Research on LCL filter considering grid impedance

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Abstract. Due to the large amount of access to distributed energy, the grid usually exhibits weak grid characteristics, which puts higher demands on the inverter. The use of LCL filters in photovoltaic grid-connected systems is beneficial to suppress high-frequency switching harmonic currents from entering the grid. However, the LCL filter increases the system order and the system stability is also affected by the grid impedance. In this paper, the non-isolated PV grid-connected inverter based on LCL filtering is studied, and the effects of grid impedance on system stability, LCL filter harmonic suppression and LCL filter parameter optimization design are studied. The influence of grid impedance on system stability is analyzed in detail. The simulation results verify the correctness of the research.

1. Introduction

At the beginning of the 21st century, survey results show that within 40 years, oil resources will be exhausted, natural gas resources will be exhausted in sixty years, and coal will be exhausted after two centuries \cite{1}. In this context, renewable energy sources such as wind, solar, fuel cells and biomass are receiving more and more attention \cite{2}. Solar energy is an important way to alleviate the global energy shortage. Photovoltaic power generation is one of the hotspots of solar energy utilization research \cite{3}. The grid-connected inverter is the core component of the photovoltaic grid-connected power generation system, and is an important device for transforming the converted direct current of the photovoltaic array into a synchronous alternating current of the power grid. The early distributed energy generation system was connected to the grid through an isolation transformer \cite{4,5}. Due to the existence of the isolation transformer, the voltage matching and electrical isolation between the system and the grid were ensured, but the isolation transformer was large in size, high in cost, heavy in quality, and inefficient in the whole machine. Therefore, in order to prevent switching harmonics from polluting the grid, a filter is usually connected between the grid-connected inverter and the grid. However, there is no electrical isolation of the LCL filter, which inevitably causes the DC component generated by the inverter to be injected into the grid. The DC injection belongs to the grid-connected power quality problem. In the early stage, due to the small grid-connected capacity of the distributed power supply, the impact on the grid can be neglected. Therefore, the research on power quality is mainly based on harmonics. In recent years, due to the large number of distributed energy sources, non-isolated grid-connected inverter systems are the main development direction in the future, so the impact of DC injection has attracted more and more attention from scholars at home and abroad.

Filters can be classified into two types: L type and inductor-capacitor-inductor LCL type. The L-type filter has the characteristics of simple structure and easy control, but its high-frequency attenuation characteristics are not ideal. When the power level is increased, the switching frequency is relatively low. In order to effectively suppress harmonics and make the output current meet the corresponding
standard, it is usually necessary to connect a large inductance value in series, which not only reduces
the dynamic performance of the system, but also increases the volume and weight of the system, and
increases the cost of the whole machine. The LCL type filter not only has low cost, small volume, good
dynamic response, but also has high frequency attenuation capability [6, 7]. The required inductance and
capacitance value under the same filtering effect is much smaller than L-type filtering. This advantage
is particularly evident in the case of high power and low switching frequency, which has attracted
extensive attention from scholars at home and abroad and a large number of applications in actual
production. However, the LCL filter is a third-order undamped system, which has resonance problems,
is prone to oscillation and causes system instability. This puts higher requirements on the parameter
design of the LCL filter and the control strategy of the system [8, 9].

Aiming at the key problems in the research of grid-connected inverters, this paper is devoted to the
research of non-isolated photovoltaic grid-connected inverters based on LCL filtering, so as to further
improve the performance of grid-connected inverters. The impact of grid impedance on the stability of
the LCL photovoltaic grid-connected inverter system is analyzed in detail.

2. Analysis of LCL filters
Figure 1 shows the amplitude-frequency characteristic curves of the L filter and the LCL filter at the
same inductance. Although the LCL filter has a -60 dB attenuation capability for higher harmonics, there
is a resonance point at a specific frequency. It is easy to cause instability of the system. In addition,
when distributed energy is accessed on a large scale, the grid will exhibit weak grid characteristics,
which puts high demands on the design of the current controller.

![Bode Diagram](image)

Figure 1. L filter and LCL filter amplitude frequency characteristic curve.

![LCL filter circuit diagram](image)

Figure 2. LCL filter circuit diagram.

Figure 2 is a circuit diagram of an LCL filter considering grid impedance. The input is the full bridge
output voltage \( u_{inv} \) and the output side is connected to the grid \( u_g \). \( L_1 \) is the inverter side inductance, \( L_2 \)
is the grid side inductance, \( C \) is the filter capacitor, and \( R_d \) is the filter capacitor and the parasitic
impedance on the line. \( L_1, C \) and \( L_2 \) form an LCL filtering network, where \( i_L \) is the inverter side inductor
current, \( u_c \) is the capacitor voltage, \( i_c \) is the capacitor current, and \( i_g \) is the grid-connected current. \( Z_g \)
is the equivalent impedance of the grid. The PCC is a common coupling point. The voltage \( u_e \) measured
at this point is usually used for the phase-locking control of the grid voltage and the grid voltage feed-
forward control in the control link. The value is the sum of the voltage drop across the actual grid voltage
\( u_g \) and the grid impedance \( Z_g \). Compared with the single-inductance filter, the LCL type filter adds the
filter capacitor \( C \) and the filter inductor \( L_2 \) to realize the shunting of the inverter side inductor \( L_1 \) current.
The filter capacitor \( C \) provides a low impedance channel of high frequency components, thereby
improving the waveform quality of the grid-connected current \( i_g \).
Taking the inverter side inductor current $i_L$, the capacitor voltage $u_c$ and the grid-connected current $i_g$ as state variables, the column state equation is as follows:

$$
\begin{align*}
L_1 \frac{dL_1}{dt} &= u_{inv} - u_c - R_d (i_L - i_g) \\
C \frac{du_c}{dt} &= L_2 (i_L - i_g) - u_g - Z_g i_g \\
L_2 \frac{di_g}{dt} &= u_c + R_d (i_L - i_g) - u_g - Z_g i_g
\end{align*}
$$

From this we can conclude that the transfer function of $i_g$ is:

$$
\frac{i_g(s)}{i_L(s)} = \left( \frac{R_d Cs + 1}{L_1 L_2 Cs^2 + (L_1 + L_2) R_d Cs + 1} \right) u_{inv}(s)
$$

(2)

3. Influence of grid impedance on LCL filter

When analyzing the characteristics of the LCL filter itself, the influence of the grid impedance is not considered at present, that is, assuming that the grid is in an ideal state, and $Z_g$ is not considered at this time, equation (2) can be expressed as:

$$
\frac{i_g(s)}{i_L(s)} = \left( \frac{R_d Cs + 1}{L_1 L_2 Cs^3 + (L_1 + L_2) R_d Cs^2 + (L_1 + L_2) s} \right) u_{inv}(s)
$$

(3)

The effect of the variable $R_d$ on the stability of the system is analyzed below.

![Bode Diagram](image)

**Figure 3.** LCL filter Bode diagram with different $R_d$ values.

It can be seen from the Bode diagram shown in figure 3 that as the parasitic resistance increases, the resonance peak of the LCL filter gradually decreases, indicating that the existence of parasitic resistance contributes to the stability of the system. Further analysis shows that the existence of the parasitic resistance $R_d$ is equivalent to giving the system passive damping effect, so the system will be stable [10,11].

In order to simulate the stability of the worst-case system, the parasitic resistance in the line is usually ignored. The transfer function of the grid-connected current $i_g$ under ideal grid conditions can be...
expressed as:

\[ i_g(s) = \frac{u_{inv}(s)}{L_1} - \left( L_1 C s^2 + 1 \right) u_g(s) \frac{L_1 L_2 C s^3 + \left( L_1 + L_2 \right) s}{L_1 L_2 C s^3 + \left( L_1 + L_2 \right) s} \]  
(4)

It can be seen from equation (4) that the LCL filter is a third-order undamped system, which is prone to resonance. There is a resonance peak at the resonant frequency, and its resonant frequency is:

\[ f_{res} = \frac{1}{2\pi} \sqrt{\frac{L_1 + L_2}{L_1 L_2 C}} \]  
(5)

4. System stability analysis when grids are of different nature

When the grid is in a non-ideal condition, the grid has an impedance \( Z_g \). The transfer function of the grid-connected current \( i_g \) relative to the inverter-side voltage \( u_{inv} \) when equation (2) can be ignored is:

\[ G(s) = \frac{i_g(s)}{u_{inv}(s)} = \frac{1}{L_1 L_2 C s^3 + L_1 Z_g C s^2 + \left( L_1 + L_2 \right) s + Z_g} \]  
(6)

For grid-connected inverters, the grid can ideally be equivalent to a large capacitor with infinite capacitance. When the grid impedance is purely resistive \( R_g \), the above equation can be expressed as:

\[ G(s) = \frac{i_g(s)}{u_{inv}(s)} = \frac{1}{L_1 L_2 C s^3 + L_1 R_g C s^2 + \left( L_1 + L_2 \right) s + R_g} \]  
(7)

It can be seen that when the grid is resistive, it is equivalent to adding the second derivative term and the constant term in the denominator of equation (7), that is, adding damping to the third-order undamped system, and its Bode diagram is shown in figure 4.

![Bode Diagram](image)

**Figure 4.** LCL filter Bode diagram when the grid is resistive.

It can be seen from figure 4 that as the resistance value of \( R_g \) increases, the resonance peak of the LCL filter becomes smaller and smaller, so the purely resistive grid impedance contributes to the stability of the system.

When the grid impedance is the pure inductive impedance \( L_g \), then equation (6) can be expressed as:
\[ G(s) = \frac{i_g(s)}{u_{inv}(s)} = \frac{1}{L_1(L_2 + L_g)Cs^3 + (L_1 + L_2 + L_g)s} \]  

(8)

It can be seen from equation (8) that the inductive impedance of the grid changes the coefficients of the third derivative term and the first derivative term of the denominator without any change in the damping of the system. The Bode diagram when the grid is inductive is figure 5.

![Bode Diagram](image)

**Figure 5.** LCL filter Bode diagram when the grid is inductive.

![Bode Diagram](image)

**Figure 6.** LCL filter Bode diagram when the grid is capacitive.

It can be seen from figure 5 that as the inductive reactance of the grid increases, the resonant frequency of the LCL filter becomes lower and lower, which will adversely affect the control of the system.

When the grid impedance is capacitive, the LCL filter Bode diagram is shown in figure 6.

It can be seen from figure 6 that as the capacitive reactance of the power grid gradually increases, the resonant frequency of the LCL filter becomes higher and higher, which is advantageous for the stability of the system.

In summary, when the grid is resistive or capacitive, it all contributes to the stability of the LCL-type grid-connected inverter system. Therefore, it is usually necessary to consider the influence of the grid on the stability of the system when it is inductive. In fact, since the electrical load is mainly an inductive load, the distribution network and the transmission network generally exhibit inductive impedance. Figure 7 shows the final simplified model of the LCL filter.

![Simplified Model](image)

**Figure 7.** LCL filter final simplified model.

5. Design of LCL filter parameters

5.1. Resonant frequency range

From the above analysis, the transfer function of the grid-connected current in the LCL filter relative to
The inverter-side voltage is:

\[ G(s) = \frac{i_g(s)}{u_{inv}(s)} = \frac{1}{L_1 L_2 C s^3 + (L_1 + L_2) s} \]  

(9)

The resonant frequency is:

\[ f_{\text{res}} = \frac{1}{2\pi} \sqrt{\frac{L_1 + L_2}{L_1 L_2 C}} \]  

(10)

Substituting equation (10) into equation (9) yields:

\[ G(s) = \frac{i_g(s)}{u_{inv}(s)} = \frac{1}{(L_1 + L_2) s} \left( \frac{s^2}{4\pi^2 f_{\text{res}}^2} + 1 \right) \left( L_1 + L_2 \right) s \]  

(11)

It can be seen from the above formula that in the low frequency band, that is, the frequency is much smaller than the resonance frequency, since the current impedance of the filter capacitor to the low frequency band is high, most of the inverter output current flows to the grid-connected inductor, and the influence of the filter capacitor can be ignored. At this time, the amplitude-frequency characteristic curve of \( G(s) \) is the same as the amplitude-frequency characteristic curve when the L-type filter is used, and its amplitude is attenuated at a speed of -20 dB, as shown in figure 1. The inductance of the L-type filter is the sum of the inductance value of the inverter side of the LCL filter and the inductance value of the grid-side side, that is, \( L_t = L_1 + L_2 \). In the high frequency band, when the frequency is much larger than the resonance frequency, since the current impedance of the filter capacitor to the high frequency band is low, most of the high-order harmonic current output from the inverter flows to the filter capacitor, so that the grid-connected current mainly includes the fundamental component. The amplitude of \( G(s) \) is attenuated at a rate of -60 dB, and the LCL filter is equivalent to a third-order integral. It can be seen that the LCL filter has a strong attenuation capability for the high frequency band.

In summary, when designing the LCL filter, the LCL filter has a -60 dB attenuation at the switching frequency only when the resonant frequency is lower than the inverter switching frequency. At this time, the LCL filter can exert its maximum effect. Therefore, the resonant frequency of the LCL filter is usually set to be less than 1/2 of the switching frequency [12]. However, when designing the current controller, the higher the resonant frequency, the wider the system bandwidth can be set, and the dynamic characteristics of the system can be guaranteed. The design of the device is also easier, so the resonant frequency is generally greater than 10 times the grid cycle frequency. The range of the resonant frequency of the available LCL filter is:

\[ 10 f_g < f_{\text{res}} < \frac{1}{2} f_s \]  

(12)

Where \( f_g \) is the fundamental frequency of the grid and \( f_s \) is the switching frequency of the inverter. In addition, there are other restrictions below when considering the design of LCL filter parameters.

5.2. Inductance limit

5.2.1. Total inductance limit. The value of the total inductance of the LCL filter needs to be compromised. It is not only effective to suppress the injection of harmonic currents in the grid-connected standard, but also to quickly track the grid-connected reference current and have a fast dynamic response capability. If the inductance is too small, the harmonic standard of the grid-connected current cannot be
met, and excessive ripple current will increase the loss and temperature rise of the power module and the inverter-side inductor, reducing the life of the device; if the inductance is too large, not only will it increase the size, weight and cost of the system, but it will also cause a large inductor voltage drop, which will cause an increase in the required bus voltage, resulting in additional switching losses. Therefore, under normal circumstances, the fundamental voltage drop on the inductor is not more than 0.1 times the grid voltage. Which is:

\[
L_i \leq \frac{0.1U_s^2}{2\pi f_g P}
\]

Among them, \(U_s\) is the effective value of the common coupling point voltage, \(P\) is the rated voltage, and \(L_i\) is the total inductance value.

5.2.2. Inverter side inductance limit. The transfer function of the inverter side current \(i_L\) with respect to the inverter side output voltage \(u_{inv}\) is:

\[
G(s) = \frac{i_L(s)}{u_{inv}(s)} = \frac{L_2Cs^2 + 1}{L_1L_2Cs^3 + (L_1 + L_2)s}
\]

Bringing equation (10) into equation (14) yields:

\[
G(s) = \frac{i_L(s)}{u_{inv}(s)} = \frac{s^2 + \frac{1}{L_2C}}{L_2s\left(4\pi^2 f_{res}^2 + s\right)} \approx \left\{ \begin{array}{ll} 
\frac{1}{(L_1 + L_2)s} & f \leq f_{res} \\
\frac{1}{L_2s} & f > f_{res} \end{array} \right.
\]

In combination with figure 1, the LCL filter can make the grid-connected current harmonics more attenuated, but the inverter-side current is still mainly determined by the inverter-side inductor \(L_i\), and the current flowing through the power-tube is equal to the inverter-side current. If the value of \(L_i\) is too small, the power tube switching loss will increase. Therefore, the value of \(L_i\) should account for the main part of the total filter inductance. The value selection is mainly related to the pulse width modulation mode, the switching frequency and the DC bus voltage.

**Figure 8.** Inverter bridge output voltage and inverter side inductor current ripple.

Figure 8 is a schematic diagram of the inverter bridge output voltage and the inverter side inductor current ripple during unipolar modulation. Where \(u_{inv}\) is the inverter side output voltage, \(i_L\) is the inverter side inductor current ripple, \(u_{dc}\) is the bus voltage, and \(\Delta i_{pp}\) is the peak-to-peak value of the current ripple. \(T_{sw}\) is the switching period, and \(T_{on}\) and \(T_{off}\) are the conduction and judgment times of the
switching tube in one cycle, respectively. The fundamental voltage drop and phase angle offset on the inverter side inductor and the dead band effect are ignored here. The inverter side current ripple amplitude $\Delta i_{pp}$ is obtained

$$\Delta i_{pp} = \frac{u_{dc} DT_{SW} - (u_{dc} - u_c) DT_{SW}}{L_1} = \frac{(1 - m \sin \omega_1 t) u_{dc} DT_{SW}}{2L_1}$$  \hspace{1cm} (16)$$

Where $D = T_{on}/T_{sw}$ is the duty cycle, $m$ is the modulation ratio, and $\omega_1$ is the fundamental angular frequency. It is known that the average value of the inverter output voltage during one switching cycle is

$$u_{avg} = \frac{1}{T_1} \int_0^{T_1} u_{in,dc} dt = Du_{dc}$$  \hspace{1cm} (17)$$

When the switching frequency is much larger than the fundamental frequency, it is approximately equal to the fundamental component of the inverter output voltage. We can get

$$D = m \sin \omega_1 t$$  \hspace{1cm} (18)$$

Substituting equation (18) into equation (16)

$$\Delta i_{pp} = \frac{u_{dc} T_{SW} (1 - m \sin \omega_1 t) m \sin \omega_1 t}{L_1}$$  \hspace{1cm} (19)$$

The maximum value of the formula (19) is

$$\Delta i_{pp_{max}} = \frac{u_{dc} T_{sw}}{4L_1}$$  \hspace{1cm} (20)$$

The lower limit of the inductance of the inverter side is

$$L_1 > \frac{u_{dc} T_{sw}}{4\lambda I_{rated}} \Delta$$  \hspace{1cm} (21)$$

Where $I_{rated}$ is the rms value of the rated output current. $\lambda$ is the ratio of the inductor side inductor ripple current to the rated current, which is generally 15% to 30%.

5.2.3. Grid side inductance limit. The transfer function of the grid-connected current $i_g$ relative to the inverter-side inductor current $i_L$ is:

$$G(s) = \frac{i_g(s)}{i_L(s)} = \frac{1}{L_2 Cs^2 + 1} \approx \begin{cases} 1 & f \leq f_{res} \\ \frac{1}{L_2 C s^2} & f > f_{res} \end{cases}$$  \hspace{1cm} (22)$$

Combined with equation (22), the grid-connected current $i_g$ has no attenuation to the inverter-side inductor current $i_L$ before the resonant frequency. After the resonant frequency, $i_g$ attenuates $i_L$ at a rate of -40 dB. It can be seen that the LCL filter is equivalent to reducing the harmonic content of the grid-connected current by two-stage attenuation.

According to the literature [13], take $L_2$ here as

$$L_2 = \frac{L_1}{L_1 C \omega_1^2 - 1}$$  \hspace{1cm} (23)$$
Where $\omega_r$ is the resonant angular frequency and $C$ is the total capacitance.

### 5.3. Filter capacitor limit

The selection of the filter capacitor needs to consider the reactive power it introduces. The larger the filter capacitor is, the larger the reactive power is introduced, the larger the current flowing through the inductor and the switch tube is, and the conduction loss of the switch tube is increased [14]. Under normal circumstances, the reactive power absorbed by the capacitor should be less than 5% of the rated power. Which is:

$$2\pi f \omega_r U_i^2 C \leq 0.05P$$  \hspace{1cm} (24)

The upper limit of the available filter capacitor is:

$$C \leq \frac{0.05P}{2\pi f \omega_r U_i^2}$$  \hspace{1cm} (25)

The limitation of the filter parameters is given above, and the range of values of the LCL filter is limited, but the range of the parameter is too large, and there is a problem that multiple attempts are required. Considering that the inductor volume is too large, the cost is high, and the inductor has a heavier volume as the magnetic component, it is generally desirable that the inductance is as small as possible. At the same time, when the inductive impedance of the power grid is present, the resonance frequency of the system is easily caused to shift. If the designed filter can minimize the frequency offset caused by the inductive reactance of the grid, and the system has certain robustness to the grid inductive reactance, it is beneficial to the stability of the system.

### 6. Simulation

According to the parameter design flow proposed above, the design filter parameters are shown in table 1. According to the data in table 1, the simulation study is carried out with MATLAB/Simulink.

| Parameter                        | Value     |
|----------------------------------|-----------|
| Bus voltage/$U_{in}$             | DC360V    |
| Grid voltage/$U_g$               | AC220V/50Hz |
| Rated current/$I_{rate}$         | 25A       |
| Inverter side inductance/$L_1$   | 600uH     |
| Grid side inductance/$L_2$       | 150uH     |
| Filter capacitor/$C$             | 10uF      |
| Switch frequency/$f_{sw}$        | 10kHz     |

In order to simulate the grid impedance, a series resistor is connected between the grid-connected inverter and the grid. Figure 9 shows the grid-connected current waveform and its spectrum analysis when connected in series with 1 $\Omega$, 5 $\Omega$, and 10 $\Omega$ resistors. It can be seen that as the resistance value increases, the harmonics at the resonant frequency are gradually reduced, indicating that the system can remain stable when the grid is resistive. However, the increase in the impedance of the grid makes the current tracking capability of the current controller worse, which is mainly due to the fact that the control parameters of the current regulator are designed according to the ideal state, and the gain at the fundamental frequency is limited.
Figure 9. Grid-connected current spectrum when grid impedance changes. (a) The grid impedance is 1 Ω, (b) The grid impedance is 5 Ω and (c) The grid impedance is 10 Ω.

Figure 10 shows the grid-connected current waveform and its spectrum analysis when the 1 mH, 2 mH, and 5 mH inductors are connected in series with the grid-connected inverter and the grid. It can be seen that when the grid inductance is 1mH, the stability of the system is hardly affected. The THD of the grid-connected current has not changed. When the grid inductance is 2 mH, the system can maintain stability and the THD increases from 2.46% to 3.55%. It can be seen that the grid-connected inverter can remain stable when the grid inductance is small. The designed LCL filter parameters have certain robustness to the grid inductive reactance. When the inductive reactance of the grid increases to more than 5 mH, the system has a very strong resonance. Therefore, the stability of the grid is not completely solved by designing the LCL filter parameters.
Figure 10. Grid-connected current spectrum when the grid is changing. (a) The grid inductance is 1 mH, (b) The grid inductance is 2 mH and (c) The grid inductance is 5 mH.

7. Conclusion
This paper mainly studies the influence of grid impedance on the stability of LCL type photovoltaic grid-connected inverter. A model of LCL filter considering grid impedance is established and a parameter design scheme is proposed. The parameters were designed using the design of this paper and simulated on MATLAB/Simulink. The analysis found that when the grid is resistive or capacitive, it is conducive to the stability of the LCL grid-connected inverter system. When the power grid is inductive, it is not conducive to the stability of the power grid. As the impedance of the power grid increases, the resonant frequency of the LCL filter will become lower and lower, which will adversely affect the system. And when the grid impedance is small, the grid-connected inverter can remain stable, which indicates that the parameter design scheme of this paper has certain robustness to the grid impedance.

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