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Optimization of the RC branch of the LCL filter of a SiC-based inverter

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Abstract. This work begins with the initial design of an LCL filter for a 20 kW SiC inverter, and its response is experimentally analysed from the perspective of grid quality. Based on these results, a sensitivity analysis is carried out by varying the parameters of the RC branch. The objective is to identify the RC branch that achieves maximum efficiency in harmonic content reduction, as well as minimising losses. The conclusions drawn relate to the sizing of the LCL filter and the various possibilities for its optimisation.

The conclusions presented have been obtained with regard to the sizing of the LCL filter and the different possibilities for its optimisation.

Key words. LCL filter, SiC inverter, filter optimization, harmonic contents.

1. Introduction

Renewable energy sources, such as wind and photovoltaic solar power, have seen significant growth and are expected to experience exponential increases in the coming years. These sources rely on DC-AC voltage conversion, typically performed by power inverters using vector modulation techniques, most commonly PWM (Pulse Width-Modulation), which generate harmonics at the modulation frequency. As a result, the quality of the injected signal can be severely disrupted.

In recent years, there has been a growing adoption of wide bandgap (WBG) semiconductor devices, with SiC MOSFETs being the most widely used. These devices operate at higher voltages, temperatures, and switching frequencies than traditional Si IGBTs, which were widely used in the past. This allows power converters based on SiC devices to achieve higher frequencies at higher efficiency.

The ability of SiC devices to switch at high speeds significantly increases power density, specially in the passive components [1],[2]. However, this increase in switching speed and frequency leads to rapid voltage (du/dt) and current (di/dt) variations, which generate high-frequency EMI in power converters. This issue becomes more significant as the switching frequency increases.

Furthermore, grid quality issues can appear, therefore it is essential to incorporate an optimised harmonic filter well-matched to the characteristics of the SiC-based power inverter.

2. Case study and initial passive filter topology

In order to meet the requirements for electrical supply quality, the solution used in most systems consists of including a filter at the output of the inverter for grid coupling. In the selection of the filter topology, a balance between size, weight, cost, and power supply quality is sought. An LCL filter is a widely used solution in grid-connected power converters.

In order to reduce the resonant peak of the LCL filter response and for stability purposes, it is common to adopt a passive damping solution [3]. The optimal configuration of passive damping is achieved by adding a damping resistor in series with the capacitor.

However, the main drawback of using an additional damping resistor in the LCL filter is the additional power losses, which requires the sizing of the heat sink (radiator). It can be replaced by a notch-type active filter, although this solution introduces a delay with consequences from the stability point of view.

A very low value of the damping resistor results in unstable operation. On the other hand, when the damping resistor value increases, the effectiveness of the LCL filter is reduced. The passive resistor must be adequate to avoid instabilities but, at the same time, it must not cause losses that can reduce the LCL filter effectiveness. So, a compromise between these two factors has to be reached.

The inverter considered as a design case study is a 20-kW two-level and three-wire one, as shown Fig. 1, which uses sinusoidal pulse-width modulation (SPWM) at 25-kHz switching frequency (f_{switch}).

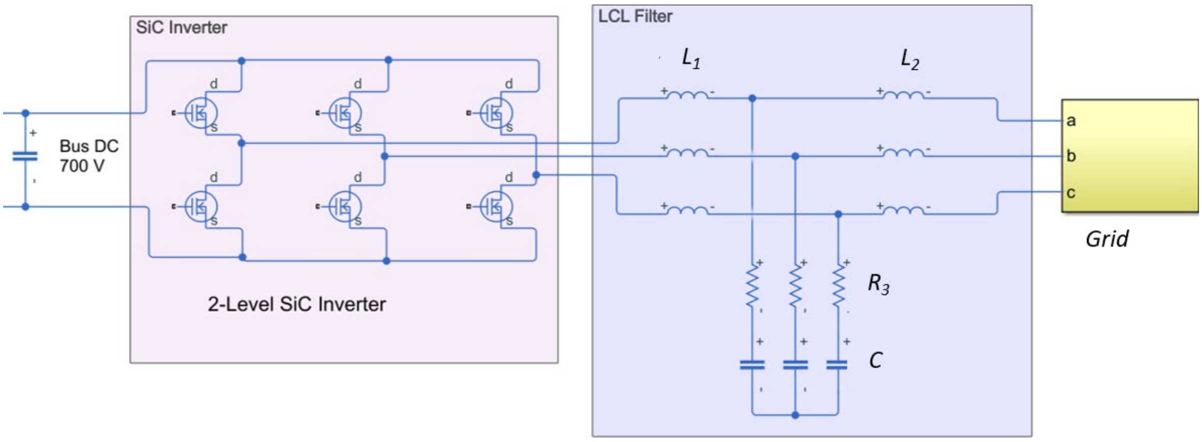

Fig. 1. Grid-connected inverter with an LCL filter.

The values of the main components that make up the LCL filter are those shown in Table I.

Table I. - Initially calculated LCL filter parameters for the 20 kW SiC-based inverter operating at 25 kHz

PARAMETER	VALUE	DESCRIPTION
L_1	142 µH	Inductance on the inverter side
C	20 µF	Capacitor
L_2	1 mH	Inductance on the grid side

Next, a sensitivity analysis is performed on the components of the RC branch. In this way, the choice of the capacitor value C, as well as the damping resistance R_3, is analysed. The aim is to find the RC branch that allows for maximum efficiency in harmonic content reduction, as well as minimising losses.

The value of the damping resistance R_3 must be sufficiently high to avoid resonances that could jeopardise the stability of the grid. However, the inclusion of resistance R_3 in series with the capacitor introduces associated losses (proportional to the square of the voltage applied to R_3), which are negligible at the grid frequency (in this case, 50 Hz), but increase as the frequency of the generated harmonic rises. According to the literature, these losses are greater the smaller R_3 is; however, increasing the damping resistance R_3.

The value of the damping resistance R_3 is set to an order of magnitude related to the impedance of the capacitor C at the resonance frequency ω_{res} [4]. More specifically, it is considered that the value of this resistance R_3 is one-third of the impedance of the capacitor C [5]-[8], as expressed in the equation (1).

$$\boldsymbol{R_3} = \frac{\mathbf{1}}{\mathbf{3} \cdot \boldsymbol{\omega_{res}} \cdot \boldsymbol{C}} \quad (1)$$

According to this equation, the value of the resistance R_3 is inversely proportional to the capacitance C of the filter, meaning that as C increases, R_3 decreases.

3. Results

To carry out this sensitivity analysis, in addition to the value of 20 µF, a capacitance of 2 µF is considered, and the losses and harmonic content of the voltage and current from the inverter (at the filter output) at the grid connection point are analysed.

For a value of C = 20 µF, a resonance frequency of f_{res} = 3162 Hz and a damping resistance of R_3 = 0.839 Ω is obtained, whereas for C = 2 µF, the resonance frequency is f_{res} = 10 kHz and R_3 = 2.653 Ω. The results obtained from the simulation are shown in Table II and Table III.

Table II. - Losses and harmonics in the 20 kW SiC inverter for different values of R_3 when C = 20 µF

R_3	Losses	$(THD_{40})I_2$	$(THD_{\infty})I_2$	$(THD_{40})V_2$	$(THD_{\infty})V_2$
17 Ω	230 W	3.42%	3.47%	1.77%	16.62%
8.5 Ω	170 W	1.81%	1.84%	1.09%	9.44%
2.5 Ω	70 W	1.21%	1.22%	0.85%	3.06%
0.8 Ω	27 W	1.08%	1.09%	0.78%	1.38%
0.5 Ω	27 W	1.08%	1.10%	0.81%	1.25%
0.26 Ω	20 W	0.92%	0.97%	0.71%	1.35%
0 Ω	Not stable				

Table III. - Losses and harmonics in the 20 kW SiC inverter for different values of R_3 when C = 2 µF

R_3	Losses	$(THD_{40})I_2$	$(THD_{\infty})I_2$	$(THD_{40})V_2$	$(THD_{\infty})V_2$
17 Ω	180 W	4.01%	4.06%	1.77%	17.87%
8.5 Ω	190 W	1.54%	1.58%	0.90%	10.83%
2.5 Ω	70 W	0.94%	0.96%	0.67%	4.96%
0.8 Ω	30 W	0.79%	0.82%	0.57%	3.99%
0.5 Ω	20 W	0.87%	0.89%	0.64%	3.99%
0.26 Ω	10 W	0.82%	0.84%	0.60%	4.01%
0 Ω	0 W	0.90%	0.93%	0.65%	4.14%

The results show losses that increase as R_3 increases. Therefore, contrary to what would be expected according to the literature, it is true that from R_3 = 8.5 Ω, the losses do indeed start to decrease in the case of C = 2 µF. This can be explained by the variation in harmonic content in the voltage applied to the RC branch. For low values of R_3, the inductance L_1 achieves better filtering, while for higher values, the harmonic components in the voltage increase.

4. Conclusion

This paper addresses the issue of grid quality in renewable energy plants. In particular, the study focuses on harmonic filtering in power inverters of renewable energy generators, with the aim of maximising the efficiency of the system while minimising harmonic content. To achieve this, a methodology has been developed to characterise and design the parameters of the harmonic filter, ensuring optimal performance that meets grid quality requirements, while minimising its weight, size, and losses. To this end, the inductances on the inverter side have been designed for an LCL filter dedicated to a high-tech SiC MOSFET-based inverter, with the aim of minimising its volume, weight, and losses. An important aspect of this work is the sensitivity analysis, in which the parameters of the RC branch of the filter are varied to study their influence, with the objective of optimising the LCL filter for SiC-based power inverters.

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