

LCL Filter Design Procedure

The LCL filter design procedure presented here is similar to that presented in references [1] and [2]. Here, the procedure is presented in a step-by-step way and the simulation file is freely available on <https://sites.google.com/site/busarellosmartgrid/home>

The Fig. 1 presents the LCL filter and its nomenclature adopted in this report.

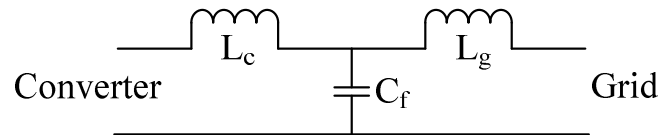


Fig. 1. The LCL filter and its nomenclature adopted in this paper.

1) Step 1: Give the system parameters

The following parameters must be given. The values in this case are an example (used in the simulation).

Parameter	Value
Grid RMS voltage	$V_{g_rms} = 127 \text{ V}$
Grid Frequency	$f_g = 60 \text{ Hz}$
Grid Inductance	$L_s = 0.3 \text{ mH}$
Distributed Generator Power Rate	$P_{DG} = 500 \text{ W}$
Switching frequency	$f_{sw} = 30 \text{ kHz}$
Inverter DC-link voltage	$V_{DC} = 250 \text{ V}$
Percentage for the converter side impedance (related to the Base Values - good choice any value between 1 and 10)	$Z_{c\%} = 10$
Desired Current Ripple (any value between 1 and 5)	$\Delta I_{\%d} = 2$
How lower the LCL capacitor should be related to its maximum allowed value? (any value between 2 and 8 is a good guess)	$n_{cap} = 3$
Ripple attenuation (20% is a good choice)	$\Delta R_{att\%} = 20$

2) Finding the Base Values

The Base Impedance is given by (1).

$$Z_b = \frac{V_{g_rms}^2}{P_{DG}} \quad (1)$$

$$\therefore Z_b = 32.258\Omega \quad (2)$$

The Capacitor Base Value is given by (3).

$$C_b = \frac{1}{2\pi f_g Z_b} \quad (3)$$

$$\therefore C_b = 82.23\mu F \quad (4)$$

3) Finding the converter side inductance (Lc)

The converter side reactance is given by (5).

$$X_{Lc} = Z_b \frac{Z_c\%}{100} \quad (5)$$

$$\therefore X_{Lc} = 3.226\Omega \quad (6)$$

Therefore, the converter side inductance is given by (7).

$$L_c = \frac{X_{Lc}}{2\pi f_g} \quad (7)$$

$$\therefore L_c = 8.557mH \quad (8)$$

4) Finding the LCL capacitor (Cf)

The maximum allowed reactive power for a maximum FP reduction equivalent to 5% is given by (9).

$$Q_{\max} = \tan(\arccos(0.95)) P_{DG} \quad (9)$$

The maximum allowed capacitor is given by (10).

$$C_{\max} = \frac{Q_{\max}}{V_{g_rms}^2 2\pi f_g} \quad (10)$$

$$C_{\max} = 27.03\mu F \quad (11)$$

The LCL capacitor is given by (12).

$$C_f = \frac{C_{\max}}{n_{cap}} \quad (12)$$

$$C_f = 9.0\mu F \quad (13)$$

5) Finding the grid side inductance (Lg)

The relationship between the LCL capacitor value and the capacitor base value is given by (14).

$$x_c = \frac{C_f}{C_b} \quad (14)$$

$$\therefore x_c = 0.11 \quad (15)$$

The following equation must be plotted. This function is the LCL current transfer function in function of r . The vertical axis corresponds to the ripple attenuation ($\Delta R_{att\%}$)

$$I_{TF}(r) = \frac{1}{\left| 1 + r \left[1 - x_c L_c C_b (2\pi f_{sw})^2 \right] \right|} \quad (16)$$

The Fig. 2 presents the equation 16 curve.

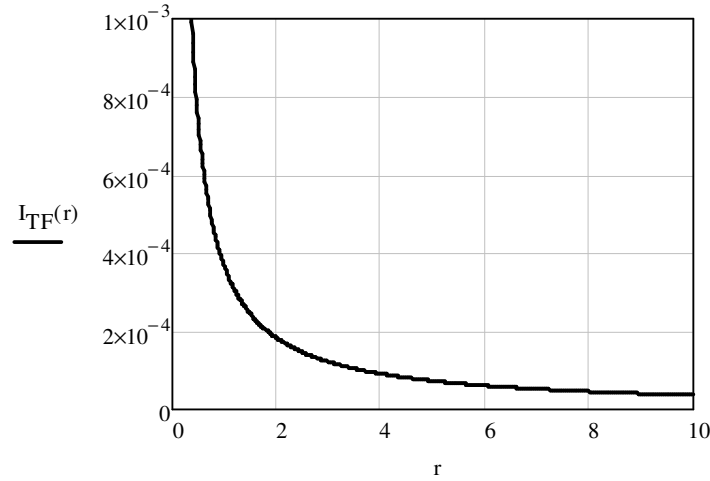


Fig. 2. The Equation 16 curve.

For the ripple attenuation chosen, the value r in the graph is:

$$r = 0.002191 \quad (17)$$

The grid side inductance is given by (18).

$$L_g = rL_c \quad (18)$$

$$\therefore L_g = 18.75\mu H \quad (19)$$

6) Checking the constraints

The LCL parameters were found. However, the reference [2] presents some constraints that must be satisfied in order to validate the calculated values. In case of violation, some parameters must be changed. Over the constraints, the main one is the LCL resonance frequency must be inside two limits. The lower limit is 10 times the grid frequency, given by (20).

$$Lower = 10f_g \quad (20)$$

$$Lower = 600Hz \quad (21)$$

The upper limit is half of the switching frequency, given by (22).

$$Upper = \frac{f_{sw}}{2} \quad (22)$$

$$\therefore Upper = 15kHz \quad (23)$$

The resonance frequency is given by (24).

$$f_{res} = \sqrt{\frac{1}{2\pi} \frac{(L_c + L_g + L_s) \frac{1}{C_f (L_s + L_g)}}{L_c}} \quad (24)$$

$$\therefore f_{res} = 7.582kHz \quad (25)$$

In this example, the constraint is satisfied.

7) Finding the passive damping

A passive damping is a resistance connected in series with the LCL capacitor. Its value must be the same to the capacitive reactance at the resonance frequency, and it is given by (26).

$$R_d = X_{cf_fres} = \frac{1}{2\pi f_{res} C_f} \quad (26)$$

$$\therefore R_d = 2.33\Omega \quad (27)$$

8) Getting the final results

The final results for this example are the following:

$$\begin{aligned} L_c &= 8.557mH \\ L_g &= 1.875\mu H \\ C_f &= 9.0\mu F \\ R_d &= 2.33\Omega \end{aligned} \quad (28)$$

9) Plot the bode diagram just for checking out

The LCL transfer function is given by (29).

$$LCL(s) = \frac{1}{L_c s} \frac{s^2 + \frac{1}{L_g C_f}}{s^2 + (f_{res} 2\pi)^2} \quad (29)$$

The Fig. 3 presents the module and phase Bode diagrams for the LCL transfer function with the adopted values. The resonance frequency is that presented in (25), as expected.

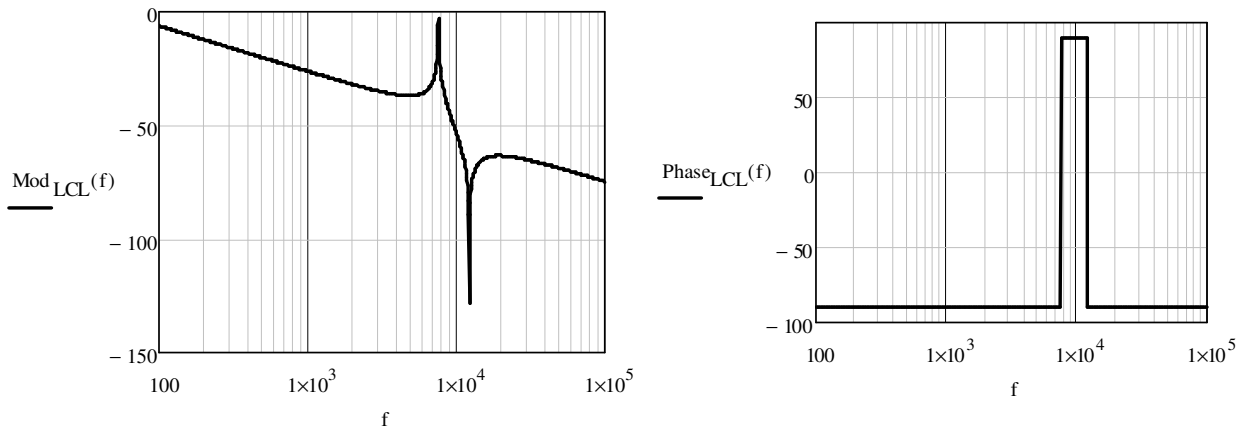


Fig. 3. Module and phase Bode diagram for the LCL transfer function.

10) Simulate

The LCL filter was simulated in distributed generator. The power circuit is presented in Fig. 4.

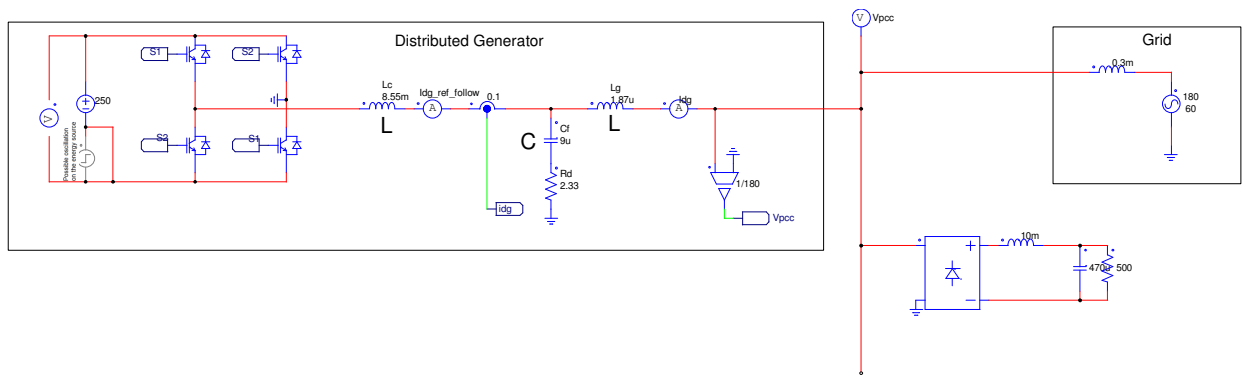


Fig. 4. The simulated power circuit.

The Fig. 5 presents the control strategy. A PLL is used to synchronize the inverter current to the PCC voltage and a type 2 controller is used. The controller was designed by frequency response technique.

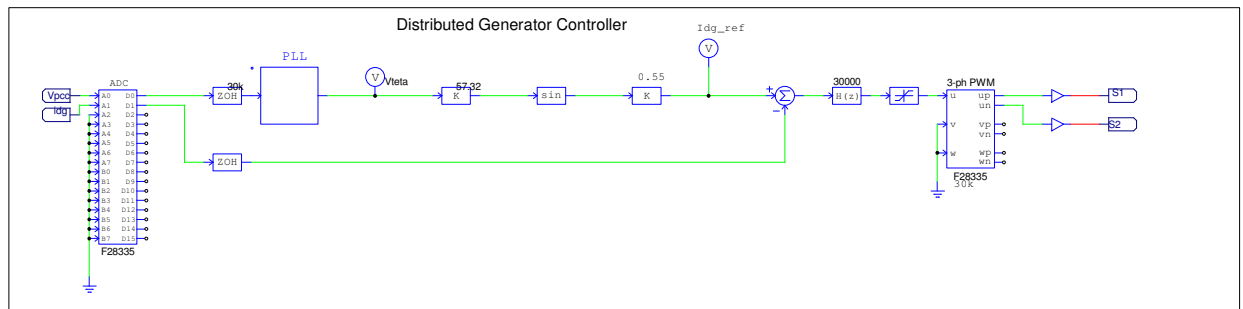


Fig. 5. The control strategy.

The Fig. 6 presents simulated results.

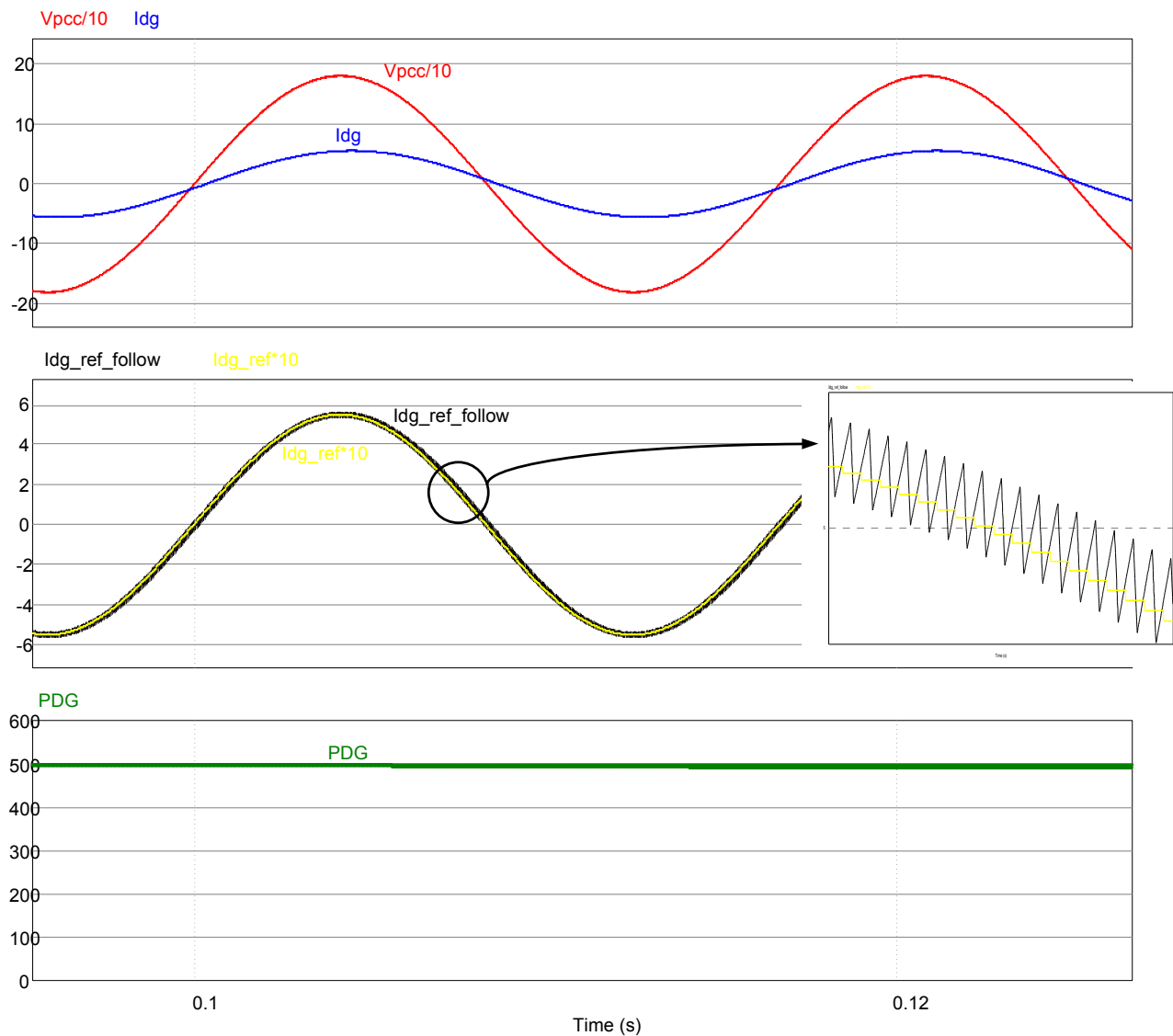


Fig. 6. Simulated Results: The PCC voltage and the DG current (top), the Lc current and its reference (middle) and the DG power transferred to the grid.

The simulation file is freely available on <https://sites.google.com/site/busarellosmartgrid/material-didatico-didactic-material/LCL%20Filter%20Design%20Procedure.psimsch?attredirects=0&d=1>

OBSERVATIONS:

This procedure was done with 30 kHz as switching frequency. However, I have tried with 10 kHz and the results were too oscillating, but not instable.

References

- [1] Teodorescu, R. ; Liserre, M. ; Rodriguez, P. . Grid Converters for Photovoltaic and Wind Power Systems. 2011, Wiley.
- [2] Liserre, M.; Blaabjerg, F.; Hansen, S., "Design and control of an LCL-filter-based three-phase active rectifier," Industry Applications, IEEE Transactions on , vol.41, no.5, pp.1281,1291, Sept.-Oct. 2005.