Improved Passive-Damped LCL Filter to Enhance Stability in Grid-Connected Voltage-Source Converters

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ABSTRACT

This paper proposes an improved passive-damped LCL filter to be used as interface between the grid-connected voltage-source converters and the utility grid. The proposed filter replaces the LCL filter capacitor with a traditional C-type filter with the resonant circuit tuned in such a way that switching harmonics due to pulse width modulation are to be cancelled. Since the tuned circuit of the C-type filter suppresses the switching harmonics more effectively, the total inductance of the filter can be reduced. Additionally, the rating of the damping resistor is lower, compared with conventional passive-damped LCL filter. To verify the benefits of the proposed filter, a comparison with the conventional LCL filter is made in terms of losses and ratings when both the filters are designed under the same condition.

INTRODUCTION

An LCL filter is usually employed to effectively reduce the switching harmonics from voltage-source converters (VSC). Lower cost and volume than the equivalent counterpart, e.g. a simple inductance, are the main reasons for adopting LCL filters [1].

The integration of renewable sources in the power grids is one of the common use of the LCL filter [2]. Other applications may also include railway systems [3], electromagnetic interference filtering (EMI) [4], power conditioning units [5], and aircraft power systems [6]. Recently, the trap filter [7] was proposed as an alternative filter solution which can suppress the switching harmonics even better than the LCL filter. As result, the size and cost of the filter can become even lower. However, similarly to other high-order passive filters, the filter resonance is challenging the system stability, which may also increase the harmonic distortion level above the acceptable limit.

Damping is usually needed in case there is a risk of instability in the control system of the VSC due to possible resonance between the capacitive and inductive elements in the system. The problem is that the grid impedance is continuously changing and it is hard to guarantee an effective damping with active damping control only [8]. On the other hand, the use of passive damping always improve the stability of the control system [9], but it is usually compromised by the inevitable Joule losses [10].

In this paper, a more efficient passive damped filter topology is proposed which may facilitate the use of passive damping in grid connected VSCs. The proposed filter replaces the LCL filter capacitor with a *C-type* filter. However, different than the traditional C-type filter, the resonant circuit of the proposed filter is tuned in such a way that switching harmonics generated from the VSC are to be cancelled from the grid current and the damping losses due to switching harmonics are thus reduced.

Since the C-type filter suppresses the switching harmonics more effectively, the total inductance of the filter can be reduced. Therefore, compared with conventional passive-damped LCL filters, the proposed filter can provide lower size/volume and lower damping losses. To verify the benefits of the proposed filter, a comparison with the conventional LCL filter is made in terms of losses and ratings with both filters designed under the same condition.

PROPOSED FILTER TOPOLOGY

Single-phase equivalent circuit of the proposed filter is illustrated in Fig. 1. The following notations and specifications are used in Fig. 1 and throughout the paper: V_c is the output voltage of the VSC with the conventional space vector modulation (SVM), a modulation index of 0.9, 10 kW rated power and 10 kHz switching frequency. V_g is the grid voltage which is assumed purely sinusoidal and equal to 220 V; i_c and i_g are the converter- and grid-side currents; L_c and L_g are the converter- and grid-side filter inductors; C_f is the filter capacitor; R_d is the damping resistor; C_t is the tuned capacitor equal to nC_f and L_t is the tuned inductor.

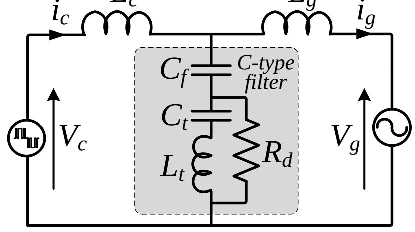


Fig. 1: Proposed passive-damped filter topology.

$$Y_{gc} = \left.\frac{i_g}{V_c}\right|_{V_g=0} = \frac{1}{s\left(L_c+L_g\right)} \frac{\dfrac{s^3}{\omega_0\omega_t^2 Q}+\dfrac{s^2}{\omega_t^2}+\left(n+1\right)\dfrac{s}{\omega_0 Q}+1}{\dfrac{s^4}{\omega_0^2\omega_t^2}+\left(\dfrac{n}{\omega_0^3}+\dfrac{1}{\omega_0\omega_t^2}\right)\dfrac{s^3}{Q}+\left(\dfrac{1}{\omega_0^2}+\dfrac{1}{\omega_t^2}\right)s^2+\left(n+1\right)\dfrac{s}{\omega_0 Q}+1} \tag{1}$$

C-type filter description

Traditionally, C-type filters are used to reduce multiple harmonic frequencies, especially above the tuning frequency of the filter given by two capacitors and the tuned inductor, where the tuning frequency is typically the most dominant harmonic frequency [11]. The tuned circuit nC_f-L_t resonates at the fundamental frequency in order to bypass the fundamental current flowing into the resistor. Therefore, the C-type filter is featured with low damping losses and good harmonic attenuation compared to more conventional passive filters. However, the C-type filter functionalities are slightly different when it is used with a VSC.

Operating principle of the proposed filter

Depending on how the damping resistor is selected, the behavior of the proposed filter will behave as either the conventional LCL filter or the trap filter. For example, when the resistor is zero, then the tuned circuit nC_f-L_t is short-circuited and the filter behavior is identical to the LCL filter. If the damping resistor is very large, then the current will flow only into the tuned circuit omitting the damping resistor. Then, the two equivalent circuits of the filters for zero damping resistor and very large resistor are illustrated in Fig. 2.

The choice of the filter parameters should ensure that harmonics in the grid current are below the limits imposed by the harmonic regulations such as IEEE 519 Std. [12]. The attenuation performance of the filter can be described from the admittance transfer function of the filter given by the ratio of the grid current to the converter voltage as depicted in (1). In fact, (1) indicates how the harmonic voltages specific to the adopted modulation strategy propagates into the grid current. In (1), the tuned frequency ω_t of the nC_f-L_t branch and the characteristic frequency, ω_0 of the filter is:

$$\omega_o = \sqrt{\frac{L_c+L_g}{L_cL_gC_f}} \tag{2}$$

$$\omega_t = \sqrt{\frac{1}{nL_tC_f}} \tag{3}$$

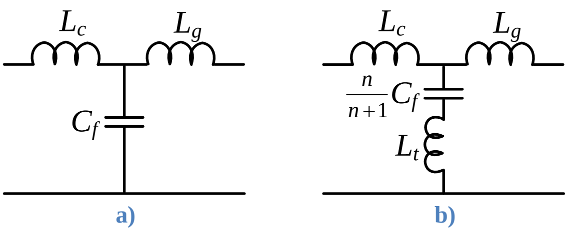


Fig. 2: Per phase filter schematics when: a) the damping resistor is zero (LCL filter); b) the damping resistor is infinite (trap filter).

The quality factor of the filter, that measures the damping effect in the circuit and whose value depends on the whole filter components, can be written as:

$$Q = \frac{R_0}{R_d} \tag{4}$$

where R_0 denotes the characteristic resistance of the filter, that is the resistance of the filter when the damping resistor is zero and whose value is:

$$R_0 = \sqrt{\frac{L_cL_g}{\left(L_c+L_g\right)C_f}} \tag{5}$$

In Fig. 3, a typical harmonic attenuation profile of the proposed filter is illustrated together with the LCL and trap filter, respectively. A trap filter provides theoretically an infinite attenuation at the switching frequency, while above the switching frequency the attenuation of the filter highly decreases. In practice, an infinite attenuation of the switching harmonics is not required. Instead, it is important to consider the attenuation of harmonics at multiples of the switching frequency. In fact, in case of the trap filter, the main limitation in the trap design is to ensure that harmonics around the twice the switching frequency are attenuated [13]. The LCL filter, provides an attenuation of 60 dB per decade, where the harmonics at the multiples of the switching frequency are over attenuated as the most dominant harmonics occurs at the switching frequency and not the multiples. On the other hand, the proposed filter provides a good trade-off between the LCL and trap filters, where the switching harmonics are attenuated more selectively. In addition, a good damping performance is obtained.

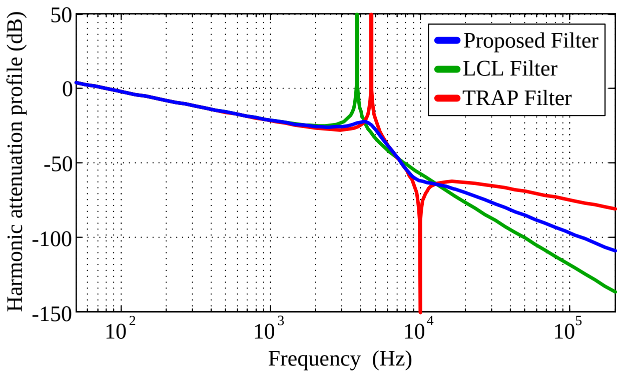


Fig. 3: Harmonic attenuation admittance of the proposed filter, LCL filter (the damping resistor is zero) and trap filter (the damping resistor is infinite).

DESIGN CONSIDERATIONS

To fully exploit the benefits of the proposed filter topology, a comparison with the conventional LCL filter (Fig. 4) with series damping resistor is made.

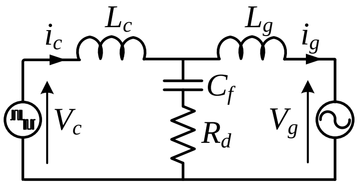


Fig. 4: Conventional LCL filter with damping resistor.

Design prerequisites

When designing a power filter for a VSC, it is required to know the harmonic current that is allowed to be injected into the grid. For this design, up to 0.3% individual harmonic content is allowed in the grid current. Additionally, the ratings of the filter capacitor or the current ripple in the converter side inductance should be known. Typically, the filter capacitor value is limited up to 5% of the base capacitance while the current ripple is limited to 10% [1]. It is assumed that harmonic spectrum of the converter voltage is also known.

Design of the conventional passive-damped LCL filter

According to the filter design procedure given in [1], the ratings given in Table I are selected for the conventional filter.

Design of the proposed passive-damped filter

For the proposed filter, the converter side inductance and the filter capacitor can be used the same as for the conventional LCL filter. Because of a more effective attenuation of the switching frequency harmonics, the grid side filter inductance can be decreased by a factor of 3 compared to that of the conventional filter. Therefore, at this point L_c, L_g and C_f are known. The remaining parameters to be found are the tuned capacitor, tuned inductor and damping resistor.

Design of the tuned capacitor

The choice of the tuned capacitor is dictated by the amount of damping that is required. For high damping of the filter resonance, the tuned capacitor is required to be in the same range as the filter capacitor or smaller. However, with larger tuned capacitor, the damping of the filter becomes very limited. The tuned capacitor can be written as:

$$C_t = nC_f \tag{6}$$

The filter capacitor and tuned capacitor are selected equal (n=1), which would ensure that the total damping can be achieved in the control to output admittance is well below 0 dB. The actual damping effect depends also on the value of the damping resistor.

Design of the tuned inductor

The tuned inductor is selected in such a way that harmonics at the switching frequency (ω_{sw}) are to be attenuated. This implies that:

$$\omega_{sw} = \sqrt{\frac{(n+1)}{nL_t C_f}} \tag{7}$$

Therefore,

$$L_t = \frac{n+1}{nC_f \omega_{sw}^2} \tag{8}$$

Design of the damping resistor

The value of the damping resistor can be designed by finding the quality factor of the filter which leads to good damping performance. By derivation of the filter admittance from (1) as function of the characteristic frequency one may find the quality factor of the filter that leads to optimum damping. A detailed derivation procedure is given in [14]. For the filter parameters given in Table I, the quality factor is about 2. Then, the damping resistor can be found from (4) as:

$$R_d = \frac{R_0}{Q} \tag{9}$$

Additionally, the damping losses can be selectively eliminated if the tuned frequency of the nC_f-L_t branch is selected at dominant harmonic order according to:

$$\omega_t = \frac{\omega_{sw}}{\sqrt{(n+1)}} \tag{10}$$

From (10) it follows that if fundamental-frequency losses are to be cancelled as in the case of conventional C-type filter, then this would imply that n to be very large. However, this would translate into the reduced damping effect from the filter. On the other hand, in PWM converters, the most dominant harmonics occurs at the switching frequency. Therefore, n can be selected low and the tuned frequency of the nC_f-L_t branch can be selected close to the switching frequency. The final ratings of the two filters are illustrated in Table I. For the proposed filter, the total inductance of the grid side inductor is highly decreased while the additional tuned inductor and capacitor are very low in size and volume. Additionally, the ratings of the damping resistor are much lower than the conventional LCL filter.

SIMULATION AND EXPERIMENTAL TESTS

To demonstrate the filter design, a 10 kW Danfoss FC302 inverter is controlled through a dSPACE 1006 platform using Proportional + Resonant (P+R) current controllers tuned with the technical optimum criterion [2]. The DC-link voltage is kept constant from a Delta DC source. The losses in the filter, damping circuit and corresponding

Table I: Filter Ratings

Filter topology	Conv. Side Inductor		Grid side inductor		Filter Capacitor		Damping Resistor		Tuned Inductor		Tuned Capacitor	
	Ap	mH	Ap	mH	Vp	μF	Wp	Ω	Ap	mH	Vp	μF
Conventional LCL	22.5	1.5	21	1.5	330	4.7	85	5.6	-	-	-	-
Improved LCL	22.5	1.5	21	0.5	330	4.7	18	3.3	2.3	0.084	9	4.7

Table II: Filter Performance Indices

Filter Topology	Resonance Frequency	Dominant Harmonic Current ($I_g(\omega_{sw})$)		Damping Losses		Filter Efficiency	THD_{Ig}	THD_{Vg}
		Sim.	Exp.	Sim.	Exp.	Experiments		
Conv. LCL	2.5 kHz	0.24 %	0.1 %	0.2 %	0.12 %	98.89 %	2.24 %	0.38 %
Improved LCL	4 kHz	0.24 %	0.23 %	0.066 %	0.04 %	99.06 %	3.43 %	0.4 %

harmonic indices are measured using N4L PPA 5530 power analyzer and presented in Table II. A California Instruments MX35 AC power source is used as a grid simulator in order to provide accurate low grid impedance.

In Fig. 5, the magnitude and phase of the open loop transfer function of the control system is illustrated under grid current feedback. From Fig. 5, it can be seen that both filters are designed to achieve same resonance damping and same attenuation of the harmonics around the switching frequency. From Table II, it can be concluded that the performance of the filters is similar except the damping losses which are reduced by a factor of 3 by adopting the proposed passive-damped filter.

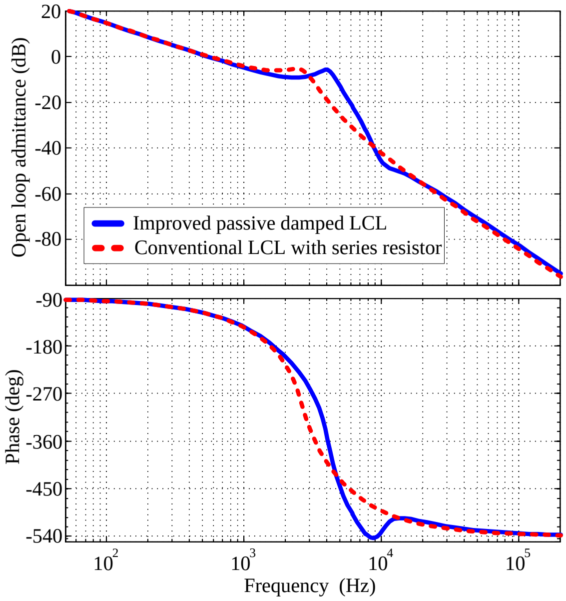
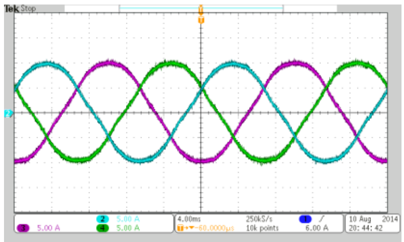


Fig. 5: Phase and magnitude of the proposed and conventional filter admittance.

In Fig. 6 and Fig. 7, the time domain waveforms and frequency spectrum of the grid current for the two filter topologies is illustrated. It demonstrates the design of the filters in steady-state condition. The VSC is operated at half of the rated power during the experimental tests.



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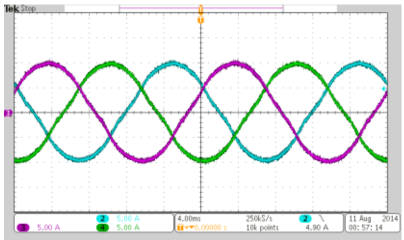

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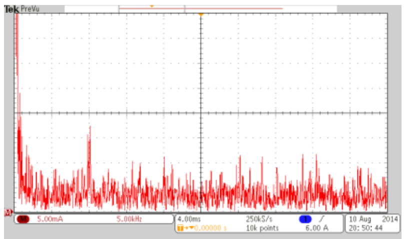
Fig. 6: Time domain waveforms of the grid current (5A/div.) for: a) conventional filter; b) proposed filter.



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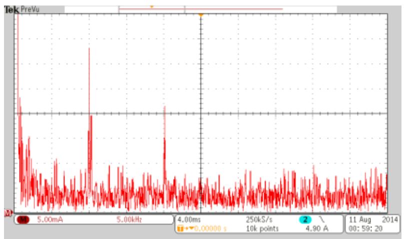

b)

Fig. 7: Frequency spectrum of the grid current (5mA/div.) for: a) conventional filter; b) proposed filter. (the 0.3 % harmonic limit of the grid current is equal with 43 mA)

CONCLUSIONS

In this paper, a more efficient passive-damped filter topology is proposed which may increase the use of passive damping in grid connected VSCs. The main benefits over the conventional topologies are lower ratings, size and volume of the passive components. For example, the grid filter inductance and the damping resistor ratings can be decreased. The resulted passive damping losses are also significantly lower compared to the conventional LCL filter with damping resistor.

As a result of multiple components in the proposed filter, more degree of freedom in the filter design is obtained. For instance, the additional tuned circuit can be designed in such a way that the trap ratings are also reduced, compared let's say to a conventional trap filter.

The complexity and physical implementation of such filter circuit are the main drawbacks in evaluation with more conventional filters.

Acknowledgments

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