LCL Filter Design for Grid-connected Voltage-source Converters in High Power Systems

Byung-Geuk Cho and Seung-Ki Sul
Department of Electrical Engineering and Computer Science
Seoul National University
Seoul, Korea
bk8089@eepel.snu.ac.kr

***Abstract*—This paper deals with an LCL filter for the grid-connected converter. Active and passive damping methods are compared in a resonance suppression point of view and necessity of the passive damping is claimed, especially for high power systems in which switching frequency is limited lower than 2.5 kHz. Based on the analysis, LCL filter design procedure with passive damping for a two level voltage source converter is introduced. The filter components are optimally selected by investigating stored total energy in the filter and capacity of the converter. Then the resistors are inserted at several locations and comparisons are made to determine the most proper way of passive damping by examining the losses. The effectiveness of the study is supported by simulation and laboratory scale experiment.**

I. INTRODUCTION

Recently, research on the grid-connected converter systems is vigorously explored due to the increased attention to new renewable energy. To prevent the incoming of harmonic sources into the grid, various types of harmonic filters are incorporated but LCL filters are overwhelmingly adopted [1]-[3] because comparatively better harmonic attenuation is achievable. Especially, LCL filters can take huge advantages of the size, weight or costs of the filter for high power systems in which available switching frequency is limited lower than 2.5 kHz.

However, LCL filters inherently suffer from the resonance problem. According to the filter components, the impedance of the filter becomes zero at a specific resonant frequency and consequently unregulated harmonic sources are likely to be injected into the grid.

To prevent the resonance effect, active and/or passive damping methods are utilized [4][5]. In active damping methods, the structure of the current controllers is configured not to excite the resonance. On the other hand, in passive damping methods, resistors are added in appropriate forms to blunt the resonance. In the existing papers, the choice for the damping method is selective or insufficient explanation for the reason is presented when the passive damping is used instead of the active damping. This paper analyzes the difference of the two damping methods in the resonance suppression point of view and claims the necessity of the passive damping for the application of LCL filters.

Based on the analysis, LCL filter design procedure with passive damping for a two level voltage source converter is introduced in this paper. Initially, each reactive component is chosen by investigating cost functions such as filter's total energy and converter capacity. Then resistors are inserted at several locations and comparisons are made to determine the most proper way of passive damping by examining the losses.

The effectiveness of the study is supported by simulation and laboratory scale experiment.

II. SYSTEM DESCRIPTION

The system dealt in this paper is shown in Fig. 1 and the corresponding specification is provided in table I. For the analysis and design of LCL filter afterwards, the grid impedances are neglected and this assumption has no crucial effect on the study.

TABLE I. SYSTEM SPECIFICATION

Rated power	1 [MW]	Switching frequency	2.5 [kHz]
Rated current	837 [Arms]	DC link voltage	1070 [V]
Rated voltage	690 [Vrms]	Grid frequency	60 [Hz]

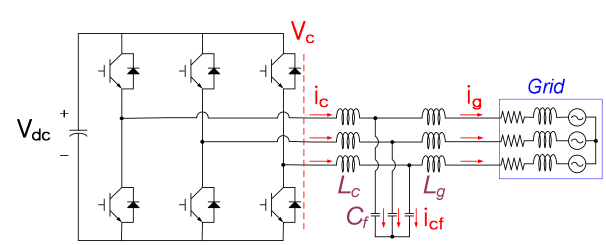

Fig. 1. Configuration of system.

III. INVESTIGATION ON LCL FILTER

An ideal LCL filter consists of pure reactance components and consumes no active power. Even though there is no way to avoid losses from ESRs or connection between components in real system, it is assumed to be lossless when designing the filter because those resistances are unintentional and unpredictable. Therefore, the same assumption is made for the investigation on LCL filters and this is very critical for the development of this paper afterwards.

The admittance transfer function of the grid current, i_g, to the converter voltage, V_c, in an lossless LCL filter is defined as in (1) and its corresponding magnitude plot is depicted in Fig. 2. Being different from the figure, theoretically it is supposed to have infinite peak at the resonant frequency, which is temporarily set around 1.24 kHz. Therefore the resultant grid current can be excessive even with small amount of voltage input with the resonant frequency. This may violate the harmonics regulation and also cause system instability.

$$\frac{i_g}{V_c} = Y_{LCL} = \frac{1}{s^3 C_f L_c L_g + s(L_c + L_g)} \qquad (1)$$

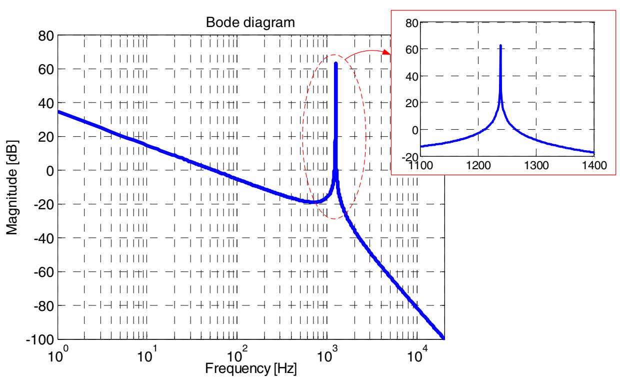

Fig. 2. Magnitude plot of i_{grid}/V_{conv} in LCL filter.

To cope with the resonance problem, active and/or passive damping methods are adopted. In conventional research, damping method is selectively chosen but active damping is more in use because it is normally recognized that active damping is sufficient to suppress the resonance. However, strictly speaking, each damping method functions differently and this paper clarifies the difference of the two damping methods to provide proper comprehension.

A. Active Damping

For the implementation of active damping, only the structure of the controllers is modified or adjusted not to excite the resonance. The most noticeable point in designing active damping methods is that PWM switching of the converter is excluded. Thus active damping methods just manipulate the voltage reference of the converter, V_c^{ref}. In this paper, typical active damping methods are divided into three groups and analyses for each group are given as following.

1) State Variables Feedback

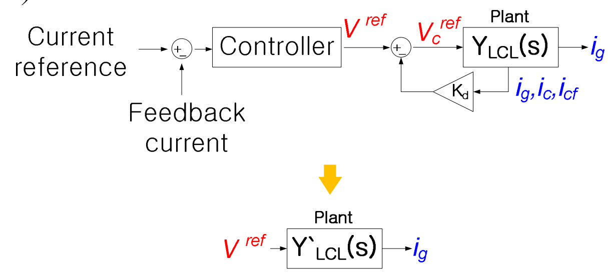

Fig. 3. Damping scheme of state variables feedback.

$$\frac{i_g}{V^{ref}} = Y`_{LCL} = \begin{cases} \dfrac{1}{s^3 C_f L_c L_g + s(L_c + L_g) + K_d}, \text{ or} \\ \dfrac{1}{s^3 C_f L_c L_g + s^2 K_d C_f L_g + s(L_c + L_g) + K_d}, \text{ or} \\ \dfrac{1}{s^3 C_f L_c L_g + s^2 K_d C_f L_g + s(L_c + L_g)} \end{cases} \qquad (2)$$

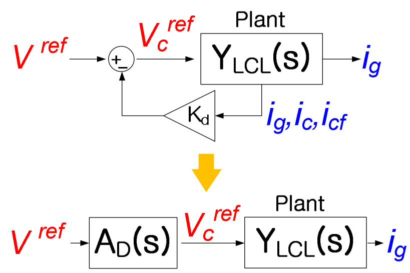

Fig. 4. Actual effect of state variables feedback.

$$A_D(s) = \frac{V_c^{ref}}{V^{ref}} = \frac{Y`_{LCL}}{Y_{LCL}} = \begin{cases} \dfrac{s^3 C_f L_c L_g + s(L_c + L_g)}{s^3 C_f L_c L_g + s(L_c + L_g) + K_d}, \text{ or} \\ \dfrac{s^3 C_f L_c L_g + s(L_c + L_g)}{s^3 C_f L_c L_g + s^2 K_d C_f L_g + s(L_c + L_g) + K_d}, \text{ or} \\ \dfrac{s^3 C_f L_c L_g + s(L_c + L_g)}{s^3 C_f L_c L_g + s^2 K_d C_f L_g + s(L_c + L_g)} \end{cases} \qquad (3)$$

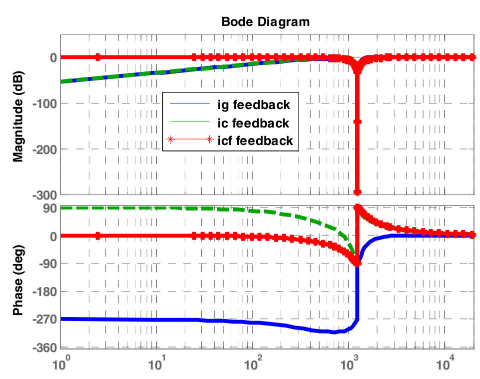

Fig. 5. Bode plot of $A_D(s)$ in state variables feedback.

By using state variables as in Fig. 3, resonance seems to be avoided because virtual damping factors are added as if the admittance transfer function were changed to (2) which represent the cases of grid current, converter current and capacitor current feedback, respectively. However, the actual filter cannot be modified and so it can be seen equivalent as inserting an active damping function at the output. From the derivation of the transfer function $A_D(s)$ given as (3), it can conclusively be said that notch filter is implemented as shown in Bode plots of Fig. 5.

2) Filter based Current Control

This method achieves active damping directly by implementing a filter, F(s), at the output as shown in Fig. 6. The filter can be a low pass filter of any order or a notch filter. If a notch filter is used, similar effect to the state variable feedback case is obtained. Anyhow, filter based current control attempts to eliminate the resonant frequency component in the voltage reference that the converter should synthesize.

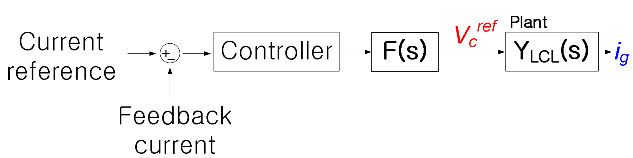

Fig. 6. Damping scheme of filter based current control.

3) Pole-Zero Cancellation : To manage the resonance expectable from the poles of the admittance transfer function, Y_{LCL}, zeroes which can cancel the poles are incorporated in the main controller as shown in Fig. 7. Therefore, the voltage reference has no resonance component and this completes the active damping.

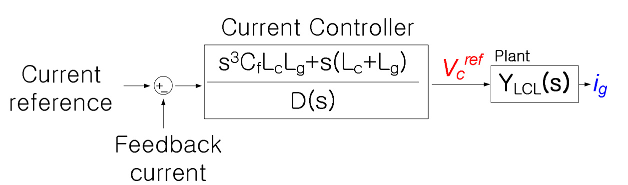

Fig. 7. Damping scheme of pole-zero cancellation.

In common of the three methods above, the active damping is to eliminate the resonant frequency component in the voltage reference.

B. Passive Damping

Even if resonant component can be eliminated in the voltage reference from the active damping, the resonance can still be excited by the PWM switching. According to [6], PWM switching patterns theoretically generate switching harmonics (V_{har}) around multiples of switching frequency and fundamental frequency as in (4). In the equation, the magnitude of each coefficient depends on PWM strategy, given DC source voltage, switching frequency, modulation index, dead-time, frequency of the reference and etc. However, when there is no other harmonics except for the fundamental grid frequency in the voltage reference, the frequency distribution of the given system can be identified. Fig. 8 shows the spectrum for the case of modulation index of 0.9 and dead time of 3us in this system. In the low frequency range of Fig. 8(a), base band of fundamental components and sideband of switching harmonics are mixed whereas sideband of switching harmonics dominates in mid and high frequency range of Fig. 8(b) and Fig. 8(c).

The most important thing is that the resonant frequency is usually set below half of the switching frequency to attenuate the switching harmonics sufficiently. Then, as can be expected in Fig. 8(a), there is high possibility for the resonance to be excited in a lossless LCL filter if any small amount of harmonics exist around the resonance frequency. This is more noticeable in high power systems in which switching frequency is limited.

Therefore the resonant frequency must be designed to be located apart from the PWM frequency distribution with great accuracy or the peak point of the admittance in the LCL filter must be brought down by passive damping. However, the values of the reactance components vary with time or stray inductance/capacitance in the system or large tolerance in the components manufacturing may exist. This means that the initially designed resonant frequency is liable to move to the harmonics range. Thus passive damping must be adopted to guarantee the stable and long-lasting operation of the system.

$$V_{har} = \sum_{n=1}^{\infty} A_{1n} \sin(n\omega_1 t + \delta_1)$$

$$+ \sum_{m=1}^{\infty} \sum_{k=-\infty}^{\infty} B_{mk} \sin\big(m(\omega_c t + \delta_c) + k(\omega_1 t + \delta_1)\big) \quad (4)$$

where ω_1/ω_c, δ_1/δ_c and A_{1n}/B_{mk} stand for fundamental/switching frequency, phase of fundamental/switching components and magnitude of fundamental/switching components, respectively.

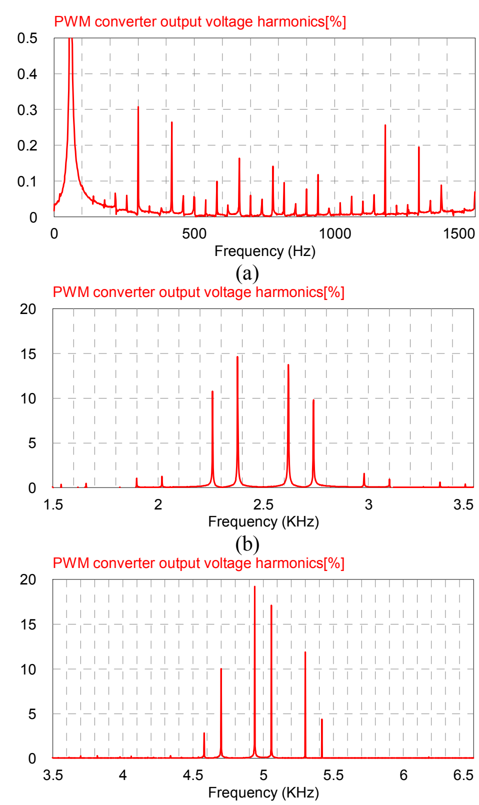

Fig. 8. Frequency spectrum of PWM converter output voltage.

For the implementation of passive damping, resistors are intentionally inserted in the filter and this blunts the resonance. However, the resistors produce undesirable losses and the minimization of the losses is the key issue in the passive damping application. In this paper, three different passive damping strategies are investigated and the detail design process is covered in IV.B.

IV. Proposed LCL Filter Design with Passive Damping

The filter design process consists of two stages: reactance components design and passive components design. For the reactance components design, ideal lossless system is assumed as mentioned previously and on the basis of the designed reactance components, passive components are intentionally added. To select the optimal combination for the filter components, the intrinsic features of the filter is investigated in the following.

A. Reactive Components Design

The most noticeable characteristic in the LCL filter is that the same total inductance and resonant frequency result in exactly the same admittance transfer function as can be deduced by (5) regardless of different LCL component values.

$$\frac{i_g}{V_c} = \frac{1}{s^3 C_f L_c L_g + s(L_c+L_g)} = \frac{\omega_{res}^2}{L_T s(s^2+\omega_{res}^2)} \quad (5)$$

where L_T is the total inductance (=L_c+L_g) and ω_{res} is the resonant frequency[rad/s] of the filter.

This means that there exist numerous combinations as long as two conditions are satisfied while three variables need to be designed. Hence additional conditions should be introduced so that the minimum converter side current ripple, or the minimum filter size, or the minimum converter capacity is guaranteed. In this paper, minimum filter energy is chosen as the third condition because the total energy of the filter can be regarded as the size of the filter.

To begin with, the resonant frequency can be easily designed. From III.B, it is considered that the voltage synthesized by PWM switching contains sideband harmonics as well as the fundamental harmonics. Specifically, in the case of SVPWM, the value of m+k is found to be odd [6] and therefore it is obvious that the resonant frequency must be located apart from the harmonics frequencies, for example 1x2500-22x60=1180 Hz or 2x2500-65x60 = 1100 Hz. In this way, the resonant frequency can be set such as 800 Hz, 920 Hz, 1040 Hz and so on.

Once the resonant frequency is fixed, the total inductance is designed. The compulsory condition for the LCL filter to meet is the grid current harmonics regulation. The harmonics attenuation performance is influenced by both the resonant frequency and total inductance as shown in Fig. 9. If the higher resonant frequency is selected, the total inductance has to be increased otherwise the grid regulation is not met. Unfortunately, the relationship between the resonant frequency and the total inductance is nonlinear because the required voltage to produce the same power becomes different, leading to different magnitude of switching harmonics. This is the main reason that the LCL filter design relies on iterative procedure.

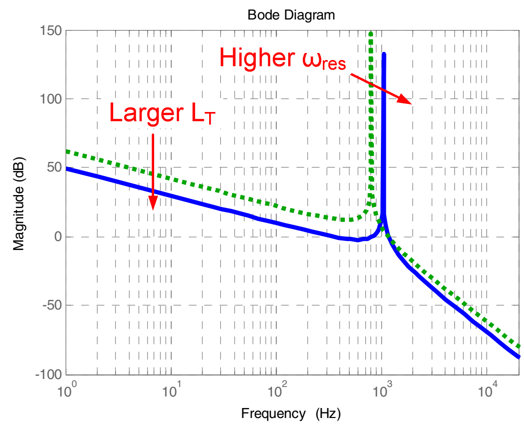

Fig. 9. Magnitude plot with different resonant frequency and inductance.

Therefore required total inductance to satisfy the harmonics regulation can be investigated in iterative way for several resonant frequencies. In Fig. 10 and Fig. 11, the frequency spectrums of the grid currents are depicted for the cases of two resonant frequencies when pure sinusoidal voltage reference is applied to generate the rated power. The designed total inductances are 0.28 p.u. and 0.34 p.u. in each case. The peaks at each resonant frequency support the necessity of passive damping claimed in III.B and the designed value is described in IV.B.

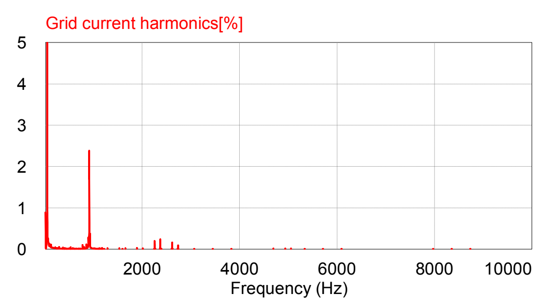

Fig. 10. Current harmonic spectrum with resonance at 920 Hz.

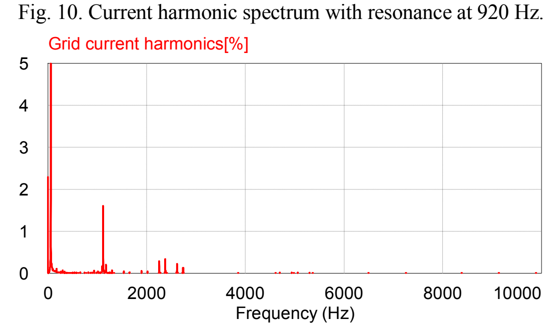

Fig. 11. Current harmonic spectrum with resonance at 1120 Hz.

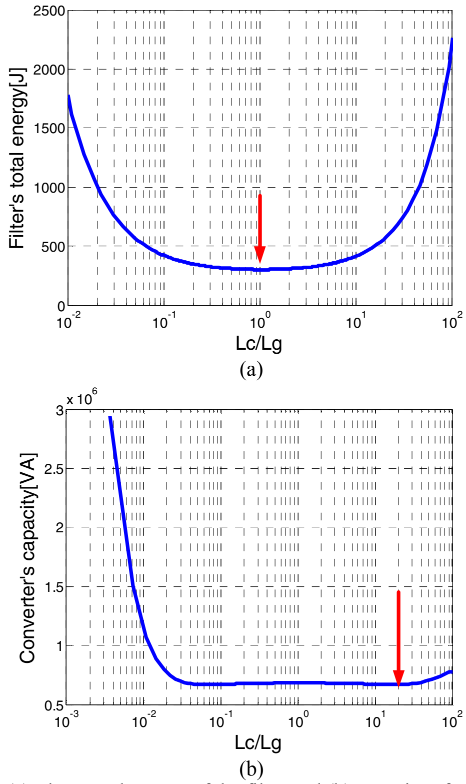

Fig. 12. (a) The stored energy of the filter and (b) capacity of converter per phase with resonance at 920 Hz.

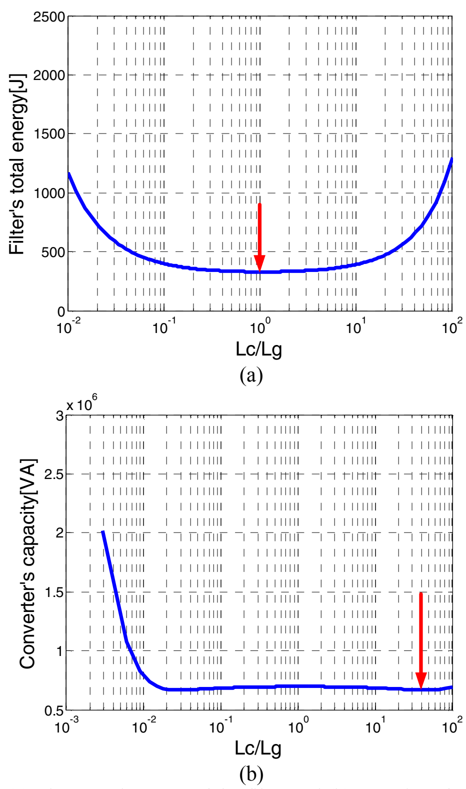

Fig. 13. (a) The stored energy of the filter and (b) capacity of converter per phase with resonance at 1120 Hz.

Finally, to assign specific values for each component, the total stored energy and the required converter capacity are calculated as in Fig. 12 and Fig. 13 according to the ratio between L_c and L_g. It is indicated that Lc ad Lg should be identical to minimize the filter size but Lc should be several tens times Lg to minimize the converter size. Because there shows small difference in converter capacity, L_c and L_g are chosen based on the filter size aspect. Among the two cases, the combination for the resonant frequency of 920 Hz yields smaller total energy and consequently is selected as the designed values.

B. Passive Components Design

The resistive elements for the passive damping can be inserted in three ways as shown in Fig. 14. Each type achieves different harmonic attenuation for high frequency range and it affects the final filter design.

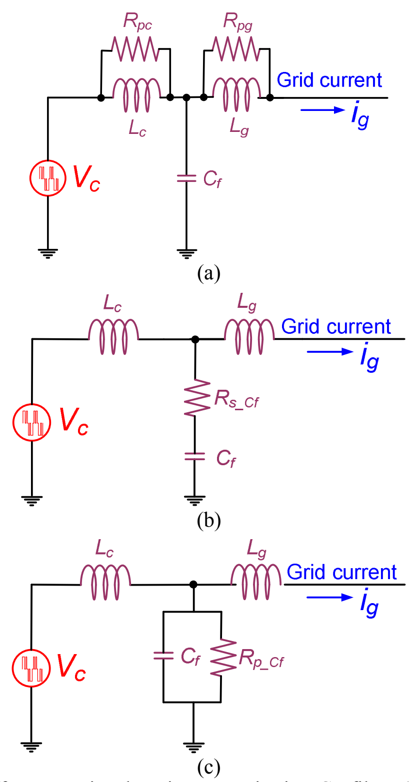

Fig. 14. Different passive damping strategies in LCL filter: (a) type 1, (b) type 2 and (c) type 3.

1) Type 1

The admittance transfer function for type 1 is given as (6). For low frequency range, the filter is equivalently the same as LCL filter because the impedance of the parallel resistors are much larger than the filter inductances. On the other hand, the parallel resistors dominate in high frequency range and accordingly LCL filter is changed to RCR filter. Due to the transition, the filter shows only -20dB/decade attenuation in high frequency range and this can invalidate the performance of the reactance components. Therefore the transition frequency should be designed with care and the final designed values for the resistors are 11 [Ohm] leading to the loss of 20[kW](0.02 p.u.). The resultant current harmonic spectrum and its Bode plot are displayed in Fig. 15 and Fig. 16.

$$\frac{i_g}{V_c} = \frac{(sL_c+R_{pc})(sL_c+R_{pg})}{s[s^2C_fL_cL_gR_{pc}R_{pg}+sL_cL_g(R_{pc}+R_{pg})+R_{pc}R_{pg}(L_c+L_g)]} \quad (6)$$

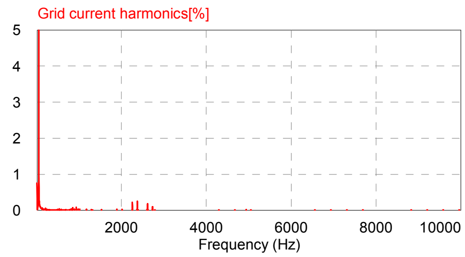

Fig. 15. Harmonic spectrum of grid current with resonance at 920 Hz in type1.

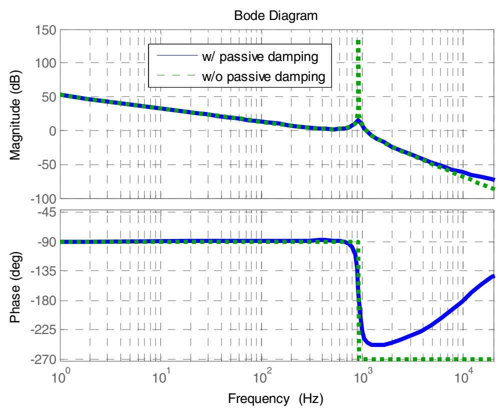

Fig. 16. Bode plot of admittance in type 1 with resonance at 920 Hz.

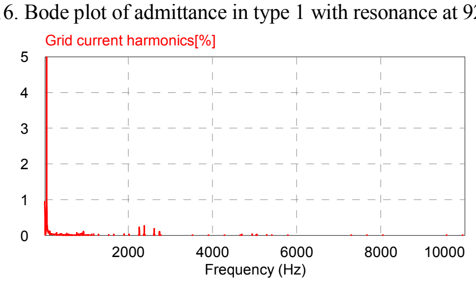

Fig. 17. Harmonic spectrum of grid current with resonance at 920 Hz in type2.

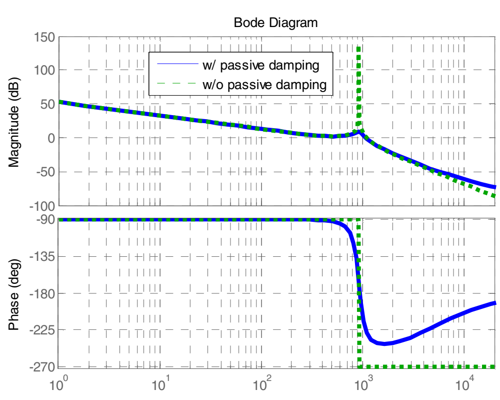

Fig. 18. Bode plot of admittance in type 2 with resonance at 920 Hz.

2) Type 2

In type 2, a resistor is inserted in series to the filter capacitor. The admittance transfer function for type 2 is given as (7). For low frequency range, the filter is equivalently the same as LCL filter because the impedance of the series resistor is much smaller than the filter capacitor. In high frequency range, as the resistor dominate over the filter capacitor but smaller than the grid inductance, the harmonic current flows through the added resistor. The final designed values for the resistors are 0.1 [Ohm] leading to the loss of 2[kW](0.002 p.u.). The resultant current harmonic spectrum and its Bode plot are displayed in Fig. 17 and Fig. 18.

$$\frac{i_g}{V_c} = \frac{sC_fR_{s\_Cf}+1}{s[s^2C_fL_cL_g+sC_fR_{s\_Cf}(L_c+L_g)+s(L_c+L_g)]} \quad (7)$$

3) Type 3

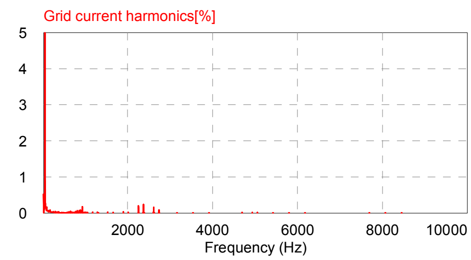

Fig. 19. Harmonic spectrum of grid current with resonance at 920 Hz in type3.

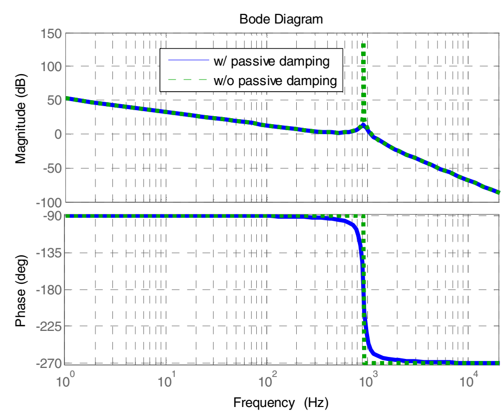

Fig. 20. Bode plot of admittance in type 3 with resonance at 920 Hz.

In type 3, a resistor is inserted in parallel to the filter capacitor. The admittance transfer function for type 3 is given as (8). On the contrary to the former two types, type 3 shows LRL filter in low frequency range while being LCL filter in high frequency range. Because of this, type 3 can maintain -60dB/decade attenuation in the switching frequency range and guarantee more harmonic suppression than the other two types. The final designed values for the resistors are 5[Ohm] but the loss must be noted. The loss occurred from the added passive resistors are found to be around 97[kW](0.097 p.u.) and this is a lot more than acceptable level. The reason for the large loss is that low frequency currents flow through the resistors. Therefore, type 3 is not recommended for the passive damping. To reduce the loss in type 3, another inductor can be connected in parallel to the passive resistor. However, in this case, the size of the additional inductor is significant and thus the filter is not optimized in terms of size.

The current harmonic spectrum and Bode plot of type 3 are displayed in Fig. 19 and Fig. 20.

$$\frac{i_g}{V_c} = \frac{R_{p\_Cf}}{s[s^2 C_f L_c L_g R_{p\_Cf} + s L_c L_g + (L_c + L_g)]} \quad (8)$$

Table II shows the design results of the three passive damping methods. In terms of the loss, type 2 exhibits the most superior performance. To improve the performance of each type, capacitors or inductors can be additionally inserted. However, it creates another resonant point and increases the size, weight or costs. Therefore it should be selectively applied by considering the tradeoffs.

TABLE II. FILTER DESIGN SUMMARY

	Damping resistor	Losses
Type 1	11[Ohm]	20kW(0.02 p.u.)
Type 2	0.1[Ohm]	2kW(0.002 p.u.)
Type 3	5[Ohm]	97kW(0.097 p.u.)

V. EXPERIMENTAL RESULTS

The effectiveness of the analyses is supported by experimental investigation. LCL filter is designed for laboratory scale of 10kW. The switching and sampling frequency of the system is set 2.5 kHz and 5 kHz, respectively to reflect the analysis in previous sectors. Passive damping resistors are inserted as in type 2 and other experimental specification is given in Table III.

TABLE III. SPECIFICATION FOR EXPERIMENT

Switching frequency (f_{sw})	2.5[kHz]
Sampling frequency (f_{samp})	5[kHz]
DC link voltage (V_{dc})	360[V]
Grid line to line voltage (V_{grid})	220[Vrms]
Grid frequency (f_{grid})	60[Hz]
Rated power (P_{rated})	10[kW]
Rated current (I_{rated})	26.24[Arms]
Filter inductor on converter side (L_c)	1.5[mH] (0.117 p.u.)
Filter inductor on grid side (L_g)	1.5[mH] (0.117 p.u.)
Filter capacitor (C_f)	22[uF] (0.04 p.u.)
Resonant frequency (f_{res})	1.24[kHz]
Passive damping resistor (R_{s_Cf})	1[Ohm]

For the experimental setup, the dc link voltage is directly supplied from a power supply (MX 30 – AMETEK) and it provides the information of the input power for the calculation of the loss. For the switching method, SVPWM is used.

To investigate the internal resistance of the system, losses of the inverter and each reactive component are measured. There exists 0.02 p.u. loss in the inverter and each filter inductor is found to produce 0.01 p.u. loss.

The grid voltages are measured and analyzed in frequency domain to see if it is likely to excite the resonance of the filter. The waveform is shown in Fig. 21 and the FFT result is in Fig. 22. Even though there are low order harmonics in the grid voltage, high order harmonics seem to be too small to excite resonance.

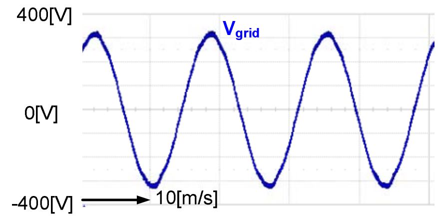

Fig. 21. Waveform of grid voltage.

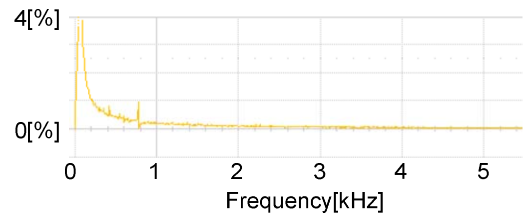

Fig. 22. Frequency spectrum of grid voltage.

For the experiment, currents on the converter side are controlled in the synchronous reference frame and PI compensators are used. The gains of the compensators are set low as 10 Hz to exclude high order harmonics in the voltage reference as if active damping is implemented. The grid voltages are measured and used for feed-forward terms in the current controller and the synchronization.

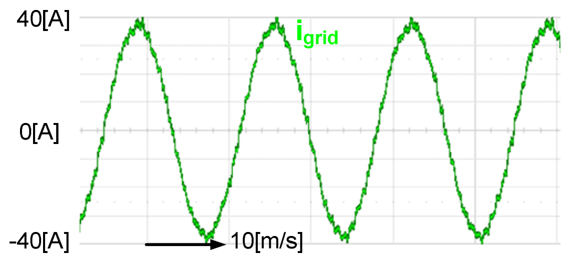

Fig. 23. Waveform of grid current without passive damping.

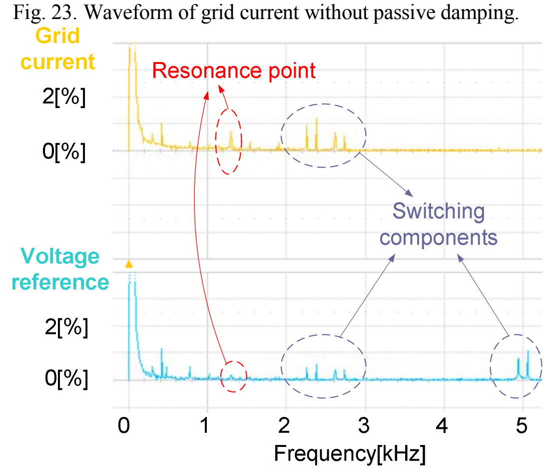

Fig. 24. Frequency spectrum of grid current and voltage reference.

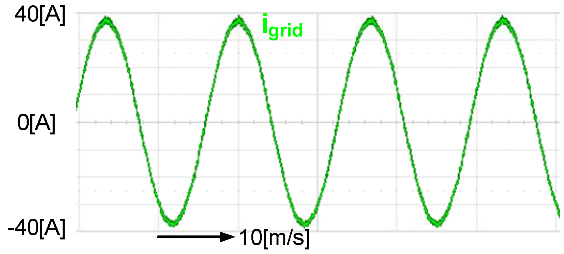

Fig. 25. Waveform of grid current with passive damping.

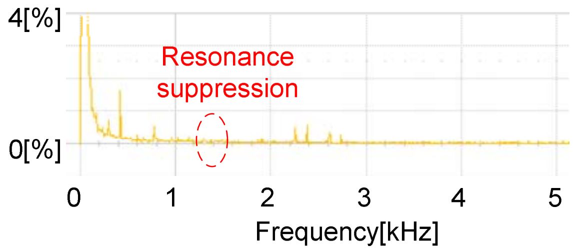

Fig. 26. Frequency spectrum of grid current.

To validate the necessity of passive damping in LCL filter, the grid current waveform and its corresponding voltage reference are depicted in Fig. 23 and Fig. 24, respectively when no passive damping resistor is inserted. In Fig. 24, there is very small resonant frequency component in the voltage reference but the grid current contains the resonant frequency component. This means that resonance can be excited by just PWM switching of the converter. Even though the amount of the resonant component is within the regulation of IEEE 519-1992, it would be seriously large if there was no internal resistance in the system.

Passive damping resistors of 1[Ohm] are inserted in series to the filter capacitor to suppress the resonance. The same operation is conducted as in Fig. 23 and Fig. 24. From the waveform of the grid current and its frequency spectrum in Fig. 25 and Fig. 26, it is seen that resonant harmonics are effectively suppressed and the losses occurred by the passive damping resistors are found to be 50[W](0.005 p.u.) by power measurement.

The experimental results reveal that PWM switching is liable to excite the resonance of LCL filter but proper passive damping strategy alleviates the problem. The loss occurred by the added resistors is verified to be acceptable

VI. CONCLUSION

To handle the inherent problem of resonance in LCL filter, proper damping methods need to be adopted. Typically, active damping and passive damping methods are selectively used but this paper demonstrates different function of each damping method. Active damping methods perform filtering for the voltage reference not to excite the resonance whereas passive damping methods suppress the resonance physically.

This paper proposed an LCL filter design method including passive damping components. By designing the total inductance and resonant frequency, a lot of filter combinations are realizable to satisfy the grid current harmonics regulation. To select optimal reactance components, third condition is introduced such as filter's total energy, ripple current on the converter side and converter capacity.

Moreover, three different types of passive damping schemes are investigated. Because the loss is the most critical factor in passive damping realization, series connection to the filter capacitor is found to be the best option. The design process is verified by simulation of 1MW.

Experiments are conducted to support the work. Laboratory scale system of 10kW is investigated and the results enhance the effectiveness. Resonance occurred by just PWM switching and passive damping resistors are designed to suppress it. The designed passive resistors are proven to produce acceptable loss.

REFERENCES

[1] Liserre, M., Blaabjerg, F. and Hansen, S., "Design and control of an LCL-filter-based three-phase active rectifier," IEEE. Trans. Industrial Applications, vol. 41, pp. 1281-1291, 2005.

[2] Jalili, K. and Bernet, S., "Design of LCL Filters of Active-Front-End Two-Level Voltage-Source Converters," IEEE. Trans. Industrial Electronics, vol. 56, pp. 1674–1689, 2009.

[3] Rockhill, A.A., Liserre, M., Teodorescu, R. and Rodriguez, P., "Grid-Filter Design for a Multimegawatt Medium-Voltage Voltage-Source Inverter," IEEE. Trans. Industrial Electronics, vol. 58, pp. 1205-1217, 2011.

[4] Dannehl, J., Fuchs, F.W., Hansen, S. and Thogersen, P.B., "Investigation of Active Damping Approaches for PI-Based Current Control of Grid-Connected Pulse Width Modulation Converters With LCL Filters," IEEE. Trans. Industrial Applications, vol. 46, pp. 1509-1517, 2010.

[5] Jinwei He and Yun Wei Li, "Generalized Closed-Loop Control Schemes with Embedded Virtual Impedances for Voltage Source Converters with LC or LCL Filters," IEEE. Trans. Power Electronics, vol. 27, pp. 1850-1861, 2012.

[6] D. Grahame Holmes and Thomas A. Lipo, "Pulse Width Modulation for Power Converters : Principles and Practice," Wiley inter-science, IEEE press, 2003.