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Analysis and Implementation of AC side filter for Grid Tied Solar Inverter

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Abstract: In Solar inverter is a power electronics based converter which acts as interfacing media between solar PV panels and utility grid. IEEE 1547 has imposed limit on the magnitude of current harmonics around the inverter switching frequency. This limit necessitates the use of AC side filter at the output of the grid connected solar inverter, for connection with grid. This filter reduces the harmonic content in grid current so as to inject pure sinusoidal waveform into the grid. The filter should be so designed that it provides sufficient attenuation for the switching frequency harmonics but at the same time should allow a low impedance path for the fundamental component. Moreover the system size / volume must not increase significantly with the addition of filter. The AC side filter design needs the trade-off when considering the efficiency / switching loss and fundamental voltage drop. In this paper control theory modelling of LCL type filter is developed. Comparison of LCL filter with other filter topologies is carried out with respect to the control theory parameters like Bode plot. Detailed calculation of LCL filter for single phase grid connected solar inverter is also elaborated.

I.INTRODUCTION

Grid connected solar inverters play an important role in feeding solar PV power generation into the grid. These inverters extract the solar energy from solar photovoltaic (PV) panels and feed it into the utility grid while ensuring the power quality follows certain grid interconnection standard such as IEEE-1547. IEEE 1547 has imposed limit on the magnitude of current harmonics at the output of the inverter around its switching frequency. This limit calls

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demands the use of AC side filter at the output of the grid connected solar inverter, for connection with grid. This filter helps reducing the harmonic content in grid current so as to inject pure sinusoidal waveform into the grid. The filter should be so designed that it provides sufficient attenuation for the switching frequency harmonics but at the same time should allow a low impedance path for the fundamental component. Moreover the system size / volume must not increase significantly with the addition of filter. The AC side filter design needs the trade-off when considering the efficiency / switching loss and fundamental voltage drop.[1]

A number of AC side filters for grid tied solar inverter are available in the literature. These are L type, LC type and LCL type. All these filter types are represented in Figure 1 and are discussed below.

L filter (shown in Figure 1a) is the simplest of all the filters listed in Figure 1. Usage of first order filter makes the closed loop design simple and also frees the designer from the worries about the resonance effect on the plant. However L filter has reduced attenuation as compared to other filters having higher order. This imposes high value of filter inductor for proper attenuation of switching harmonics. This makes the system bulky and costly. Large value of L filter also increases voltage drop across the filter and makes the system dynamics sluggish in nature.

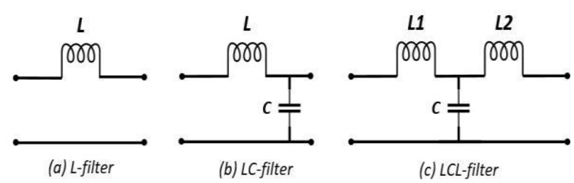

Figure 1 Various filter types

LC filter (shown in Figure 1b) represents second order filter and provides increased harmonic suppression. By increasing the capacitance value of the LC filter, low value of converter side inductance can be used for the same attenuation. This makes the system smaller in size as compared to L filter. But, usage of high value of capacitance is not

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recommended as the system may draw inrush current on account of high reactive current fed to capacitor at the fundamental frequency and because of possibility of resonance phenomenon at the grid side. Moreover for LC filter system, the resonance frequency varies with time as the inductance value of grid varies.

Use of three order filter like LCL filter (shown in Figure 1c) provides better harmonic attenuation with comparatively reduced inductance and capacitance values. LCL filter also ensures better decoupling between the filter and the grid impedance. This reduces the dependence of the filter on grid impedance. However, the designer has to take into account various constraints like resonance phenomenon, current ripple through inductor, attenuation of current harmonics at switching frequency, reactive power absorption by capacitor etc. [2]

In this paper, first, control theory modelling and theoretical analysis of LCL filter is explained. In further sections, a comparison between the designed LCL filter with other filter topologies are carried out. In next section, detailed calculation of LCL filter for single phase grid connected solar inverter of 5 kW rating will be taken up.

II. CONTROL THEORY MODELLING OF LCL FILTER

The analysis considers the ideal filter components. LCL filter without any external damping is shown in Figure 2. Here L, Lg and C are the converter side inductor, grid side inductor and filter capacitor respectively.

A. State Space Representation of LCL Filter

It is assumed that all the passive elements are ideal hence parasitic resistance of all the filter elements are negligible

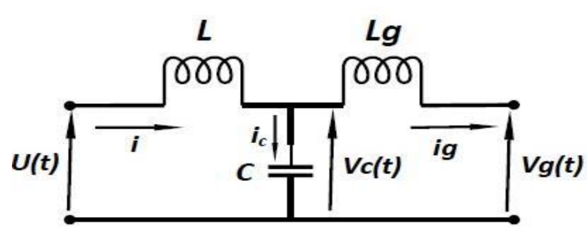

Figure 2 LCL filter

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and magnetic saturation associated with inductors is nil. The dynamic equations of this third order plant can be written as:

$$L\frac{di(t)}{dt} = u(t) - v_c(t)$$

$$L_g\frac{di_g(t)}{dt} = v_c(t) - V_g(t)$$

$$C\frac{dv_c(t)}{dt} = i(t) - i_g(t)$$

where u(t) is the input to the filter and ig(t) the output variable, which is to be controlled and Vg(t) is the grid side voltage. [3]

The three state equations of the plant are as below:

$$\frac{d}{d(t)}\begin{bmatrix} i(t) \\ i_g(t) \\ v_c(t) \end{bmatrix} = \begin{bmatrix} 0 & 0 & -\frac{1}{L} \\ 0 & 0 & \frac{1}{L_g} \\ \frac{1}{C} & -\frac{1}{C} & 0 \end{bmatrix}\begin{bmatrix} i(t) \\ i_g(t) \\ v_c(t) \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \\ 0 \end{bmatrix}u(t) + \begin{bmatrix} 0 \\ -\frac{1}{L_g} \\ 0 \end{bmatrix}V_g(t)$$

This is of the form

$$\frac{dx(t)}{dt} = Ax(t) + Bu(t) + Ed(t)$$

where, x(t) represents the state vector, u(t) the input and d(t) the disturbance input to the plant. The output equation is represented as

$$i_g(t) = \begin{bmatrix} 0 & 1 & 0 \end{bmatrix}\begin{bmatrix} i(t) \\ i_g(t) \\ v_c(t) \end{bmatrix}$$

B. System Transfer Function

Applying Laplace transform to the state space equations and by considering initial conditions as zero and by simplification, we get

$$Y(s) = [C(sI - A)^{-1}B]U(s) + [C(sI - A)^{-1}E]D(s)$$

where Y(s) is the overall plant response.

Considering Gc(s) as control to output transfer function and Gd(s) disturbance to output transfer function, Gc(s) and Gd(s) can be written as [4]

$$G_c(s) = \frac{1}{s[LL_gCs^2 + (L + L_g)]}$$

$$G_d(s) = \frac{L_gCs^2 + 1}{s[LL_gCs^2 + (L + L_g)]}$$

If a damping resistor to avoid resonance phenomenon is considered in series with the capacitor, then control to output transfer function, Gc(s) can be derived as

$$G_c(s) = \frac{RCs + 1}{s[LL_gCs^2 + (L + L_g)RCs + (L + L_g)]}$$

The resonant frequency of the system is as below

$$\omega_{res} = \sqrt{\frac{L + L_g}{L\, L_g C}}$$

C. Single Phase Grid connected PV Inverter System

The block diagram of single phase grid connected solar inverter is shown in Figure 3.

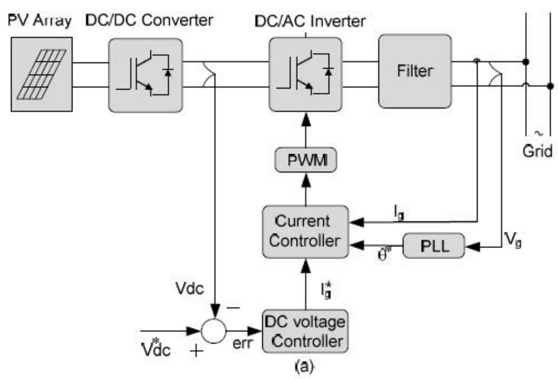

Figure 3 Block diagram of single phase grid connected solar inverter

III. DESIGN PROCEDURE OF LCL FILTER

The LCL filter procedure is explained in this section. LCL filter is developed for single phase, 5 kVA, grid tied solar inverter. Table 1 shows the various parameters of the grid tied solar inverter used for designing of the LCL filter.

Table 1 Various parameters of Grid tied solar inverter

Grid voltage, rms value	:	230 V
kVA rating of the inverter	:	5 kVA
DC link voltage	:	400 V
Grid frequency	:	50 Hz
Switching frequency	:	5150 Hz

Let us introduce following constraints as the primary design goal of LCL filter.[5]

Converter side inductor: Choose an attenuation of atleast -40 dB for the converter side inductor at switching frequency. It is given by

$$\frac{i_{f(s\omega)}}{u_{f(s\omega)}} = \frac{1}{\omega_{s\omega} L}$$

where if(sw) and uf(sw) are the converter side current and output voltage of the H-bridge at switching frequency at ωsw rps respectively.

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Filter capacitor: Fundamental current flowing through the filter capacitor should not exceed 20% of the rated current. By neglecting the voltage drop across the filter inductors, the capacitor current expression is given by:

$$i_c = j\omega_0 C V_g \quad (13)$$

Maintain a proper clearance of the resonant frequency (ωres) with fundamental frequency (ω0) and switching frequency (ωsw) to avoid possibility of resonance in lower and upper part of the harmonic spectrum. Filter resonant frequency should be atleast 20 times larger than the fundamental component and less than 0.5 times the switching frequency.

$$20\omega_0 < \omega_{res} < 0.5\,\omega_{sw} \quad (14)$$

Choose Lg in such a way that voltage drop across the impedance (L + Lg) does not exceed 2% of the rated voltage.

$$\omega_0(L + L_g) < 0.02\, V_g \quad (15)$$

The LCL filter can contain a damping resistor to avoid the resonance phenomenon and it can be calculated using following equation

$$R = \frac{1}{3\omega_{res} C} \quad (16)$$

Following these constraints, the LCL filter parameter have been obtained as follows:

Table 2 Calculated LCL filter parameter values

Converter side inductor, L	:	2 mH
Filter Capacitor, C	:	10 uF
Grid side inductor, Lg	:	2 mH
Damping resistor, R	:	3.2 Ω

IV. RESULT

A. Results

The frequency response of the various filter types are plotted in Figure 4. It can be seen that the bandwidth of filters are almost the same below the resonant frequency. It can be seen that with the introduction of damping resistor in LCL filter, the resonance phenomenon is almost eliminated.

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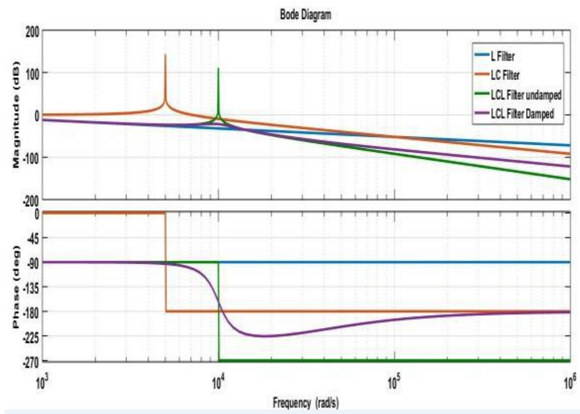


Figure 4 Frequency response for L, LC, LCL undamped and LCL damped filters

The model for the 5 kW grid connected solar inverter is developed in Matlab Simulink as shown in Figure 5.

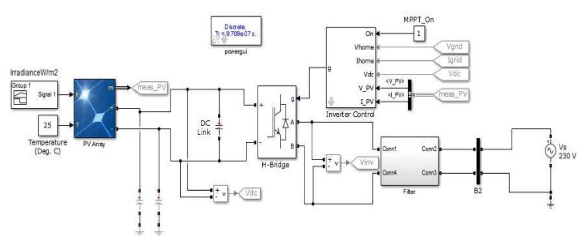
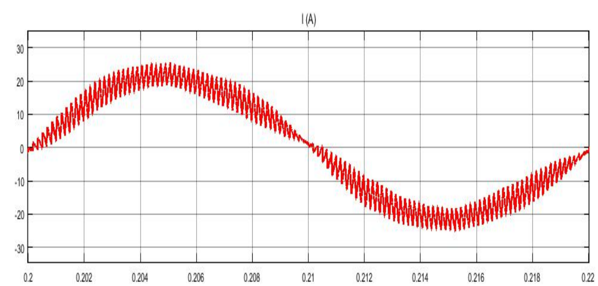
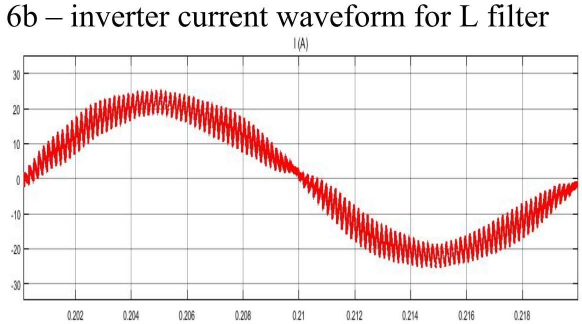


Figure 5 Matlab Simulink model of 5 kW single phase grid tied solar inverter

For comparison of performance of different types of filters, in this paper, the calculated values of the LCL parameters were used (L = 2 mH, Lg = 2 mH, C = 10 uF) and for L filter L = 4 mH is considered whereas for LC filter, L = 4 mH and C = 10 uF is used. The simulation results for inverter output voltage waveform at the output terminals of the filter is presented in Figure 6a. This voltage waveform remains the same for all types of filters types. The current waveform injected into grid (at the output of the filter) are also presented for different case of filter – Figure 6b for L filter, 6c for LC filter and 6d for LCL filter. It can be seen that LCL filter has better distortion elimination in current waveform as compared to L and LC type filter.



6b – inverter current waveform for L filter



6b – inverter current waveform for LC filter

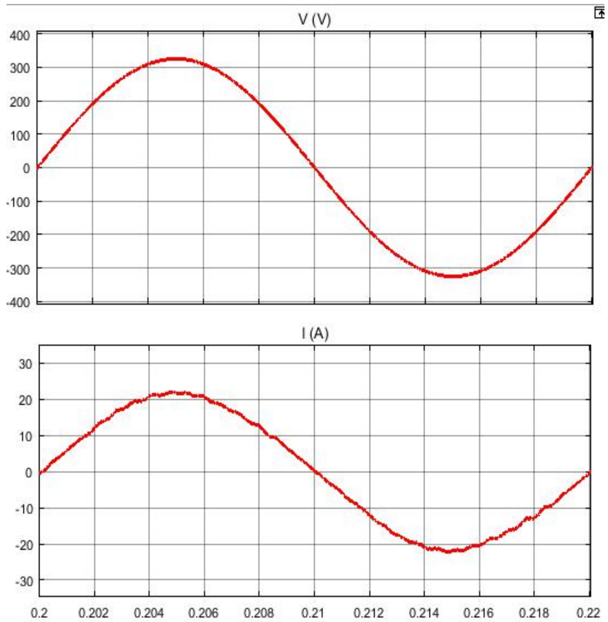


Fig: inverter output voltage and current waveforms with Filter.

The THD of the inverter current fed to grid is presented in Table 3 below:

Table 3 Percentage THD in inverter current fed to grid for various filter types

Filter type		% THD
L filter	:	9.06%
LC filter	:	7.08 %
LCL filter	:	3.11%

CONCLUSIONS

In this paper, design constraints for LCL filter design for single phase grid tied solar inverter has been discussed. Also the comparison of LCL filter with L filter and LC filter has been presented. The result of comparison shows that LCL filter has better ripple elimination as compared to L and LC type filter. The frequency response of various types of filter were plotted and it has been found that with the introduction of damping resistor in series with the capacitor of LCL filter, the resonance phenomenon is almost eliminated.

Hence it has been shown in this paper that LCL filter has better performance than other filter types in case of same inductance, capacitance and damping resistance values.

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