Harmonic Mitigation in Modelled Grid Connecting Solar Photovoltaic Array System in MATLAB

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Abstract

The paper here presents the modelling of grid-connected solar photovoltaic system with LCL filter design with Voltage Source Converter control. The system model comprises of PV Array, Boost Converter, Voltage Source Inverter, LCL Filter, Utility Grid and Loads. The Boost converter makes fluctuating input DC to constant output DC. Voltage Source Inverter converters DC boost voltage to three phase AC voltage. The VSC is switching through the PWM technique has been controlled through a control unit comprising of the outer and inner control loops. The harmonics in the system has been caused by the power electronics devices and non-linear loads connected in the system and the presence of these harmonics in the system has reduced the power quality and operation of the system. The synchronization of the three phase output of the inverter to grid has been done through PLL. The modelling of the system has been done in MATLAB and an analysis of THD will be done on steady state of the grid voltage and current and inverter current. The THD of the grid currents has also been compared at two different values of solar irradiance. In order to mitigate the harmonics and improve the power quality of the system an LCL filter has been used and its value has been calculated to reduce voltage and current THD below IEEE standards.

Keywords
LCL Filter, Harmonics, Voltage Source Inverter (VSI), Total Harmonic Distortion (THD) and Boost Converter.

1. Introduction
As with the demand for electricity has been grown in the past years, the need for renewable energy has grown which can provide cheap energy and are abundant in nature to cater the large demand. As the conventional energy resources availability are limited, the need for renewable energy sources are on the rise in the world. Solar as the renewable energy source is by far the best choice for tropical zone due to abundance of availability, less running cost, less wear and tear due to less moving parts and low noise production. The utilization of the solar PV power is better when it is connected to grid but there are some problems with the solar power system as unbalancing of voltage, sag and swell in the voltage, low power factor and harmonics in current and voltages. The major problem with the solar integrated grid system is the power quality in the voltage source inverter as well as grid, as the VSC converter output contain some harmonics. The VSC output is connected to grid which need to be synchronized and the harmonics of VSC output current should also be reduced. In order to reduce harmonics of output current of VSC an LCL filter with damping resistance has been used for this model. The damping resistance reduces the resonating problem in the system. The non-linear loads in the modelled system also produces some harmonics in the system. The modelled system contains solar PV array with Perturb and Observe MPPT algorithm, a DC-DC Boost converter controlled by duty cycle through P&O algorithm, a Voltage source converter and its dual loop control circuit, LCL filter, utility grid and non-linear and linear loads. And the THD of voltage and current of the grid and inverter current is calculated with and without LCL filter and the THD of grid current with LCL filter has been compared at two different values of irradiance. The LCL filter has been the most effective passive filters among all the passive filter in grid-connected photovoltaic system as conventional L and LC filter are less effective in harmonic attenuation, larger in size and

heavier in weight.

1.1 Objectives

(i)   To design an LCL filter for the modelled system to mitigate voltage and current harmonics.

(ii)   Analysis of the THD values of grid current and voltage and inverter current and compare THD of grid current at different irradiance values.

2. Literature

Many researchers have proposed passive filter design for harmonic mitigation in Solar PV integrated grid-connected system (Sampath Jayalath and Moin Hanif 2016) has stated the benefit of using LCL filter over conventional L-filters in an integrated system of grid and VSC. The proposed paper highlighted the various important LCL filter design parameters and their interrelationship for efficient filter. The parameters μ, the ratio of grid to inverter side inductance and resonance frequency of LCL filter design has to be selected appropriately for the optimal design. The design also consider a balance between passive damping loss, higher order harmonic mitigation, minimizing the stored energy and size of the passive components. The design also considers the limitation on the production of the reactive power by the filter and the harmonic mitigation limits proposed under IEEE standards. (A. Reznik et al.2013) uses systematic design method for LCL filter with state-space mathematical modeling approach and also compared two different topologies of LCL filter, i.e. wye connected LCL filter with damping resistance and delta connected LCL filter. These two filter designs has been comprehensively studied in the inverter connecting grid application in wind or photovoltaic system. The state space modelling makes the analysis of frequency response easier. The design method can be easily incorporated to medium and large-scale grid integrated inverter system.

This research proposes the systematic mathematical state space model for the design of LCL filter making the calculations of the components systematic and the design an optimal solution for the given system. With this improved design, the proposed model is able to achieve the desired harmonic distortion. The research will provide better and easier solution to the harmonic mitigation of grid connected inverter in wind or photovoltaic application. This research will also provide valuable input to the academics and industry for better power quality solution.

3. Modelling and System Description

The system modelled here comprises of PV Array, DC-DC Boost converter, dc-link capacitors along with VSC converter, LCL Filter and utility grid. The components of the system will be discussed in the subsections (Figure 1).
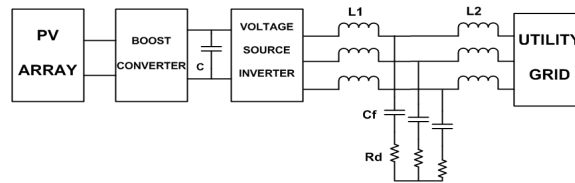

Figure 1. Modelled PV System

3.1 Solar PV Array

For PV module model design, a single diode model of PV cell has been considered. The specifications of solar cell is given in Table 1-3. The solar power is taken as 100KW and the power of solar cell is 305W, so the parallel and series connection are made .The solar modules are chosen with the consideration of the geographical location to harness the maximum sun light power. The solar irradiance also varies throughout the day, so an MPPT is needed as it helps to harness the varied power throughout the day and the variable DC voltage from the solar module also need to be boost to feed into the inverter. So to make output constant from fluctuating DC voltage, we need to change the duty cycle with the help of MPPT algorithm to get the constant output voltage (Table 1). The output voltage and current produced by the solar is variable here due to the ramp input type solar irradiance which is making the variations in output current and voltage for the small time period. The solar irradiance are varying but after that the irradiance is constant, its value is taken as 1000W/m^2.

Table 1. Sunpower SPR-305-WHT Specifications

Parameters	Values
Voltage at peak power point (Vp)	54.70 (V)
Current at peak power point (Ip)	5.580 (A)
Open circuit voltage (Vocv)	64.20 (V)
Short-circuit current (Iscc)	5.960 (A)
Coefficient of Temp (Vocc)	-0.177 (V/deg. C)
Coefficient of Temp (Iscc)	0.003516 (A/deg. C)
Coefficient of Temp (Vp)	-0.186 (V/deg. C)
Coefficient of Temp (Ip)	-0.00212 (A/deg. C)
Modules connected in series	5
Strings in parallel	66

3.2 Perturb And Observe (P&O) Algorithm

The P&O MPPT technique has been used for maximum power tracking as it also increases efficiency of solar array. It depends on iterative method to get the array voltage in periodically method to compare the present and previous values of power of solar ΔP_{pv}. If the change in the power is positive, the voltage follows the direction of the increment, otherwise negative, it reverses direction from the maximum power point. The iteration continues till the change in power becomes zero and maximum power has been achieved.

3.3 Boost Converter (DC TO DC)

Boost converters are designed to change the increased output voltage coming from solar PV panel to the required input voltage of the inverter. The boost converter connects the PV array to the voltage source converter and with the help from MPPT input, it also helps in finding the maximum power point on voltage current graph. The capacitor and inductor on the output terminal of the boost converter filter out the non-required harmonic signals. The output of the boost converter is given by the equation (3.0).The boost converter consist of a switch, inductor and capacitor.

$$V_O = \frac{V_S}{1-D} \tag{3.0}$$

Where, Vo is output voltage, Vs is supply voltage and D is duty cycle.

3.4 VSC Controller

The inverter operation depends upon the modulation schemes, the switching of inverter at the time base interval gives the average of the output which are filtered by the inductor and capacitor to have the sinusoidal waveform with less distortion. The controller here is designed to reduce the unbalancing and fluctuation in the voltage of the inverter. The main controller is made up of two loop controllers: First Outer loop controller, Second Inner loop controller. Along with these controller a PLL measurement block is there. The power controller or the voltage controller is responsible for active and reactive power control in the circuit by taking voltage and current measurements from the grid (I_d and I_q) which is the inner loop control of the VSC. The dc–link voltage is controlled under outer control loop. PI controller is responsible for i_{ref} , which is set as zero for so that reactive power becomes zero and power factor will be one. The output voltages (V_d and V_q) of the current controller along with PWM generator produces three phase abc input signal for the converter. The systematic block diagram of control system is shown in Figure 2.
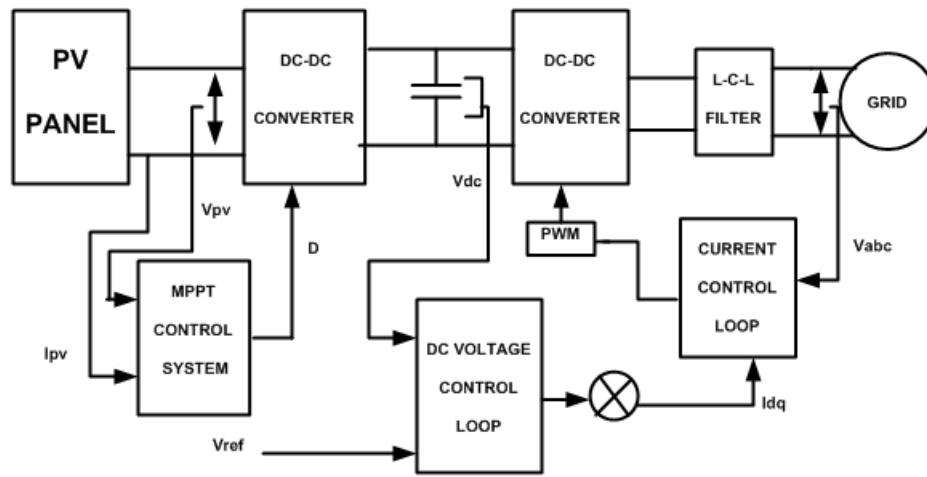
Figure 2. Block Diagram of Control system

3.5 LCL Filter

The LCL passive filter of third order is very efficient in controlling voltage and current harmonics in the grid connected PV system. The high frequency harmonics are eliminated by using less number of passive components, so the size of the filter used get reduced and hence reducing the cost. It has the advantage of eliminating switching harmonics but it has a disadvantage of resonance production due to requirement of reactive power in the circuit. For the suppressing of the resonance phenomenon a damper resistance is needed along with capacitor. The flow chart for the LCL filter calculations are given below where V_{LL} is line voltage, P is power of the grid, V is the voltage of the inverter connecting grid, f_g is grid frequency and f_{sw} is switch frequency (Figure 3).
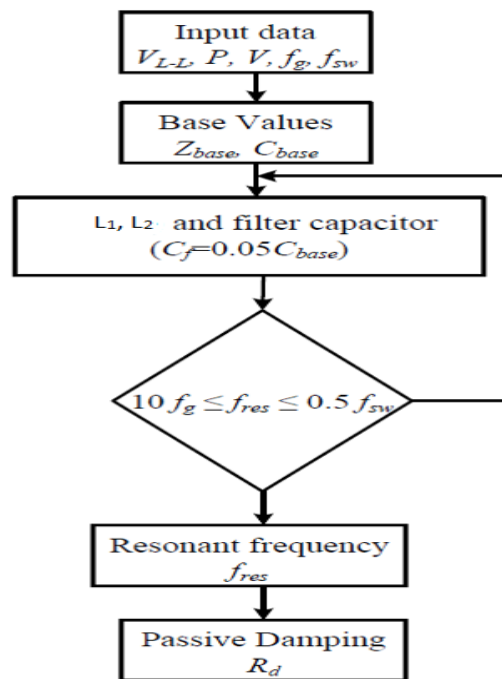

Figure 3. Flow Chart of LCL Filter Calculation

4. Design Calculations of the Proposed System Components

4.1 DC-DC Boost Converter Value

The boost converter has output voltage of 'V$_{dc}$' and PV array has output voltage of 'V$_{pv}$' and the duty ratio given by 'D' of the converter is related as in equation (4.1).

$$D = 1 - \frac{V_{pv}}{V_{dc}} = \frac{260}{500} = .52 \tag{4.1}$$

The minimum value of inductance 'L$_b$' which is required to operate boost converter in CCM modes is given in equation (4.2).

$$L_b = \frac{V_{pv}DT}{\Delta I_{pv}} = \frac{V_{pv}D}{0.1*I_{pv}} = \frac{R_{pv}DT}{0.1} = \frac{Vpv^2}{0.1*Ppv}\left(1 - \left(\frac{Vpv}{Vdc}\right)\right)$$
$$= \frac{260^2*(50*10^{-6})}{0.1*(100*10^3)}\left(1 - \left(\frac{260}{500}\right)\right) = 1.6224mH \tag{4.2}$$

Here ΔI_{pv} value is the permissible for currents in the PV array, switching time period is given by T and P$_{pv}$ is power of the solar array. So from the considered design value the minimum value of the inductance L$_b$ required is 1.6224mH.

4.2 DC-link Capacitance Value

The capacitance of the dc-link operates to maintain dc input voltage for the voltage source converter and its calculation is given in equation (4.3).

$$C_{dc} = \frac{\left(\frac{Pdc}{Vdc}\right)}{2*\omega*Vdcripple} = \frac{\left(\frac{100*10^3}{500}\right)}{2*(2*3.14*50)*(.01*500)} = 127324\mu F \tag{4.3}$$

4.3 LCL Filter Calculated Values

The base impedance is given by Z$_b$ and capacitance is given by C$_b$ and its values are calculated as in equations (4.4) and equation (4.5).

$$Z_b = \frac{V_{LL}^2}{P} = \frac{(25\sqrt{3}*10^3)^2}{100*10^3} = 18750\Omega \tag{4.4}$$

$$C_b = \frac{1}{\omega_g*Z_b} = \frac{1}{2\pi f*Z_b} = \frac{1}{(2*3.14*50)*18750} = 16.97\mu F \tag{4.5}$$

For designing of the filter capacitance, it is considered that the highest power factor fluctuation in the grid should be 5% as given in equation (4.6).

$$C_f = (.05)C_b = .8488\mu F \tag{4.6}$$

The maximum variation in ripple in the current is presented in equation (4.7).

$$\nabla L_{max} = \frac{2*V_{dc}}{3*L_1}(1 - M) * M * T_{sw} \tag{4.7}$$

Here M is the modulating index of voltage source converter, its value is taken as 0.5, putting in equation (4.7) gives equation (4.8).

$$\Delta L_{Lmax} = \frac{V_{dc}}{6 f_{sw} L_1} \tag{4.8}$$

The inductance at inverter side is L$_1$ and for design purpose ripple current of 10% of the rated current is considered, so ripple current is given as in equation (4.9).

$$\Delta I_{Lmax} = 0.1 * I_{Lmax} \tag{4.9}$$

Where

$$I_{Lmax} = \frac{P\sqrt{2}}{3*V_{ph}} \tag{4.10}$$

By putting the value of I_{Lmax} from equation (4.10) in ΔI_{Lmax}, we have equation (4.11).

$$I_{Lmax} = 0.1 * \frac{P\sqrt{2}}{3*V_{ph}} \tag{4.11}$$

The inverter side inductance is given by L$_1$, the value is given in equation (4.14).

$$L_1 = \frac{V_{dc}}{6f_{sw}\Delta I_{Lmax}} = \frac{3*V_{dc}*V_{ph}}{6*f_{sw}*0.1*P\sqrt{2}} \tag{4.12}$$

Where, $V_{pp} = \frac{V_{LL}}{\sqrt{3}}$ (4.13)

$$L_1 = \frac{3*500*\left(\frac{340}{\sqrt{3}}\right)}{6*(20*10^3)*0.1*\left(100*10^3*\sqrt{2}\right)} = 1.735mH \tag{4.14}$$

The grid side inductance is given by L_2, and its value is calculated in equation (4.17)

$$L_2 = \frac{\sqrt{\left(\frac{1}{q^2}\right)}+1}{C_f w_{sw}{}^2} \tag{4.15}$$

Here, C_f is filter capacitance, q is attenuation constant, w_{sw} is switching frequency and v is ratio of the inverter to grid side ratio.

$v = 0.8$ (4.16)

Hence,$L_2 = v * L_1 = 1.39mH$ (4.17)

To eliminate resonance in the circuit a damping resistance R_d is used which value should be 1/3 of the capacitive impedance of the filter calculated at resonating frequency. The value of resonating frequency and damping resistance is calculated as shown in equation (4.18) and equation (4.19) respectively.

$$w_r = \sqrt{\left(\frac{L_1+L_2}{L_1L_2C_f}\right)} = \sqrt{\left(\frac{3.123*10^{-3}}{2.044*10^{-12}}\right)} = 3.91*10^4 Hz \tag{4.18}$$

The limit of resonating frequency should be as given below

$$10F_g < F_{res} < 0.5F_{sw} \tag{4.19}$$

$$R_d = \frac{1}{3w_rC_f} = \frac{1}{3*(3.9*10^4)(.866*10^{-6})} = 10.02\Omega \tag{4.19}$$

5. Discussion and Simulation Results
MATLAB simulation results for the modelled system without filter and with LCL filter are as shown below. The grid voltage and current waveform are shown in Figure 4 and 5. Fourier analysis results has been shown below in Figure respective figures. The total harmonic distortion without filter of grid voltage and currents are 0.7 and 10.61% respectively as shown in Figure 4, 5, 6 and 7. After using LCL filter at the output side of VSC connecting to grid the total harmonic distortion of grid voltage and currents has been improved to .06% and 4.77% respectively.
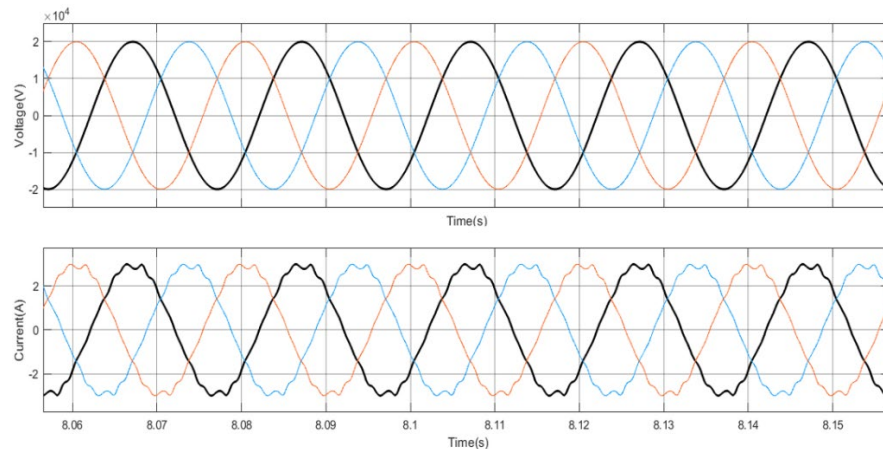

Figure 4. Phase Grid Voltage and Current waveform without filter

The Figure 4 shows the waveform of the three-phase grid voltage and current after using LCL filter and the distortion are very less.
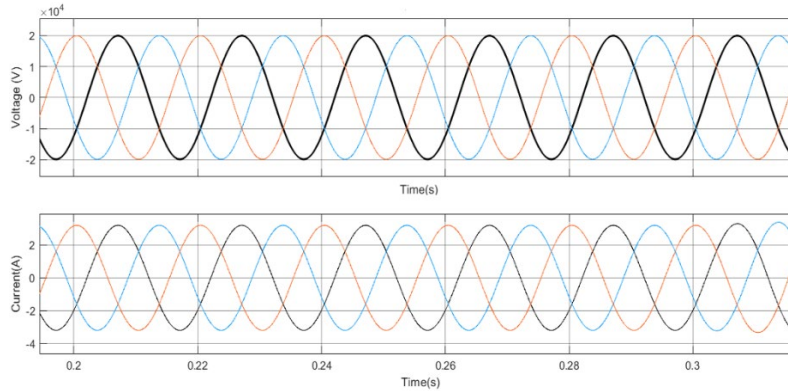

Figure 5. Phase Grid Voltage and Current waveform with LCL filter

The Figure 5 shows the Fourier analysis graph of the grid voltage without filter and it shows that the modelled system grid voltage is almost a constant source and it has no effect of load due to infinite voltage source.
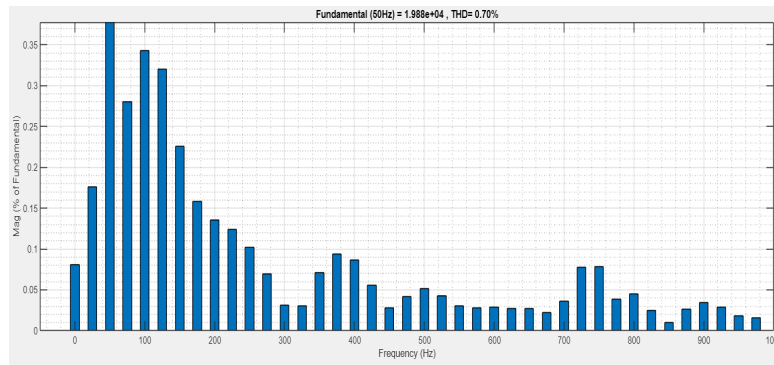

Figure 6. Grid Voltage THD without filter

The Figure 6 shows the grid current Fourier analysis without any filter. The THD is obtained 10.61% which is relatively high. The magnitude of the fundamental is 3.209.
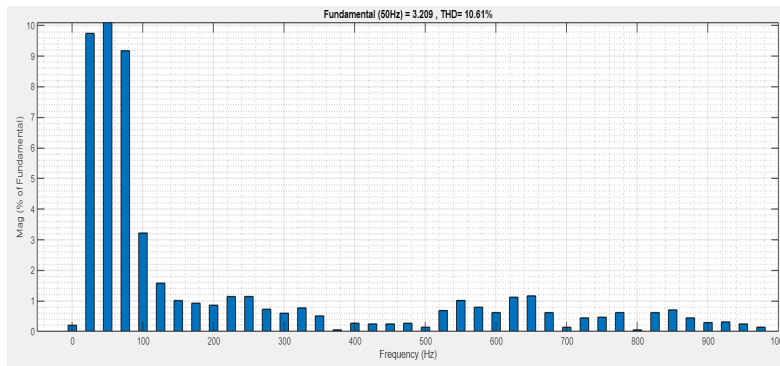

Figure 7. Voltage THD without filter

The Figure 6 and Figure 7 shows the Fourier analysis of the grid voltage after the use of the filter and the grid voltage THD is 0.06% and the magnitude of the fundamental is 1.989e4. So, it is evident here that the grid voltage is purely sinusoidal with or without filter. The grid here is behaving like a constant source without having any effect of load. The magnitude of the fundamental of voltage and current waveforms after LCL filter has decreased which indicate some harmonics magnitude suppression of the waveform. The Figure 8 shows the Fourier analysis of the grid current with LCL filter and the THD has improved to 4.77% and the magnitude of fundamental is 3.016 which is lower than the fundamental without filter.
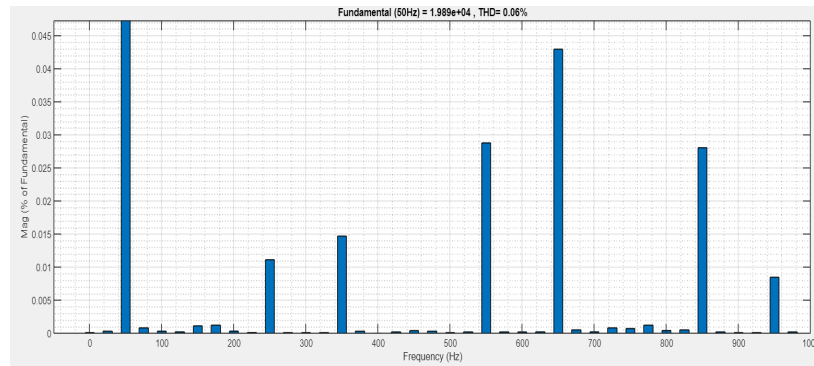

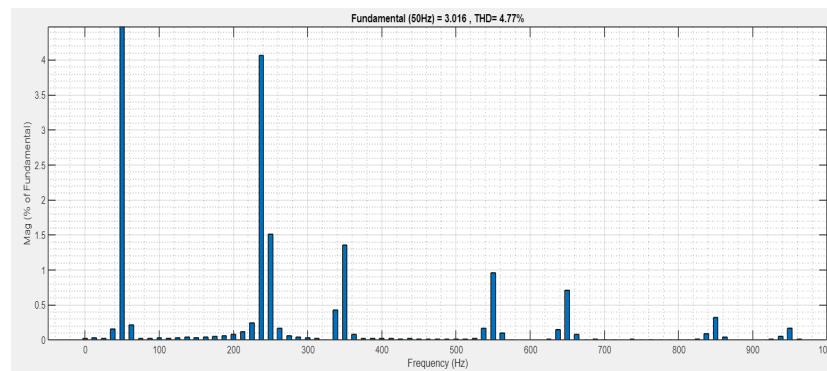Figure 8. Grid Voltage THD with LCL filter

Figure 9. Grid Current THD with LCL filter at 1000 W/m^2 Irradiance

The Figure 7 and Figure 8 shows the Fourier analysis of the grid current with filter at 800 W/m^2 irradiance and the THD is 5.10% and the magnitude of fundamental is 3.224. So it is evident here that the low irradiance increases the THD in this system (Figure 9).
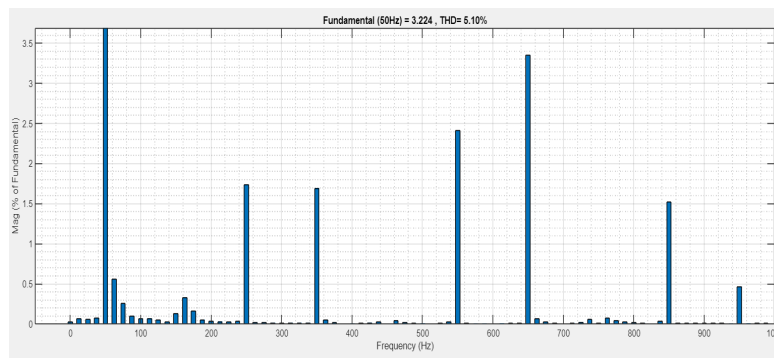

Figure 10. Grid Current THD with LCL filter at 800 W/m^2 Irradiance

The above Figure 10 shows the inverter current waveform without any filter use and the waveforms are distorted due to the harmonics present in the system and Figure 11 shows the inverter current waveform in the system with LCL filter and the waveform has become quite smooth in comparison which shows that the harmonics has been reduced to the better value. The inverter current waveform shown in Figure 12 indicates that the PWM switching of the inverter creates harmonics in the system but we also know that the PWM switching in the VSI mitigates lower order harmonics and for higher order harmonics in the system LCL filter is used and the result after the use of the filter is that the THD of the inverter current has reduced to 2.96% which is shown in the Figure 11.
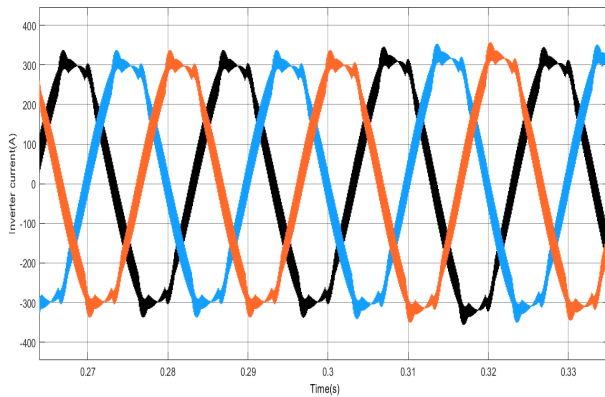

Figure 11. Inverter Current without filter
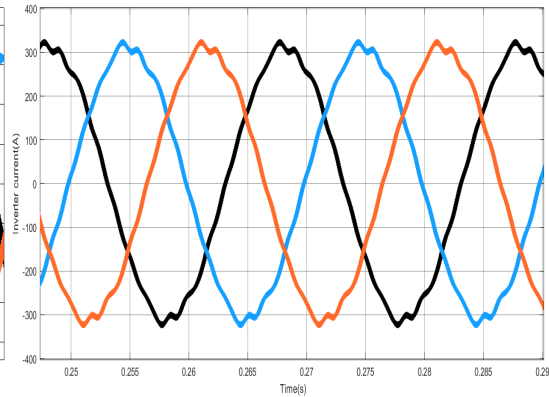

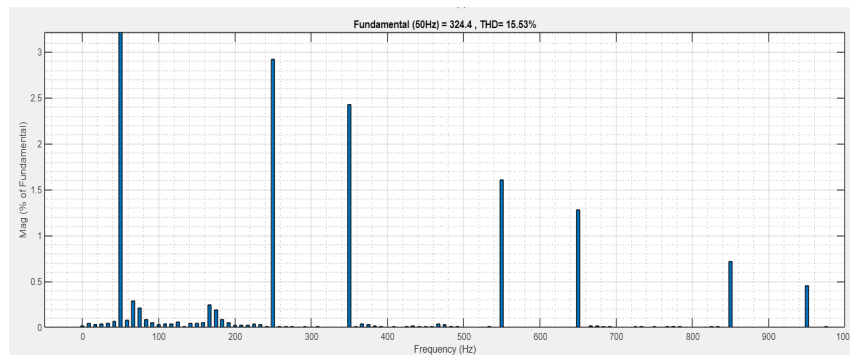Figure 12. Inverter current with filter

Figure 13. Inverter Current THD without filter

The Figure 13 shows the inverter current Fourier analysis without filter and the THD is 15.53% and the magnitude of the fundamental is 324.4. The Figure 14 shows the inverter current Fourier analysis with LCL filter and the THD is 2.96% and the magnitude of the fundamental is 314.5.
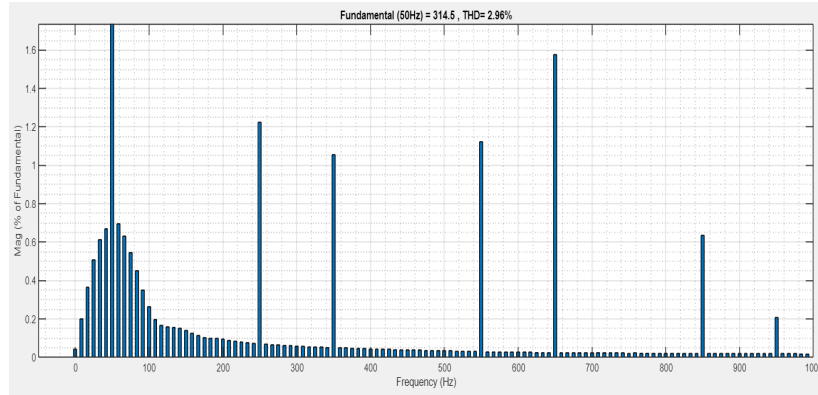
Figure 14. Inverter Current THD with LCL filter

The Fourier analysis of the Inverter current shows that the filter reduces the harmonics quite efficiently and the current fed to the grid is balanced and in harmony to the grid current. The LCL filter topology used here is discussed above which is wye connected LCL with damping resistance, the inductors are connected in series on the inverter side as well as on the grid side and the capacitor is placed in between the inverters in parallel and the damping resistance is also is in series with the capacitor.

The Table 2 shown below indicates the THD comparison of grid voltage, grid current and the inverter output current without the use of any filter and after the use of the LCL filter with damping resistance. From the Table 2, it is evident that the LCL filter helps in reducing harmonics in both grid and inverter current. The effect on grid voltage is negligible here as the grid is almost acting as a constant voltage source without any effect of the load.

Table 2. Comparison of voltages and current THDs

Filter	THD (%)		
	Grid Voltage	**Grid Current**	**Inverter Current**
Without Filter	0.70	10.61	15.53
With LCL Filter	0.06	4.77	2.96

6. Conclusion

The modelled PV system of 100 Kw, grid connected LCL filter with dual loop control gives THD values within limits without resonance problem, so the modelling design is functioning within limits. The system modelled here has been analyzed with and without filters and it can be seen that a filter is very necessary for the harmonic mitigation if the control scheme of inverter is not able to eliminate the total harmonics. The control scheme here was only able to reduce the lower order harmonics and the higher order harmonics are eliminated through the LCL filter with resistance damping with optimal values of inductor and capacitor. The solar irradiance also affects the THD, as can be seen from the Fourier analysis of inverter current with LCL filter. The inverter current at 1000 W/m^2 has THD as 4.77% but at 800 W/m^2 irradiance the THD is 5.10% which is slightly more when irradiance is decreased in this system. The system parameters which are taken and are calculated has been given in the Table 3 below.

Table 3. System Specifications and Value

Parameters	Symbols	Values
PV Module Power	P_{pv}	100kw
PV Module Voltage	P_v	260V
Switching Frequency	F_{sw}	20KHz
DC-Link Capacitor	C_{dc}	127324μF
DC- link Voltage	V_{dc}	500 V
Converter Inductance	L_c	1.6224mH
Inverter Input Voltage	V_{dc}	260V
Step-up Transformer	Trs	260V/25KV
Inductor (Inverter Side)	L_1	1.735mH
Inductor (Grid Side)	L_2	1.39mH
Filter Capacitor	C_f	.8488μF
Damping Resistor	R_d	10.02Ω
Grid Voltage	V_g	25KV
Frequency of Grid	f_g	50Hz
Power factor	Pf	1

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