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INTERNATIONAL JOURNAL
OF CURRENT RESEARCH

International Journal of Current Research
Vol. 9, Issue, 09, pp.58015-58018, September, 2017

ISSN: 0975-833X

REVIEW ARTICLE

A NEW APPROACH TO PASSIVE FILTER DESIGN FOR VOLTAGE SOURCE CONVERTERS

***Amin Farajollahi**

University of Azad, Tehran, Iran

ARTICLE INFO

Article History:
Received 19th June, 2017
Received in revised form
24th July, 2017
Accepted 05th August, 2017
Published online 30th September, 2017

Key words:

LCL filter,
Passive filter,
Voltage source converter.

ABSTRACT

Designing passive filter for the voltage source converter is very popular. In this paper a new approach to design a LCL filter is proposed. The step by step design procedure is shown which is missing in most of the papers published recently. The proposed method meets the traditional practical limits, while guarantees more stability even in the presence of wide grid inductance variations and filter parameter uncertainties. The performance of the proposed method are verified by simulation results

Citation: Amin Farajollahi, 2017.“ A New Approach to Passive Filter Design For Voltage Source Converters”, *International Journal of Current Research*, 9, (9), 58015-58018.

INTRODUCTION

Renewable energy is at the centre of the transition to a less carbon-intensive and more sustainable energy system. Renewables have grown rapidly in recent years, accompanied by large cost reductions for solar photovoltaics and wind power in particular (Chitsazan *et al*., 2017). The increase of power electronics in power systems has begun national and international activities to change standards and regulations concerning harmonics (Mohan *et al*., 2003). Furthermore, with the developments of power semiconductors and power electronics technologies, grid connected converters is found extremely wide and important applications in modern electric power systems, e.g. photovoltaic inverters for distributed generation, active power filters for power quality enhancement. Moreover, increasing energy demands as well as rising cost and environmental concerns about conventional energy resources have absorbed considerable attention to distributed generation powered by renewable resources. IEEE Std. 519-2014 includes suggested limits on harmonic currents injected by nonlinear loads along with the quality of voltage, a utility can supply to a consumer at any point in a distribution system (Araujo *et al*., 2007). The limits on harmonic currents is used to design the filters when grid characteristics are unknown (Carrasco *et al*., 2006). Voltage-source converters (VSCs) injects the generated power in distributed generation systems (Blaabjerg *et al*., 2006; Wu *et al*., 2012). In order to reduce the switching harmonics, a low-pass filter is used to connect VSCs to the grid. This filter is customarily a simple inductance. Besides the simple L filter, the higher order filters, for example LCL provide better reduction performance with lesser total inductance, which results in considerable reduction in the volume and the total cost of the filter (Chitsazan *et al*., 2012; Xu *et al*., 2014; Li *et al*., 2017). But, the inherent resonance of high-order filters may affect the stability of the current control loop. To solve the instability problem, different methods such as passive damping, active damping, and delay-based stabilization have been presented (Bloemink, 2011; Tang *et al*., 2016). As mentioned before, the LCL-filter is a third-order Low Pass Filter considered as an effectives witching harmonic attenuation with decreased inductance requirement (Liserre, 2005; Chitsazan, 2016; Pe˜na-Alzola, 2013). Consequently, according to achieve high quality sinusoidal grid current to comply with the strict grid code, LCL filter is usually chosen. Several papers have been presented to propose methods to deal with the LCL resonance. The simplest way is to add a damping resistor in series with the capacitor of the LCL-filter which reduces the resonance peaks while controlling the stability of current in a wide range of frequencies.

****Corresponding author:*** **Amin Farajollahi**
University of Azad, Tehran, Iran

Although its simplicity and effectiveness, it results in power loss in the system and decrease the efficiency and reliability of passive components. For voltage sourced grid-connected converters, an L or an LCL filter should be used at the output to diminish the harmonic pollution and the pulsed voltages. This filter is usable to converters with low to medium switching frequencies, where the switching sideband frequencies are comparatively close to the fundamental frequency. In this situation, an effective harmonics filtering by the conventional filters may affect the fundamental component. The other potential application, as recommended by (Chitsazan, 2012), is for the converters with a low converter side inductor. In this paper, a new approach to an LCL filter is proposed. First, the stability conditions, by means of the delay-based stabilization method, for the resonance frequencies are reviewed, considering the folding effect of the digital system. Then, the resonance frequencies of the proposed LCL filter are calculated used for the filter parameter design. Subsequently, a filter design procedure, simultaneously considering some practical criteria, is proposed. The proposed filter design algorithm is also robust against a wide range of grid inductance variations and filter elements uncertainties. The theoretical achievements are verified by simulation. The proposed filter is presented in Section II. Filter design procedure is explained in Section III. Simulation of a case study is described in Section IV, and Section V concludes the considerations.

Proposed Filter

Fig. 1 shows a single-phase VSC, which is connected to the grid through a proposed LCL filter. In this filter several LC branches are connected in parallel with the capacitor branch of the conventional LCL filter. The filter combines the advantages of both LCL and tuned trap filters.

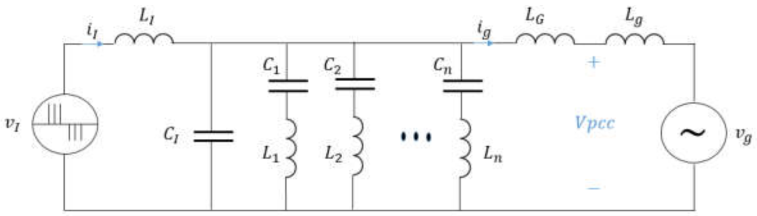


Fig. 1. The proposed filter

In Fig. 1, (L_I, L_G, C_I) and (L_i, C_i) are the parameters of LCL and i_{th}trap, correspondingly. The transfer function of the converter output voltage to the grid current is calculated as

$$G_{ig}(s) = \frac{i_g(s)}{v_I(s)} = \frac{1}{L_I.(L_G + L_g).C_I.s.(S^2 + \omega_{res,I}^2)} \prod_{i=1}^{n} \frac{(S^2 + \omega_{f,i}^2)}{(S^2 + \omega_{res,i}^2)} \tag{1}$$

where$\omega_{f,i}$and$\omega_{res,i}$are the tuned and resonant frequency of the i_{th}trap respectively.

Filter Design Procedure

Closed-loop stability must be certain without any spare resistors, sensors. Consequently, all resonance frequencies must lie inside the stable region. But, the main problem is the uncertainties due to component tolerances which may cause significant deviations of the resonance frequencies from the design values. Also, the resonance frequencies is kept in the stable range in all situations. As mentioned before, the filter resonance frequencies regulate the stability of the closed-loop system. The resonance frequencies of the proposed filter are derived as a function of the filter parameters. The resonance frequencies of a circuit are independent of the sources and are only determined by the passive elements and their arrangement in the circuit. Hence, for the sake of simplicity all sources are removed from the circuit. The filtered VSC of Fig. 1, without the sources, simplifies to Fig. 2.

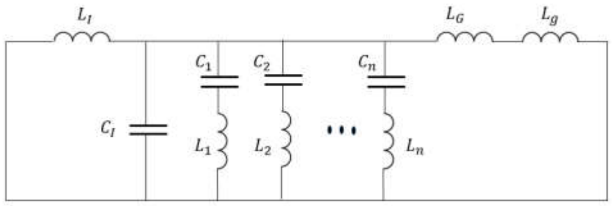


Fig. 2: The simplified circuit of grid-connected convert

To attain a robust filter design in contradiction of the grid inductance variations and filter parameter uncertainties, the stable range of resonance frequency must be met for all resonance frequency variation range determined in previous sections. Also, the designed filter should meet some practical restrictions, such as the converter current ripple and the grid current harmonics. In the following, the step-by-step design procedure of the *MLCL* filter is suggested. For the sake of simplicity, in the design procedure only one trap for the *MLCL* filter is considered. System parameters and design constraints are listed in Table I. it should be mentioned that the maximum converter current ripple is 25% of the rated current. Also uncertainty factor for all elements is considered 50%.

Table 1. System Parameters and Design Constraints

Parameters	Value
Grid Vol./Freq. ($\boldsymbol{V_{rms}/f}$)	220/60
DC-Link ($\boldsymbol{V_{dc}}$)	400 V
Switch. Freq. ($\boldsymbol{f_{sw}}$)	6 KHz
Sampling Freq. ($\boldsymbol{f_s}$)	12 KHz
VSC Rated Power ($\boldsymbol{S\_rated}$)	5 KVA

In the first step, the minimum value of $\boldsymbol{L_I}$is determined according to the maximum allowed converter current ripple (Carrasco *et al*., 2006)

$$L_I = \frac{V_{dc}}{2.4\, I_{rated}.\, f_s} \tag{2}$$

With the parameters of Table 1, L_I is calculated as 611.11 μH. Also, the maximum decrease in the resonance frequency value is occurred when L_G is considered as infinite value and the max uncertainty.

The resultant minimum resonance frequency is calculated as

$$f_{res} = \frac{1}{4\pi^2}\sqrt{\frac{1}{50\%.\,L_I}(50\%.\,C_I + \frac{C_1}{1 - L_1 C_1.\,\omega_s^2})} \tag{3}$$

Therefore if $L_1.\,C_1$is replaced by $\frac{1}{\omega_s^2}$, the values of C_I and C_1 can be written as

$$C_I = \frac{1}{50\%.\,50\%.\,L_I}\left(\frac{0.82}{f_s}\right)^2 \tag{4}$$

$$C_1 = 0.972 * 0.361 * 50\% * C_I \tag{5}$$

The minimum value for $\boldsymbol{L_G is\ as\ follow}$ ($\boldsymbol{Pe\tilde{}na - Alzola\ et\ al., 2013}$)

$$L_2 = \frac{V_{max}}{5.95.\, I_{rated}.\, L_I.\, C_I.\, f_s^3} \tag{6}$$

Simulation results

Figure 3 shows the case study introduced in (Mohammad Amin Chitsazan, *et al*., 2017; Mohammad Amin Chitsazan *et al*., 2017).

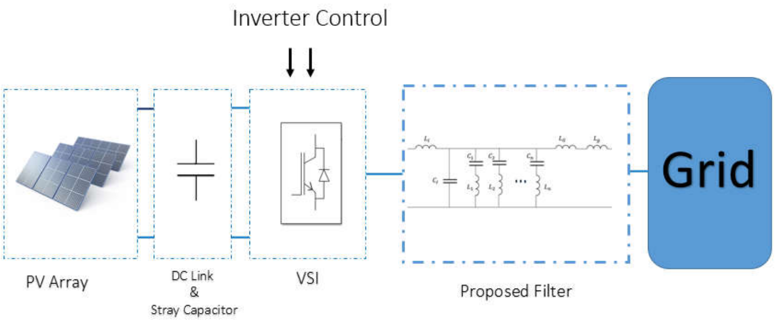


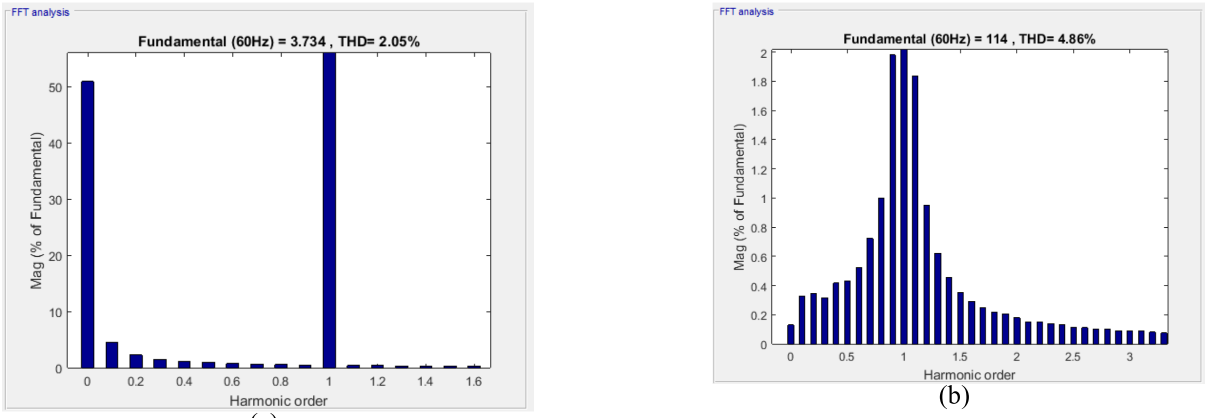
Fig.3. The case study

The parameters are listed in Table.2.

Table. 2. The simulation results

Type	$\boldsymbol{L_1}$	$\boldsymbol{L_2}$	$\boldsymbol{L_I}$	C	$\boldsymbol{C_I}$
MLCL	656 μH	220 μH	210 μH	4.3 μF	2.3μF
LCL	656 μH	1345μH	-	7.5μF	-

Fig. 4 shows waveforms and FFTs of currents injected into grid by the LCL and MLCL filters. It can be seen that in comparison with the LCL filter the harmonic currents in the MLCL filter have been considerably reduced. Also, the total harmonic distortion in the LCL filter is 4.86%, while in the PST-LCL it decreased to 2.05%.



(a) (b)

Fig.4. FFT analysis of the case study with a) MLCL, b) LCL filter

Conclusion

A new approach to LCL filter design for grid interconnected inverter systems has been proposed. A trap filter is added to the regular LCL filter, creating a MLCL filter with enhanced performance. Harmonic currents are significantly reduced improving operation of the involved utility grid. The projected fully controllable filter allows mitigating the current THD to a preferred range while allows the system to respond to load and switching frequency changes rapidly. The inclusive design procedure of the MLCL filter has been described indetail.

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