MODELLING, DESIGN AND PERFORMANCE ANALYSIS OF LCL FILTER FOR GRID CONNECTED THREE PHASE POWER CONVERTERS

Abstract
The use of Power Converters to integrate renewable sources of power with the ac grid has been on the increase in the last two decades. An LCL filter is often used to interconnect the Power Converters to the utility grid in order to filter the high order harmonics produced by the Converter. To achieve the high filtering performance that meet the stringent grid code requirement and also balance cost and effectiveness, an optimal design of the LCL filter is required. This paper presents the modelling and a comprehensive design methodology of an LCL filter for grid – interconnected converters using analytical approach. The simulation results show that with this design method, 98.51% of the current harmonics present at the converter output is mitigated.

Keywords: LCL Filter, Power Converter, Total Harmonic Distortion (THD), Passive Damping.

1.0 Introduction

Use of Power Converters to interconnect to the grid has been on the increase in applications such as power quality, regenerative motor drive and distributed generation (DG) (John *et al.*, 2009). Various distributed generation systems like photo-voltaic (PV) and fuel cells produce energy in the form of DC voltage sources. Moreover, wind produces variable AC and is most times converted to DC also. Thus, when interfaced with a DC/AC inverter, these DG systems can supply energy into the utility grid. However, the power electronic devices used in these voltage source inverters (VSI), inject undesirable harmonics affecting the nearby loads at the point of common coupling (PCC) to the utility grid breaching the typical standards for grid interconnection.

Hence, to interface these power converters (VSI) to the utility grid, a filter is often required to reduce harmonics in the output current to desirable limits (Sarkar, 2015). LCL-filter is among the best performing filters for grid-connected voltage source inverters (VSI) (Jayalath and Hanif, 2017b). Design of filters used in grid-connected inverter applications involves a large number of constraints. The filter requirements are driven by tight tolerances of standards such as IEEE 519-1992–IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems, IEEE 1547.2-2008–IEEE Application Guide for IEEE Standard, IEEE 1547-2005 – IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems (John *et al.*, 2009; IEEE Standard 519 – 1992 1993; IEEE Standard 1547.1 – 2005 2005), reactive power compensation limit and maximum allowable voltage drop across the filter to limit the switching losses (John *et al.*, 2009; Jayalath and Hanif, 2017b). Higher order LCL filters are essential to achieve these regulatory standard requirements at compact size and weight (John *et al.*, 2009). Designing of the LCL filter parameters (grid-side and inverter-side inductors and capacitor), takes an iterative approach due to the coherence between the filter parameters and these design requirements (Jayalath and Hanif, 2017a). The objective of this paper is to propose design procedures for such higher order LCL filters and to provide insight into methodologies for optimized filter design.

1.1 Advantage of High order Filter over First order Filter

A simple first order L filter is not only bulky but fails to meet the stringent specifications for harmonic attenuation (Channegowda *et al.*, 2010). A third order LCL filter is now commonly used to achieve a higher attenuation (Karshenas and Saghafi, 2006) and standards with significant size and cost reduction of the components (Liserre *et al.*, 2005; Channegowda *et al.*, 2010). However designing an LCL filter systematically is a complex task (Jayalath and Hanif, 2017a). Quite a number of important factors namely output current ripple, current harmonics sourced by insulated gate bipolar transistor (IGBT) switches, series fundamental drop, desirable power factor, resonance frequency, control stability are needed to be considered carefully (Liserre *et al.*, 2005; Channegowda *et al.*, 2010). Also, attention must be paid to the overall filter size and cost of its components while selecting various parameters for an efficient design. Figure 1 gives a comparison between a first order (L) filter and a third order (LCL) filter. It shows that a third order filter is superior at attenuating higher harmonic frequencies and can therefore be designed to meet the stringent specifications for harmonic attenuation. This is because for the same (or lower) net inductance ($L1+L2$) we have better attenuation (60dB/decade) in third order filter at frequencies above the resonance frequency.

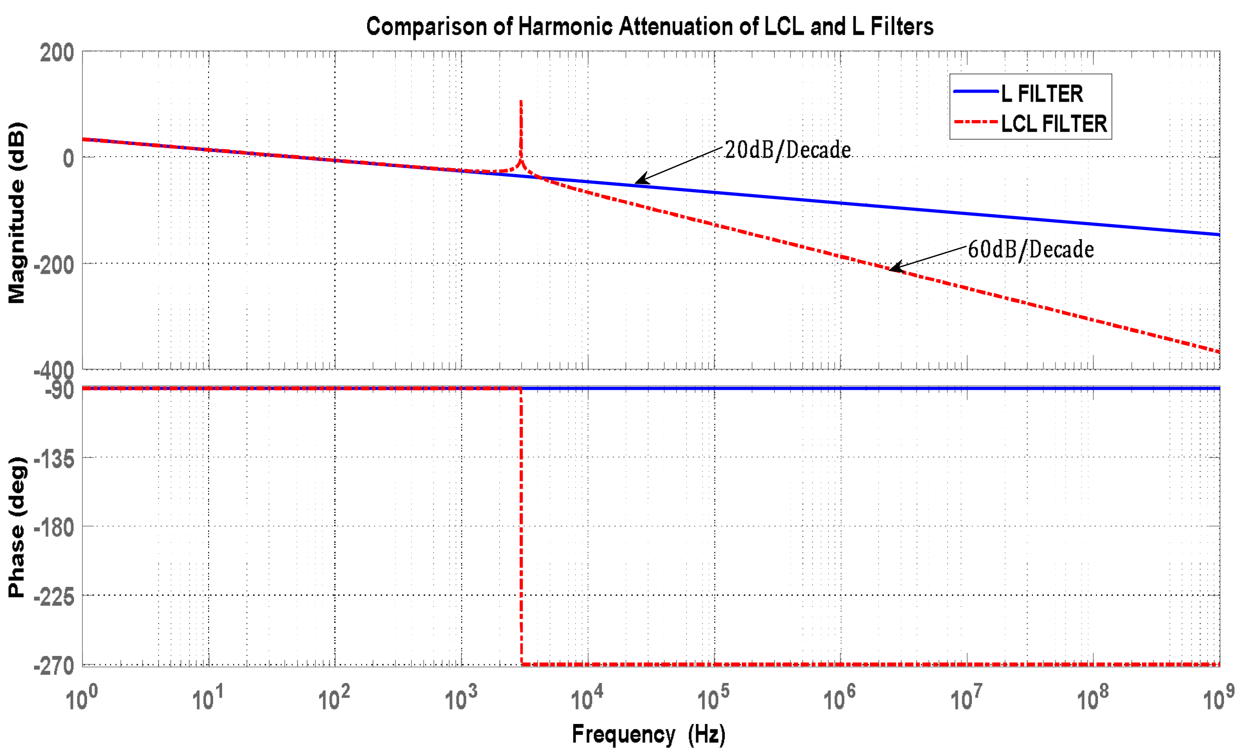


Figure 1: Comparison of Harmonic Attenuation of LCL and L Filters

2.0 Characterization of Harmonics in PV Inverter System

The level and order of harmonics present in the output of a Voltage Source Inverter (VSI) is determined. The characterization is done to know the level of harmonics that is present in the output of a VSI.

Here, the Voltage Source Inverter (VSI) was implemented in a Simulink window and the output of the VSI is analyzed in terms of the harmonic content and distortion in the current waveform. Figure 2 shows the Simulink model for the characterization.

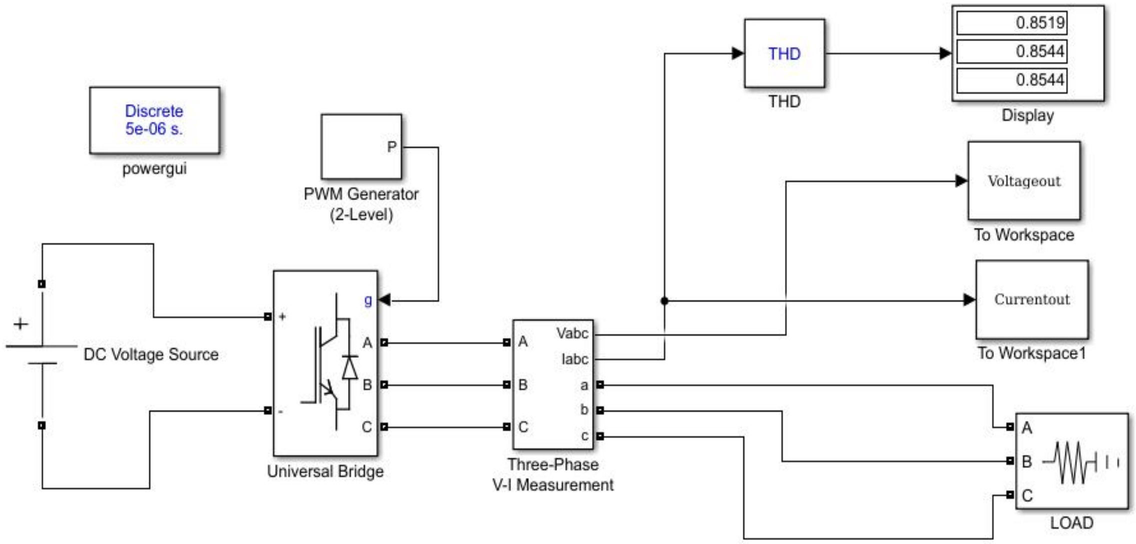


Figure 2: Simulink Model for Characterization of Harmonics in PV Inverter System

2.1 Modeling and Design of LCL Filter

The transfer function model of the LCL filter is developed and the parameters of the model gotten through a clear design procedure. The modeling and the design of the LCL filter are done to determine the values of the parameters of the filter. The LCL filter is used to mitigate higher order harmonics present at the output of the VSI. A mathematical model is developed using the power circuit of a three phase grid connected VSI with LCL filter. The three phase power circuit is reduced to a single phase equivalent circuit and the transfer function of the LCL filter derived using the circuit parameters.

2.1.1 LCL Filter Mathematical Model

The power circuit of a three phase grid connected power converter is presented in Figure 3. As depicted in this figure and in the Single Phase equivalent circuit of Figure 4, the LCL filter is used to interface between the grid and the power converter. Vg refers to the grid voltage, while $L_1$and L_2 are the converter side inductor of the LCL filter and the grid side inductor of the LCL filter respectively. C refers to the LCL filter capacitor and R_D is the damping resistor. V_{DC} is the DC – Bus Voltage.

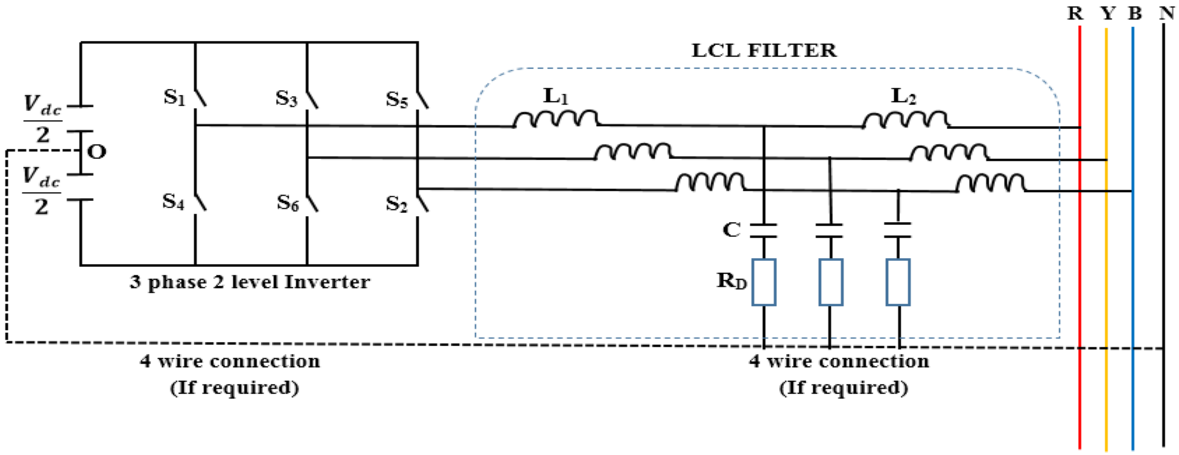


Figure 3: Power circuit of the three phase grid connected Inverter with LCL filter

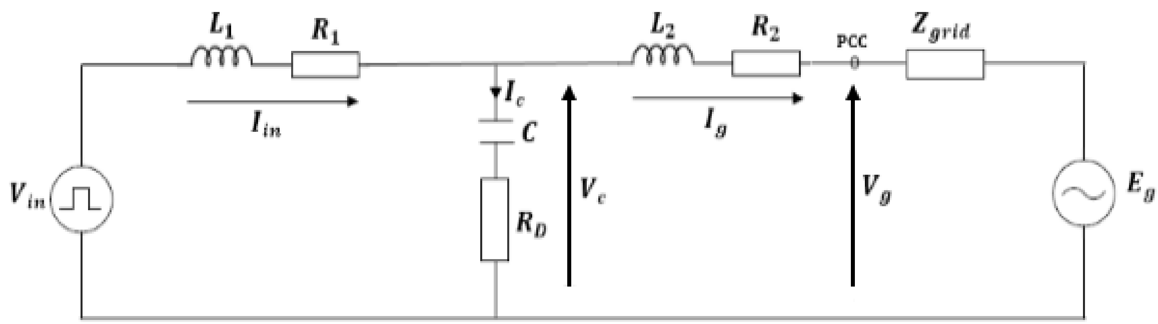


Figure 4: Single Phase equivalent circuit

In the model of the LCL filter, we consider that;

- At frequencies other than the fundamental frequency, the grid behaves essentially as a short circuit, i.e. Vg = 0.

An important transfer function for the LCL filter is given as;

$$H = \frac{i_g}{V_{in}} = \frac{Filter\ output\ current}{input\ voltage} \quad (2.1)$$

Therefore, H is an admittance transfer function and in the complex S domain, we have;

$$H(s) = \frac{I_g(s)}{V_{in}(s)} \quad (2.2)$$

Applying Kirchhoff's laws, the equivalent circuit in Figure 4, the mathematical model of the filter in s-plane is given by these equations:

$$I_{in} - I_c - I_g = 0 \quad (2.3)$$

$$V_{in} - V_c = I_{in}(sL_1 + R_1) \quad (2.4)$$

$$V_c - V_g = I_g(sL_2 + R_2) \quad (2.5)$$

$$V_c = I_c\left(\frac{1}{sC} + R_D\right) \quad (2.6)$$

The circuit parameters are defined as;

V_{in}	Inverter Voltage
I_{in}	Inverter Current
V_c	Voltage across Filter Capacitor
I_c	Filter Capacitor Current
I_g	Grid Current
L_1	Inverter side inductor
L_2	Grid side inductor
C	Capacitor
R_D	Damping Resistor
V_g	Grid voltage
R_1	Inverter Side Parasitic Resistance
R_2	Grid Side Parasitic Resistance

Figure 5 gives the block diagram of the LCL Filter in the frequency domain.

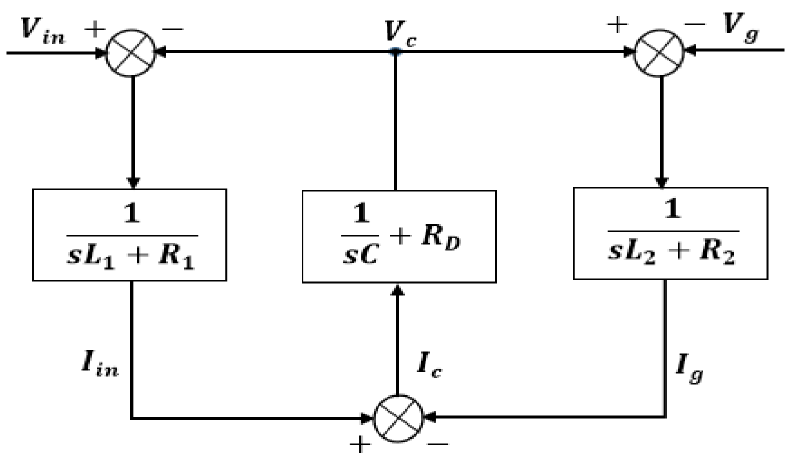


Figure 5: Block diagram of LCL Filter in S – Plane

Recall that for frequencies other than the fundamental frequency, Vg = 0.

Putting Vg = 0 in equation 2.5, gives;

$$V_c = I_g(sL_2 + R_2) \qquad (2.7)$$

Equating 2.6 with 2.7 yields;

$$I_g(sL_2 + R_2) = I_c\left(\frac{1}{sC} + R_D\right) \qquad (2.8)$$

This implies that;

$$I_c = I_g\left(\frac{s^2CL_2 + sCR_2}{sCR_D + 1}\right) \qquad (2.9)$$

From equation 2.3,

$$I_{in} = I_c + I_g \qquad (2.10)$$

Putting equation 2.9 into equation 2.10 gives;

$$I_{in} = I_g + I_g\left(\frac{s^2CL_2 + sCR_2}{sCR_D + 1}\right) \qquad (2.11)$$

Also, from equation 2.4,

$$V_{in} = V_c + I_{in}(sL_1 + R_1) \qquad (2.12)$$

Substituting equations 2.7 and 2.11 into 2.12 gives;

$$V_{in} = I_g(sL_2 + R_2) + (sL_1 + R_1)\left[I_g + I_g\left(\frac{s^2CL_2 + sCR_2}{sCR_D + 1}\right)\right] \qquad (2.13)$$

$$V_{in} = I_g\left[(sL_1 + R_1) + (sL_2 + R_2) + \frac{(sL_1 + R_1)(s^2CL_2 + sCR_2)}{sCR_D + 1}\right] \qquad (2.14)$$

$$V_{in} = I_g\left[\frac{s^3CL_1L_2 + s^2C(L_1(R_2 + R_D) + L_2(R_1 + R_D)) + s\left(L_1 + L_2 + C(R_1R_2 + R_1R_D + R_2R_D)\right) + R_1 + R_2}{sCR_D + 1}\right] \qquad (2.15)$$

Therefore, the transfer function according to equation 2.2 is:

$$Hd_{LCL}(s) = \frac{sCR_D + 1}{s^3CL_1L_2 + s^2C(L_1(R_2 + R_D) + L_2(R_1 + R_D)) + s\left(L_1 + L_2 + C(R_1R_2 + R_1R_D + R_2R_D)\right) + R_1 + R_2} \qquad (2.16)$$

Without the damping resistance R_D, equation 2.16 becomes;

$$H_{LCL}(s) = \frac{1}{s^3CL_1L_2 + s^2C(L_1R_2 + L_2R_1) + s\left(L_1 + L_2 + C(R_1R_2)\right) + R_1 + R_2} \qquad (2.17)$$

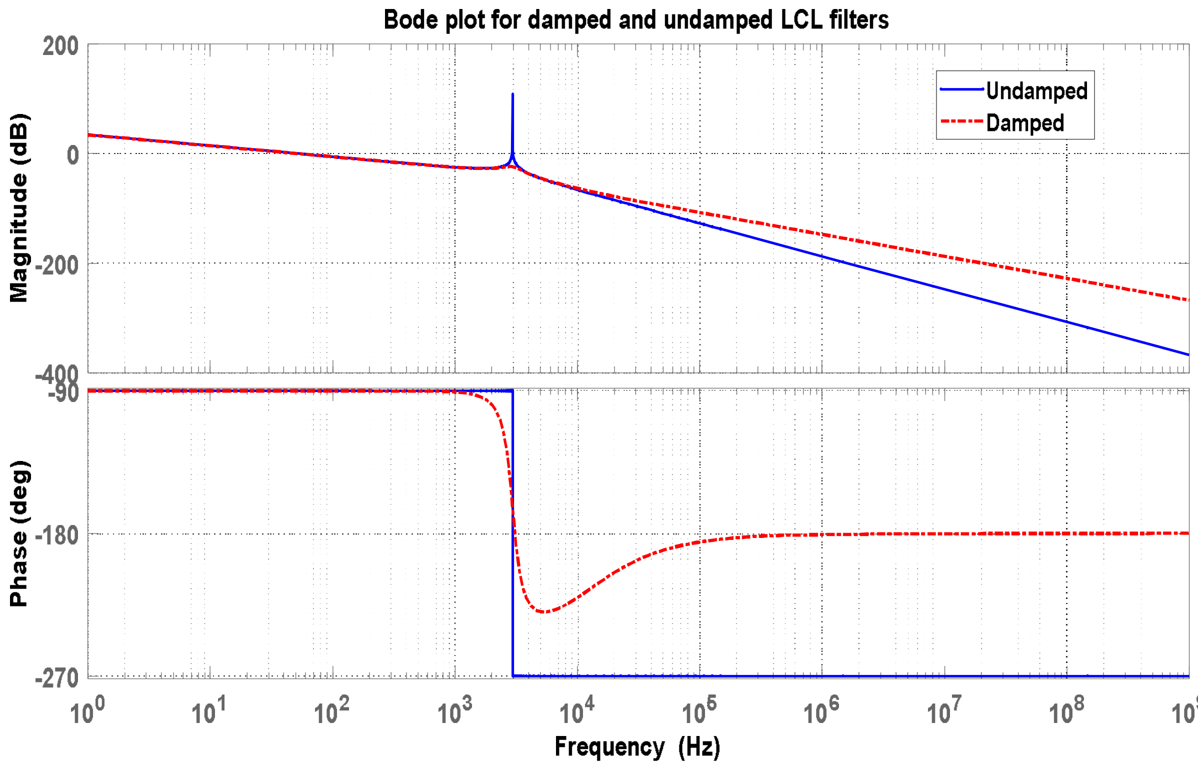


Figure 6: Bode plot for damped and undamped LCL filters

The Bode plots of the LCL filter without and with damping are shown in Figure 3.6. 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. The LCL filter can achieve high performance at high frequency with an attenuation rate of -60 dB/decade.

2.2 LCL Filter Design Procedure

The LCL filter design methodology is aimed to meet grid code requirements through efficient attenuation of high order current harmonic components on the grid side. It requires the following nominal system parameters. Table 1 shows the nominal system parameters used in the design.

Base Values:

$$\text{Base voltage} = V_B = E_n = \sqrt{3} \times V_g = \sqrt{3} \times 240 = 415V$$

$$\text{Base Impedance} = Z_B = \frac{{E_n}^2}{P_n} = \frac{415^2}{100000} = 1.7223\Omega$$

$$\text{Base angular frequency} = \omega_g = 2\pi f_g = 2\pi \times 50 = 314.2\, rads$$

$$\text{Base Capacitance} = C_B = \frac{1}{\omega_g Z_B} = \frac{1}{314.2 \times 1.7223} = 1847.93\mu F$$

$$\text{Base Inductance} = L_B = \frac{Z_B}{\omega_g} = \frac{1.7223}{314.2} = 5.482mH$$

Any quantity when divided by its base value is expressed in p.u. (per unit)

Important Ratios:

- Ratio between the LCL filter inductances, otherwise called split factor

$$r_l = \frac{L_2}{L_1} \tag{2.18}$$

- Ratio between the LCL filter capacitance and total inductance in p.u.

$$r_q = \frac{c}{l_T} = \frac{{Z_B}^2 C}{L_T} \tag{2.19}$$

- Ratio between the switching and resonance frequency

$$r_f = \frac{f_{sw}}{f_{res}} = \frac{\omega_{sw}}{\omega_{res}} \tag{2.20}$$

2.2.1 LCL Filter Design Criteria

The following are some important design criteria for the LCL filter.

- Fulfillment of reactive volt-ampere (VAR) limits (power factor nearly equal to 1)
- Optimal volume and weight with resulting minimum cost of passive (inductive and capacitive) components
- Attenuation of higher order harmonics from the output current (THD$\leq$ 0.03)
- Proper choice of resonance frequency such that the switching harmonics are sufficiently attenuated and the size of the filter components is not too large (Sarkar, 2015; Karshenas and Saghafi, 2006; Ben Said-Romdhane *et al.*, 2017) $(10f_g \leq f_{res} \leq 0.5f_{sw})$.

2.2.2 Inverter side Inductance Design

For the first step, we have to design the inverter side inductance. To do this, the approach propose by (Reznik *et al*., 2013) is adopted.

Here, we consider the maximum current ripple present at the output of an inverter which is given as;

$$\Delta I_{Lmax} = \frac{2V_{DC}}{3L_1}(1-m)mT_{sw} \tag{2.21}$$

Where m is modulation index and $T_{sw} = \frac{1}{f_{sw}}$

But, maximum peak to peak current ripple occurs when m is 0.5. Thus, equation 2.21 becomes;

$$\Delta I_{Lmax} = \frac{V_{DC}}{6f_{sw}L_1} \tag{2.22}$$

Considering a 10% ripple of the rated current for the design parameters, equation 2.21 is given by:

$$\Delta I_{Lmax} = 0.1I_{max} \tag{2.23}$$

Where;

$$I_{max} = \frac{\sqrt{2}P_n}{3V_{ph}} \tag{2.24}$$

$$L_1 = \frac{V_{DC}}{6f_{sw}\Delta I_{Lmax}} \tag{2.25}$$

From equation 2.25, we have;

$$L_1 = \frac{800}{6 \times 16000 \times 19.642} = 0.424mH$$

2.2.3 Maximum LCL Filter Capacitor Value

A lesser value of the filter capacitor C will reduce unnecessary flow of larger reactive currents through it. We know that the flow of reactive power is tied to voltage stability. Therefore, a larger value of C can introduce voltage instability problems in the grid. In this case, the LCL filter capacitor C is designed so that its consumption of reactive power is less than n% of the rated power P_n as shown in Equation (3.26a) (Ben Said-Romdhane *et al.*, 2017). In this equation, Q_c denotes the reactive power consumed by the filter capacitor and n is a positive factor chosen and is generally equal to or less than 5% (Sarkar, 2015; Ben Said-Romdhane *et al.*, 2017). According to Equations (2.26a) and (2.26b), the maximum value of the filter capacitor can be expressed as in Equation (2.26c):

$$Q_C = n\%. P_n \qquad 2.26a$$

But,

$$Q_C = -{E_n}^2 C \omega_g \qquad 2.26b$$

This implies that for n = 5%,

$$C_{max} = 0.05\left(\frac{P_n}{3{V_g}^2\omega_g}\right) \qquad 2.26c$$

$$C_{max} = 92.4\mu F$$

In this case, C = C_{max} and is exactly 5% of the base capacitance C_B.

2.2.4 Grid side Inductance Design

To obtain a ripple attenuation of 20% on the grid side with respect to the current ripple on the inverter side.

$$L_2 = \frac{\sqrt{\frac{1}{k^2}} + 1}{C{f_{sw}}^2} \qquad (2.27)$$

The attenuation factor k in equation 2.27 is set to a value of 20% (0.2).

$$L_2 = \frac{\sqrt{\frac{1}{0.2^2}} + 1}{92.4 \times 10^{-6} \times 16000^2} = 0.254mH$$

2.2.5 Resonance Frequency Design

The resonance frequency depends on the filter inductors L_1 and L_2 and the filter capacitor C.

Let $L = L_1 + L_2 \ and \ L_p = \frac{L_1 L_2}{L_1 + L_2}$

But generally for any given tank circuit, $\omega_{res} = \frac{1}{\sqrt{LC}}$

Thus, for the LCL filter,

$$\omega_{res} = \frac{1}{\sqrt{L_p C}} \qquad 2.28$$

Also, the calculated value of ω_{res} must satisfy the inequality given in equation 2.29. Otherwise, the values of equation 3.27 is re-chosen.

$$10 f_g \leq f_{res} \leq 0.5 f_{sw} \qquad (2.29)$$

Note that ω_{res} is in radians.

From equation 2.28;

$$\omega_{res} = \frac{1}{\sqrt{0.000158843 \times 92.4 \times 10^{-6}}} = 8254.29\, rads/sec$$

$$f_{res} = \frac{8254.29}{2\pi} = 1313.71 Hz$$

In this case, f_{res} is taken to be 1500Hz (i.e. $w_{res} = 9425$ rads/sec) and this satisfies the inequality in equation 2.29.

2.2.6 Minimum DC Bus Voltage

According to Ben Said-Romdhane *et al.* (2017), For Voltage source converter, the DC-bus voltage will decide the maximum AC voltage that can be generated. A general guideline will be that the minimum DC voltage should be equal to the maximum line-to-line voltage of the grid. For three-phase grid, this will be the peak value of the line-to-line voltage.

Thus,

$$V_{DCmin} = \sqrt{2}.V_L \qquad (2.30)$$

V_L is the line-to-line voltage of the grid.

$V_{DCmin} = 587V$

In this design, V_{DC} is 800V.

2.2.7 Damping Resistor Design

For this design, we consider a simple passive damping where a resistor R_D is inserted in series with the capacitor to attenuate part of the ripple on the switching frequency in order to avoid resonance. According to Reznik *et al.* (2013), the value of this resistor should be one third of the impedance of the filter capacitor at the resonance frequency. That is;

$$R_D = \frac{1}{3\omega_{res} C} \qquad (2.31)$$

$$R_D = \frac{1}{3 \times 238.73 \times 92.4 \times 10^{-6}} = 15\Omega$$

But Pena-Alzola *et al.* (2013), gives an expression for the minimum damping resistor R_{Dmin}. The authors revealed that for the system to be stable and in order to achieve a positive gain margin in the control of the system, the damping resistor value must comply with equation 2.32.

$$R_{Dmin} = \frac{1}{3} f_{sw} \left(\frac{{L_2}^2}{L_1 + L_2} \right) \qquad (2.32)$$

$R_{Dmin} = \frac{1}{3} \times 16000 \times 0.000095156 = 0.51\Omega$

This means that the choice of R_D should be such that it satisfies the relation;

$0.51 \leq R_D \leq 15$

Note: R_1 and R_2 are parasitic resistances of the inductors L_1 and L_2 respectively and their values can be chosen directly from the manufacturer's datasheet. In this case; $R_1 = 0.380\Omega$ and $R_2 = 0.162\Omega$.

Table 1 shows the design system parameters that will be used for the simulation.

2.2.8 Simulink Model of the Inverter System with the LCL Filter

Figure 7 shows the Simulink model of the Inverter system with the LCL filter. Here, the design parameters as shown in Table 1 was used to develop a Simulink model to carry out performance analysis on the LCL filter.

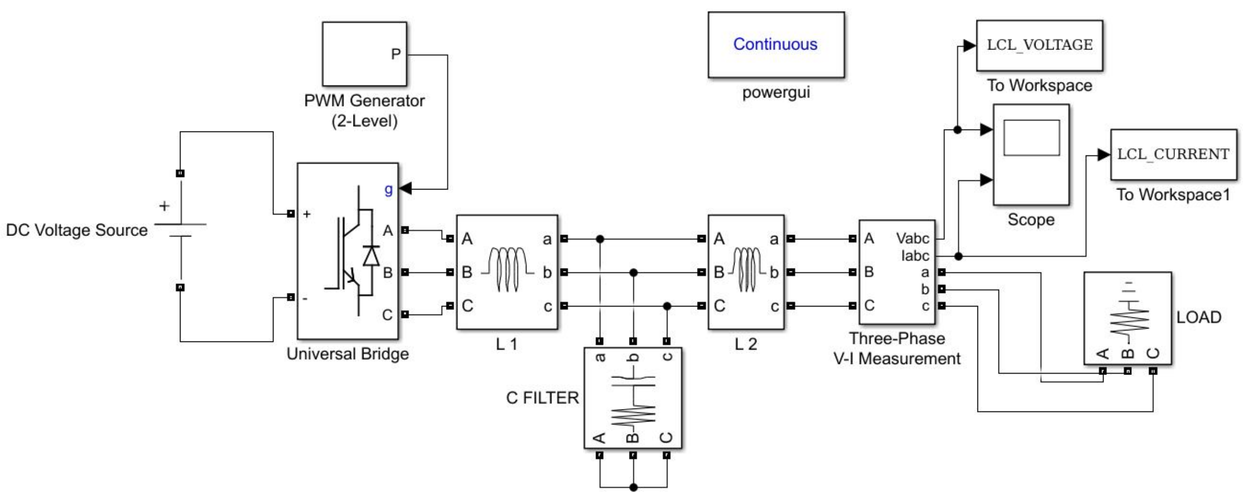
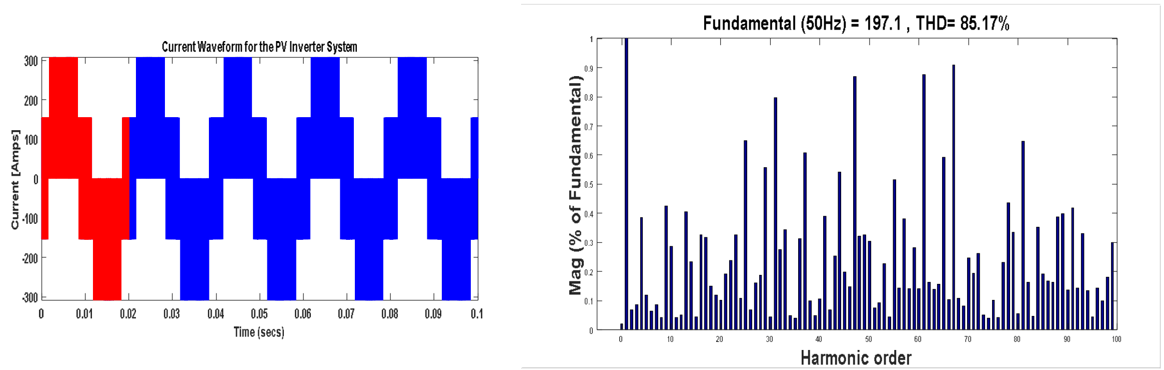


Figure 7: Simulink Model of the Inverter System with the LCL Filter

3.0 Results and Discussion

3.1 Harmonics in the PV Inverter System

In this section, the harmonic content in the unfiltered PV inverter system is presented. The current waveform and the Fast Fourier Transform (FFT) analysis are considered. From Figure 8 (a), it is seen that the current waveform is actually far from being sinusoidal due to very high content of harmonics. Figure 8 (b) gives the FFT analysis of this system, the Total Harmonic Distortion (THD) is as high as 85.17%, making it impossible and unsuitable for grid connected application. Utility operators accept a THD of less than 5% for all grid connected systems.



(a) Current waveform of the PV Inverter System (b) FFT analysis of the PV Inverter System

Figure 8: Current Waveform and FFT analysis of the PV Inverter System

3.2 The PV Inverter System Simulation Parameters

The inverter system is simulated using the design parameters obtained in section 2. The nominal system parameters and the design parameters are given in table 1.

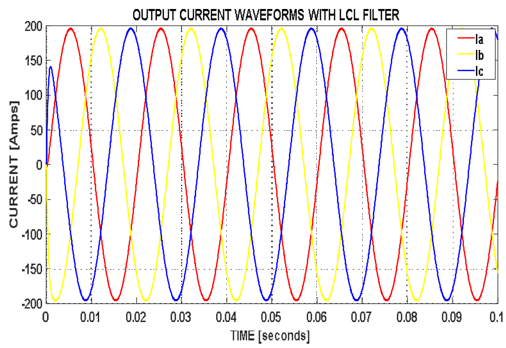
Table 1: Design System Parameters

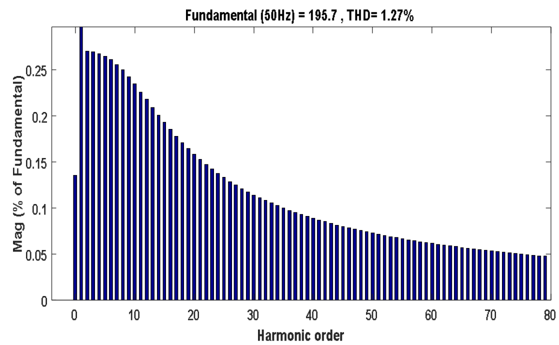
f_g	Grid frequency or fundamental frequency	50Hz
f_{sw}	PWM carrier frequency	16KHz
W_{res}	Resonance frequency	9425 rads/sec
P_n	Rated active power	100KW
E_n	Line to line RMS voltage	$\sqrt{3} \times 240$V
V_{DC}	DC Bus voltage	800V
L_1	Inverter side inductor	0.424mH
L_2	Grid side inductor	0.254mH
R_1	Inverter Side Parasitic Resistance	0.380 Ω
R_2	Grid Side Parasitic Resistance	0.162 Ω
C	Capacitor	92.4μF
R_D	Damping Resistor	2.2Ω
V_g	Grid voltage	240V

3.3 Simulation Results of the LCL Filter

Figure 9 (a) shows the output current waveform of the inverter system with the LCL filter. Here, it is seen that the waveforms are all sinusoidal at this point since a greater percentage of the harmonics present at the output of the PV inverter system has been filtered out by the well-designed LCL filter. The harmonic content has also been reduced from 85.17% to 1.27%.

However, Figure 9 (b) reveals that the LCL filter cannot optimally handle the low order harmonics, hence the need for a current controller. The current controller is needed to filter out the low order harmonics to make the PV inverter system meets utility 'Standard for Interconnecting Distributed Resources with Electric Power Systems'.





(a) Three – phase Output Current Waveforms with LCL Filter (b) FFT analysis of the PV Inverter System with LCL filter

Figure 9 : Current Waveforms and FFT of the Current of the Inverter System with LCL Filter

5. Conclusion

This paper proposes a simple, robust and systematic design methodology for an LCL filter, used to interface between three phase power converter and the utility grid. This filter is used to reduce the switching frequency current harmonics produced by the power converter. The proposed design methodology is simple, efficient and aimed to meet the grid code requirements. Compared to classical design methodologies, the proposed method is simple and straightforward. Moreover, it takes into account four paramount design criteria - fulfillment of reactive volt-ampere (VAR) limits, optimal volume of the filter, THD $\leq$ 0.003 and proper choice of resonance frequency. The obtained filter parameters were tested using MATLAB-Simulink software tool. The obtained simulation results show the reliability, efficiency and high filtering performances of the proposed design methodology. The simulation results show that with this design method, over 98% of the current harmonics present at the converter output is mitigated.

List of Symbols and Abbreviations Used

Currents

Ig	Grid Current
Ic	Filter Capacitor Current

Voltages

Vg	Grid Voltage
Vc	Voltage across Filter Capacitor

Vin	Inverter voltage
VB	Base Voltage
VDC	DC Link Voltage

Inductances

L1	Inverter Side Inductor
L2	Grid Side Inductor
LB	Base Inductance

Resistances

R1	Inverter Side Parasitic Resistance
R2	Grid Side Parasitic Resistance
RD	Damping Resistor

Impedances

ZB	Base Impedance

Letters

S	Laplace transform operator
F	frequency [Hz]
L	Inductor
LC	Inductor Capacitor
C	Capacitor
fsw	Switching Frequency
fres	Resonance Frequency
Pn	Rated Active Power
En	Line to Line RMS Voltage

Greek letters

ωres	Resonance Frequency of the LCL filter in radians/sec

Acronyms

MATLAB	Mathematics Laboratory
AC	Alternating Current
DC	Direct Current
FFT	Fast Fourier Transform
RES	Renewable Energy Sources
Kw	Kilowatt
EMI	Electromagnetic Interference
IEC	International Electrotechnical Commission

PV Photovoltaic
DG Distributed Generation
VSI Voltage Source Inverter
KHz KiloHertz
IEEE Institute of Electrical and Electronics Engineers
THD Total Harmonic Distortion
LCL Inductor Capacitor Inductor

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