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LCL filter design for photovoltaic grid connected systems

A.E.W.H. Kahlane [*], L. Hassaine [†] and M. Kherchi

Centre de Développement des Energies Renouvelables, CDER
B.P. 62, Route de l'Observatoire, Bouzaréah, 16340, Algiers, Algeria

Abstract - The use of power converters is very important in maximizing the power transfer from solar energy to the utility grid. A LCL filter is often used to interconnect an inverter to the utility grid in order to filter the harmonics produced by the inverter. This paper deal design methodology of a LCL filter topology to connect à inverter to the grid, an application of filter design is reported with m-file in Matlab.

Keywords: LCL Filter – Inverter - Grid connected - Passive damping - Photovoltaic systems.

1. INTRODUCTION

Recently, the development of renewable energy technologies have been accelerating, making the simultaneous development of power conversion devices for applications, such as wind and solar power systems extremely important, the development of these technologies are actively underway.

The harmonics caused by the switching of the power conversion devices are the main factor-causing problems to sensitive equipment or the connected loads, especially for applications above several kilowatts, where the price of filters and total harmonics distortion (THD) is also an important consideration in the systems design phase [1].

The inductance of the input or output circuits of the power conversion devices have conventionally been used to reduce these harmonics. However, as the capacity of the systems have been increasing, high values of inductances are needed, so that realizing practical filters has been becoming even more difficult due to the price rises and the poor dynamic responses [1].

An L filter or LCL filter is usually placed between the inverter and the grid to attenuate the switching frequency harmonics produced by the grid-connected inverter. Compared with L filter, LCL filter has better attenuation capacity of high-order harmonics and better dynamic characteristic [2, 3].

However, an LCL filter can cause stability problems due to the undesired resonance caused by zero impedance at certain frequencies.

To avoid this resonance from contaminating the system, several damping techniques have been proposed. One way is to incorporate a physical passive element, such as, a resistor in series with the filter capacitor [4].

This passive damping solution is very simple and highly reliable. However, the additional resistor results in power loss and weakens the attenuation ability of the LCL filter. This drawback can be overcome by employing active damping [5].

2. FILTER TOPOLOGIES

The output filter reduces the harmonics in generated current caused by semiconductor switching. There are several types of filters. The simplest variant is filter inductor connected to the inverter's output. But also combinations with capacitors like LC or LCL can be used. These possible topologies are shown in Fig. 2.

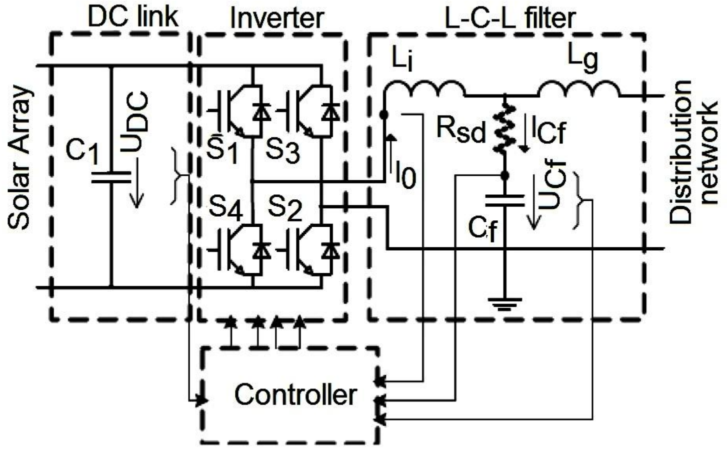

Fig. 1: Block diagram of the VSI

[*] h.kahlane@cder.dz
[†] l.hassaine@cder.dz ; m.kherchi@cder.dz

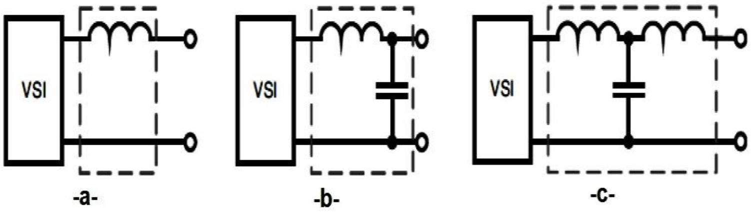

Fig. 2: Basic filter topologies

2.1 L-Filter

The L-filter (Fig. 2a-) is the first order filter with attenuation 20 dB/decade over the whole frequency range. Therefore the application of this filter type is suitable for converters with high switching frequency, where the attenuation is succient. On the other side inductance greatly decreases dynamics of the whole system converter-filter. Transfer function of the L-filter is depicted in Fig. 3 as a black dashed line.

2.2 LC-Filter

The LC-filter is depicted in Fig. 2b-. It is second order filter and it has better damping behaviors than L-filter. This simple configuration is easy to design and it works mostly without problems.

The second order filter provides 12 dB per octave of attenuation after the cut-off frequency f_0, it has no gain before f_0, but it presents a peaking at the resonant frequency f_0. Transfer function of the LC-filter is,

$$F(s) = \frac{1}{1 + s \times L_F + s^2 \times L_F \times C_F}$$

The own design of the filter is a compromise between the value of the capacity and inductance.

The high capacity has positive effects on the voltage quality. On the other hand higher inductance value is required to achieve demanded cut-off frequency of the filter. Connecting system with this kind of filter to the supply grid, the resonant frequency of the filter becomes dependent on the grid impedance and therefore this filter is not suitable, too.

2.3 LCL-filter

The attenuation of the LCL-filter is 60 dB/decade for frequencies above resonant frequency, therefore lower switching frequency for the converter can be used. It also provides better decoupling between the filter and the grid impedance and lower current ripple across the grid inductor. Therefore LCL-filter fits to our application.

The LCL filter has good current ripple attenuation even with small inductance values. However it can bring also resonances and unstable states into the system. Therefore the filter must be designed precisely according to the parameters of the specific converter.

In the technical literature we can find many articles on the design of the LCL filters. Important parameter of the filter is its cut-off frequency. The cut-off frequency of the filter must be minimally one half of the switching frequency of the converter, because the filter must have enough attenuation in the range of the converter's switching frequency.

The cut-off frequency must have a sufficient distance from the grid frequency, too. The cut-off frequency of the LCL filter can be calculated as,

$$f_{res} = \frac{1}{2\pi} \times \sqrt{\frac{L_i + L_g}{L_i \times L_g \times C_f}}$$

The LCL filter will be vulnerable to oscillations too and it will magnify frequencies around its cut-off frequency. Therefore the filter is added with damping. The simplest way is to add damping resistor. In general there are four possible places where the resistor can be placed series/parallel to the inverter side inductor or series/parallel to filter capacitor.

The variant with resistor connected in series with the filter capacitor has been chosen. The value of the damping resistor can be calculated as,

$$R_{sd} = \frac{1}{3\omega_{res} C_f}$$

The peak near resonant frequency has nearly vanished. This is simple and reliable solution, but it increases the heat losses in the system and it greatly decreases the efficiency of the filter. This problem can be solved by active damping. The resistor reduces the voltage across the capacitor by a voltage proportional to the current that flows through it.

This can be also done in the control loop. The current through C_f is measured and differentiated by the term $(s \times C_f \times R_{sd})$.

A real resistor is not used and the calculated value is subtracted from the demanded current. In this way the filter is actively damped with a virtual resistor without losses. The disadvantage of this method is that an additional current sensor is required and the differentiator may bring noise problems because it amplifies high frequency signals [6].

A functional block diagram for the grid connected inverter using this LCL filter is shown in Fig. 2.

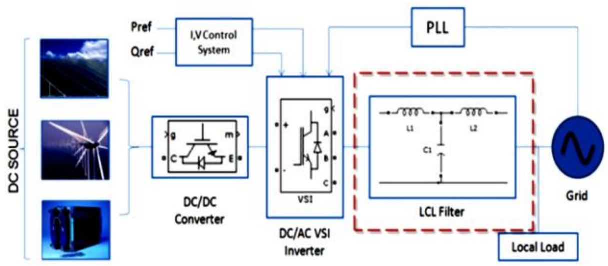

Fig. 3: General schematic for grid **interconnected** DC power source [7]

3. FILTER LCL DESIGN

Analysis and estimation approach of the L-C-L filter with damping resistance as seen in Fig. 4.2 have been discussed in. The simplified formulae to estimate the parameters of the filter has stipulated in these literatures. The same approach will be used in this thesis to determine inverter side inductance, L_i, grid side inductance, L_g, filter capacitance, f_c and the damping resistance R_d.

The main function of the LCL filter is to reduce high-order harmonics on the output side; however poor design may cause a distortion increase. Therefore, the filter must be designed correctly and reasonably.

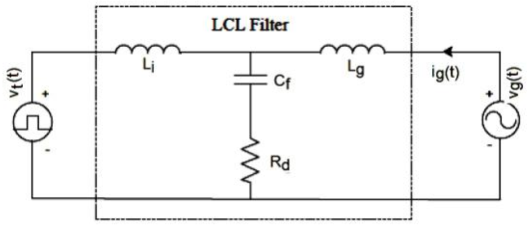

Fig. 4: L-C-L filter and components

3.1 Filter LCL frequency response

An important transfer function is:

$$H_{LCL} = i_g / v_i$$

where the grid voltage is assumed to be an ideal voltage source capable of dumping all the harmonic frequencies. If one sets $V_g = 0$, conditions for current-controlled inverters, the transfer function of LCL filter (neglecting damping) is:

$$H_{LCL}(s) = \frac{1}{L_1 C_f L_2 s^3 + (L_1 + L_2)\, s}$$

And with some simple algebraic manipulations the transfer function with damping resistance becomes:

$$Hd_{LCL}(s) = \frac{C_f R_f s + 1}{L_1 C_f L_2 s^3 + C_f (L_1 + L_2) R_f s^2 + (L_1 + L_2)\, s}$$

The Bode plots of the LCL filter without and with damping are shown in Fig. 4. The insertion of a series resistance with the capacitor eliminates the gain spike, smoothing the overall response and rolling-off to (-180) degrees for high frequency, instead of (-270) degrees. It is possible to observe in this Bode diagram, that the closed loop bandwidth must be within 1000 Hz where the phase shift is around (-90) degrees.

3.2 Filter design procedure

Several characteristics must be considered in designing a LCL filter, such as current ripple, filter size and switching ripple attenuation. The reactive power requirements may cause a resonance of the capacitor interacting with the grid.

Therefore, passive or active damping must be added by including a resistor in series with the capacitor. In this work, the passive damping solution has been adopted, but active solutions can also be applied.

The following parameters are needed for the filter design:

U_n - line to line RMS voltage (inverter output), C_{WX} -phase voltage (inverter output), P_n -rated active power, V_{dc} -DC link voltage, f_n grid frequency, f_{sw} -switching frequency, f_{res} -resonance frequency.

Thus, the filter values will be referred to in a percentage of the base values [7, 8]:

$$Z_b = U_n^2 / S_n \qquad C_b = 1 / \omega_n \times Z_b$$

The first step in calculating the filter components is the design of the inverter side inductance L_i, which can limit the output current ripple by up to 10% of the nominal amplitude. It can be calculated according to the equation derived in [9]:

$$L_i = \frac{U_{DC}}{16\, f_s \times \Delta I_{L-max}}$$

Where ΔI_{L-max} is the 10 % current ripple specified by:

$$\Delta I_{L-max} = 0.01 \frac{P_n \sqrt{2}}{U_n}$$

The design of the filter capacity proceeds from the fact that the maximal power factor variation acceptable by the grid is 5%. The filter capacity can therefore be calculated as a multiplication of system base capacitance C_b:

$$C_f = 0.05\, C_b$$

The grid side inductance L_g can be calculated as:

$$L_g = r \times L_i$$

The last step in the design is the control of the resonant frequency of the filter. The resonant frequency must have a distance from the grid frequency and must be minimally one half of the switching frequency, because the filter must have enough attenuation in the switching frequency of the converter. The resonant frequency for the L-C-L filter can be calculated as:

$$f_{res} = \frac{1}{2\pi} \times \sqrt{\frac{L_i + L_g}{L_i \times L_g \times C_f}}$$

In order to reduce oscillations and unstable states of the filter, the capacitor should be added with an in series connected resistor. This solution is sometimes called ‘passive damping’. It is simple and reliable, but it increases the heat losses in the system and it greatly decreases the efficiency of the filter. The value of the damping resistor can be calculated as:

$$R_{sd} = \frac{1}{3\omega_{res}\, C_f}$$

4. PARAMETER DESIGN FOR AN INVERTER

Table 1 summarizes parameters for calculating filter components.

Table 1: Parameters of inverter

Parameter	**Value**
Grid voltage	230 V
Output power of the inverter	1kVA
DC-Link voltage	400 V
Grid frequency	50 Hz
Switching frequency	10 kHz
Power factor	1

The Program in m-file:

```
% System parameters
Pn = 1000; % Inverter power : 1000 W
En = 230; %Grid voltage : 230 V
Vdc=400; %DC link voltage : 400V
```

```
fn = 50; %Grid frequency : 50 Hz
wn = 2*pi*fn;
fsw = 10000; %Switching frequency : 10000 Hz
wsw = 2*pi*fsw;
% Base values
Zb = (En^2)/Pn
Cb = 1/(wn*Zb)
% Filter parameters
delta_Ilmax=0.1*((Pn*sqrt(2))/En)
Li=Vdc/(16*fsw*delta_Ilmax) %Inverter side inductance
x = 0.05;
Cf = x*Cb %Filter capacitor
% Calculation of the factor,r,between Linv and Lg
r = 0.6;
% Grid side inductance (including transformer inductance)
Lg = r*Li
% Calculation of wres,resonance frequency of the filter
wres = sqrt((Li+Lg)/(Li*Lg*Cf));
 fres=wres/(2*pi)
%Damping resistance
Rd = 1/(3*wres*Cf)
```

Obtained: L_i = 4 mH C_f = 3 μF L_i = 2.4 mH f_{res} = 2.3 kHz R_d = 7.5 Ω

5. SIMULATION

Neglecting damping

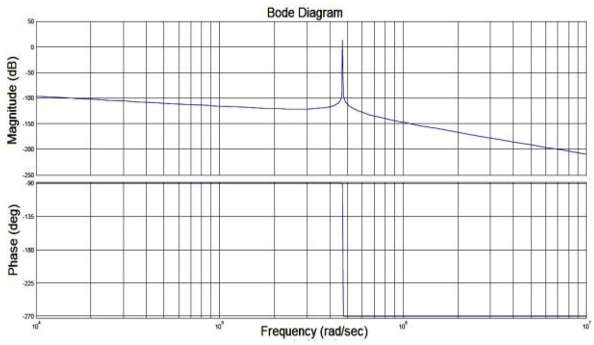

Fig. 5: Bode diagram of LCL Filter

6. CONCLUSION

In this paper, the design guideline for the LCL filter used in grid-interconnected inverter has been systematically addressed.

Future research includes applying the control of LCL filter and different topology of filters.

At the end, the LCL filter topology showed as main advantages: the design flexibility, which allows further Optimization, reduced size in comparison to other topologies.

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