Design and Research on the LCL Filter in Three-Phase PV Grid-Connected Inverters

Xu Renzhong, Xia Lie, Zhang Junjun, and Ding Jie

***Abstract*—Aiming at the problem of filtering in the three-phase PV grid-connected inverters, the mathematics models for L filter and LCL filter are established. The values of capacitances and inductances are calculated by analyzing the related constraint conditions for the main parameters of LCL filter. There are two ways to increase the value of damping resistor of the filter capacitor. The impacts on the stability and filtering property, in both ways, are analyzed. The simulation result indicated that the LCL filter achieve the best performance than L filter and LC filter. Under the prerequisite of increasing system stability, parallel resistor is even more advantageous than series resistor. And the validity of theoretical results is confirmed.**

***Index Terms*—LCL Filter, Series damping resistors (SDR), parallel damping resistors (PDR), harmonic.**

I. Introduction

With the energy crisis and environment revolution are becoming more and more serious, renewable power generation system is drawing more and more attention. We vigorously developed clean energy such as wind, and solar power. The control technology of grid-connected inverter is the key technology in renewable power generation. In the grid-connected inverter, the all-controlled power electronic devices IGBT and GTO are be used, which is modulated by the high frequency PWM. As the result, the du/dt and di/dt are ever large. Due to the presence of some vagrant parameters, the current included high order harmonic flow into the power grid, which made the harmonic pollution. The most common filter is L in the grid-connected inverter. In order to decrease current ripple, the inductance have to be increased. As a result, the volume and weight of the filter increased. Although the structure and the parameter of the LC filter are easy, the filtering effect is not good because of the uncertainty of network impedance. LCL filter had an inherently high cut-off frequency and strong penetrating ability in low frequency. So LCL filter has come into wide use in the inverter. What is the most difficult is that how to select the parameter and control resonance.

In this paper, with the three-phase PV grid-connected inverters topology, firstly analyze the inductance, the ration of two inductances, selecting the filter capacitor and resonance resistance. Based on these theories, a LCL filter is designed. The simulation result proved that the LCL filter achieve the best performance, and indicated the impacts on the stability and filtering property from the parallel resistor or the series resistor.

II. Principle of LCL Filter

The classical topological structure is shown in Fig. 1. This topology is general use in three-phase PV grid-connected inverters. Where U_{dc} is the voltage of DC bus, I_{dc} is the current of DC bus, S1~S6 six-switch made up three-phase inverter, L_1, C_s, L_2 made up third-order LCL filter[1].

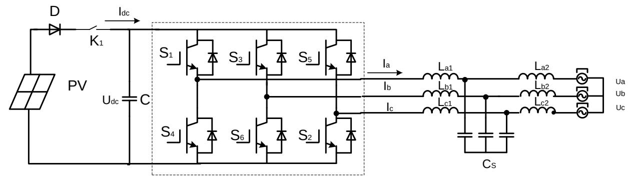

Fig. 1. Topological structure of three-phase PV grid-connected inverters wit h LCL filter

For easy to study, equivalent single-phase circuit of LCL filter is analyzed instead of three-phase circuit. The inverter is voltage-mode. So the simplified circuit model of Fig.1 is shown as Fig. 2.

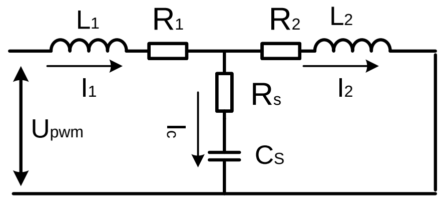

Fig. 2. Circuit diagram of LCL filter

The internal resistances of inductance and capacitance are negligible. The transfer-function of the I_2 to U_{pwm} is given as

$$G(s)=\frac{I_2}{U_{pwm}}=\frac{1}{s^3 L_1 L_2 C+(L_1+L_2)s} \tag{1}$$

where I_2 is the output current of LCL filter, U_{pwm} is the output voltage of PWM.

The transfer-function of L filter is given as

$$G(s)=\frac{I_2}{U_{pwm}}=\frac{1}{Ls} \tag{2}$$

The first-harmonic, low order harmonic and high order harmonic current could be got by decomposing the output current of inverter. As shown in Fig. 2, the current ripple is decreased because of inductance L1 that the current flow

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through. The capacitance is features low resistance to high order harmonic, but the inductance is features high resistance, so the high order harmonic can only flow through capacitance. Then the left current of first-harmonic and low order harmonic flow through inductance L2 into power grid.

The bode diagram of L and LCL filters is shown in Fig. 3

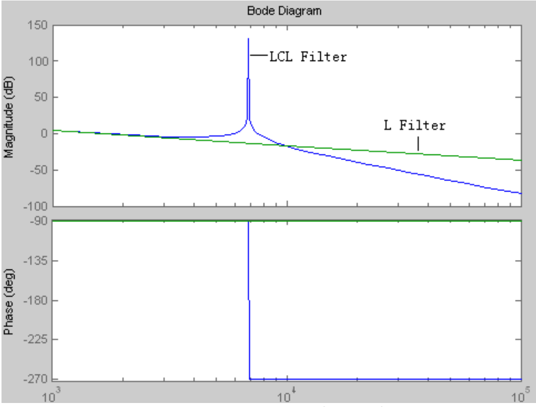

Fig. 3. Bode diagram of LCL filter

As shown in Fig. 3, in the range higher than resonance frequency, the attenuation rate of LCL filter is －60dB/dec and the L filter is －20dB/dec. In the high frequency range the LCL filter achieves the better performance than L filter. In the low frequency range the LCL filter achieves the performance as the same as L filter, and the inductance of LCL could be considered L1 plus L2[2].

Therefore, in the high frequency range the LCL filter has the good attenuation characteristics. To achieve the same filtering effect of the case, the LCL filter core is smaller and lower cost.

III. The Design of Filter Parameters

A. Filter Inductor

Given the condition of DC bus voltage and AC output voltage, the bigger the L is, the smaller ripple would be got. But the tracking speed of current is reduced. And given the condition of the current, the bigger the L is, the greater the weight and volume, and the higher cost. Under the premise of the cost saving, how to design the inductance parameters for the best effect is the key question. Based on great reference [1][2][3], the constraints could be got as

1) The voltage drop of the filter inductor is smaller than 5% of the network voltage under the rated circumstances.

2) The peak to peak amplitude of harmonic current will be controlled within 10%~20% of the rated value of the inverter.

3) The inrush current of inverter should be as small as possible.

4) In order to achieve the best performance of LCL filter, in the low frequency range the current should be as smooth as possible, and in the high frequency range the attenuation rate of should be as fast as possible.

5) Let the high order harmonic flow through the capacitance, and the low order harmonic flow through the inductance.

$$X_c = \frac{1}{cs};\ X_{L2} = sL_2$$

Therefore, f is as bigger and X_c is as smaller as better or both the f and X_{L2} is as smaller as better.

P is defined as the rated output power of three-phase grid-connected inverter $\cos\varphi$ is power factor, U is rated network voltage, and f is driven frequency.

Then (3) could be got form the constraint 1).

$$\frac{4\pi fPL}{3U^2\cos\varphi} \le 5\% \tag{3}$$

$$\Delta i_{\max} = \frac{2U_{dc}/3 + U}{2Lf} \tag{4}$$

$$\Delta i_{\max} \le \frac{2P}{3U\cos\varphi} * (0.1 \sim 0.2) \tag{5}$$

(4) and (5) could be got from constraint 2) and reference[3][4]:

The constraints 2)~5) show that the values of L and C are as bigger as better.

Considering the above constraints, the value 682uH<L<796uH could be got by calculating. The response rate is considered, and L is certainty as 720uH. According to the reference [1], the recommended values of L1 and L2 are between 4-6. Thus, L1 is 0.6mH, and L2 is 0.12mH.

B. Filter Capacitance

How to design the capacitance parameters is another key question. If the X_c got too much, the high frequency harmonics that flow through the shunt capacitor branch is not enough. As a result, the great high-frequency harmonic current flow into the grid. If the X_c got too small, which will lead to the great reactive current flow though the capacitor branch, thereby increasing the inverter output current, and increasing system losses.

According to experience, when the resonant frequency of filter capacitance and inductor is inside the range 1/4 to 1/5 carrier frequency, the filtering performance is the best. The resonant frequency of LCL filter could be described as

$$f = \frac{1}{2\pi}\sqrt{\frac{L_1 + L_2}{L_1 L_2 C}}.$$

Generally, the resonant frequency is bigger than the 10 times the power frequency and smaller than 1/2 times the switching frequency.

$$C = \frac{1}{4\pi^2 f^2 L} \tag{6}$$

In order to avoid the power factor of grid-connected inverter is over lower, the reactive power that is absorbed by filter capacitance should not exceed 5% of the rated active power. Where,

$$C \le \frac{\lambda P}{6\pi f E_m^2} \tag{7}$$

Considering the (6) and (7), in this paper C is 375uF.

C. Damping Resistance

As shown in Fig. 3, because the LCL filter exists resonance, the some order harmonic current that come from the PV grid-connected inverters may be due to sudden increases rapidly. What is more, that will cause the output current out of control. For this reason, adding the damping resistance into filter to suppress the resonances. Generally, it is resistor. The block diagrams of series damping resistor and parallel damping resistor are shown respectively in Fig. 4 and Fig. 5.

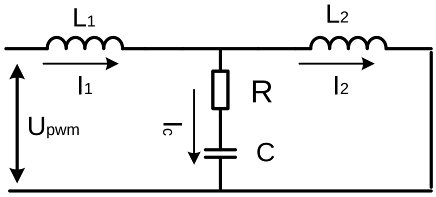

Fig. 4. Block diagram of series damping resistor

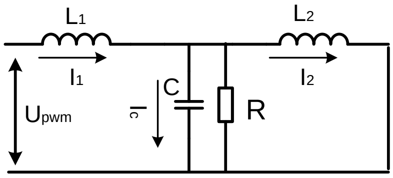

Fig. 5. Block diagram of parallel damping resistor

The transfer function of series damping resistor is

$$G(s)=\frac{I_2}{U_{pwm}}=\frac{sCR+1}{s^3L_1L_2C+s^2(L_1+L_2)CR+s(L_1+L_2)} \quad (8)$$

The transfer function of parallel damping resistor is

$$G(s)=\frac{I_2}{U_{pwm}}=\frac{R}{s^3L_1L_2CR+s^2L_1L_2+sR(L_1+L_2)} \quad (9)$$

The bode diagrams are shown in Fig. 6 and Fig. 7.

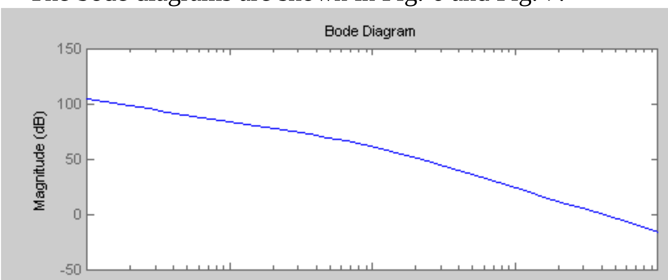

Fig. 6. Bode diagram of series resistor

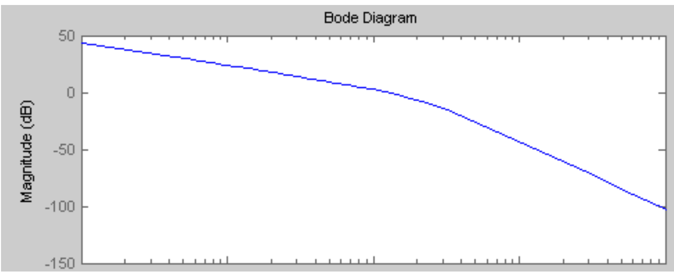

Fig. 7. Bode diagram of parallel resistor

Both the series resistor and parallel resistor are good at filtering. Which one is better?

The parallel resistor could be described as:

$$X_R=\frac{R}{1+CSR}$$

and the series resistor could be described as

$$X_R=R+\frac{1}{CS} \quad (10)$$

Due to the value of series resistor is larger than the parallel resistor, when the resistor is series connection, the high-frequency harmonic current flow though capacitance is greater than parallel. Therefore, the filter has better effect of suppressing the high frequency. The spectrum characteristics are shown in Fig. 7 and Fig. 8, and the above point of view was further proved and verified [5]-[8].

IV. Simulation

Matlab/Simulink power system toolbox software is used to simulate the power system. In this paper, the simulation modes for the LCL filter of the PV gird-connected inverter are designed. Where, the system rated power is 250kW, the line voltage is 270V, the switching frequency is 2K, the fundamental frequency is 50Hz. Then the values of parameters could be calculated. The L1 is 600uH, L2 is 120uH, C is 200uF, and the damping resistor R is 0.3Ω.

In this paper, the simulation modes for L filter, LC filter and LCL filter are designed. The presented simulation results were obtained. The harmonic current waveforms of Ia are shown in follow diagrams.

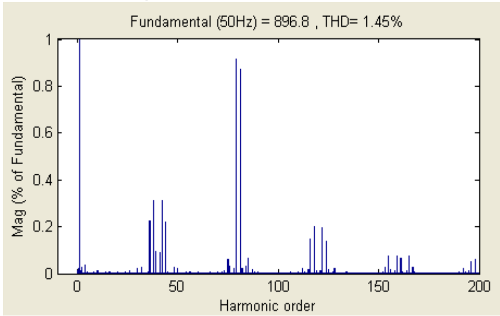

Fig. 8. Harmonic diagram of L filter

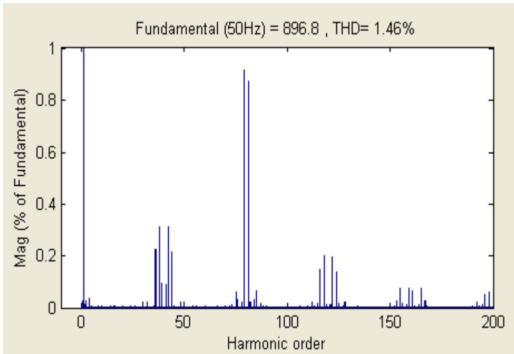

Fig. 9. Harmonic diagram of LC filter

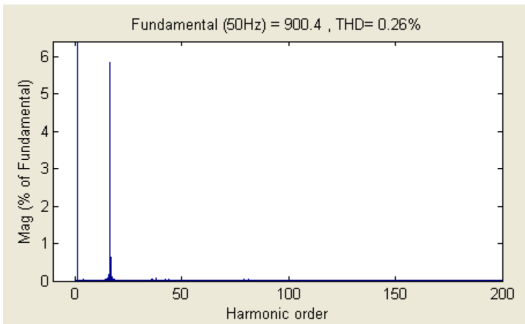

Fig. 10. harmonic diagram of LCL filter

As shown in Fig. 8, the THD is 1.45% with L filter; as shown in Fig. 9, the THD is 1.46% with LC filter; as shown in Fig. 10, the THD is reduced markedly just 1.45% with LCL filter. Around the resonant frequency, the harmonic current are sudden amplified many times, which will cause the filter instability even out of control. Therefore, it is need install damping resistor on capacitor. In order to compare the effect of series and parallel damping resistor simulated respectively, and the harmonic waveforms are shown as followed:

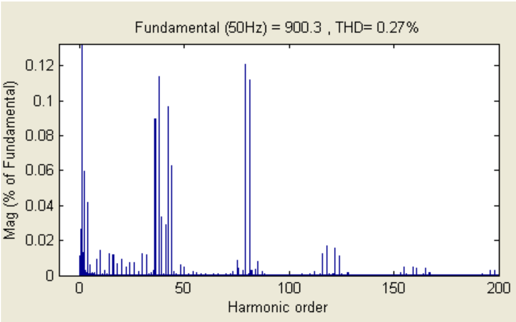

Fig. 11. Harmonic diagram of LCL filter with series resistor

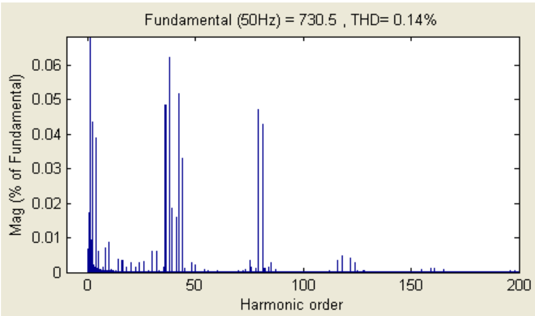

Fig. 12. Harmonic diagram of LCL filter with parallel resistor

When the damping resistor is series connected, THD is 0.27%, as shown in Fig. 11. When the damping resistor is parallel connected, THD is 0.14%, as shown in Fig. 12.

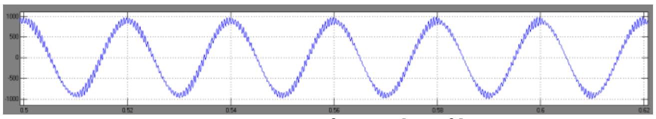

Fig. 13. Current waveform without filtering

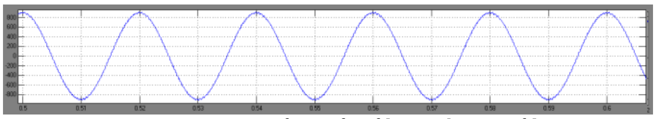

Fig. 14. Current waveform after filtering by LCL filter

Fig. 13 and Fig. 14 are the current waveform without filtering and after filtering by LCL filter. Obviously, current after filtering by LCL filter, the distortion is lower.

V. Conclusion

From the analysis and experiment, it is well known that:

1) The simulation result indicated that the LCL filter has best high frequency attenuation characteristics, so the LCL filter achieves the best performance than L filter and LC filter.

2) With the same the premise of the suppressing resonance, LCL filter would get better filtering effect when the damping resistor is parallel connected rather than series.

All these features indicate that it is the best design the PV gird-connected inverters with LCL filter parallel-connected damping resistor, especially for small and medium-power inverter PV gird-connected inverters.

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