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Performance comparison of passive series R and shunt R-C damped LCL filter for grid-connected inverters

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Abstract: LCL filters are widely used in distributed power-generation systems to attenuate high-frequency harmonics caused by pulse-width modulation switching of grid-connected inverters. A resonance occurs due to the series-connected reactive components. In order to damp resonance effects, active and passive damping methods are used. Lower switching frequencies are typically preferred to decrease switching power losses with high-power applications. Thus, control bandwidth of the system is limited and implementation of active damping gets harder. As a result, passive damping methods are commonly used in high-power applications. In this study, performances of two most commonly used passive damping methods which are series R damped and shunt R-C damped are analysed and compared in terms of resonance damping, grid current attenuation at high frequencies, and power losses on damping circuits.

1 Introduction

The share of renewable energy sources in electricity generation market is continuously increasing. Grid integration of photovoltaic and wind power plants requires low-pass filters to attenuate high-frequency current emissions caused by switching of the inverters. Grid filters have two important roles in grid-connected voltage source inverters (VSI). First one is that they provide an inductive behaviour to replicate the behaviour of synchronous generators and transmission lines. Second one is that they attenuate the current harmonics which are generated at PWM carrier and sideband frequencies.

With low-power applications like photovoltaic systems, a single inductor is typically employed as low cost and simple grid filter solution. However, in high-power applications above several hundreds of rated kW, switching frequencies of the inverters are limited by the switching power losses. Hence, high value filter inductors become necessary to satisfy grid code harmonic emission requirements but their utilisation is not feasible due to the elevated voltage drop across the inductor, and also being bulky and not cost-effective. LC filters give better performance thanks to the ability of cut-off frequency adjustment. However, high-order LCL filters, which provide higher attenuation for switching and sideband frequency harmonics, are generally preferred in industrial applications [1]. Also, thanks to its more inductive behaviour LCL filters can prevent the system against inrush currents come from the grid. It should be noted that high-order transfer functions of LCL filters come up with resonance effects which need to be damped by passive or active methods, but its interaction with the controller bandwidth is usually ignored and needs detailed stability analysis during early design phase.

Existing LCL filters are commonly considered for low-power rated (<20 kW) inverters. Required inductance values for LCL filters typically become infeasible in terms of volume and cost for medium- and high-power inverters. In this study, design trade-off points will be evaluated, such as choosing lower values of LCL filter inductors and higher values of filter capacitors in such a way that the same filter attenuation performance is maintained for medium- and high-power inverters. As a consequence of using higher capacitance, power factor of the inverter measured at the grid-connection point decreases. Furthermore, the filter frequency response is affected from the grid-side equivalent impedance. Most of the grid-interfaced inverters are connected to grid via an isolation transformer whose reactance is comparable with grid-side inductor value. Therefore, the frequency response of the filter changes and system stability is adversely affected.

Passive damping methods which do not require additional sensors are more favourable in industrial applications compared to active damping methods, as they ensure robustness against to parameters, although they cause additional power losses on the damping resistor. As the most basic passive damping method, the damping resistor is series connected to the filter capacitor. Further improvement in power loss minimisation can be achieved in such that the demanded filter capacitance is shared among two parallel capacitors without loss of damping performance as depicted in Fig. 1.

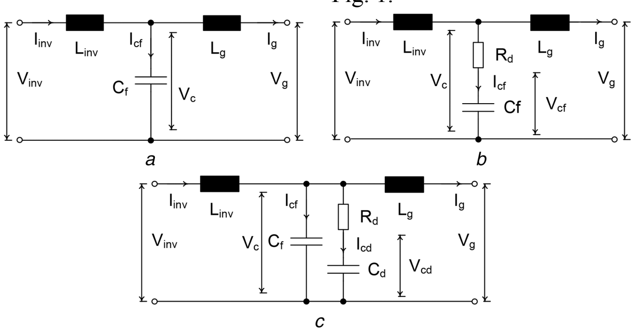

Fig. 1 *Per phase equivalent circuits of undamped*
(a) Series *R* damped, ***(b)*** Shunt *R-C* damped LCL filters

In the study, performances of series R and shunt R-C damped LCL filters are compared for a 300 kW grid-connected wind turbine inverter. In Section 2, optimum LCL filter design process is given. In Section 3, frequency responses of two damping methods are given and their resonance damping capabilities are compared. In Section 4, current ripple attenuation performances of the studied damping methods at high frequencies are analysed. In Section 5, power losses on damping circuits of both methods are derived and calculated. The results acquired in previous sections are verified by laboratory experiments.

2 LCL filter design

Design of LCL filters have a crucial importance for grid-connected PWM-based inverters. A filter which is not well designed can cause instabilities because of insufficiently damped resonance effects. Also, it can be inadequate to attenuate high-frequency ripples at switching frequency and its sideband harmonics. In addition, high-power losses can occur on damping circuits and get worse overall efficiency of the system. In this part, a systematic optimum design procedure is given for a grid-connected high-power (>100 kW) inverters.

i. Total inductor value should be limited at 0.1 pu to not have a large voltage drop on the inductors [2]. Then, maximum total inductor value can be found by

$$L_{T\max} = 100\% \frac{V_{g\max}^2}{2\pi f_g P_n} \tag{1}$$

where $V_{g\max}$ is the maximum grid voltage, f_g is the grid frequency and P_n is the rated power.

ii. Maximum filter capacitance $C_{\max}$ can be selected by

$$C_{\max} = x\% \frac{P}{2\pi f_g V_g^2} \tag{2}$$

where x is the percentage of the base capacitance at rated conditions. Reactive power consumed by the capacitors should not exceed 5% of the rated active power in order not to decrease power factor. In low-power applications, choosing capacitor value as half of the maximum capacitance value is recommended to decrease reactive power consumed by capacitor. However, inductor values should be increased to have a similar attenuation performance with lower capacitor value. For this reason, capacitor value is selected with upper limit in high-power applications.

iii. Converter-side inductor value (L_{inv}) can be selected by

$$L_{\text{inv}\min} = \frac{V_{\text{dc}}}{24 f_S \Delta i_1 \max} \tag{3}$$

where $\Delta i_{1\max}$ is the maximum current ripple in the inductor defined by

$$\Delta i_{1\max} = k_a \frac{\sqrt{2} P_n}{\sqrt{3} V_g} \tag{4}$$

where k_a is the desired current ripple on the inductor current at switching frequency [3]. Current ripple limit in the converter-side inductor is generally determined as 10%. Improved attenuation performance requires larger inductor value and causes larger size and cost. Selecting close inductor values can provide optimum cost and size for design $L_{\text{inv}}/L_g = 3$ can be selected as a reference value. If the system is connected to the grid by an isolation transformer, $L_{\text{inv}}/L_g = 2$ is a better ratio [4].

iv. Grid-side inductor value L_g is determined using the relation between L_{inv} by

$$\delta = \left|\frac{i_{\text{gsw}}}{i_{\text{csw}}}\right| = \frac{1}{\left|1 + a\left(1 - L_{\text{inv}} \times C_f \times \omega_{\text{sw}}^2\right)\right|} \tag{5}$$

where $a = (L_g/L_{\text{inv}})$ $0 \le a \le (L_{T\max}/L_{\text{inv}}) - 1$ Also, δ represents harmonic attenuation of the grid-side inductor. Upper value for grid-side inductance L_g is limited by the voltage drop for unity power factor operation. Lower value is determined to satisfy IEEE 519-1992 high-frequency grid current harmonic specifications [5]. To ensure this requirement, current ripple attenuation at switching frequency should be lower than 2%.

v. When the reactive filter components are determined, resonance frequency of the LCL filter is calculated by

$$f_{\text{res}} = \frac{1}{2\pi}\sqrt{\frac{L_{\text{inv}} + L_g}{L_{\text{inv}} L_g C_f}} \tag{6}$$

It must satisfy the requirement

$$10 f_g \le f_{\text{res}} \le \frac{f_{\text{sw}}}{2} \tag{7}$$

to avoid from resonance at high and low frequencies.

vi. In order to avoid resonance problem, a series resistor can be added to filter capacitor as shown in Fig. 1*b*. Series R damped is the simplest passive damping solution and it provides nearly 40 dB/decade current attenuation after resonance frequency. Disadvantage of the method is that large amount of power loss occurs on the damping resistor R_d. The value of the damping resistor should be limited by (8) considering power loss.

$$P_{\text{loss}} = 3 R_d \sum_n i_{R_n}^2 \tag{8}$$

where i_{R_n} is the current goes through the resistor at nth harmonic frequency. Power loss on the resistors should be limited at most 1% of the rated power [6].

vii. In order to improve attenuation performance and decrease the damping resistor losses of the LCL filter passive shunt R-C damped whose per phase equivalent circuit is given in Fig. 1*c* can be utilised instead of series R damped. Shunt R-C damped filter can provide approximately 60 dB/decade current attenuation at frequencies larger than resonance frequency. The predetermined capacitor value is divided between filter and damping capacitors. Larger damping capacitor provides better attenuation performance but increases current goes through the resistor and larger power loss occurs on the damping circuit. Therefore, there is a trade-off between attenuation capability at high frequencies and power losses [7] of the LCL filter.

Considering given design procedure an LCL filter is designed as shown in Table 1. The parameters are determined and given for the shunt R-C damped LCL filter. In the study, when analysing the series R damped LCL filter performance, filter capacitance is considered as the sum of two capacitors in shunt R-C damped case.

An experimental setup is built based on predetermined parameters to validate the results through the study. Overall block diagram and a picture of the used setup is given in Figs. 2 and 3, respectively.

In the configuration, DC link of the VSI is connected to a constant DC voltage source and voltage controller loop is removed. 2 level VSI is controlled by Proportional Resonant + Harmonic Compensator (PR + HC) current controller and switched by space vector pulse width modulation (SVPWM) technique. By changing cable connections, LCL filter damping method is adjusted as series R and shunt R-C damped. The system is connected to the grid by a 120 kVA isolation transformer. For this reason, the experiments were done while the inverter is supplying 100 kW power to the grid at unity power factor.

Table 1 Designed LCL filter parameters

	Symbol	Value	Unit
grid frequency	f_g	50	Hz
switching frequency	f_s	5000	Hz
active power	P_n	300	kW
grid voltage	V_g	380	V_{rms}
dc link voltage	V_{dc}	700	V_{DC}
Inverter-side inductor	L_1	125	μH
Grid-side inductor	L_2	60	μH
filter capacitor	C_f	100	μF
damping capacitor	C_d	200	μF
damping resistor	R_d	0.9	Ω

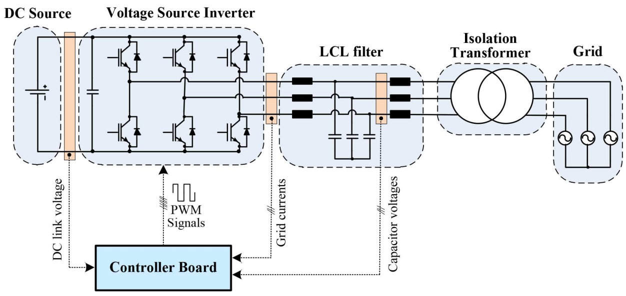

Fig. 2 *Block diagram of the experimental setup*

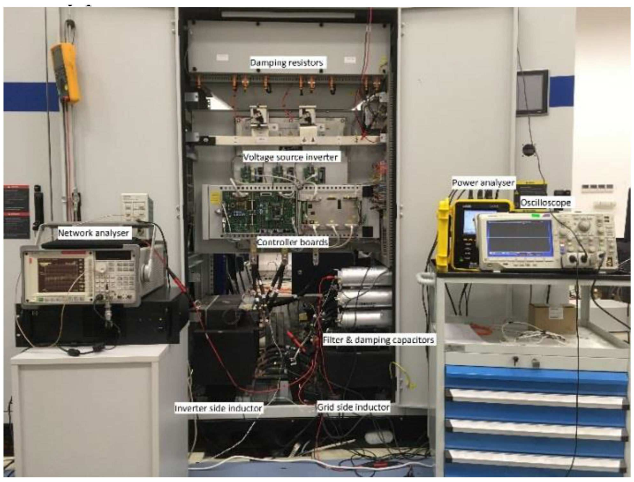

Fig. 3 *Experimental setup*

3 Resonance damping

Resonance damping capabilities and current ripple attenuations of LCL filters can be analysed via frequency responses. Transfer function of an LCL filter is $H_{\mathrm{LCL}} = (i_g/v_{\mathrm{inv}})$, is found by assuming that the grid side is short circuited due to having no high-frequency components. The transfer function of undamped LCL filter is found as

$$H_{\mathrm{LCL}} = \frac{1}{s^3 C_f L_g L_{\mathrm{inv}} + s(L_g + L_{\mathrm{inv}})} \tag{9}$$

The series R damping adds a zero to the transfer function and it becomes

$$H_{\mathrm{LCL}} = \frac{sR_dC_f + 1}{s^3 C_f L_g L_{\mathrm{inv}} + s^2 R_d C_f (L_g + L_{\mathrm{inv}}) + s(L_g + L_{\mathrm{inv}})} \tag{10}$$

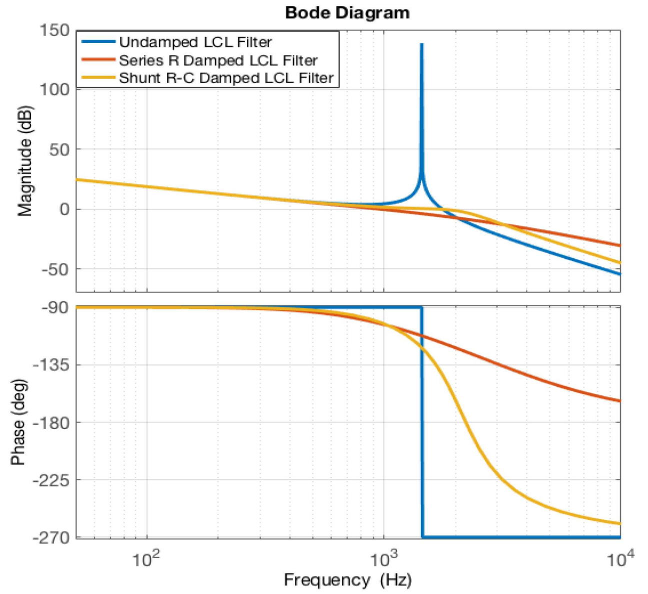

Fig. 4 *Frequency responses of the undamped, the series R damped and the shunt R-C damped LCL filter*

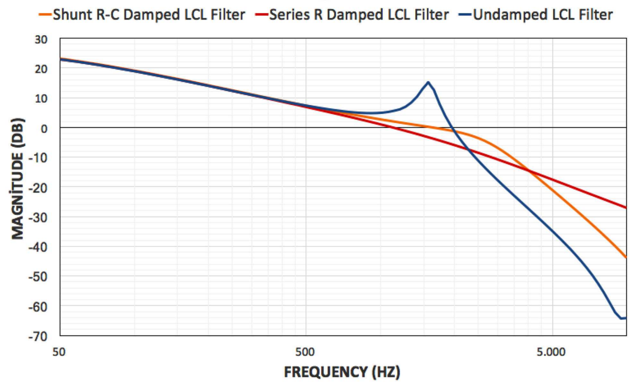

Fig. 5 *Measured frequency responses of undamped, series R damped and shunt R-C damped LCL filter*

The shunt R-C damping adds a pole to the transfer function and increases its degree (see (11)) . Based on predetermined LCL filter parameters and their transfer functions, frequency responses of undamped, series R damped and shunt R-C damped LCL filters are plotted as in Fig. 4.

According to Fig. 4, resonance frequency of the LCL filter is ∼1440 Hz and satisfies the condition given by (8). 139 dB gain is observed at the resonance frequency for the undamped LCL filter. At this frequency, the gain is damped down to − 3.82 and 0.4 dB for the series R and the shunt R-C damped filters. As seen from these results, the shunt R-C damped LCL filter has a larger control bandwidth than that of the series R damped filter.

To verify analytical results, magnitude frequency responses of the LCL filter for the undamped, the series R and the shunt R- C damped cases were measured via a network analyser and plotted as in Fig. 5. When measured magnitude response of the undamped LCL filter is compared with the theoretical one, it is seen that measured resonance frequency shifts to 1565 Hz. Also, magnitude of the gain spike is obtained as 15.2 dB thanks to its natural damping caused by series resistances of the filter inductors. Measured magnitudes at resonance frequency for both cases are very close to theoretical ones as seen in Table 2.

4 Attenuation performance

$$H_{\mathrm{LCL}} = \frac{sR_dC_d + 1}{s^4 R_d C_d C_f L_g L_{\mathrm{inv}} + s^3 L_g L_{\mathrm{inv}}(C_d + C_f) + s^2 R_d C_d (L_g + L_{\mathrm{inv}}) + s(L_g + L_{\mathrm{inv}})} \tag{11}$$

Table 2 Theoretical and experimental gain magnitudes at resonance frequency

	Undamped	Series *R* damped	Shunt *R-C* damped
theoretical	139 dB	−3.82 dB	0.4 dB
experimental	15.2 dB	−3.3 dB	0.1 dB

Table 3 Grid current attenuation of series R and shunt R-C damped LCL filter

	@5, kHz	@10, kHz	@15, kHz	@20, kHz
series *R*	−19.5 dB	−30.7 dB	−37.6 dB	−42.5 dB
shunt *R-C*	−26.2 dB	−45.1 dB	−55.9 dB	−63.4 dB
$\frac{i_{seriesR}}{i_{shuntRC}}$	2.15	5.25	8.22	11.09

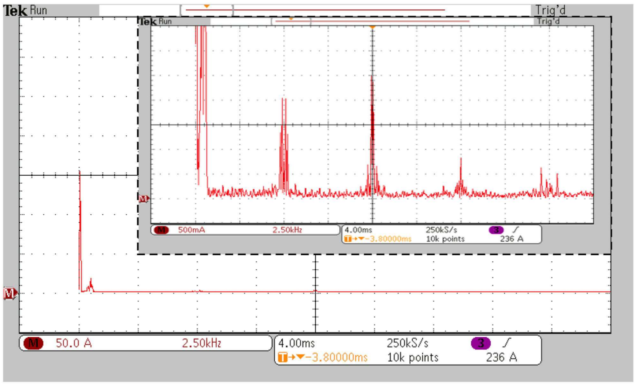

Fig. 6 *Grid current frequency spectrum for series R damped LCL filter (50 A/div (0.5 A/div), 2.5 kHz/div)*

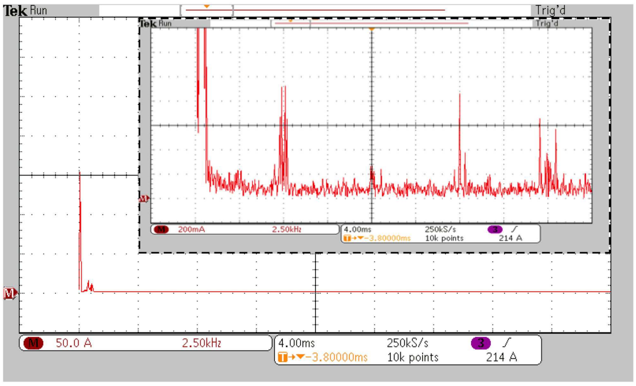

Fig. 7 *Grid current frequency spectrum for shunt R-C damped LCL filter (50 A/div (0.2 A/div), 2.5 kHz/div)*

Table 4 Grid current at switching frequency and its sideband harmonics for series R and shunt R-C damped LCL filters

	@5, kHz	@10, kHz	@15, kHz	@20, kHz
series *R*	2 arms	2.5 arms	0.8 arms	0.6 arms
shunt *R-C*	0.9 arms	0.3 arms	0.8 arms	0.6 arms
$\frac{i_{seriesR}}{i_{shuntRC}}$	2.22	8.33	1	1

As of PWM switching, grid-connected VSIs inject harmonic current ripples at switching and its sideband frequencies. According to IEEE 519-1992, harmonic current distortion after 35th harmonics must be smaller than 0.3% of the rated current. In IEEE 519-2014 [8], there is no limitation after 50th harmonics but satisfying given condition in IEEE 519-1992 is recommended. While designing the LCL filter, one of the main considerations is to attenuate the grid current ripple below the specified limits. As stated before, while the series R-damped LCL filter can provide 40 dB/decade grid current attenuation, the shunt R-C-damped filter can reach up to 60 dB/decade above the resonance frequency. Grid current attenuations of both cases are given in Table 3 for switching frequency and its harmonics under ideal conditions.

Grid current frequency spectrums for series R and shunt R-C-damped LCL filters are given in Figs. 6 and 7, respectively while 100 kW power supplying to the grid.

The most dominant harmonic appeared on the current frequency spectrums is the second one because of SVPWM. Measured current magnitudes at switching frequency and its sideband harmonics are given in Table 4.

When the results are compared, it can be said that, the shunt R-C-damped filter provide ∼2 times better grid current attenuation at switching frequency and eight times better attenuation at two switching frequency. The results are consistent with the given values in Table 3. To satisfy IEEE 519-1992 grid current ripple requirement, current magnitude at switching frequency and its sideband harmonics should be smaller than 1.36 Arms for 300 kW inverter. When the results are analysed, it is seen that the shunt R-C damped filter satisfy this requirement at all switching frequency harmonics. However, inductors of the series R-damped filter should be increased to have a better attenuation performance.

5 Power loss

A significant amount of power dissipates on damping resistors and inductors of LCL filters. The power loss on the inductors is due to core and copper losses. Damping resistors' power losses will be taken into account here in order to compare efficiency of series R and shunt R-C-damped LCL filters.

Dissipated power on the damping resistor is caused by low- and high-frequency components of the current goes through it. The low-frequency current harmonics caused by SVPWM are neglected in this calculation because of its relatively small magnitudes. At fundamental frequency, the power loss is calculated by

$$P_{\text{fund}} = \frac{V_c^2 \omega_g^2 C_d^2 R_d}{1 + \omega_g^2 C_d^2 R_d^2} \tag{12}$$

where ω_g is the fundamental frequency in radian per second [9].

High-frequency power loss occurs only at the switching frequency and its sideband harmonics. The power loss for series R-damped circuit at high frequencies can be calculated by

(see (13))

where ω_{sw} is the switching frequency in radian per second and V_{inv} is the inverter output voltage ripple at switching frequency. The power loss for shunt R-C-damped circuit at high frequencies can be calculated by

(see (14))

Total power loss can be found by,

$$P_{\text{tot}} = P_{\text{fund}} + P_{\text{sw}} \tag{15}$$

To calculate damping circuit power losses, damping resistor current spectrum of designed series R- and shunt R-C-damped LCL filters are given in Figs. 8 and 9, respectively, while 100 kW power supplying to the grid.

By using (8), power loss on the damping circuits for series R- and shunt R-C-damped LCL filter are founded as given in Table 5. High-frequency power losses of damping circuits are much smaller than fundamental one. Thus, when selecting LCL filter damping topology power losses of the damping circuit can be considered

$$P_{\text{sw}} = V_{\text{inv}}^2 \frac{L_g^2\left(1 + \omega_{\text{sw}}^2 R_d^2 C_f^2\right)}{\left(L_{\text{inv}} + L_g - \omega_{\text{sw}}^2 C_f L_{\text{inv}} L_g\right)^2 + \omega_{\text{sw}}^2 R_d^2 C_f^2 (L_{\text{inv}} + L_g)^2} \frac{\omega_{\text{sw}}^2 R_d C_f^2}{1 + \omega_{\text{sw}}^2 R_d^2 C_f^2} \tag{13}$$

$$P_{\rm sw} = V_{\rm inv}^2 \frac{L_g^2\left(1+\omega_{\rm sw}^2 R_d^2 C_d^2\right)}{\left(L_{\rm inv}+L_g-\omega_{\rm sw}^2 L_{\rm inv} L_g (C_d + C_f)\right)^2 + \omega_{\rm sw}^2 R_d^2 C_d^2 \left(L_g + L_{\rm inv} - \omega_{\rm sw}^2 C_f L_{\rm inv} L_g\right)^2} \frac{\omega_{\rm sw}^2 R_d C_d^2}{1+\omega_{\rm sw}^2 R_d^2 C_d^2} \tag{14}$$

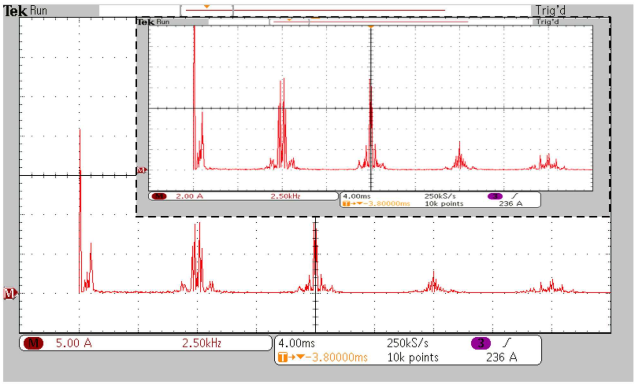

Fig. 8 *Damping resistor current frequency spectrum for series R damped LCL filter (5 A/div (2 A/div), 2.5 kHz/div)*

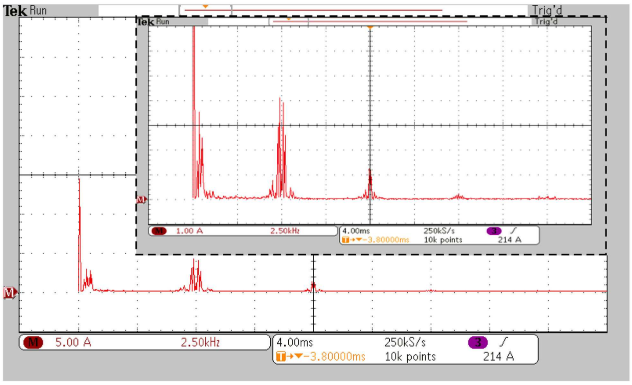

Fig. 9 *Damping resistor current frequency spectrum for shunt R-C damped LCL filter (5 A/div (1 A/div), 2.5 kHz/div)*

Table 5 Damping circuit power loss of series R and shunt R- C damped LCL filters

	Fundamental power loss, W	High-frequency power loss, W	Total power loss, W
series *R*	1148	12	1160
shunt *R-C*	512	1	513

only for fundamental frequency. Power loss on the series R damped LCL filter is two times larger shunt R-C-damped LCL filter.

6 Conclusion

In the study, LCL filter design procedure for high-power grid-connected inverters has been presented. By using proposed method an LCL filter has been designed for 300 kW wind turbine inverter by considering commonly used passive damping methods which are series R and shunt R-C damping. Performances of both methods have been analysed in terms of resonance damping, attenuation of switching current harmonics, and power loss on damping circuits. Analytically obtained results were verified by experiments. According to results, resonance damping capabilities of both methods are close to each other and quite good. Shunt R-C-damped filter can provide much better grid current attenuation at high frequencies than series R damped. In addition, power loss on damping circuits of shunt R-C damped LCL filter is ∼2 times lower than series R-damped one. In conclusion, while designing an LCL filter selection of shunt R-C-damped LCL filter instead of series R-damped one, better attenuation performance is obtained with lower damping circuit power loss.

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