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An efficient procedure to design passive *LCL*-filters for active power filters

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ABSTRACT

Variable high switching frequencies in grid-connected active power filters could lead to low harmonic performance and expose power systems to EMI issues too. A low-pass passive *LCL*-filter is usually used to interconnect a power electronic converter to a grid system. (This can also be done by using a passive *L*-filter.) Nevertheless, designing an *LCL*-filter is not simple because of high compensating bandwidth and variable frequency modulations involved in active filters. This paper examines various effective conditions on designing this kind of passive *LCL*-filters. Then it will propose a comprehensive design procedure in which both the outcomes of the active filter and the network obligations are taken into account. Principal advantages of this proposal are reduction of power losses of the passive filter, lowering the converter's switching ratings and the simplicity of the suggested design algorithm. A typical grid-connected shunt active filter is considered, and the needed interconnecting *LCL*-filter is designed using the proposed method. Then, the whole system is simulated with SIMULINK to verify the discussed procedure. Simulations confirm substantial reduction in power losses and converter current ratings.

1. Introduction

Active power filters are gaining more popularity due to their ability of handling higher switching frequencies by using faster power switches (e.g. IGBT) and employing digital signal processors with ultra-fast processing time. Conventionally, an inductance *L* interconnects the converter of the active filter to the grid network, thus acting like a passive low-pass filter. The bigger the inductance *L*, the higher the attenuation of high frequency components will be. Another reason for increased popularity of passive *LCL*-filters is that they show higher harmonic performances compared to a single inductance. Improper design of *LCL*-filters could lead to some inefficiency in active filters' performance [1], resonance, and instability amongst other possible consequences.

Various approaches are suggested to analyze passive *LCL*-filters for utilization as an interface between power electronic converters and grid systems [1]. However, deciding on the *LCL* parameters is not discussed there. Further, steady state and dynamic performance of passive *L*-filters are compared with those of *LCL*-filters when they interconnect power electronic converters to the power networks [2]. Also, in [3], the design of PI-controller is analyzed for the grid-connected converters, and so are the effects of the parameters of an *LCL*-filter on the performance of the controller.

A modern recursive method was suggested in [4] by trial and error method to decide on *LCL* parameters of a grid-connected voltage source inverter. But the design characteristics have no mechanism to prevent the possible increase of both power losses and the ratings of the switches. Also, selection of the initial values of the inductors is difficult at the start of the design process. Later, a method is proposed in [5] to select the initial values of inductors of the *LCL*-filter, for the purpose of simplifying the cited method in [4]. This proposal is based on using phasor relations, which is clearly not useful for active filter applications. In general, the whole method is still complex. Further, *LCL*-filters for grid-connected distributed generations are considered in [6] by focusing on the ratio of the two inductances on the two arms of the filter along with the relation of this ratio to the capacitance of the passive filter.

It should be noted, however, that the design of an *LCL*-filter for the *grid-connected active filter applications* is not reported in the literatures. Proper design of a passive *LCL*-filter for active-filtering applications is a crucial and delicate task. The reason is that control and modulation of active filter applications are different from those of voltage regulators, reactive power controllers, speed controllers of electric rotating machineries, or renewable energy applications. Since active filters are ideally designed to operate within a possible wide frequency bandwidth of the load, design and configuration of the parameters of the *LCL*-filter is a sensitive action.

This situation becomes more challenging when active filters are modulated with a typical hysteresis-like current-control technique, as shown in Fig. 1(a). The inductance and the instantaneous voltage along with the hysteresis-band determine variable duration

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switching instants. Therefore, although exhibiting fast dynamic approach to the reference waveform target, a variable frequency modulator is introduced here. Moreover, due to the switch-on and switch-off transitions, high frequency spectra cause electromagnetic interference that calls for a proper electromagnetic interference (EMI) filter design. It is noticeable that these kinds of emissions can be attenuated by appropriate physical development of inductances and capacitance of the *LCL*-filter [7]. Considering Fig. 1(b), the performance goal of the passive *LCL*-filter designed for an active filter can be summarized as lowering high frequency distortions and disturbances on i_2 due to the switching as much as possible. This depends on the compensating bandwidth of the active filter and poles of the *LCL*-filter in order to avoid instability. Other problems also are taken into consideration such as power losses on stabilizing resistance, cost and ratings of the switches.

This paper contributes a comprehensive analysis of designing a passive *LCL*-filter for the shunt active filter that is modulated by using variable switching frequency techniques. Different aspects of designing an *LCL*-filter are discussed, and a design procedure is subsequently presented for passive *LCL*-filters. First, the total required inductance is decided on, such that the switching frequency remains lower than a certain upper-limit. Then, the resonance frequency is discussed wherein two design parameters have to be decided on; the inductance ratio and the capacitance of the *LCL*-filter. Then the stabilizing resistance of the passive *LCL*-filter is selected, which is worked out in accordance to the power losses of the passive filter. Proper design of these parameters is also discussed, that is crucially important for the efficiency and converter current rating. Furthermore, the insertion loss related to the EMI is analytically discussed. To verify the proposed design algorithm, a passive *LCL*-filter is designed for a typical grid-connected active power filter. It is then simulated with SIMULINK. Simulations together with the provided comparative results confirm the usefulness of the suggested procedure on lowering the power losses and current rating of the switches of the active filter.

2. Design considerations

To design a passive *LCL*-filter for active-filtering applications, the following characteristics could be taken into consideration:

- *Cost of the total inductor*: Considering Fig. 1(b), let us define two parameters (L_d and k) for the two inductances of the *LCL*-filter (L_1 and L_2) as below:

$$L_d = L_1 + L_2, \quad L_2 = kL_1 \tag{1}$$

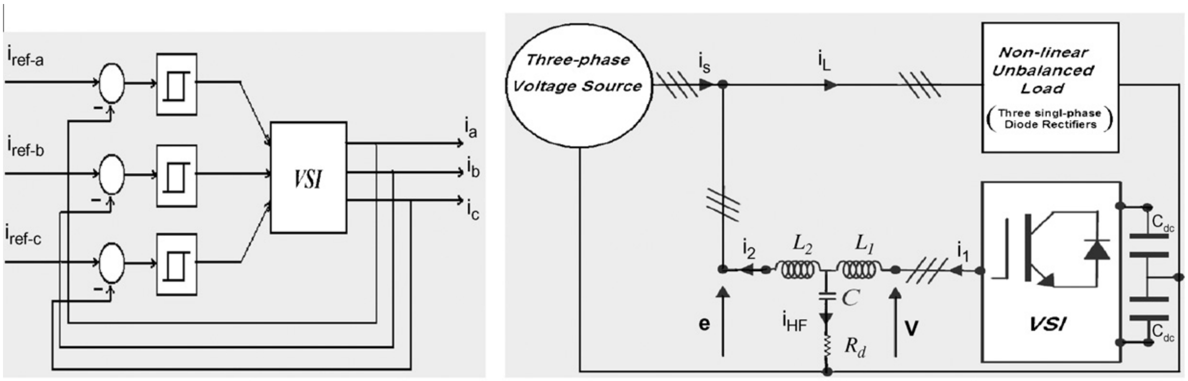
The total inductance L_d sets an upper-limit to the switching frequency such that a bigger L_d is related to a lower switching frequency. Therefore, a minimum inductance is worked out using the parameters of both the converter and the switching modulation technique to limit the switching frequency to a certain value. Then, this minimum inductance is slightly increased to get a total inductance L_d that establishes a switching frequency margin to the upper-limit. Thus, the total inductance obtained proves to be physically smaller and thus, less expensive.

- *Resonance frequency of the filter*: The frequency bandwidth in active filters is wide (defined by various harmonic standards). They are principally different from those of grid-connected reactive compensators. In this design, however, the resonance frequency (f_{res}), as the nonzero poles of the admittance seen from the ac/dc converter (see (2)), depends on the highest frequency component of the load which is compensated by an active filter.
- *Minimization of stabilizing resistors*: The equivalent impedance of the passive *LCL*-filter approaches zero at the resonance frequency and it will consequently lower the stability margin of the system down. To avoid instability, a resistor R_d is used in series with the capacitor. The resistance R_d is normally selected in proportion to the capacitive reactance of the filter at the resonance frequency $(1/2\pi f_{res}C)$ [3]. This resistance can be chosen such that it minimizes the power dissipation too.
- *Maximizing the attenuation at switching frequency*: Using Fig. 1(b), three transfer functions can be worked out that describe the passive filter behavior:

$$\begin{cases} Y_{12}(s) = \dfrac{i_1(s)}{v(s)} = \dfrac{(1/L_1)(s^2 + (1/L_2C))}{s(s^2 + (L_1 + L_2/L_1L_2C))} \\ Y_{21}(s) = \dfrac{i_2(s)}{v(s)} = \dfrac{(1/L_1L_2C)}{s(s^2 + (L_1 + L_2/L_1L_2C))} \\ h_{22}(s) = \dfrac{i_2(s)}{i_1(s)} = \dfrac{(1/L_2C)}{(s^2 + (1/L_2C))} \end{cases} \tag{2}$$

The required performance from the passive *LCL*-filter can be assessed under different conditions. For high frequencies (e.g. switching frequency f_{sw}), the admittance $Y_{12}(s)$ approaches $(1/L_q s)$. This shows the importance of choosing a proper value for the inductance L_1. Considering the IEC standard 61000-3-4 [1], the amplitudes of the currents above the 33rd harmonics have to be smaller than 0.6% of the fundamental harmonic. This can be applied to the passive filter to attenuate harmonic currents at the switching radian frequency ϖ_{sw}:

$$\left| Y_{21}(s = j\varpi_{sw}) \right| \leq 0.006 \tag{3}$$



(a) (b)

Fig. 1. (a) A typical current-control of a voltage-sourced inverter using the hysteresis modulation technique, (b) an active filter consists of an *LCL* passive filter that interconnects a VSI to the grid system.