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Design of LCL-Filter Based Three-Level Active Power Filters

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Abstract

This paper proposes an improved design of LCL-Filters for Three-Level Shunt Active power filters (APF). Available design principles are presented to achieve high compensation bandwidth and low switching frequency current. Then, affecitons of different parameters are taken into consideration of constraints on LCL-Filter design with detail analysis of ripple current. A simple and practical design procedure of LCL-Filter for Three-Level APF is subsequently proposed. The first step is to choose the resonant frequency of LCL-Filter according to the highest order harmonic needed to be compensated. Then it is aim to optimize the parameters of the LCL-Filter based on the design principles and constraints. The simulation results verify the effectiveness of the proposed method.

***Keywords**: active power filters; LCL-Filter; Three-Level; passive damping; power management.*

1. Introduction

As electronic non-linear loads are widely applied in industry, the reactive and harmonic problem turns more severe. Active power filter is an effective way to eliminate the harmonic current and enhance the power quality [1]-[3].

Compared with traditonal two-level APF, Three-Level APF can achieve lower harmonic distortion and less power loss with lower switching frequency under a higher voltage. Three-level APF is more suitable for medium and high voltage application [3]-[5].

The LCL-Filters have advantages in lower cost and higher dynamic response, since smaller inductors can be used compared to L-filters. However, LCL-filter is a third-order system, which may cause oscillation. A damping method is adopted to ensure the stability of the system. Moreover, both high compensation bandwidth and low switching ripple current are desired for APF. Different from the PWM rectifier producing a sinusoidal current, APF is design to cancel the harmonic current of the non-linear loads, which has a wide range of bandwidth(from 100Hz to 2500Hz). This makes an appropiate LCL-Filter design more complicated. Recently, more attention is paid to design and control of LCL-Filter. However, most researches are focused on two-level APF.

O. Vodyakho and C. C. Mi presented a direct current control scheme of an active power filter with LCL-ripple filter based a Three-Level neutral-point-clamped (NPC) voltage-source inverter with high steady-state accuracy and fast response. However, the design method of the LCL-Filter is not proposed [3]. A modern design of LCL-filter based on voltage source inverter (VSI) is proposed in Ref [6], both design and control of PWM rectifier with LCL-Filter are analyzed. But it is a challenge to choose an initial value of the inductor. In Ref [7], comparison and analysis of the parameters of LCL-Filter is given based Shunt Active Power Filter. A design procedure is presented in detail, while it is based on hysteresis control which does not apply to other current tracking method. In Ref [8], a design method of grid-connected rectifier based on three-level NPC was proposed, which can reduce the switching frequency ripple current effectively, but it is not applicable to APF.

This paper focuses on Three-Level APF, the ripple current of three-level APF is analyzed in detail. Then the effect of different parameters to the system is compared and discussed. After that, it proposes the design and control method of LCL-filters based three-level APF. The first step is to choose the resonant frequency of LCL-filter according to the highest order harmonic needed to be compensated. Then it is aim to optimize the parameters of the

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LCL-Filters based on the design principles and constraints. The simulation results verify the effectiveness and practicality of the proposed method.

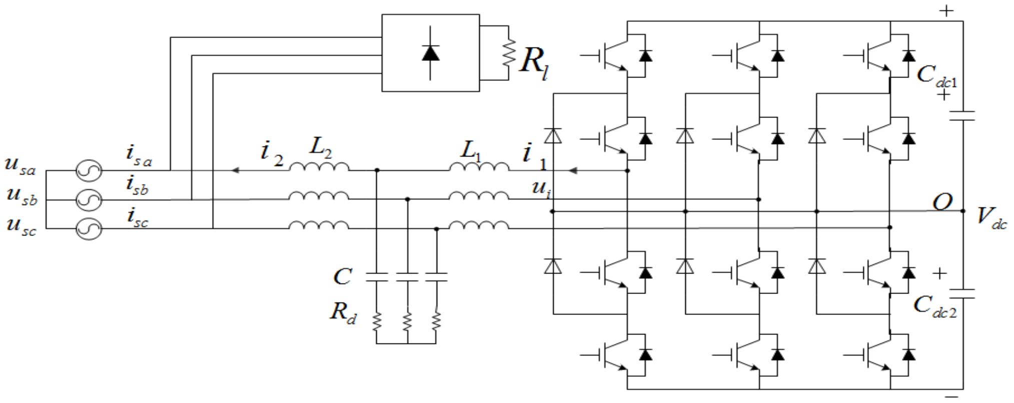


Figure 1. Three-level APF circuit diagram

2. Analysis of LCL-Filter

An APF is considered as a controlled current source. Figure 1 shows the circuit structure of an APF based on three-level NPC converter with an LCL-filter.

Firstly, to design an appropriate LCL-filter, the principles should be introduced.

2.1. Maximize Attenuation of Switching Frequency Current

As is shown in Figure 1, The transfer function G_{1i}(s), related to the converter output voltage u_i and converter current i_1, G_{2i}(s) ,the transfer from u_i to grid current; H_{21}(s), the transfer from i_1 to i_2, can be described as:

$$\begin{cases} G_{1i}(s)=\dfrac{i_1(s)}{u_i(s)}=\dfrac{(1/L_1)(s^2+1/L_2C)}{s(s^2+(L_1+L_2)/L_1L_2C)} \\ G_{2i}(s)=\dfrac{i_2(s)}{u_i(s)}=\dfrac{1/L_1L_2C}{s(s^2+(L_1+L_2)/L_1L_2C)} \\ H_{21}(s)=\dfrac{i_2(s)}{i_1(s)}=\dfrac{1/L_2C}{s^2+1/L_2C} \end{cases} \tag{1}$$

The transfer function of converter side inductor from voltage to current is: $G_1(s)=1/L_1s$.

As is shown in Figure 2, G_{1i}(s) and G_1(s) have the same amplitude and frequency characteristics after the resonant frequency. For high frequency switching ripple current, $G_{1i}(s)\approx 1/L_1s$, it is extremely important to choose an appropriate converter side inductorL_1. From the view of circuit, for high frequency current, filter capacitor C is equivalent to short-circuited. The switching frequency ripple current is determined by L_1. Therefore, the inhibition of ripple current is the first issue to be considered when designing the converter side inductor L_1.

2.2. Minimize the Cost of the Inductor

The Filter inductor results in loss of converter output voltage and lower gain of low frequency current. Since the output voltage of converter is limited, the total inductance is a deterministic constraint in APF. Besides, APF can track the reference current faster with a smaller inductance, while it has a better performance in attention switching ripple current with a bigger inductor. Considering the cost, the inductors should be decreased as small as possible.

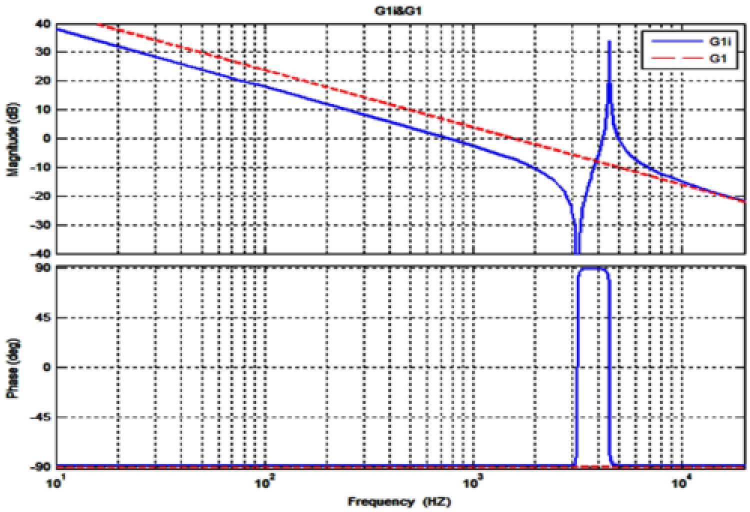


Figure 2. Bode Plot of G_{1i}(s) and G_1(s)

2.3. Reduction of Power Loss

A straightforward passive damping method is adopted by inserting a resistor R_d in series with the capacitor in LCL-filters. A big R_d would lead to a pure real pole which might attenuate the current of all frequency and generate more loss. On the other hand, the resistor should be big enough to ensure the stability of the system. So the resistor should be chosen proportional to capacity at resonance frequency.

2.4. Resonance of LCL-filter

Different from the PWM rectifier, with a wide bandwidth, the design of LCL-filters based APF needs to consider gain of low frequency current and attenuation of high frequency current. The resonant frequency generally depends on the highest order of the harmonic current.

3. Constraints on Design LCL-Filter

Having the principles of design, some limits of the parameters should also be taken into consideration.

3.1. Total Inductor L_T

The total inductor should be less than 0.1 per unit (pu) to limit the ac voltage drop during operation[6]. The model of phase a for three-level APF with L-Filter can be simplified as:

$$L\frac{di_a}{dt} = e_a - (\frac{V_{dc}}{2}S_a - \frac{V_{dc}}{6}\sum_{i=a,b,c} S_i), (S_i = 1, 0 or -1) \quad (2)$$

The inductor should decrease to ensure the rapid current tracking response. In order to meet the fast tracking current requirement, it must obey:

$$L \le V_{dc} / 3I_m\omega = V_{dc} / 6\pi f I_m \quad (3)$$

Where I_m is the rated current of APF.

On the other hand, As Figure 3 shows, ripple current turns most severe at the peak of sine wave current, considering the current transient process at the peak ($\omega t = \pi / 2$) of a cycle.

In steady state,

$$L\frac{di_a}{dt}=\begin{cases}E_m+V_{dc}(S_b+S_c)/6\approx L\Delta i/T_{off},\left(0\le t\le T_{off}\right)\\E_m+V_{dc}(-2+S_b+S_c)/6\approx L\Delta i/T_{on},\left(T_{off}\le t\le T_{on}\right)\end{cases} \tag{4}$$

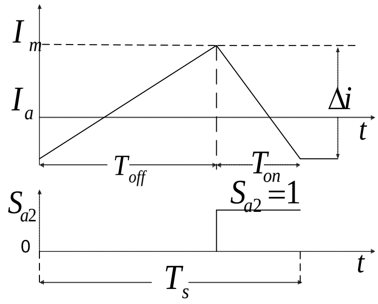


Figure 3. a cycle of the current transient process at the peak

Equation (4) can be simplified as:

$$L\frac{\Delta i}{T_s}=\left(\left[(E_m+\frac{V_{dc}(S_b+S_c)}{6})-\frac{V_{dc}}{6}\right]^2-\frac{V_{dc}^2}{36}\right)/(-\frac{V_{dc}}{3}) \tag{5}$$

So Ld_i/d_t get max value of $V_{dc}/12$, which means the ripple current maximize at the same time. Suppose 20% of rated current as max ripple current, the lower limit of L can be obtained:

$$L\ge 5V_{dc}T_s/12I_{\mathrm{m}} \tag{6}$$

Without a damping resister R_d,

$$G_{2i}(s)=\frac{1}{(L_1+L_2)s}*\frac{1}{1+(s/\omega_{res})^2}\le\frac{1}{3(L_1+L_2)s} \tag{7}$$

So the total inductance of LCL-filter should be 1/3 of single L-Filter：

$$L_T=L_1+L_2\ge 5V_{dc}T_s/36I_{\mathrm{m}} \tag{8}$$

3.2. Capacitance C and Damping Resister R_d

In general, reactive power should be limited to 5% of rated power to ensure the high power factor of the system：

$$C\le 5\%P_n/6\pi f_nE_n^{\ 2} \tag{9}$$

The damping method should be sufficient to avoid resonance. While choosing a big Rd would lead to a pure real pole which might attenuate the current of all frequency and produce more losses. So the resistor should be chosen proportional to capacitor at resonance frequency.

3.3. Inductor Ratio

Transfer G_{1i}(s) includes two zeros and three poles:

$$\begin{cases}z=\pm j\sqrt{1/L_2C},\ p=\pm\sqrt{(L_1+L_2)/L_2C}\\L_2=\lambda L_1,\ p=\lambda' z=\sqrt{1+\lambda}z\end{cases} \tag{10}$$

The poles would depart away the zeros when λ turns bigger, which might result in overshoot amplitude and weaker system stability. The ratio of L_1 to L_2 would affect the compensation result with a determined total inductor L_T. The transfer $G_{2i}(s)$ can be described as:

$$G_{2i}(s) = \frac{i_2(s)}{u_i(s)} = \frac{(1+\lambda)^2 / \lambda L_T^2}{s[s^2 + (1+\lambda)^2 / \lambda]} \quad (11)$$

When grid side inductor L_1 equals to converter side inductor L_2, $G_{2i}(s)$ produce the smallest value, the system has the best performance. Under the condition of the same total inductor L_T and C, by changing the ratio of the inductor, different amplitude and frequency plot can be obtained. As is shown in Figure 4, the system has best performance grid side inductor equal to grid side inductor which is consistent with the theory analysis.

Table 1. Parameters of different ratio λ

λ	$L_1(uH)$	$L_2(uH)$	$C(uF)$
0.33	50	150	25
1	100	150	25
3	150	50	25

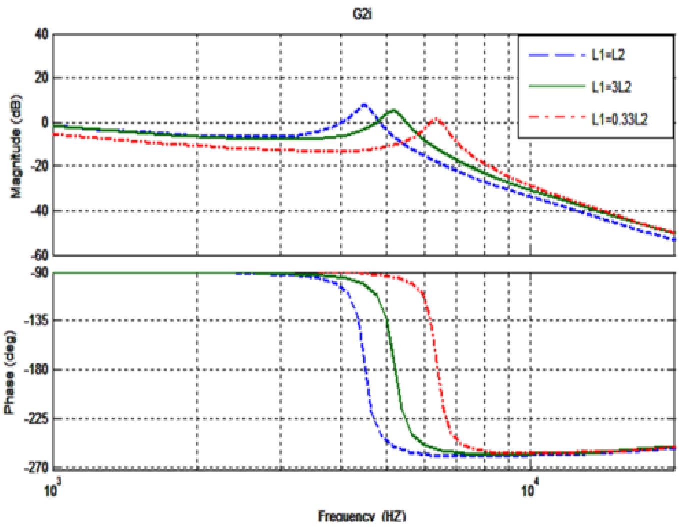


Figure 4. Bode Plot of different inductor ratio

3.4. The Resonant Frequency

Active power filters compensate $6n\pm1$ harmonic current in general. Therefore, the harmonic current through LCL-filters include low frequency harmonic current and high frequency switching ripple current. The low frequency harmonic current can be declined if the LCL-Filter has a small resonance frequency f_{res}, which would affect the compensation result. On the other hand, the resonant frequency should be high enough to avoid grid current distortion. Different from normal PWM rectifier, the resonant frequency should be a range between the highest order of the harmonic component and half of the switching frequency to ensure the gain of low frequency current and attenuation of high frequency[9].

4. Proposed Design Method

Based on the principles and constraints of design, the LCL-Filter can be designed with the followed flowchart in Figure 5.

Step 1: define the highest order harmonic needed to be compensated as *k*. According to literature, the cut-off frequency should satisfy: $\omega_c > k\omega_n, \omega_{res} > k\omega_n / 0.3$, ($\omega_n$ is the rated frequency). As it is illustrated in section 3.4, to suppress the switching ripple current and prevent the amplification of low frequency current, switching frequency should be 2 times bigger than resonance frequency f_{res}. With a higher switching frequency, it would generate more loss.

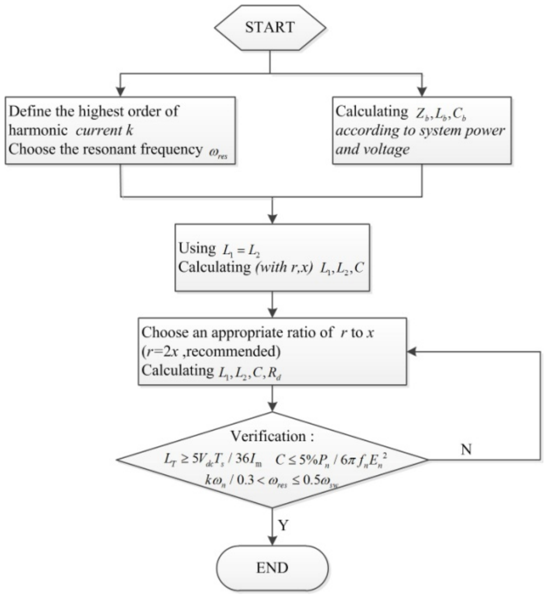


Figure 5. Flowchart of the proposed design algorithm

Therefore, it is recommended: $k\omega_n / 0.3 < \omega_{res} \le 0.5\omega_{sw}$ [9]. Synthesis of harmonic compensation and resonance factor, it can be set as: $\omega_{res} = k\omega_n / 0.25$.

Step 2: after setting ω_{res}, other parameters of LCL-filters can subsequently be determined:

$$Z_b = E_n / P_n, C_b = 1/\omega_n Z_b, L_b = Z_b / \omega_n \quad (12)$$

Where Z_b is the base impedance, E_n is the rated voltage, P_n is the rated power.

Step 3: as it is analyzed in the section 3.3, the converter side inductor L_1 should be set to equal to grid side inductance L_2 to minimize the resonance frequency such to maximize the attenuation of the switching ripple current.

$$L_1 = L_2 = rL_b = rZ_b / \omega_n, C = xC_b = x / \omega_n Z_b \quad (13)$$

Where *r* and *x* is pu of the inductor and capacitance. Combining equations above,

$$rx = 2(\omega_n / \omega_{res})^2 = 2(1/4k)^2 \quad (14)$$

Step 4: apparently, the equations have infinite solutions. To simplify the process, it is recommended: $r = 2x$. And equation (13) can be described as:

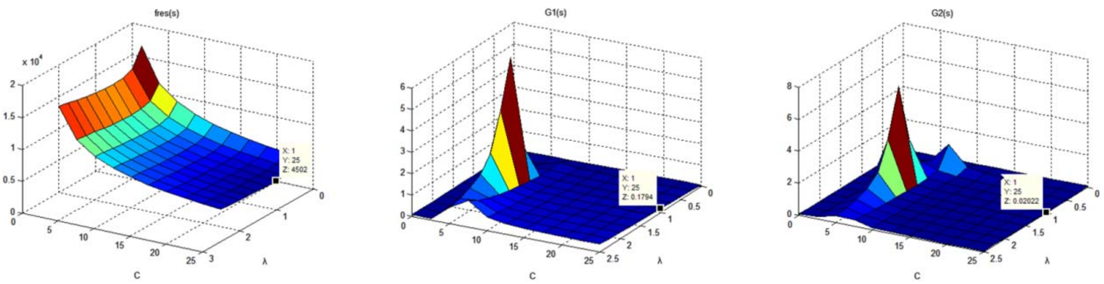
$$L_1 = L_2 = L_b / 4k, C = C_b / 2k, R_d = 3/2\pi f_{res} C \quad (15)$$

Step 5: verification of resonant frequency and constraints. If the parameters could not fulfill the constraints in section 3, go back to step 4, change the ratio of *r* to *x* until the condition verification is satisfied.

The step-by-step design procedure has been applied to a system with a nominal power of 50*kW*, rated voltage of 380*V*, DC bus voltage of 800V. The loads compose of 5^{th} to 25^{th} harmonic current. The procedure of design is as follows:

Define the highest order harmonic *k* as 25^{th}, which is 1250*Hz.* According to the analysis in section 2, the resonant frequency should be bigger than 4167 *Hz*. Therefore, *5000 Hz* is chosen as the resonant frequency.

The base impedance Z_b is 2.888, C_b is 0.0011, L_b is 0.0092. By using the recommended ratio of r to x, L_1, L_2 and *C* is given by:L_1=L_2=0.000092,*C*=0.000023. Considering the practical application,choose L_1=L_2=0.0001,*C*=0.000025.Verification of resonant frequency and constraints: ω_{res} satisfies the constraint $k\omega_n / 0.3 < \omega_{res} \le 0.5\omega_{sw}$. The inductors and the filter capacitor fulfill the constraints (8) and (9). As is shown in Figure 6, magnitude of the transfer $G_1(s)$ is only 0.1794 at 10kHz and $G_2(s)$ is only 0.02 which means the switching frequency current is reduced efficiently.



(a) (b) (c)

Figure 6. (a) resonance frequency versus inductor ratio λ and capacity *C*; (b) magnitude of the transfer $G_1(s)$; (c) magnitude of the transfer $G_2(s)$

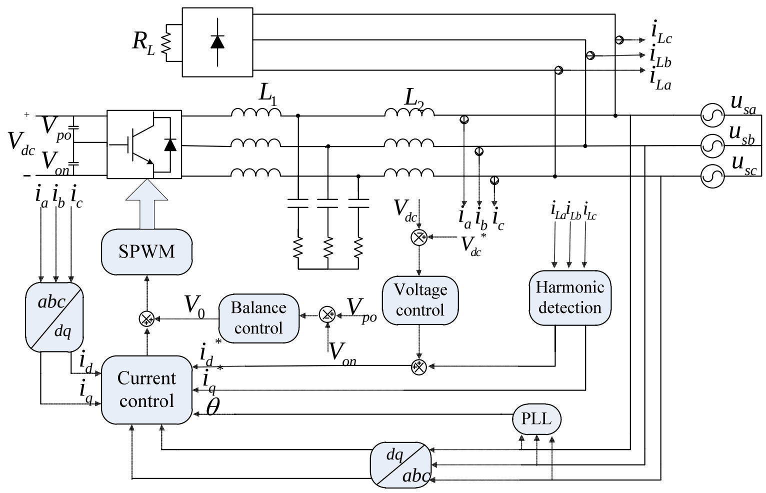


Figure 7. The diagram of control system

5. Simulation Results and Discussion

To verify the performance of the proposed design for LCL-Filter of APF, the control platform of three-level APF is constructed, which is shown as Figure 7. The current track algorithm is implemented in synchronous dq frame by using PI and multi-paralleled Proportional resonant control (PR) controllers [9-10].

Simulation is performed to evaluate and compare APF with simple L-Filters and LCL-Filters. Figure 8 and Figure 9 show the APF operation with *RL* load, the total harmonic distortion (THD) of the load current is up to 25.02%, meanwhile the THD of grid current after compensation is reduced to 1.68% with a ripple filter which is high to 3.98% without a ripple filter. Figure 10 and Figure 11 show the performance of the system with RC loads. The THD of grid current has been reduced to 2.48% by decreasing the switching frequency current ripple even though the total harmonic distortion (THD) of load current is up to 71.05%. While by a single L-filter the THD of the grid current is just decreased to 6.09%. As Figure 9 and Figure 11 Show, In areas with a big d_i/d_t, compensation current is distorted with a L-Filter, unable to trace the reference current, and there is burr and considerable ripple current in grid current. While with a LCL-Filter, the output current can track the reference current well even in big di/dt areas. The grid current is smooth and stable, the ripple current is reduced effectively.

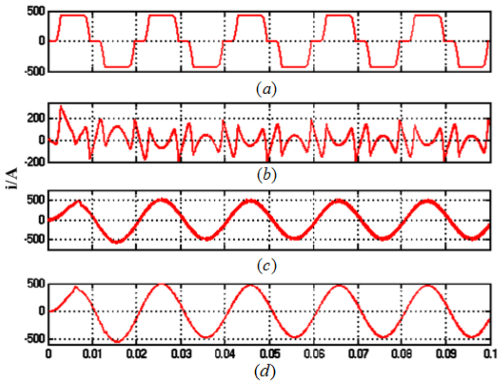


Figure 8. (a) load current (b) compensation current (c) grid current without ripple filter (d) gird current with ripple filter

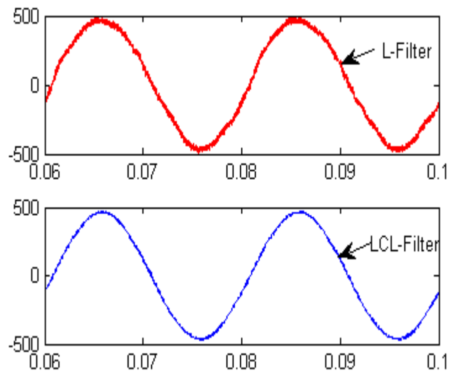


Figure 9. grid current with LCL-Filter and L-Filter

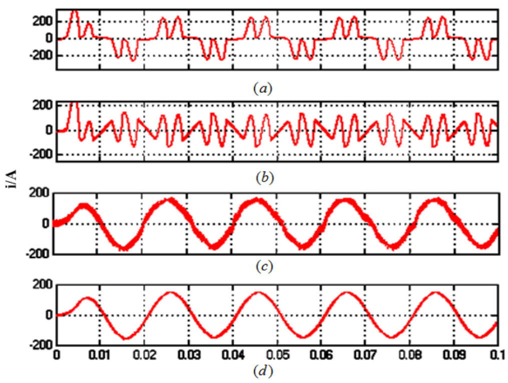


Figure 10. (a) load current (b) compensation current (c) grid current without ripple filter (d) gird current with ripple filter

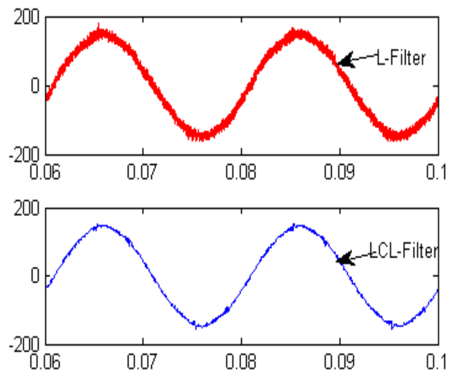


Figure 11. grid current with LCL- Filter and L-Filter

6. Conclusion

In this paper the principles and constraints of LCL-Filter are discussed. APF is designed to compensate the harmonic current of a wide bandwidth. The current through the LCL-Filter is highly sensitive to the parameters. The ripple of three-level Active Power Filter is analyzed in detail and then based on the two-level APF LCL-filters design, a simple and practical design procedure for LCL-filter of three-level APF is proposed. Then the LCL-filters with the designed parameters based on three-level APF is simulated in SIMULINK, and the results validate the effectiveness and practicality of the system.

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