Comparative Analysis of LCL and LLCL Filters for Three-level PWM Converters

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Abstract

In this paper, a comparative analysis of LCL and LLCL filters connected to three-level T-type PWM converters is presented, in which the filter inductor sizes are investigated in view of total harmonic distortion (THD) in grid phase currents. The analysis results are verified by simulation and experiments.

1. Introduction

In the PWM converters, due to the current harmonics around switching frequency (2-15 kHz), a high value of input filter inductance is unavoidable. Since the large inductance deteriorates the system dynamics, the LCL filter is preferred to the L filter for grid-connected PWM converters [1]. To decrease the total inductance of the LCL filter, the LLCL filter topology has been proposed in [2], where the series inductor in the capacitor branch makes a zero-impedance in switching frequency, which results in lower grid-side inductor due to the lower harmonics. However, there is a resonance problem in LCL and LLCL filters, in which more complex current control strategies are needed to maintain the system stability. To suppress the resonance, various passive and active damping methods have been proposed [3]-[4]. Although the passive damping method has advantages like reliability and simplicity, it has also a disadvantage of additional power loss [3]. So, the active damping methods are more preferable, where the control algorithm is modified to stabilize the system without any additional power loss.

In this paper, the comparative analysis for the LCL and LLCL filters connected to the three-level T-type PWM converter is investigated. The active damping scheme using the PR controllers is applied to damp out the resonance for the designed parameters of LLCL and LCL filters. The simulation and experiment results are shown to validate the analysis results.

2. System modeling

The three-level T-type AC/DC PWM converter is shown in Fig.1, which is connected to the grid through the LLCL filter. The grid is modeled as an ideal sinusoidal voltage source without line impedances. A resistive load is connected to the DC output terminal of the converter.

A. Converter modeling

For the PWM converter, the voltage equations are expressed in the synchronous reference frame as

$$e_{de} = Ri_{de} + L\frac{di_{de}}{dt} - \omega L i_{qe} + v_{de} \tag{1}$$

$$e_{qe} = Ri_{qe} + L\frac{di_{qe}}{dt} + \omega L i_{de} + v_{qe} \tag{2}$$

where,

e_{de}, e_{qe} : dq-axis grid voltages,

i_{de}, i_{qe} : dq-axis converter currents,

v_{de}, v_{qe} : dq-axis converter voltages,

ω : angular frequency of the grid voltage,

R : resistance of inductors, ($R_1 + R_2$),

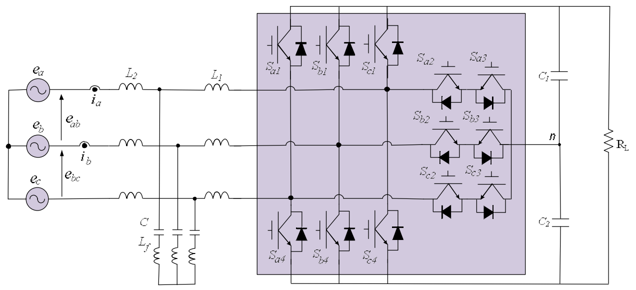

Fig. 1 LCL/LLCL filter connected for grid-connected T-type three-level converter.

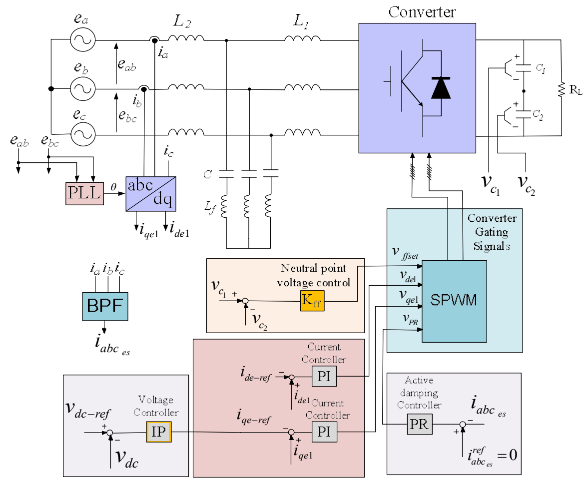

Fig. 2. Control block diagram of the grid-connected PWM converter with LLCL filter.

L : sum of grid- and converter-side inductors ($L_1 + L_2$).

By aligning the q-axis of the synchronous reference frame to the grid voltage, $e_{de} = 0$.

3. Proposed converter control method

Fig. 2 shows the control block diagram of the grid-connected T-type converter with the LLCL filter.

3.1 DC-link voltage and input current control

The integral-proportional (IP) controllers are used for an outer DC-link voltage control. The proportional-integral (PI) controllers are used for the inner dq–axis current control. The q-axis current reference is generated from the DC-link voltage controller. The d-axis current is controlled to zero for a unity power factor. The PI current controllers are equipped with the anti-wind-up function. The neutral-point voltage control of the three-level converter is added, which utilizes the offset voltage that is found from the difference between the upper and lower capacitor voltages in the DC-link.

3.2 Active Damping Control

The PR controllers works at the abc-stationary reference frame, in which the steady-state errors can be eliminated at the specified resonant frequency. The transfer function of the PR controllers is given by

Table 1 PWM converter parameters for simulation/experiment.

Parameters	Value
Power rating (kW)	25/3
Line to line input RMS voltage (V)	380/220
DC-link voltage (V)	600/340
Switching frequency (kHz)	4/5
DC-link capacitance (μF)	2,500

Table 2 Filter parameters for simulation/experiment.

Parameters	LLCL		LCL	
	L_1	L_2	L_1	L_2
Converter-side inductor-L_1(mH)	1 2/3	0 2/0 4	1 2/3	0 8/0 8
Grid-side inductor-L_2 (mH)				0 2
Capacitor (μF)	35/20		35/20	
Series inductor (μH)	45/50		0/0	

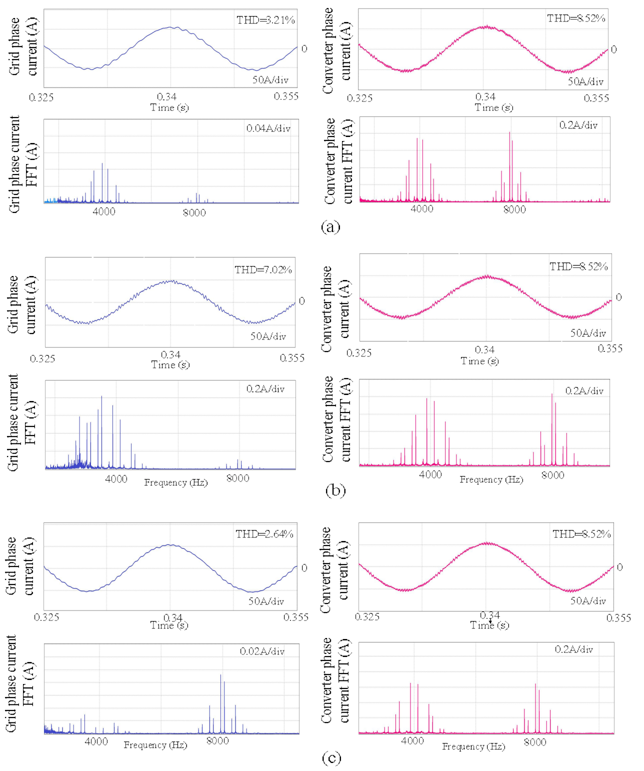

Fig. 3. Grid and converter currents with FFT spectra in different cases. (a) LCL filter case I: L_1=1.2 mH, L_2=0.8 mH. (b) LCL filter case II: L_1=1.2 mH, L_2=0.2 mH. (c) LLCL filter case III: L_1=1.2 mH, L_2=0.2 mH, L_f=0.045 mH. (Simulation results).

$$G_{PR}(s) = K_{pr} + \frac{K_r s}{s^2 + \omega_{res}^2} \qquad (3)$$

where K_{pr} and K_r are the proportional and resonant gains, respectively, and ω_{res} is the resonance frequency. In this work, the resonance frequency of the filters is designed to be lower than a half of the switching frequency (4 kHz). To extract the resonant component in the grid currents, the band-pass-filers (BPF) are applied.

4. Simulation and experimental results

The simulation has been performed under the condition as listed in Table I and II for the T-type three-level PWM converter and filter parameters, respectively. The grid and converter currents and their FFT spectra are shown in Fig. 3 for the different cases of the LCL and LLCL filters. The grid current harmonics should meet the IEEE standard 519-1992. In the case I of the LCL filter (L_1=1.2 mH, L_2= 0.8mH), the magnitude of the dominant harmonic component in the grid current is lower than 0.11 A (0.26% of the fundamental component). The total harmonic distortion (THD) factor is 3.21% (Fig. 3(a)). Fig. 3(b) illustrates the case II of the LCL filter (L_1=1.2mH, L_2= 0.2mH), where the dominant harmonic magnitude in the grid current is lower than 0.83 A (1.43 % of the fundamental current) with THD of 7.02%. It is obvious that the case II of the LCL filter doesn't meet the requirement of IEEE standard. However, in the case III of the LLCL filter (L_1 =1.2mH, L_2=0.2mH, and L_f =0.045mH) shown in Fig. 3(c), the magnitude of the dominant harmonic in the grid current is lower than 0.1 A (0.21% of the fundamental component) where the THD is 2.64%.

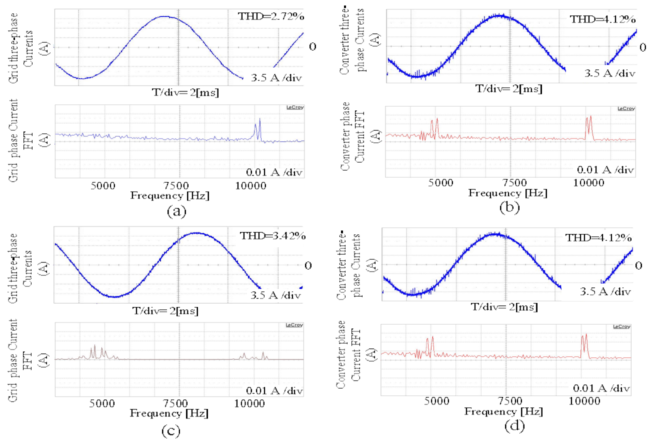

Fig. 4. Grid and converter currents with FFT spectra in different cases. (a) LCL filter grid phase current. (b) LCL filter converter phase current. (c) LLCL filter grid phase current. (d) LLCL filter converter phase current. (Experimental results).

Some experimental results are shown for a 3-kW converter system in the case I of the LCL and LLCL filters. Under this condition, the THD of grid phase current in LCL and LLCL filters are 2.72% and 3.42%, respectively, which are lower than the IEEE standard limit. The converter phase currents are illustrated in Fig. 4(b) and (d) which are more distorted than the grid phase currents.

5. Conclusion

In this paper, a comparative analysis of LCL and LLCL filter performance for the T-type three-level converter has been investigated. In the LLCL filter, the grid-side inductor has been reduced by 75% (from 0.8-mH to 0.2-mH), compared with the LCL filter, in which the THD and dominant harmonic component of the grid current have met the IEEE standard. The comparative analysis has been verified by simulation and experimental results.

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References

[1] M. Liserre, F. Blaabjerg, and S. Hansen, "Design and control of an LCL-filter-based three-phase active rectifier," *IEEE Trans. on Ind. Applicat.,* vol. 41, no. 5, pp. 1281-1291, Sep/Oct. 2005.

[2] W. Wu and F. Blaabjerg, "An LLCL power filter for single-phase grid-tied inverter," *IEEE Trans. on Power Electron.,* vol. 27, no. 2, pp. 782-789, Feb. 2012.

[3] W. Wu, Y. He, T. Tang, and F. Blaabjerg, "A new design method for the passive damped LCL and LLCL filter based single phase grid tied inverter," *IEEE Trans. on Industry Applicat.,* vol. 60, no. 10, pp. 4339-4349, Oct. 2013.

[4] P. Alemi and D.-C. Lee, "Active damping control of LLCL filters for three-level T-type grid converters," *in Proc. of IPEC-ECCE Asia*, May, 2014, CD-ROM Format.