between a 1.5 kV DC grid and the 230 V, 50 Hz AC grid. After validation in single-phase case, it will be extended to three-phase.

Table 1 provides the parameters as well as the sizing results. The sized MMC is simulated using a high-fidelity PLECS model of the converter and module losses, in order to validate the sizing before producing the prototype. In simulation the system tracks a power set point that sweeps the operating range up to nominal power. The MMC control architecture implementing the CCCS is described in [5].

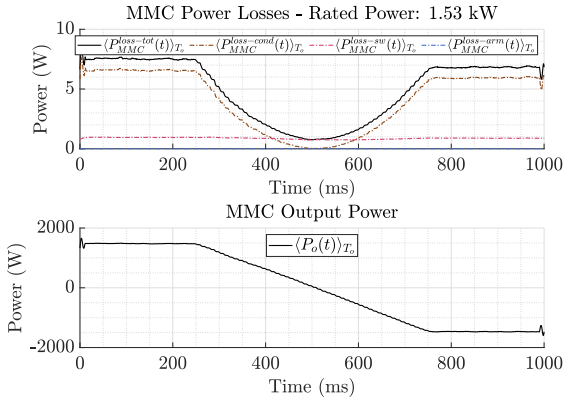
Figure 2 (a) shows the simulation results for the converter. Total converter losses are shown in black on the top plot with a maximum of 7.5 W for a power delivered to the AC grid of 1.53 kW, i.e. a 99.5% efficiency. Simulations show that the evolution of the efficiency versus the operating point is over 99% throughout the operating range from 5% to 100% of rated power. These results will be compared with those of the prototype in the full version of the paper. As the prototype is currently under production, the 3D computer-aided design (CAD) rendering is shown in Fig. 2 (b).

References

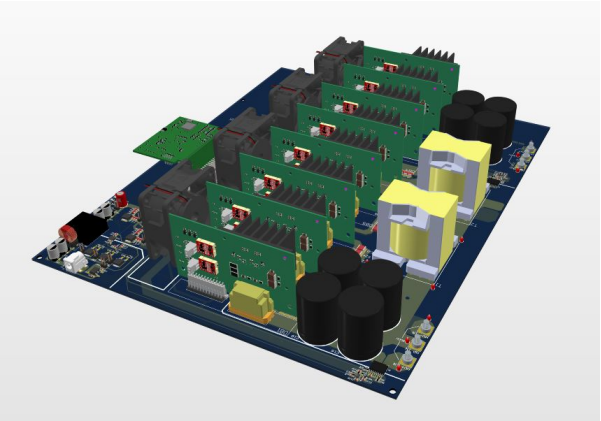
[1] J. Millán, P. Godignon, X. Perpiñà, A. Pérez-Tomás, and J. Rebollo, "A Survey of Wide Bandgap Power Semiconductor Devices," *IEEE Transactions on Power Electronics*, vol. 29, no. 5, pp. 2155–2163, May 2014. DOI: 10.1109/TPEL.2013.2268900.

Tab. 1: Parameters of the MMC

Description	Value
Sizing procedure inputs - single-phase case	
DC bus voltage	$V_{DC} = 1.5\ kV$
DC bus impedance	$R_s = 0\ \Omega$, $L_s = 0\ H$
AC voltage amplitude	$\hat{V}_{AC} = 230\sqrt{2} \simeq 327\ V$
AC grid frequency and period	$f_o = 50\ Hz$, $T_o = 20\ ms$
AC-side power factor	$\cos\varphi = 0.93$
AC-side impedance	$R_o = 0\ \Omega$, $L_o = 2.1\ mH$
Arm current limit	$\hat{i}_{xy}^{lim} = 5\sqrt{2} \simeq 7.07\ A$
Capacitor nominal voltage	$v_C^{nom} = 1.6\ kV$
Stack voltage ripple ratio	$\delta\bar{V}_C^{\Sigma} = 5\ \%$
DC bus current gradient limit	$G_n^{DC} = 12000\ s^{-1}$
Sizing procedure outputs - single-phase case	
MMC rated apparent power	$S_{AC}^{nom} = 1.64\ kVA$
Number of SMs per arm	$N = 4$
SM Capacitor	$C = 330\ \mu F$
Arm impedance	$L = 61\ mH$



(a) Conduction, switching and arm power losses.



(b) 3D CAD rendering of the MMC prototype (40 x 30 x 7 cm).

Fig. 2: Simulation result using the GaN submodule losses detailed model.

[2] I. Chorfi, C. Alonso, R. Monthéard, and T. Sutto, "A GaN-Based Three-Level Dual Active Half Bridge Converter With Active Cancellation of the Steady-State DC Offset Current," English, in *IECON 2022 – 48th Annual Conference of the IEEE Industrial Electronics Society*, Brussels, Belgium: IEEE, Oct. 2022. DOI: 10.1109/IECON49645.2022.9968579.

[3] F. Gruson, "Contribution au développement de convertisseurs modulaires et multiniveaux pour les réseaux électriques," Français, L2EP, Tech. Rep., 2022, p. 187.

[4] G. Le Goff, M. Fadel, and M. Bodson, "Scalable Control-Oriented Model of the Modular Multilevel Converter for Polyphase Systems," *IEEE Transactions on Industry Applications (TIA)*, vol. 58, no. 3, pp. 4050–4061, May 2022, Conference Name: IEEE Transactions on Industry Applications. DOI: 10.1109/TIA.2022.3152470.

[5] G. Le Goff, "Scalable Control Allocation Methods for the Modular Multilevel Converter: From Modelling to Real Time Implementation," en, PhD Thesis, Institut National Polytechnique de Toulouse (INPT), Nov. 2022.