II. LCL FILTER AND PASSIVE DAMPING

The output filter helps in decreasing the harmonics in generated current caused by semiconductor device switching. There are several types of filters. The simplest one is the filter inductor connected to the inverter's output. But several combinations of inductor and capacitors like LC or LCL can be used. L and LC filters are not meet standard requirements that is the reason for LCL filter is utilize. But LCL filter suffer from resonance frequency. To damp out this frequency passive damping methods are used.[4-5]

A. LCL filter:

This is a third order filter with an attenuation of 60dB/decade beyond resonant frequency. Therefore it can be used for converters with low switching frequency. It is a third order filter which is difficult to be stable and introduces resonance. Thus to damp out the resonance passive damping methods are used. The LCL filter topology is shown in below figure.

The transfer function of the LCL filter and LCL filter with passive damping methods is

\[ F(s) = \frac{1}{L_1 L_2 C f S^2 + (L_1 + L_2) S} \] (1)

\[ F(s) = \frac{1}{L_1 L_2 C f S^3 + (L_1 + L_2) R d C f S^2 + (L_1 + L_2) S} \] (2)

The bode-plot for different filter topologies is as shown in below. From the bode-plot it is clear that the LCL filter with damping method has improved performance characteristics when compared with other filter topologies.

![Bode plot of L and LC filter](image_url)
Passive damping: Passive damping is done by adding a resistance in series or in parallel with the capacitance or inductance of the filter.[6-7] The four possible positions are shown in below.

### III. DESIGN OF LCL FILTER

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 damping must be added by including a resistor in series with the capacitor.[8-10] The following parameters are needed for the filter design:

- Grid line to line voltage: $E_n^2$
- Phase voltage (inverter output): $V_{ph}$
- Rated active power: $P_n$
- DC link voltage: $V_{dc}$
- Grid frequency: $\omega_g$
- Switching frequency: $\omega_{sw}$

The base impedance and base capacitance are defined by below equations. Thus, the filter values will be referred to in a percentage of the base values.

$$Z_b = \frac{E_n^2}{P_n}$$  \hspace{1cm} (4)

$$C_b = \frac{1}{\omega_g Z_b}$$  \hspace{1cm} (5)

For the design of the filter capacitance, it is considered that the maximum power factor variation seen by the grid is 5%, indicating that the base impedance of the system is

$$C_f = 0.05 \times C_b$$  \hspace{1cm} (6)

The maximum current ripple at the output of DC/AC inverter is

$$\delta I_{L_{max}} = \frac{V_{dc}}{6 \omega_{sw} L_1}$$  \hspace{1cm} (7)

Where, $L_1$ is the inverter side inductor. A 10% ripple of the rated current for the design parameters is

$$\delta I_{L_{max}} = 0.1 \times I_{max}$$  \hspace{1cm} (8)

Where

$$I_{max} = \frac{P_n V_{ph}^2}{3 V_{ph} V_{dc}}$$  \hspace{1cm} (9)

$$L_1 = \frac{6 \omega_{sw} V_{dc}}{I_{L_{max}}}$$  \hspace{1cm} (10)

Equations (9) and (10) relate the harmonic current generated by the inverter with the one injected in the grid:

$$I_g(h) = \frac{1}{1 + r [1 - L_1 C_b \omega_{sw}^2 \delta]} = K_a$$  \hspace{1cm} (11)

Or

$$L_2 = \frac{V_{dc} K_a}{\omega_g R_f}$$  \hspace{1cm} (12)

Where, $K_a$ is the desired attenuation.

The constant $r$ is the ratio between the inductance at the inverter side and the one at the grid side is

$$L_2 = r L_1$$  \hspace{1cm} (13)

Plotting the results for several values of $r$ helps in evaluating the transfer function of the filter at a particular resonant frequency, depending on the nominal grid impedance.

$$\omega_{res} = \sqrt{L_1 + L_2 \frac{L_1 L_2}{\omega_g R_f^2}}$$  \hspace{1cm} (14)

$$10 f_g < f_{res} < 0.5 f_{res}$$  \hspace{1cm} (15)

The resonant frequency range must be considered to satisfy (15). The resistor in series with the filter capacitance is given by (16).

$$R_f = \frac{1}{3 \omega_{res} f_g}$$  \hspace{1cm} (16)

### IV. SIMULATIONS

#### A. Grid connected inverter with LCL filter: 2-level grid connected inverter with LCL filter diagram shown below:

This simulation is done in Powersim(PSIM) software. The simulation parameter is shown in below table.

<table>
<thead>
<tr>
<th>Simulation Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid voltage</td>
<td>400 V</td>
</tr>
<tr>
<td>Grid frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>DC-link Voltage</td>
<td>680 V</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>4 KHz</td>
</tr>
<tr>
<td>Inductor filter (Converter side)</td>
<td>220 $\mu$H</td>
</tr>
</tbody>
</table>
Table 1: Simulation parameter of LCL filter for grid connected inverter

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacitor filter</td>
<td>40 µh</td>
</tr>
<tr>
<td>Inductor filter (Grid side)</td>
<td>80 µh</td>
</tr>
<tr>
<td>Damping resistor</td>
<td>0.5 Ω</td>
</tr>
</tbody>
</table>

The above simulation results are shown below:

Fig. 5(a): Waveform of current before filter

Fig. 5(b): Waveform of current injected into the grid

Fig. 5(c): Waveform of voltage at the point of common coupling

Fig. 5(d): Waveform of inverter output voltage

Fig. 5(e): Waveform of DC link voltage

Fig. 5(f): Waveform of FFT of phase voltage

Above Figure 5(a) shows the waveform of current before filter and THD of this current is 11.16 %. Figure 5(b) shows waveform of current injected to Grid and THD of this current is 2.34 %. Figure 5(c) shows waveform of Voltage at the point of common coupling. Figure 5(d) shows waveform of inverter output voltage. Figure 5(e) shows DC link voltage. And Figure 5(f) shows the FFT of phase voltage.

V. CONCLUSIONS

This paper presents design procedure for LCL filter for grid connected inverter and implementations of this filter is done in powersim simulation software. LCL filter has lower inductance value compared to L and LC filter. Thus reducing size and cost of the filter. In addition, LCL filter has lower grid injected current THD with IEEE standard requirements. The drawback of LCL filter is suffered from resonance. But this can be solving by Passive damping methods. This paper conclude that the LCL filter with passive damping is the right choice for grid connected inverter.

REFERENCES


