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International Journal of
Electrical and Electronics Research (IJEER)
Research Article | Volume 11, Issue 2 | Pages 283-290 | e-ISSN: 2347-470X

Power Quality Improvement Grid Integrated Photovoltaic with LCL Filter Using DQ Controller

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ABSTRACT- Grid-interactive solar photovoltaic (PV) systems are necessary for the current global scenario owing to their low cost and pollution-free energy source. The integration of PV systems in the power grid needs to be stabilized. To address this, this paper presents a composite controller that can synchronize Photovoltaic (PV) to the Grid, with bidirectional power flow in Grid. The proposed technique is explored with both RL and LCL filters. With grid synchronization of PV power generation, a control loop for power quality disturbance mitigation is simulated. The multicarrier SVPWM with DQ controller is used on the Grid Connected converter to mitigate Power Quality disturbances. MATLAB Simulink model is developed for the PV Grid setup and the validity of the composite controller is evaluated. The PI controllers are applied in the DQ-controlled PV integrated with the grid. Power quality parameters THD are found to be intact for both RL and LCL filters. The MATLAB simulation developed showed that the LCL filter has an incremental performance progression than using the RL filter. There is around a 3 to 4% improvement in the grid current THD while using the LCL filters instead RL filter for PV integration.

Keywords: Power Quality, Total Harmonic Distortion (THD), Grid Synchronization, PV integration, DQ controller.

ARTICLE INFORMATION

Author(s): R. Senthil Kumar, Dr. Prabakaran. S and Dr. S. Sentamil Selvan;

Received: 02/02/2023; **Accepted**: 17/04/2023; **Published**: 18/05/2023;
e-ISSN: 2347-470X;
Paper Id: IJEERSI23MB04;
Citation: 10.37391/IJEER.110206
Webpage-link:
https://ijeer.forexjournal.co.in/archive/volume-11/ijeer-110206.html

Crossref member — CROSSREF.ORG THE CITATION LINKING BACKBONE

This article belongs to the Special Issue on **Environmental Sustainability through Alternative Energy Sources and Electronic Communication**

1. INTRODUCTION

As a consequence of the overwhelming population, the power demand increases up to 45% by the end of 2035 [1]. Non-renewable energy sources like oil, gas and coal pollute the environment, though it meets 75% of electrical demand globally [2]. Exploration of non-renewable sources leads to deforestation, pollution, and environmental issues [3]. These sources lead to greenhouse gas emissions [4]. On other hand, Renewable Energy Resources (RES) give assurance for a guaranteed, eco-friendly and ceaseless energy supply. The RES like solar PV, Biofuel, Geothermal, Biomass, Hydro energy and wind energy are free from CO2 emissions. [5, 6]. A higher penetration level of the PV source in the grid improves the stability for grid integration by minimizing the distorting in sinusoidal waveform [7]. Integrating solar PV power into the grid needs sophisticated technology and an advanced control system. The size of PV systems differs according to the end user, it varies from small to tremendous power distribution systems [8-9]. Islanding and grid-connected mode are two ways the PV energy can be used. The first kind is the standalone system, in which power generation is preferable in the dark hours. Therefore, this system needs energy storage capability. The second kind of power generation is a grid-connected solar photovoltaic panel [10]. The PV system generates AC power parallel with the utility in power network. A vital role is played by the multilevel inverter for conversion of high power in the solar PV systems [11]. The grid-connected systems need a synchronization technique to match frequency and the voltage of the PV system to the grid. Power quality (PQ) issues are due to the voltage and current variation. The power quality problems are mainly voltage rise, voltage dip, interruptions, transients, and voltage flickers. The power quality can be significantly improved and the issues are mitigated using UPQC controllers [12-13]. The equipment in the grid causes failure from the voltage and current oscillations in the transmission line.

The output voltage contains minimum level of THD using selective harmonic elimination-based Inverter [14]. An effective filter unit is needed to improve power quality by controlling the voltage and current harmonics. The LCL filter used in this system enhances power quality, boosts system stability, and eliminates resonance issues. In [15] the power quality improvement with a PV power plant is explained with the technique that incorporates the charging of batteries during the lean demand period and discharging during the higher demand period. Hosting capacity is the measure of power that is linked to the power network without disturbing the power quality [16]. Quite a few LCL filter design methods used in the PV integrated grid are presented by various researchers [17-20].

The main focus is the regulation of the LCL filter based on various constraints [21]. The key focus is to recover the THD

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value of grid current followed by consumed reactive power [22]. Also, the resonant frequency and ripples are considered [23]. However, limited works can be observed on robust LCL filter on integration of PV with the grid system. It is observed that LCL filters help in improving active damping control. In addition to the use of resonant frequency variation, the grid current feedback helps to tune a stable power delivery. Recently hybrid damping technique, integrated passive and active damping method are proposed [24-25]. This paper presents a DQ controller on the grid integrating a PV source with both RL and LCL filters. The control approach is applied to mitigate the power quality issues raised at the grid-connected PV system. *Section 2* discusses the methodology of the controller. *Section 3* discusses the results; *section 4* discusses the simulation followed by a conclusion and references.

2. PROPOSED METHODOLOGY

In this work, a three-level inverter with multicarrier SVPWM is explained for power quality issues when it is connected to the linear and non-linear load at the point of common coupling (PCC). The PV power generation is integrated into this inverter to transfer the power to the grid. MATLAB is used to carry out the experimentation of various cases. Introducing a DQ-based composed controlled inverter to check the performance of the power quality improved. At the same time, PV integration to the power grid and the power quality disturbance mitigations form another loop with three-level inverters. The LCL filter offers good harmonic elimination with low values of inductors and capacitors which is chosen in this proposed work. Also, galvanic isolation is used in this method. PI DQ control and Multicarrier SVPWM controller aides in the overall power quality disturbance mitigation. Synchronization of the PV power generator with the distribution system maintains the 50Hz specification at the PCC. This implementation is best suited for smart building applications since the bidirectional operation is adopted. The power flow diagram with complete blocks which is implemented is shown in *fig. 1*. Power grid will have bidirectional power flow since the inverter linked to the grid supply power to the grid when excess power is generated from the PV.

The complete configuration of the power quality disturbance mitigation is performed with MPPT (Maximum Power Point Tracking) of (P&O) Perturb and Observe Algorithm. This proposed method implementation develops the harmonics mitigation in Grid Connected PV Distributed, the grid synchronization loop then a power quality disturbance mitigation loop. The boost converter is regulated by an MPPT control feed-forward loop, which generates pulses to the boost converter following MPPT. Boost converter output connected to the DC link supplies a grid-integrated three-level inverter controlled by multicarrier SVPWM. The inverter has to take care of the power quality problems created by these loads. Vital parameters (V and I) from the inverter output are decoupled to obtain the synchronous reference frame components. PV arrays act as the source of the system, which generates Direct Current power. This power is converted into AC power while using the (VSI). The actual output from the VSI can be linked with the grid by way of an LC filter along with (PCC). When grid synchronization is performed, keeping track of grid code parameters is crucial. PLL-based synchronization is effective for delivering power with good power quality.

Synchronous reference frame PLL is the name given to the phase locking since it takes place in the orthogonal domain (SRFPLL). The complexity of phase locking is raised by noise, distortions, and frequency variations. Synchronous reference frame PLL is the most advanced grid synchronization method utilized in three-phase systems (SRF-PLL). The investigation and regulator design of three-phase inverters primarily use DQ rotating Frame Transformation. It involves a conversion between still and moving frames. The parallel connected proportional component and integrator are shared to form the PI controller. The sum of the phase quantities is always 0 since the majority of three-phase systems are symmetrical. Due to the requirement of at least two independent phases to establish a DQ model, single-phase converters cannot use the notion because there is only one available phase in the system. The grid sideways active and reactive power control is managed by the control technique that maintains the DC link voltage to be continuous and also maintains the grid encryption at the output of converter. Using current and voltage sensors the grid terminal voltage V_{abc} and grid terminal current I_{abc} are measured respectively. PLL (Phase Locked Loop) is used to measure the viewpoint of grid voltage ω is given by *equation (1)*, is used for *abc* to *dq* transformation or *dq* to *abc* transformation and ω is obtained using *abc* to *αβ* transformation.

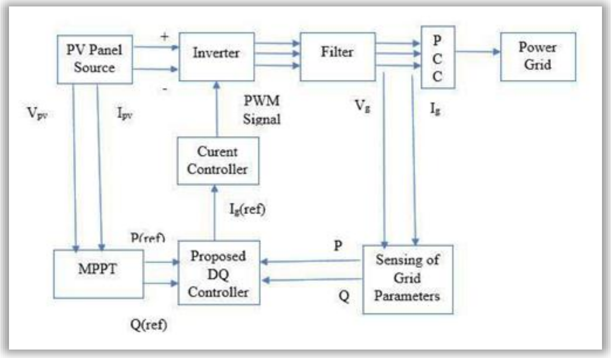

Figure 1: Power Flow Diagram in the Proposed Implementation

$$\omega = tan(\frac{V\beta}{V\alpha}) \quad (1)$$

where Vα and Vβ are the two-phase αβ components of grid voltage given by Equations (2 and 3),

$$V_\alpha = \frac{2}{3}\left(V_{ag} - 0.5V_{bg} - 0.5V_{cg}\right) \quad (2)$$

$$V_\beta = \frac{2}{3}(0.866V_{bg} - 0.866V_{cg}) \quad (3)$$

Where *Vag*, *Vbg*,*Vcg* and *Vcg* are the grid voltage components. The instantaneous three-phase AC voltages are represented by *equations (4-6)*,

$$V_{ag} = V_p sin(\omega_t) \quad (4)$$

$$V_{bg} = V_p sin(\omega_t - 120^o) \quad (5)$$

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$$V_{cg} = V_p sin(\omega_t + 120^o) \quad (6)$$

Using *abc* to *dq* conversion, these three-phase rotating voltage components *Vag, Vbg Vcg* are converted into stationary components *Vdg, Vqg, V_o* as given by *equation (7),*

$$\begin{bmatrix} V_{dg} \\ V_{qg} \\ V_o \end{bmatrix} = \frac{3}{2} \begin{bmatrix} sin\omega t & sin(\omega t - 120^o) & sin(\omega t + 120^o) \\ cos\omega t & cos(\omega t - 120^o) & cos(\omega t + 120^o) \\ 0.5 & 0.5 & 0.5 \end{bmatrix} \begin{bmatrix} V_{ag} \\ V_{bg} \\ V_{cg} \end{bmatrix} \quad (7)$$

Similarly using *abc* to *dq* transformation, three-phase current components *Iag, Ibg, Icg* are converted into stationary components *Idg, Iqg, I_o* has given by the *equation (8)*.

$$\begin{bmatrix} I_{dg} \\ I_{qg} \\ I_o \end{bmatrix} = \frac{3}{2} \begin{bmatrix} sin\omega t & sin(\omega t - 120^o) & sin(\omega t + 120^o) \\ cos\omega t & cos(\omega t - 120^o) & cos(\omega t + 120^o) \\ 0.5 & 0.5 & 0.5 \end{bmatrix} \begin{bmatrix} I_{ag} \\ I_{bg} \\ I_{cg} \end{bmatrix} \quad (8)$$

Figure 2 shows the *abc* coordinate and *dq* coordinate frames. Reactive power and Real power calculated through direct and quadrature axis component is as given in *equations (9 and 10).*

$$P_{grid} = 1.5(V_{dg}I_{dg} + V_{qg}I_{qg}) \quad (9)$$
$$Q_{grid} = 1.5(V_{qg}I_{dg} - V_{dg}I_{qg}) \quad (10)$$

For the dynamic decoupling, the quadrature axis voltage V_{qg} is made to zero by positioning the direct axis component with the voltage space vector, which makes the quadrature axis component zero always. If the reference frame is $V_{qg}=0$ then the active power and reactive power is specified by *equations (11 and 12)*. It is clear that, from *equations (11), and (12)*, for a particular d-axis voltage, reactive and active powers are controlled independently by the d-axis current component I_{dg} and q-axis current component I_{qg} respectively. The d-axis and q-axis current regulators are shown in *figure 3* and *figure 4*.

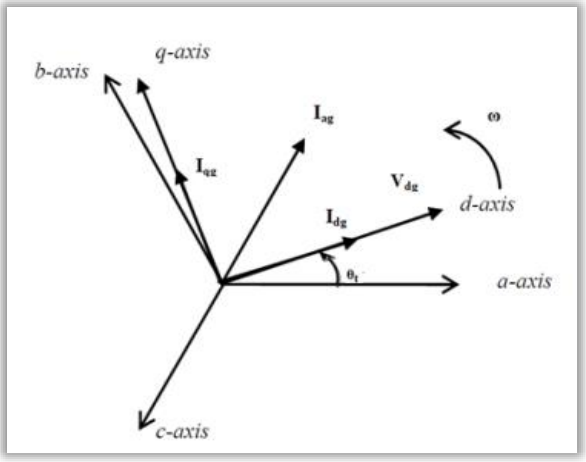

Figure 2: Time-varying three-phase *abc* to stationary *dq* Frame transformation

$$P_{grid} = 1.5V_{dg}I_{dg} \quad (11)$$
$$Q_{grid} = -1.5V_{dg}I_{qg} \quad (12)$$

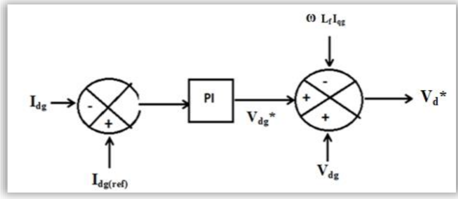

Figure 3: Flow diagram of d-axis current regulator

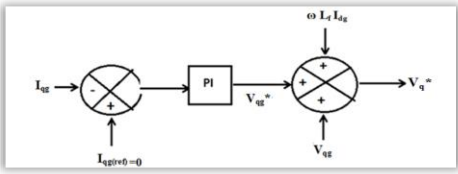

Figure 4: Flow diagram of q-axis current regulator

The d-axis reference current I_{dg} (ref) is derived from the PI regulator. The fault between DC link voltage $V_{dc}$and reference DC link voltage Vdc ref is given to the PI controller. The q-axis reference current I_{qg} (ref) is forced to zero. Grid side line resistance Rf, the dq coordinate control equations are given by the *equations (13 and 14),*

$$V_d *= V_{dg} * -\omega_t I_{qg} L_f + V_{dg} \quad (13)$$
$$V_q *= V_{qg} * +\omega_t I_{dg} L_f + V_{qg} \quad (14)$$

V_{dg}* and V_{qg}* are the reference voltage for d-axis and q-axis voltages respectively given by the *equations (15 and 16),*

$$V_{dg} *= (Kp + \frac{Ki}{s})(I_{dg(ref)} - I_{dg}) \quad (15)$$
$$V_{qg} *= (Kp + \frac{Ki}{s})(I_{qg(ref)} - I_{qg}) \quad (16)$$

The V_d* and V_q*components are then converted into three-phase time-varying AC components using *dq* to *abc* transformation as given in *equation (17),*

$$\begin{bmatrix} V_a * \\ V_b * \\ V_c * \end{bmatrix} = \begin{bmatrix} sin(\omega t) & cos(\omega t) & 1 \\ sin(\omega t - 120^o) & cos(\omega t - 120^o) & 1 \\ sin(\omega t + 120^o) & cos(\omega t + 120^o) & 1 \end{bmatrix} \begin{bmatrix} V_d * \\ V_q * \\ 0 \end{bmatrix} \quad (17)$$

V_a*,V_b*,V_c* are compared with the triangular wave carrier signals in the PWM controller, and the gate signals generated from the PWM controller are used to trigger the three-phase inverter switches. DC linkage voltage and V_{dc} ref error signal will be the input to the PI controller. Depending on K_p and *Ki* values the controller gives the I_{dg}*(ref)* reference current as shown in *figure 5*.

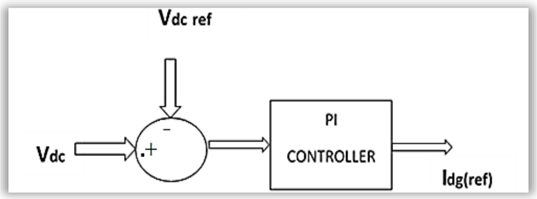

Figure 5: d axis reference current generation using the PI controller

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Research Article | Volume 11, Issue 2 | Pages 283-290 | e-ISSN: 2347-470X

3. RESULTS AND DISCUSSION

MATLAB Simulink-based simulation of PV integration to Grid is developed for both linear and nonlinear load. The resistance inductance (RL) load is considered for the linear loading condition while the rectifier is used for the nonlinear loading condition. Grid integration using direct and quadrature axis (DQ) controllers is developed with the idea of improving the power quality while the nonlinear load is connected and synchronization through the grid. The simulation specification of the complete grid synchronization system is given in *table 1*. The proportional-integral (PI) controller-based grid synchronization is established to control both the link voltage (DC), and improve power quality due to the nonlinear load synchronizing the PV-based inverter to the grid. Using the LCL filter the power quality is improved due to the filtering action. The LCL filter as shown in *fig.6* is connected to inverter output towards getting better power quality in the grid-synchronized PV inverter.

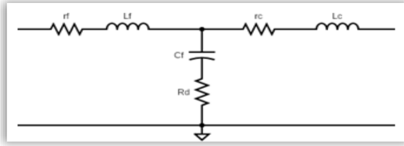

Figure 6: LCL Filter

Table 1. Simulation specification for grid-connected Inverter

PV module rating	**PV module number of cells**	96
	Series-connected PV modules	6
	Parallel PV strings	50
LCL Filter	Lf	4.2e-3
	Rf	0.50
	Lc	0.50e-3
	Rc	0.09
	cf rd	15e-6 2.025
Load		16KW
Grid generation type		Slack

There are four cases considered in the implementation. Those cases are as given in *table 2*.

Table 2: Simulation specification for grid-connected Inverter

Case 1	PV grid synchronization without nonlinear load and with RL filter
Case 2	PV grid synchronization with nonlinear load and with RL filter
Case 3	PV grid synchronization without nonlinear load and with LCL filter
Case 4	PV grid synchronization with nonlinear load and with LCL filter

Table 3: Comparison of THD and settling time

Parameters	PI Controller [25]	Fuzzy Space Vector [19]	FLC [22]	LCL DQ (Proposed Method)
Settling Time	3.0 sec	3.02.sec	2.08 sec	1.65 sec
THD	4.6%	3.47	4.5%	2.5%

The results obtained for all four cases shown in *table 2* are as shown in the following. The results obtained for *Case 1* are as follows. The PV power generated as per the irradiance variation is given in *figure 8*. This is common for all the cases considered

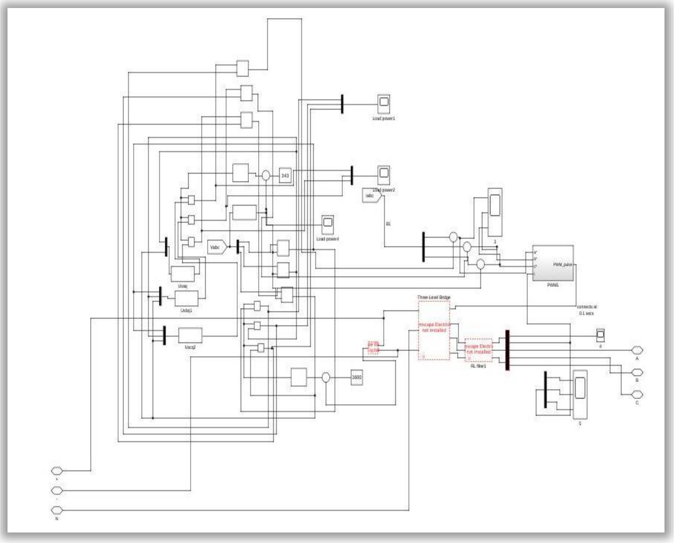

Figure 7: Simulink model of PV integration to grid for linear and nonlinear load

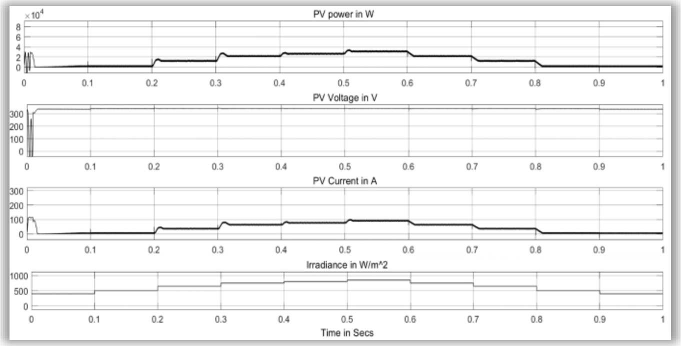

Figure 8: PV side response

The PV power in watts is due to the irradiation variation in the PV panel. Voltage is maintained constant with PV current varying according to the varying irradiation. The PV side response of irradiance, current, voltage and power waveform of PV is given in *figure 10*. It can be observed that due to the surge in irradiance, the power drawn from the PV increases in steps until 0.6 secs and reduces till 1 sec. When the PV output is higher the grid power is negative since it received power from the PV source as given in *figure 8*. The bidirectional operation of the inverter to maintain the DC relation voltage constant is

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Research Article | Volume 11, Issue 2 | Pages 283-290 | e-ISSN: 2347-470X

evident from the graphs. Grid power is negative when solar power is higher. And it is positive when the PV power is lesser.

***Case1*:** The grid voltage and current, and load voltage and current with linear load and without LCL filter are given in *figure 9*. The grid current is sinusoidal which can be observed from waveform. This is because the DQ controller is used for synchronization. Since nonlinear load is not introduced in the current waveform is a sinusoidal waveform. FFT analysis for Grid voltage, Grid current, Load current is given in *figure 11*.

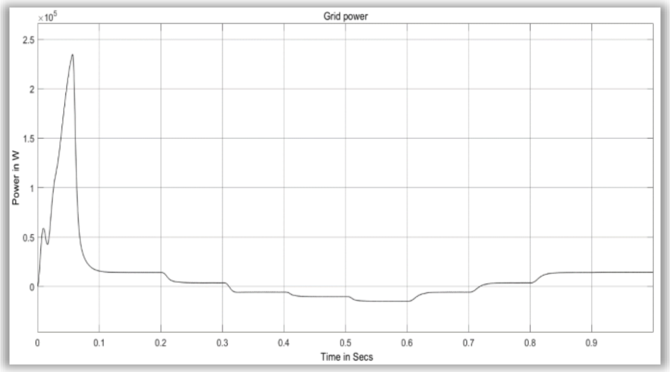

Figure 9: Grid Power

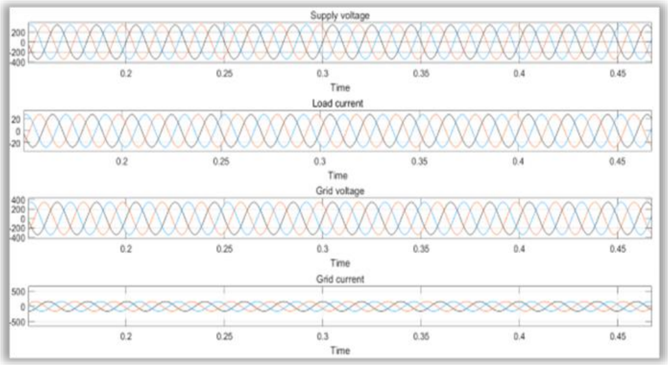

Figure 10: Supply Voltage, Load Current, Grid Voltage, and Grid Current with Linear Load

Figure 11: Grid Voltage THD with Linear Load

***Case2*:** The grid voltage and current waveform, load voltage and current with nonlinear load and without LCL filter are as given in *figure 16*. Sinusoidal waveform can be observed. This is because the DQ controller is used for synchronization. And the load current is seen to be deadbeat since the rectifier load is connected. FFT analysis for Grid voltage, Grid current, Load current is given in *figure 14- figure 17*.

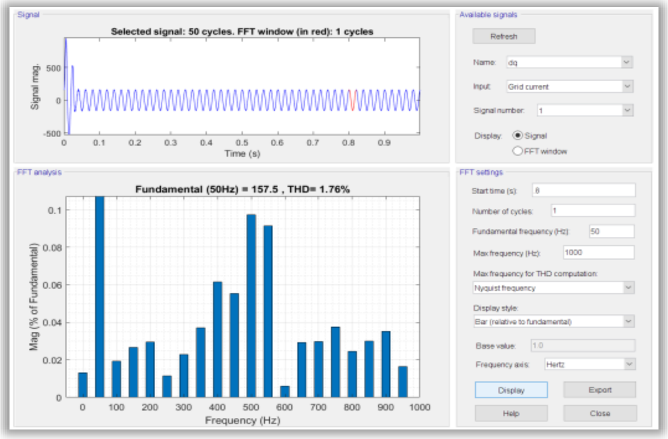

Figure 12: Grid Current THD with Linear Load

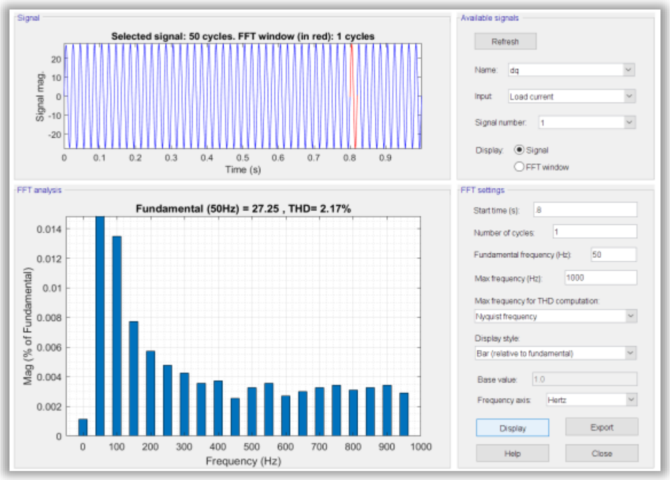

Figure 13: Load Current T HD with Linear Load

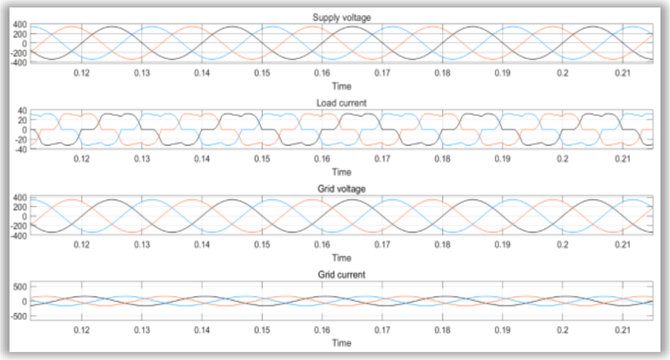

Figure 14: Supply Voltage, Load Current, Grid Voltage, and Grid Current with Nonlinear load

Case3: PV integrated grid with LCL filter connected linear load gives the following results revealed in *figure 18*. With the linear load the obtained waveform can be inferred from the study. It can be observed that the load current is sinusoidal with the linear load connected. Since the DQ controller controls the synchronization the grid current is in phase and sinusoidal. FFT investigation for Grid voltage, Grid current, Load current is given in *figure 19 - figure 21*.

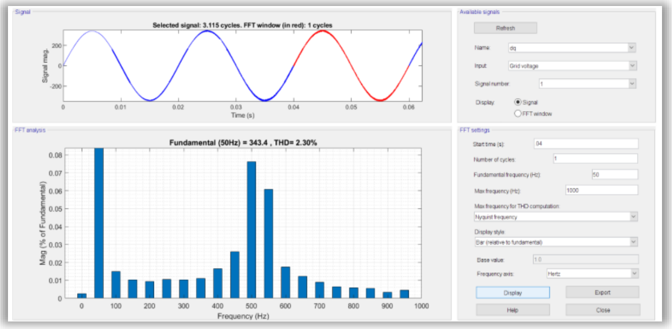

Figure 15: Grid Voltage THD with nonlinear load

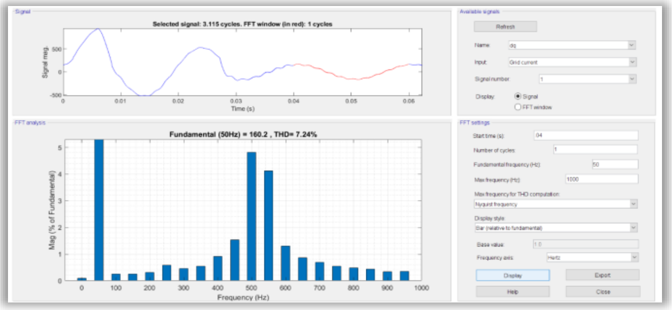

Figure 16: Grid Current THD with nonlinear load

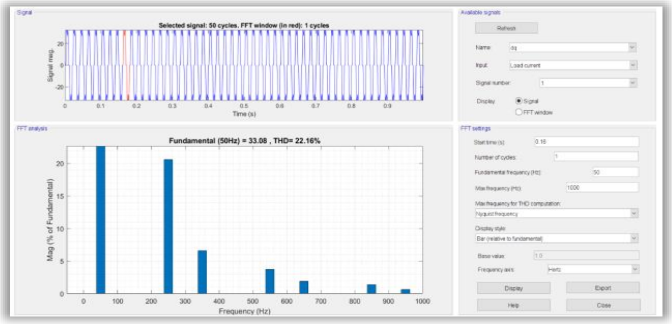

Figure 17: Load Current THD with nonlinear load

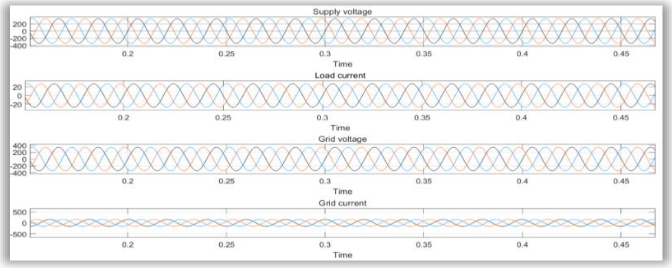

Figure 18: Supply Voltage, Load Current, Grid Voltage, and Grid Current with Linear Load

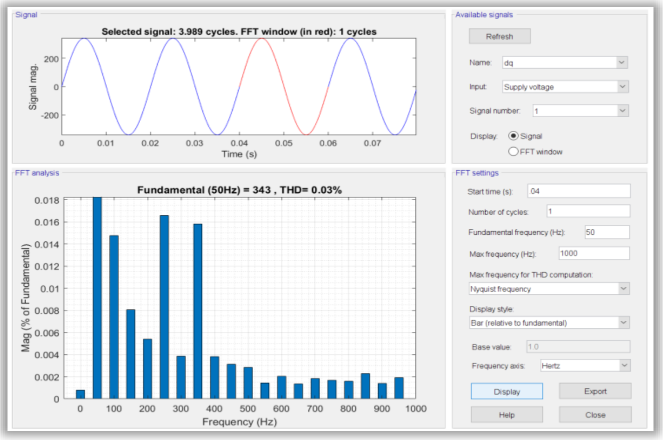

Figure 19: Grid Voltage THD with LCL filter

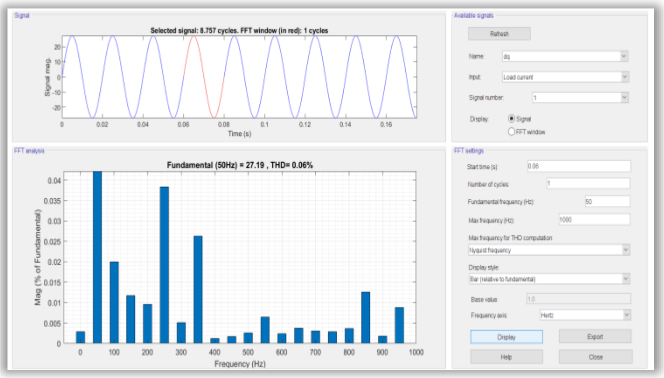

Figure 20: Grid Current THD with LCL filter

4. DISCUSSION

The THD of the LCL filter-based PV grid integration has reduced the grid voltage and current THD to well below the expected 5%. The tabulation indicates that the LCL filter has performed better than the RL filter-based implementation. Although the LCL filter takes some time to get settled to the steady state waveforms. THD values of grid voltage and grid current are tabulated in *Table IV*. It can be observed that the THD obtained for the LCL filtered output is providing THD within the 5% limitation of IEEE 519 standards. Thus, the LCL filter in the PV grid integration is providing a competitive output compared to RL-filtered inverters. Thus, the LCL filter is found to be advantageous compared to the RL-filtered PV integration. There is around a 3 to 4% improvement in the grid current THD while the LCL filters is used instead of the RL filter in the PV integration.

5. CONCLUSION

MATLAB-based simulation for PV integrated grid is developed with LCL filter implementation. The system is checked for Total Harmonic Distortion (THD) performance. The magnitudes of different harmonics are high. This is not alarming because the magnitude of harmonic current is low, even though its relative distortion is high. The PV-integrated system is checked for THD with the LCL filter and compared for the performance without the LCL filter. The proposed controller aids to compensate the swells, disruptions, flicker, reactive

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currents, unbalance voltage, unbalance current and sags all at an instant. This technique provides better interference between the power grid and power converter. This filter aids to reduce switching frequency of the power converter. The results obtained from the PV integrated system give better performance while using the LCL filter than the RL filters. The Grid current with nonlinear load is higher and the LCL filter is bettered

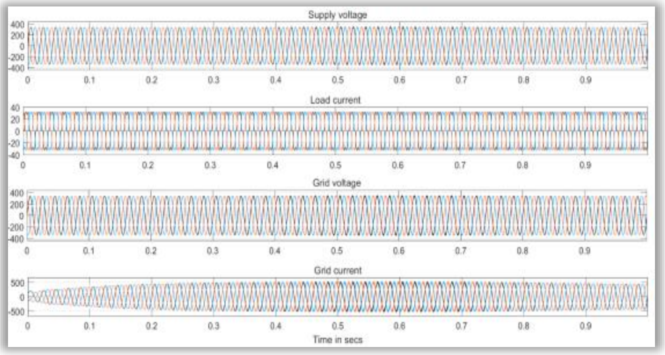

Figure 21: Supply Voltage, Load Current, Grid Voltage, and Grid Current with non-Linear Load

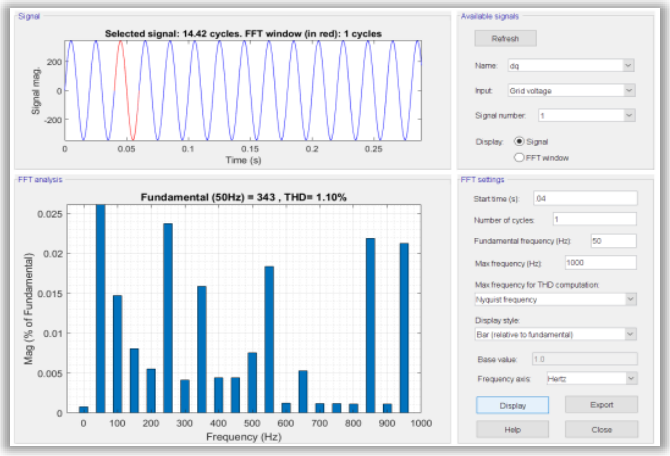

Figure 22: Grid Voltage THD nonlinear load and LCL filter

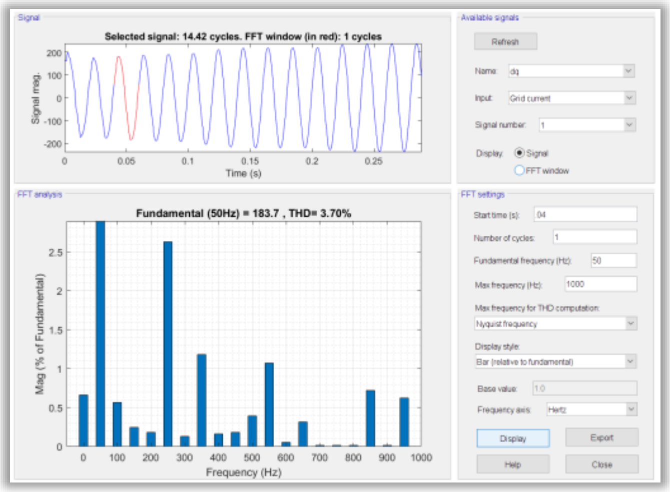

Figure 23: Grid Current THD nonlinear load and LCL filter

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International Journal of
Electrical and Electronics Research (IJEER)
Research Article | Volume 11, Issue 2 | Pages 283-290 | e-ISSN: 2347-470X

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