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Simple and systematic *LCL* filter design for three-phase grid-connected power converters

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Abstract

The objective of this paper is to propose a simple, less intuitive and systematic design methodology for the tuning of *LCL* filter parameters. The considered design methodology takes into account the *LCL* filter topologies, which can be based either on wye or delta connected capacitors. The advantages and drawbacks of each topology are discussed in order to achieve an optimal design. The obtained filter parameters have been firstly tested using Matlab-Simulink software tool. After that, they have been tested through an experimental set-up. The obtained simulation and experimental results show the performances and effectiveness of the proposed design methodology.

Keywords: *LCL* filter; Design methodology; Grid connected power converter

1. Introduction

Nowadays, high price, lack and polluting effects of fuel sources make them less and less attractive solutions to generate electrical power. For these reasons, electrical power generation based on renewable energy sources (like photovoltaic systems, wind turbine systems, biomass units...) becomes one of the biggest concerns of our time [1,10, 11,19]. Moreover, this kind of electrical power generation does not harm to the environment and its cost will decrease in the near future. The power generated through renewable energy sources is conditioned by grid connected power converters [17,6,23]. These power converters are usually associated to high order filters such as *LCL* filters in order to meet standards and grid code requirements [4,22]. The common use of *LCL* filters is due to their high filtering performances and their minimized cost, size and weight compared to the conventional *L* filter [5,8,2]. Besides, this kind of filters is suitable to meet harmonic constraints as defined by standards like IEEE-1547 and IEEE-519. Furthermore, the *LCL* filter allows working with relatively a low switching frequency since it allows attenuation of

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60 dB per decade of the switching harmonics. However, they have to work at different operating conditions, which make the tuning of their inductor and capacitor parameters complex, since they must achieve efficient current harmonic attenuation.

Several methods for *LCL* filter design were presented and discussed in literature [10,12,14,16]. All of them tried to perform efficient tuning of *LCL* filter parameters according to different constraints and requirements. However, up to now, there is no fixed reference or guide line for the *LCL* filter components selection [3,9,13,20]. In fact, it has been noticed that there is few research that provides a systematic, less intuitive and comprehensive *LCL* filter design methodology. Moreover, practical cases of wye and delta connected filter capacitors are not considered in most existing design methodologies [7]. The objective of this paper is to propose a simple, less intuitive and systematic design methodology for the tuning of *LCL* filter parameters. The considered design methodology combines the benefits of the existing design methodologies and attempts to overcome their drawbacks. These drawbacks can be the difficulty and the complexity of the design methodology [3,20], and/or the non consideration of some constraints and requirements [9,13,5]. Moreover, it takes into account the *LCL* filter topologies, which can be based either on wye or delta connected capacitors. The advantages and drawbacks of each topology and the tuning of filter parameters in each case are discussed and taken into account in the proposed *LCL* filter design methodology.

This paper is organized as follows. Firstly, in Section 2, the mathematical models and transfer functions of both *LCL* filter topologies are presented. Then, in Section 3, the step-by-step *LCL* filter design methodology is detailed and discussed in order to achieve an optimal tuning of the filter parameters. After that, in Section 4, the designed *LCL* filters for both topologies (i.e. with wye and delta connected capacitors) are presented and tested through simulation under Matlab-Simulink software tool. Finally, in Section 5, the proposed design methodology was verified through experimental tests. The obtained experimental results are quite similar to those of simulation. This shows that the proposed design methodology presents a simple and powerful tool for the design of *LCL* filters.

2. *LCL* filter mathematical model

The power circuit of a three phase grid connected power converter is presented in Fig. 1. As depicted in this figure, the *LCL* filter is used to interface between the power converter and the grid. $V_{i(a,b,c)}$ (respectively $i_{i(a,b,c)}$) refer to the components of the output power converter voltage vector (respectively the components of the output power converter current vector) in the stationary reference frame, while $V_{g(a,b,c)}$ (respectively $i_{2(a,b,c)}$) refer to the components of the grid voltage vector (respectively the components of the grid current vector) in the stationary reference frame. L_2 (respectively L_i) refer to the grid side inductor of the *LCL* filter (respectively the converter side inductor of the *LCL* filter), while R_2 (respectively R_i) refer to the internal resistance of the grid side inductor, (respectively the internal resistance of the converter side inductor). C_f (respectively R_d) refer to the *LCL* filter capacitor (respectively the damping resistor), while $V_{c(a,b,c)}$ (respectively $i_{c(a,b,c)}$) refer to the components of the voltage across the capacitor in series with the damping resistor (respectively the components of the capacitor current vector) in the stationary reference frame.

There are two possible ways to connect an *LCL* filter to a three phase system depending on the capacitor connection. The first one is based on wye connected capacitors, while the second one is based on delta connected capacitors.

2.1. Wye topology

Fig. 2(a) shows the equivalent single phase representation of the three phase grid connected power converter with *LCL* filter in case of wye connected capacitors. According to this figure, the wye topology *LCL* filter equations are as follows

$$i_i(s) = \frac{V_i(s) - V_c(s)}{sL_i + R_i} \quad \text{(a)} \qquad i_2(s) = \frac{V_c(s) - V_g(s)}{sL_2 + R_g} \quad \text{(b)} \qquad V_c(s) = \left(R_{dY} + \frac{1}{sC_{fY}}\right) i_c(s) \quad \text{(c)}. \tag{1}$$

Based on Eqs. (1.a), (1.b) and (1.c), the wye topology *LCL* filter model is given by Fig. 2(b). The transfer function of the *LCL* filter is the ratio between the output current i_2 and the input voltages V_i and V_g. It is computed based on the superposition principle. To this purpose, two modes were considered: a first mode in which the $V_g(s)$ input is considered equal to zero and a second one in which the input $V_i(s)$ is considered equal to zero.