

# Design of LCL Filter to Mitigate Harmonics in Grid Interconnected System

Sumeet T. Sonule<sup>1</sup>, R. S. Desai<sup>2</sup>

Bharati Vidyapeeth Deemed University, College of Engineering, Pune, Maharashtra, India<sup>1</sup>  
ssonule7178@gmail.com

Bharati Vidyapeeth Deemed University, College of Engineering, Pune, Maharashtra, India<sup>2</sup>  
rsdesai@bvucoep.edu.in

## ABSTRACT

Due to increasing power demand and bad effects of conventional energy sources on the environment, renewable energy sources are being important. For maximizing the power extracted from renewable energy sources such as solar and to transfer it to utility grid, power converters are being used. For maximizing the power, DC-DC boost converter plays an important role. The power generated from solar is DC and most of electrical equipments run on AC hence an inverter is required. Due to use of inverter, harmonics are generated in system. To mitigate the harmonics an LCL filter is often used. LCL filter design method with proper control technique is described in this paper. This design procedure and control techniques can be used for small and medium scale renewable energy sources.

**Keywords:** DC-DC Boost Converter, Power Quality, Inverter, Harmonics, Filter, Pulse-Width Modulated (PWM) Inverters

## I. INTRODUCTION

In present, due to increasing world population a widely interconnected power system network is used, as requirement of the power is increasing day by day, load demand increases. Because of increasing load demand, the generated power is not sufficient for providing load requirements efficiently and effectively therefore power quality of utility is decreasing day by day. Due to bad effects of conventional energy sources on the environment and increasing power requirement, renewable energy sources are being important. For increasing the power transmission from renewable energy i.e. solar, power converters is very important. A DC-DC converter is power electronic converter which converts voltage directly from DC to DC. The input of DC-DC converter is fluctuating and uncontrolled and output of this converter is not fluctuating, regulated and controlled. This converter has variable turns ratio which is practically equivalent to transformer which works on AC. It can be used to increase or decrease a DC signal [1], [2].

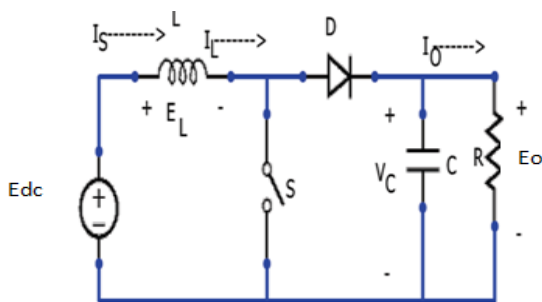
As output of solar is DC and most of the electrical equipments is worked on the AC hence inverter is used [6]. Most of the inverter are Voltage Source Inverters (VSIs), which converts the DC power into AC. A filter is need to be placed between the utility grid and VSI, for mitigating the harmonics generated by inverter. We can use a series connected inductor but the harmonic mitigation of series connected inductor is not good. Also it produces the high voltage drop and required size of inductor is very large [5]. We can use LC filter, as the structure and parameter are easy, but due to uncertainty of network impedances, filtering effect is not good.

Instead of series connected inductor or LC filter, for smoothing the output from the VSI, an LCL filter is used [5],[6]. By using LCL filter higher attenuation can be achieve also we can achieve cost saving and there is reduction in size and weight of the components. In grid connected inverter, pulse width modulation (PWM) is used along with LCL filter because they lowers the amount of current distortion generated by inverter in the

utility grid [5]-[7]. We can achieve good performance in the range of power levels up to several kilowatts. As LCL filter has higher harmonic attenuation which allows the use of lower switching frequency to meet the harmonic constrains as defined by IEEE standards viz. IEEE-519 and IEEE-1547[9][10]. By the observation, for designing of LCL filter sufficient information is not available. For effective result of filter we have to design appropriate mathematical model for it. The objective of this paper is do modelling and analyses of three phase LCL filter connected to inverter which transfers solar energy to grid.

## II. BOOST CONVERTER

DC-DC boost converter is shown in figure1, where  $E_{dc}$  is output from PV panel, L is inductor, C is a capacitor and R is resistance of load. A circuit contains the inductor in series and capacitor in parallel with the load. Boost converter operation is depends on the operation of the switch. DC-DC converter output is regulated and controlled [1].



**Figure1.** Schematic diagram of Boost Converter

Maximum power from the PV panel can be obtained by the DC-DC boost converter. IGBT is used as a switch in boost converter. We can control the ON-OFF of switch by giving proper gate pulses. The operation of boost converter is controlled by this switch[2].

For designing of boost converter we need to assume certain parameters which can be useful for designing L, C for boost converter. Table 1 shows the parameters which are consider for designing of boost converter.

With the help of parameters from the table 1, we can design the component L and C for boost converter. In the boost converter operation there is an important role of duty cycle. For controlling the switch, proper control technique has to be provide to supply the gate pulses to the converter.

Table 1

Parameter	Symbol	Value
Open Circuit Voltage	$E_{dc}$	205 V
Desired output Voltage	$E_o$	400 V
Load current	$I_o$	6 A
Switching frequency of IGBT	$f_{sw}$	20000 Hz

With the help of parameters from the Table 1, we can design the component L and C for boost converter. In the boost converter operation there is an important role of duty cycle. For controlling the switch, proper control technique has to be provide to supply the gate pulses to the converter.

Duty cycle (D) can be find by the following formula,

$$D = 1 - \frac{E_{dc}}{E_o} * \eta \quad (1)$$

Where,  $\eta$  is converter efficiency i.e. 90%.

For finding the value of inductor L, value of ripple current (di) is needed.

$$di = 2 * I_o * \frac{E_{dc}}{E_o} \quad (2)$$

As value of ripple current is known, the value of inductor can given by,

$$L = \frac{E_{dc}(E_o - E_{dc})}{f_{sw} * E_{dc} * di} \quad (3)$$

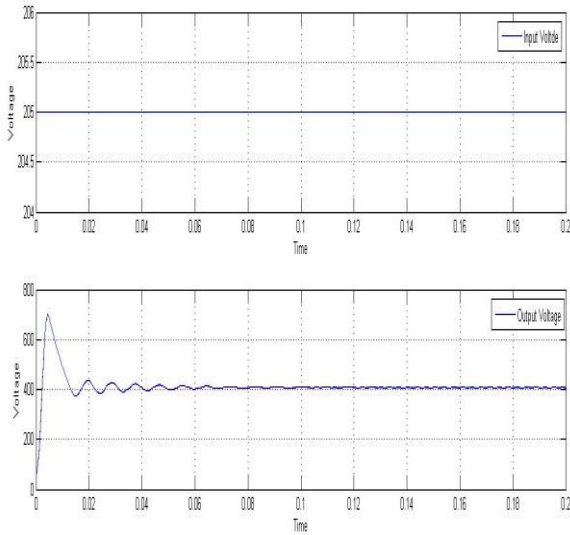
Similarly, for finding the value of capacitor, value of ripple voltage (dv) is needed.

$$dv = \frac{1}{1-D} * \frac{di}{2} \quad (4)$$

As value of ripple voltage is known, the value of capacitor is given by,

$$C = \frac{I_o * D}{f_{sw} * dv} \quad (5)$$

Hence, from equations (1)-(5) designing of boost converter is possible. With value of the L and C the simulation is done in MATLAB and results are given below,



**Figure 2.** Input and Output Voltage of Boost Converter

### III. INVERTER

The power generated by the solar sources is in DC. There is need of conversion of DC power to AC, as most of the equipments connected to utility runs on AC power. The conversion of DC-AC is done by DC-AC converter which is usually known as inverter[3]. For operating of these converters, proper gate pulse is required. Gate pulse can be generated by various means as there is lots of literature available. For generating gate pulses proper control algorithm is required.

We need to convert three phase to single phase as control of three phase is very complicated process. The conversion of three phase to single phase can be achieved by Clarke's transformation [3]-[4]. Reference waves can be generated by using proper control algorithm and we can provide pulses using PWM technique. The equations for conversion of three phase to single phase are given below,

$$\begin{bmatrix} Vd \\ Vq \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} Va \\ Vb \\ Vc \end{bmatrix} \quad (6)$$

When the error is find out from actual and reference value, conversion of single phase to three phase signal is required. For this conversion inverse Clarke transform is used.

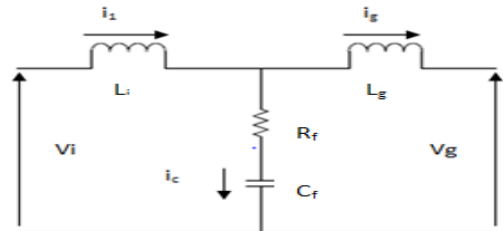
$$\begin{bmatrix} Va \\ Vb \\ Vc \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} Vd \\ Vq \end{bmatrix} \quad (7)$$

Hence, from the above equation three phase control signal is generate. By using these three phase controlled signal as a reference wave and comparing it to carrier wave, gate pulses can be generated. By providing these generated pulses to inverter, conversion of DC-AC occurs.

### IV. LCL FILTER

While injecting power in to the grid, concern about power quality is important. As the conversion of AC-DC is done by means of power converter viz. inverter, due to switching it contains harmonics. Hence modeling and designing of filter is important for mitigation of harmonics. In this paper 3<sup>rd</sup> order LCL filter is designed, which is connected in between inverter output and load[6].

#### A. Pre- Phase Equivalent Modeling



**Figure 3.** Pre- phase model of LCL filter

Figure 3 shows the schematic model of LCL filter, Table 2 shows the parameter used in figure 3.

Table 2

Symbol	Parameter
$L_i$	Inverter side inductor
$L_g$	Grid side inductor
$C_f$	Capacitor
$R_f$	Damping resistor
$V_i$	Input voltage
$V_g$	Output voltage
$i_i$	Inverter output current
$i_g$	Grid current
$i_c$	Capacitor current

### V. FILTER DESIGN PROCEDURE

While designing an LCL filter, many characteristics must be considered, such as filter size, switching ripple attenuation and current ripple. The capacitor interacting with grid may cause resonance due to reactive power requirement. Therefore by connecting resistor in series

with capacitor, active or passive damping must be added [6].

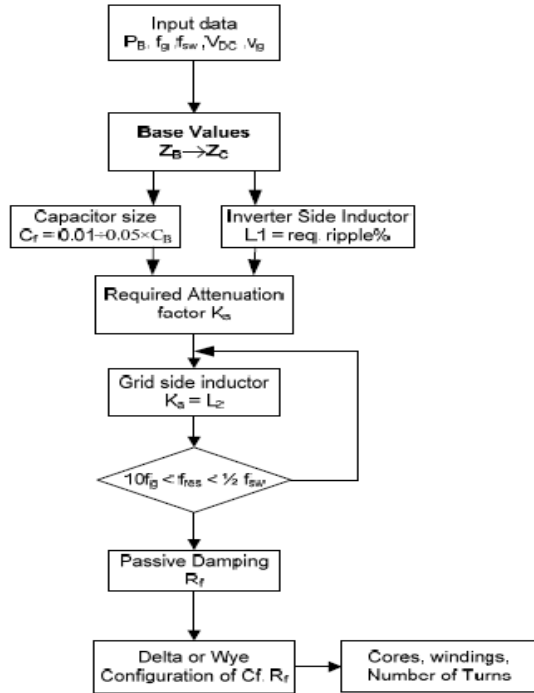


Figure 4. LCL filter design algorithm

Appropriate procedure should be used for designing the LCL filter. For designing of LCL filter we have to consider certain parameters. With help of these parameters we can calculate the values of  $L_i$ ,  $L_g$ ,  $C_f$  and  $R_f$ . Figure 4 shows the proper procedure for LCL filter design. We can calculate the values of  $L_i$ ,  $L_g$ ,  $C_f$  and  $R_f$  from the following formula

$$L_i = \frac{V_{dc}}{6f_{sw}\Delta I_{max}} \quad (8)$$

Where  $V_{dc}$  is DC-link voltage and  $f_{sw}$  is switching frequency.

$$C_f = 0.05C_b \quad (9)$$

Where  $C_b$  is base capacitance

$$L_g = \frac{\sqrt{\frac{1}{ka}+1}}{C_f\omega_{sw}^2} \quad (10)$$

Where  $k_a$  is desired attenuation factor

$$R_f = \frac{1}{3\omega_{res}C_f} \quad (11)$$

Where  $\omega_{res} = \sqrt{\frac{Li+Lg}{LiLgCf}}$  (resonance angular frequency)

For the calculation of  $L_i$ ,  $L_g$ ,  $C_f$  and  $R_f$  following parameters must be consider,

Table 3

Parameter	Symbol	Value
Input DC voltage	Vdc	400V
PWM carrier frequency	$f_{sw}$	15kHz
Nominal power	$P_n$	5kW
Attenuation factor	$k_a$	20%
Line-to-line RMS voltage	$V_{rms}$	$120\sqrt{3}$

## VI. FREQUENCY RESPONSE OF LCL FILTER

Transfer function (T.F.) of LCL filter is  $H_{LCL} = \frac{ig}{Vi}$ , assume grid voltage as ideal voltage source, which can damp all harmonic frequencies. If  $V_g = 0$ , i.e. condition for current controlled inverters, the T.F. of LCL filter with neglecting damping is,

$$H_{LCL}(s) = \frac{1}{LiCfLgs^3 + (Lg+Li)s} \quad (12)$$

and T.F. with damping resistance is,

$$H_{dLCL}(s) = \frac{RfCfs+1}{LiCfLgs^3 + Cf(Li+Lg)Rfs^2 + (Lg+Li)s} \quad (13)$$

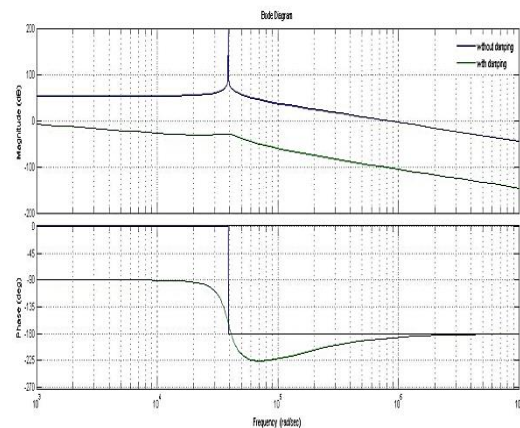


Figure 5. Bode plot for damped and undamped system

Figure 5 shows the bode plot of LCL filter With damping and without damping. Capacitor with series resistance eliminates the gain spike. Also helps to smooth the overall response.

## VII. SIMULATION RESULTS

Figure 6 shows the MATLAB/Simulink model of grid connected LCL filter. Table 4 shows the tested system parameters. With the help of these parameters system is analyzed. The output of system is analyzed for total harmonic distortion (THD) with and without filter. THD analysis is observed by the FFT tool available in MATLAB.

Table 4

Parameters	Symbol	Value
Inverter side inductor	$L_i$	2.33mH
Grid side inductor	$L_g$	0.045mH
Filter Capacitor	$C_f$	15 $\mu$ F
Damping resistor	$R_f$	0.55 $\Omega$

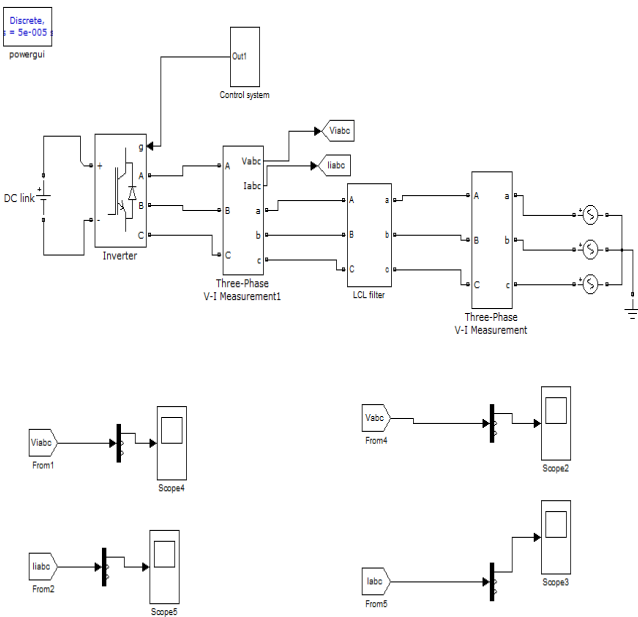


Figure 6. MATLAB model of grid connected LCL filter.

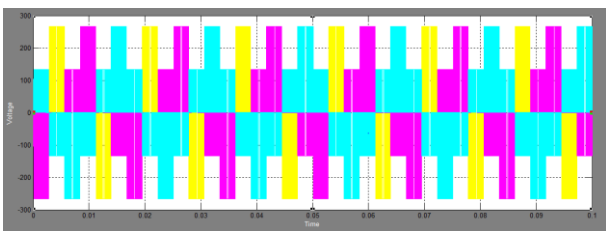


Figure 7-A. Voltage waveform before filter

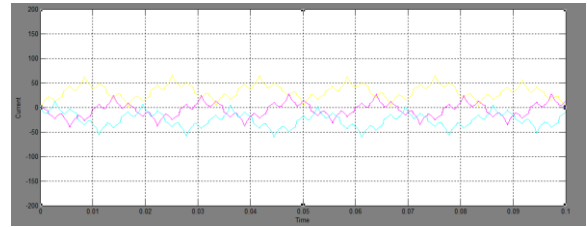


Figure 7-B. Current waveform before filter

First the THD analysis of the system is done without filter. The total harmonic distortion (THD) analysis of the system without filter is found to be 64.55%. Figure 7-A and 7-B shows the waveform of voltage and current before filter and THD analysis is shown in figure 8.

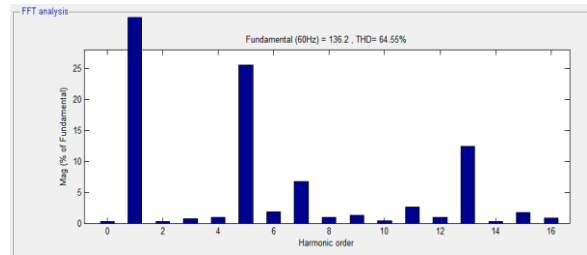


Figure 8. THD analysis before filter

As the harmonics of the system is above the prescribed limit given by IEEE standards viz. IEEE-519 and IEEE5147 [9][10]. So we need to connect the LCL filter in series with system to mitigate harmonics. After connecting the filter, THD analysis of the system is found to be 0.19%, which is in prescribe limit. Figure 9-A and 9-B shows the waveform of voltage and current after filter and THD analysis is shown in figure 10.

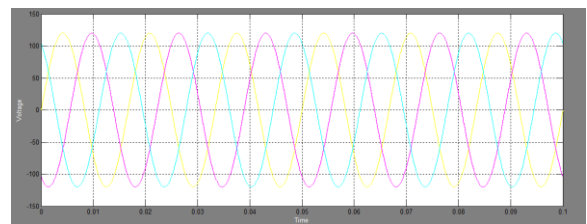


Figure 9-A. Voltage waveform after filter

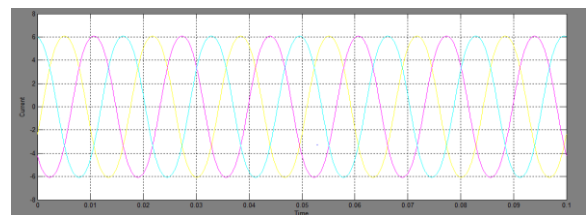
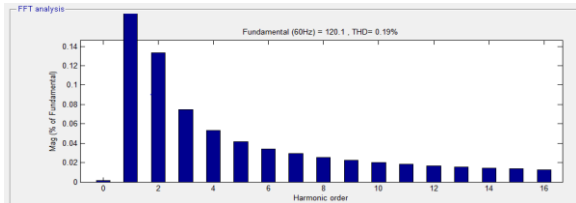


Figure 9-B. Current waveform after filter





**Figure 10.** THD analysis after filter.

## VIII. CONCLUSION

This paper propose the systematic design module of boost converter to increase the energy of solar. Also it proposes the LCL filter design model to connect the DC power generated form solar to grid with inverter and proper control technique is described. The LCL filter mitigates the harmonics present in the system. THD analysis of the system shows that the simulation model reduces the THD within prescribed limit. This design procedure and control techniques can be used for small and medium scale renewable energy sources.

## IX. REFERENCES

- [1]. "Design, simulation and Analysis of microcontroller based DC-DC Boost converter using Proteus design" Suiet S. Sheik Mohammed, D. Devaraj Faculty of Engineering Dhofar University, PB No.2509, Salala, Oman.
- [2]. S. Masri, P. W. Chan, School of electrical and electronics Engineering, University Sains Malaysia "Design and development of DC-DC boost converter with constant output voltage."
- [3]. Irvin J. balaguer, Quin Lei, ShuitaoYangandZhengPeng "Control For Grid Connected and Intentional Islanding Operations of Distributed Power Generation" IEEE Trans. On Industrial Electronics, Vol. 58, No. 1, January 2011,pp- 147-157.
- [4]. J.Selvarajand, N.A.Rahim, "Multilevel inverter for grid- Connected PV system modeling using digital PI controller", IEEE Trans. Ind. Electronics vol.56, no.1, pp.149 158, Jan 2009.
- [5]. F. Bouchafaa, D. Beriber, and M. S. Boucherit, "Modeling and control of a grid connected PV generation system," in Proc. 18th MED Conf. Control Autom., 2010, pp. 315–320.
- [6]. M. Liserre, F. Blaabjerg, and S. Hansen, "Design and control of an LCL filter- based three-phase active rectifier," IEEE Trans. Ind. Appl., vol. 41, no. 5, pp. 1281–1291, Sep./Oct. 2005.
- [7]. V. Blasko and V. Kaura, "A novel control to actively damp resonance in input LC filter of a three-phase voltage source converter," IEEE Trans. Ind. Appl., vol. 33, no. 2, pp. 542–550, Mar./Apr. 1997.
- [8]. Y. Tang, S. Member, P. C. Loh, P. Wang, and F. H. Choo, "Generalized design of high performance shunt active power filter with output LCL filter," IEEE Trans. Ind. Electron., vol. 59, no. 3, pp. 1443–1452, Mar. 2012.
- [9]. 519-1992 IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems, IEEE Std 519-1992, 1993.
- [10]. 1547.1 IEEE Standard Conformance Test Procedures for Equipment Interconnecting Distributed Resources with Electric Power Systems, IEEE Std 1547.1-2005, 2005.
- [11]. S. V. Araújo, A. Engler, B. Sahan, V. U. Kassel, F. Luiz, and M. Antunes, "LCL filter design for grid-connected NPC inverters in offshore wind turbines," in Proc. 7th Int. Conf. Power Electron., 2007, pp. 1133–1138.