

Performance Evaluation of Single-Phase Grid-Connected Photovoltaic Inverter Using LC and LCL Filter Based on the Reduction of THD

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Abstract

Solar photovoltaic (PV) energy and its applications continue to grow in popularity as a means of enhancing society's sustainable development. There are a lot of issues to consider when PV systems are linked to the grid. One of the challenges, particularly only with large-scale use of PV systems, is harmonics in PV systems. This research investigates the use of well-known filters to reduce harmonics in PV systems. Filtering is required to decrease the harmonics due to the non-sinusoidal nature of PWM voltages at the converter output. To join the converter to the grid and decrease harmonics, a simple LC filter has traditionally been utilized. The use of LCL filters, on the other hand, has been proposed. The purpose of this research is to look at the impact of T-filters or LCL Filters on the overall working of a photovoltaic system that is connected to a grid. The perturb & observe algorithm is used for MPPT operation and the proportional-integral controller (PI) is used as the current controller in the closed-loop grid-connected PV system for the generation of pulses. The single-phase Grid-Connected Photovoltaic System for both LC & LCL Filters is implemented in this paper using MATLAB/Simulink. Total Harmonic Distortion is utilized as the performance metric in this comparison. The value of %THD for the proposed system i.e.8.06% emphasizes its necessity for implementation in practicality.

1. Introduction

Nowadays, several photovoltaic (PV) systems have been attached to the grid as a result of the growing need for sustainable environment energy systems. Huge PV system connections to the grid, on the other hand, provide a variety of challenges, including concerns with electricity purity and grid stability [1]– [6]. From grid-connected Photovoltaic systems, harmonics are transmitted to the grid, resulting in bad power quality [7–12]. In a new analysis, various efforts (attempts) were made to define harmonics from grid-connected PV inverters that have a significant influence. PV inverters, in general, generate harmonics as a result of the non-ideal performance of power supplies. There are various solutions for reducing harmonics in the literature [11–15]. Harmonics mix with the fundamental voltage or current to produce a non-sinusoidal shape, resulting in a power quality problem known as waveform distortion. The overall harmonic spectrum, including magnitudes and phase angles for each harmonic component, can be used to describe harmonic deformation stages. The Total Harmonic Distortion is a commonly used metric for determining the accurate value of harmonic distortion. Because of the expanding use of power electronics equipment, it has become a growing source of concern for many end-users and the broader power system. The nonlinear properties of loads and equipment on the electrical power system cause harmonics.

As a result of the nonlinear voltage dips across the system impedance caused by these currents, voltage distortion occurs. To calculate the total harmonic distortion of a signal, you add up all of the harmonics and divide them by the Fundamental frequency. In the vast majority of circumstances, a system's transfer function is linear and time-invariant. Additional information is added to a signal as it travels through a non-linear device at the harmonics of the original frequencies. THD is a measurement of how much distortion there is.

$$THD = \sqrt{\frac{V_2^2 + V_3^2 + V_4^2 + \dots}{V_1}} \tag{1}$$

The output of the inverter is not sinusoidal and demands filters to reduce harmonics from entering the grid [12]. therefore, a simple LC filter has traditionally been utilized. The use of LCL filters, on the other hand, has been proposed. The purpose of this research is to look at the impact of T-filters on the overall working of a photovoltaic system that is connected to the grid.

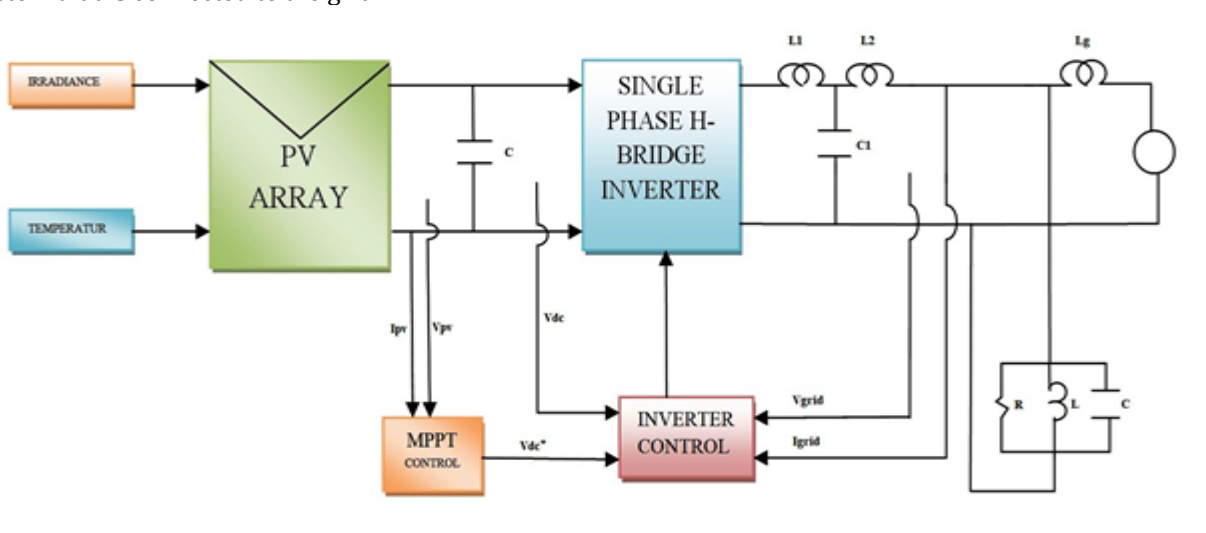


Fig. 1 Block diagram of photovoltaic system connected to the grid

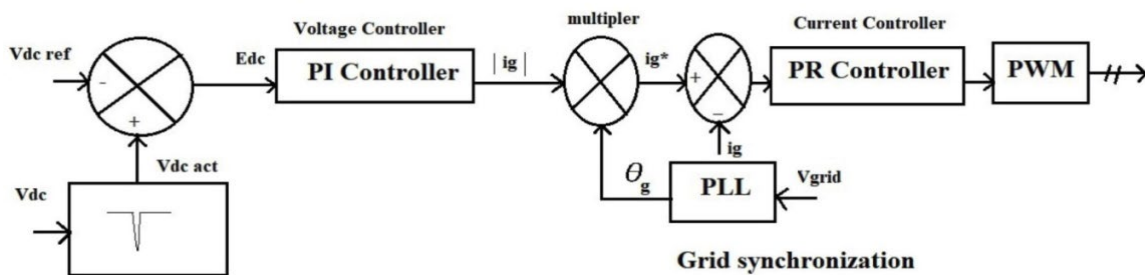


Fig. 2 1-phase grid-connected photovoltaic system control structure

2. Control Structure and System Configuration

Simulation tests on a 1-Phase grid-connected Photovoltaic system were done to examine harmonics from grid-connected Photovoltaic systems. Figure 1 reveals the general figure of the system. The PV system is linked to the inverter via the DC-link in the above block diagram, and the inverter is attached to the grid via the filter. The irradiance and temperature are the Photovoltaic array's inputs. Through a dc-link, the PV array's output, which is nothing more than DC voltage, is sent to the inverter. The dc-link regulates the PV array's output and the inverter's input. The inverter converts DC voltage to AC voltage. The grid-connected gadget receives the inverter's output after passing through the filter. In this single-stage system, the Photovoltaic inverter, also known as a full-bridge inverter, is critical for power distribution from Photovoltaic panels to the AC grid. An MPPT approach, i.e.

perturbation and observation – P&O, is used to acquire a reference dc-link voltage V_{dc}^* , which is nothing but the Photovoltaic voltage during operation, to provide high current collection from Photovoltaic systems. A proportional-integral (PI) controller, for example, controls the amplitude of the grid current i_g , which is acquired from a phase-locked loop, to modify the DC-link voltage V_{dc} (PLL) [16-18]. The performance of the Photovoltaic system's control is illustrated by using an LCL filter at the inverter's output. The THD percent has altered, as can be observed from the simulation results. In the simulation results, the FFT spectrum of the grid current is depicted. By upgrading the grid current filter from an LC to a T- filter, the harmonics of the grid current can be decreased.

2.1.1 Model of Photovoltaic Cell

A genuine diode is connected in series with an ideal current source in a basic equivalent circuit model for a Photovoltaic cell. The ideal current source generates current proportional to the amount of sunlight it receives. There are three significant points in the I-V characteristics of PV cells.

1. The 1st point is a short circuit point denoted as I_{sc}
2. The 2nd point is V_{oc} which is an open circuit point
3. The third significant point is related to the maximum power that can be transferred from the PV cell.

Shorting the terminals of the analogous circuit for the Photovoltaic cell together disables the flow of current through the (actual) diode, so the entire current flows through the shorted leads. Because I_{sc} is the short-circuit current, the magnitude of the ideal current source must also equal I_{sc} . When PV cells' leads are open, there is no load current and no-load voltage [4].

When the more difficult PV equivalent circuit is needed (for example, when shading occurs), a circuit that involves a few resistive modules for a power outage is used, such as with a parallel discharge (or shunt) resistance R_p and a series resistance R_s (contact resistance from the cell's bond with its wire leads plus the semiconductor's resistance) [5]. A circuit like this is shown in Figure 3.

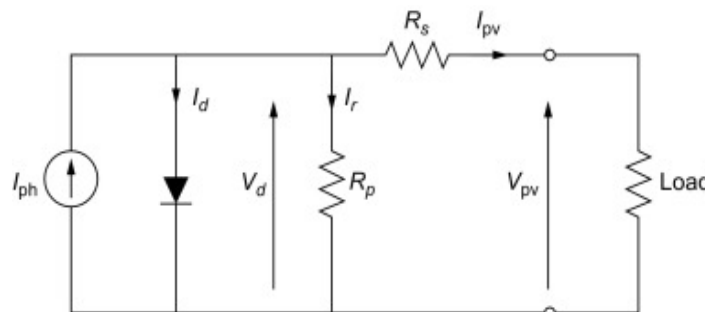


Fig. 3 Equivalent circuit of photovoltaic cell

The model characteristic equation is obtained by balancing the currents through the resistors and diode at a point to the left of R_p , as illustrated in Fig. 3,

$$I_{pv} = I_{ph} - I_d - I_p = I_{ph} - I_0 \left(e^{V_{pv} = \frac{R_d I_{pv}}{n_s V_g Q_d} - 1} \right) - \left\{ \frac{V_{pv} + R_s I_{pv}}{R_p} \right\} \quad (2)$$

Where

- V_{pv} is the voltage of a Photovoltaic module (V)
- I_{pv} is the current of a Photovoltaic module (A)
- I_{PH} = current of light (A)
- I_0 = reverse saturation current in a diode (A)
- Q_d is the ideality factor for diodes.
- n_s denotes the no of cells in a series.
- R_s = resistance in series (Ω)
- R_p = resistance to shunting (Ω)
- The thermal voltage (V) is given by $V_t = kT_c/q$, where k is Boltzmann's constant, T_c is the cell temperature, and q is the charge of an electron.

3. MPPT (Maximum Power Point) Operation

Perturb and Observe MPPT is used here due to its simplicity. It is the Perturb and Observe MPPT algorithm that is most widely used, and it has been around for a long time. As the flowchart in Figure illustrates, the Perturb & Observe algorithm is widely used due to its simplicity [7]. After a series of observations and perturbations, the operating point converges to the MPP. An algorithm is used to determine the time needed to reach MPP by combining the power and voltage of time (K) with samples at a time (K-1). In positive power changes, a little voltage perturbation affects the panel's power, and the voltage perturbation continues as before. The MPP lies far from the MPP if delta power is negative, so the perturbation must be reduced to approach it. This is summarized in Table 2. Therefore, the MPP is discovered by minor perturbations of the PV curve, which increases the algorithm's response time. With the perturbation size increased, steady-state oscillations are observed around the MPP.

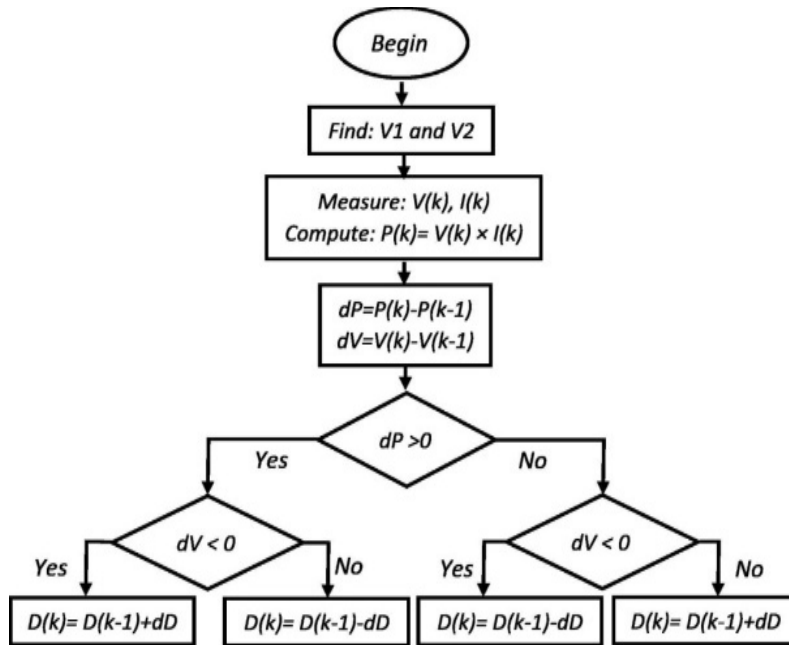


Fig. 4 Flowchart of P & O algorithm

4. Single-phase Full-bridge Inverter (H-bridge)

An H-bridge inverter with a full-bridge topology is used to convert DC voltage into AC voltage. The conversion components are two times more expensive than those used in single-phase half-bridge inverters. A full-bridge inverter's circuit consists of four diodes and four controlled switches, as shown below in Figure 5. Because these diodes transmit the stored energy in the load back into the DC source, they are known as freewheeling diodes or feedback diodes. When the load is not purely resistive, the feedback action occurs. Full-bridge inverters can use BJT, IGBT, MOSFET, or thyristor-controlled switches.

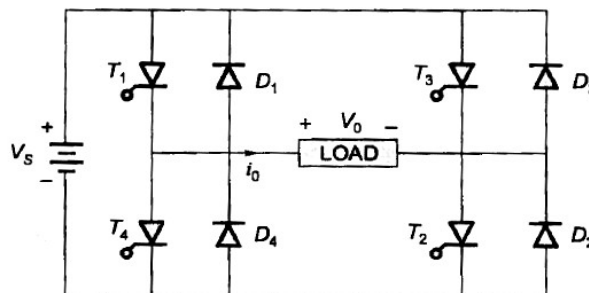


Fig. 5 Single-phase full bridge inverter

An H-bridge inverter works by using two switches at the same time to change the sign of the voltage across the load. The operation of T1 and T2 for half duration will produce a positive input voltage across the load. By activating T3 and T4, the polarity of the voltage across the load will be altered during the remaining halftime. Figure 6 reveals the pulse generation for the h-bridge inverter.

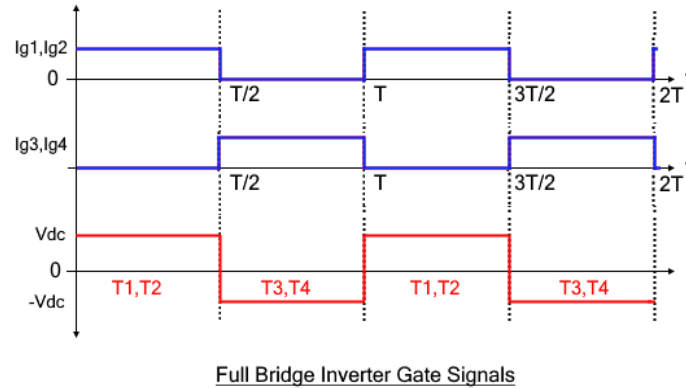


Fig. 6 Single-phase full bridge inverter pulses

5. Proportional Integral (PI) Controller

Proportional plus integral (PI) controllers are another name for integral controllers. It's a controller that combines proportional and integral control actions into one. As a result, it's known as a PI controller. As indicated in Figure 2, the present controller is a PI controller. For a traditional PI controller, the transfer function is as follows:

$$G_s = K_P + (K_I/s) \quad (3)$$

The proportional gain term is K_P , and the integral gain term is K_I . In this simulation, the trial-and-error method is utilized to find an appropriate value for K_P and K_I .

6. Phase-locked Loop (PLL)

An inverter module that incorporates a phase-locked loop (PLL) is necessary for the grid-connected mode. It uses the measured grid AC voltage as a reference to calculate a determined grid frequency and a determined phase angle for phase control of the inverter output signal. PLLs minimize output and reference phase errors as a result of their closed-loop design. The working of a PLL module directly affects the inverter [20].

7. LC Filter

This second-order filter attenuates at -40dB/dB. It is fairly simple to construct an LC filter. The following figure 7 shows the construction of the LC filter. Capacitance can reduce the cost of the inductor, which is the trade-off in the design. However, at the fundamental frequency [13], the capacitor may experience inrush current and significant reactive current flow. Inverters connected to grids via LC filters have a resonance frequency determined by the grid impedance. Small size and high attenuation performance make the LC filter a popular choice for standalone inverters.

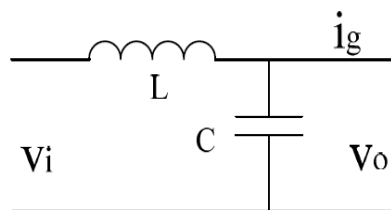


Fig. 7 LC filter

7.1.1 Design of LCL Filter (T Filter)

Because of its substantial attenuation more than resonance frequency (shown in Fig.8), the third-order LCL filter is often used with grid-connected inverters. In comparison to the LC filter, the T-filter decouples the filter more effectively from the grid impedance [13]. During the design phase, the resonance of the T-filter, as well as the current ripple flowing through the inductors, must be considered. The T-filter design processes are discussed in the following section.

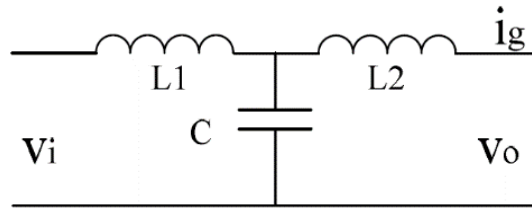


Fig. 8 LCL filter

An LCL-type filter was chosen based on the inverter filter study because of its better performance and simplicity. [24-27] Describe and discuss the T filter design processes. The grid-tied mode's filter design requirements are typically stricter than the stand-alone inverter's design requirements. An inverter-side filter's inductance is determined by how much attenuation of harmonic currents and power ripple can be tolerated. In a rated environment, the capacitance is calculated by using the power factor absorbed. There are several guidelines to consider while designing a T-filter. There shouldn't be more than a 10% difference in inductance between the two inductors (L1 + L2) to prevent a significant voltage drop. The current ripple should be kept to a maximum of 20% of the rated current. There can't be too much or too little capacitance. A tiny value capacitance reduces the LCL filter's attenuation capability, whereas a large value capacitance results in a high reactive power [23]. To guarantee acceptable system dynamics and avoid resonance difficulties, the T filter's resonance frequency should always be built within the range of equation (4). Grid fundamental frequency is f_g in an equation, and sample frequency is f_s . To ensure system stability, the grid-side inductance L2 should be a bit of the inverter-side inductance L2 [24-30].

$$10f_g < f_{res} < 0.5f_s \tag{4}$$

7.1.2 Parameters of the Single-Phase Grid-Connected Photovoltaic System for the LC Filter and T-Filter (LCL) are Shown in Table 1

Table 1 Parameters of the 1-phase grid-connected PV system for the LC filter and LCL filter

Name of the parameter	Ratings
Photovoltaic Rated Power	1
Inverter Input capacitor (DClink)	$C_{dc} = 1100 \mu\text{F}$
LC Filter	$L_{inv} = 4.8 \text{ mH}$, $C_f = 4.3 \text{ nF}$
LCL Filter	$L_{inv} = 4.8 \text{ mH}$ $C_f = 4.3 \text{ nF}$ $L_g = 15 \text{ mH}$
Switching Frequency	$f_{inv} = 8 \text{ kHz}$
Controlling Sampling Frequency	$f_s = 20 \text{ kHz}$
DC Link Frequency	
Grid Nominal Voltage (RMS)	$V_{dc} = 512 \text{ V}$
Grid Nominal Frequency	$V_g = 230 \text{ V}$
	$f_g = 50 \text{ Hz}$

8. MATLAB Simulink

As mentioned in the introduction, MATLAB/Simulink is used as the working platform to interpret the results in this research. The following figure shows the design of the grid-connected photovoltaic system, where the PV panel, Inverter, filter, and grid are connected.

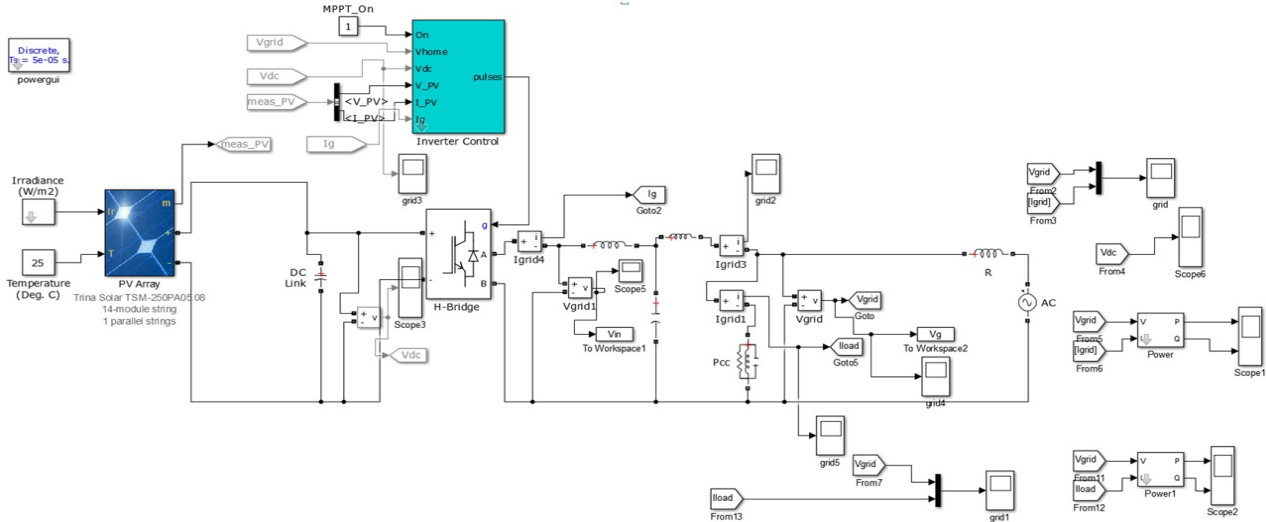


Fig. 9 Grid-connected PV system in MATLAB/Simulink

8.1 Simulation Results and Discussion

Current-voltage & power-voltage characteristics of photovoltaic module: The below figure 10 is the current-voltage and power voltage results of the photovoltaic system that is connected to the grid. From the figure, we can say that voltage i.e. Voc decreases with an increase in the temperature which is the negative temperature coefficient, whereas current i.e. Isc increases with an increase in the temperature which is a positive temperature coefficient. As the power is the product of voltage and current power is decreasing with the increase in the temperature which is also a negative temperature coefficient. the PV system is run at the standard irradiance i.e. 1000 W/m² and a standard temperature of 25°C.

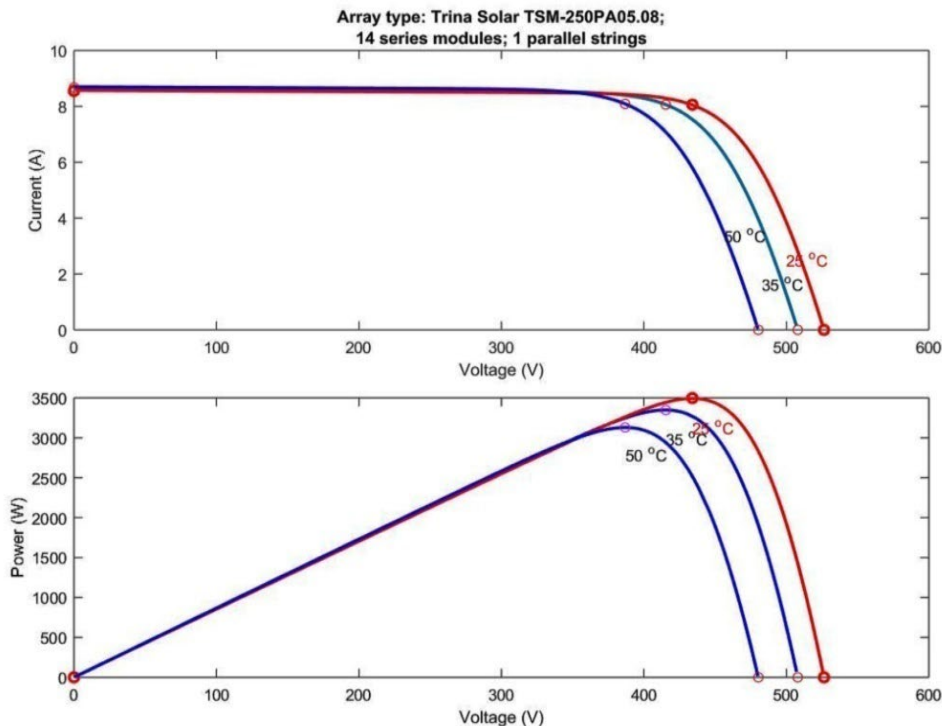


Fig. 10 Current-voltage & power-voltage characteristics of photovoltaic module

8.1.1 Grid Voltage and Grid Current with an LC-Filter in a Grid-connected Photovoltaic System

Below figure 11 is grid voltage and grid Current with an LC-Filter in a grid-connected photovoltaic system. The figure gives the picture that from the time 0.25 sec when the PV system is connected to the grid by giving the pulses to the H-Bridge inverter there is a distortion or appearance of harmonic in the grid voltage and grid current. As we know harmonics increase the distortion power, i.e., increase the apparent power required by the system, while the effective real power at the fundamental frequency [25]. Therefore, this has to be reduced by improving the filter from LC to LCL.

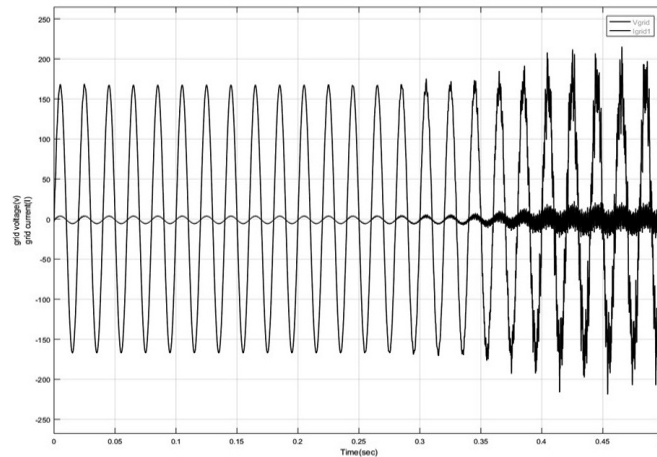


Fig. 11 Grid voltage and grid current with an LC-Filter in a grid-connected photovoltaic system

8.1.2 FFT Spectrum for LC-Filter-based Grid-connected Photovoltaic System

Below Figure 12 is the FFT spectrum for an LC-Filter-based Grid-connected Photovoltaic System. The FFT spectrum for the LC filter gives the %THD as 9.54% which is not the acceptable value in grid-connected photovoltaic systems where a modification has to be made to reduce the harmonic value.

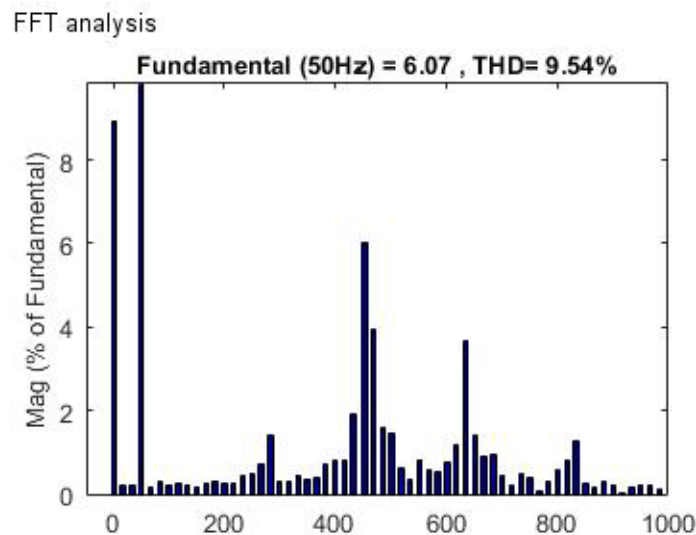


Fig. 12 FFT spectrum for LC-Filter based grid-connected photovoltaic system

8.1.3 Grid Voltage and Grid Current with T-Filter Based Grid-connected Photovoltaic System

Below Figure 13 is Grid Voltage and Grid Current with an LCL(T)-Filter in a Grid-connected Photovoltaic System. The figure gives the picture that from the time 0.25 sec when the PV system is connected to the grid by giving the

pulses to the H-Bridge inverter there is less distortion or appearance of low harmonic compared to the LC filter. Therefore, the system has been improved by replacing the LC filter with the LCL or T filter.

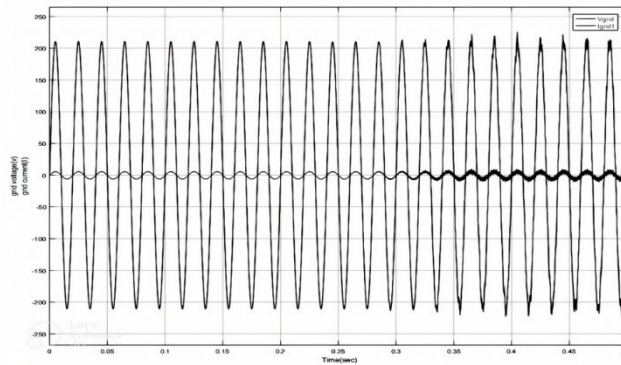


Fig. 13 Grid voltage and grid current with T-Filter based grid-connected photovoltaic system

8.1.4 FFT Spectrum for a Grid-connected Photovoltaic System Using an LCL Filter

Below figure 14 is the FFT spectrum for LCL (T-Filter based grid-connected photovoltaic system). The FFT spectrum for the LC filter gives the %THD as 8.03% which is the acceptable value in the grid-connected photovoltaic systems when compared with the LC filter. The harmonic can still be reduced by improving the LCL parameters.

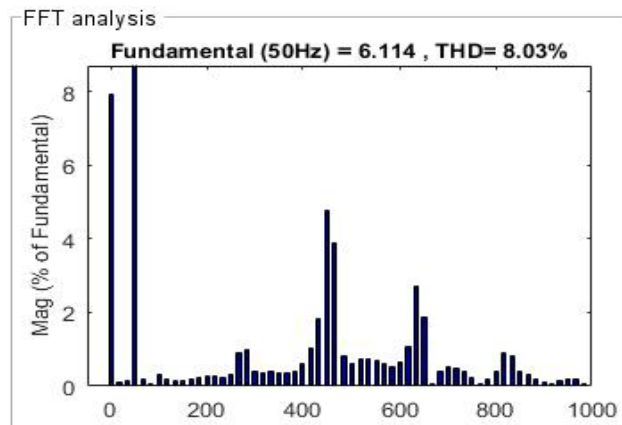


Fig. 14 FFT spectrum for a grid-connected photovoltaic system using an LCL filter

The following is the table that explains the value of grid voltage, grid current, power factor, and %THD for various loading conditions from 20% to 100% for the proposed grid-connected photovoltaic systems using LCL filter

Table 2 Output of the system at different load variations

Load Variations(%)	Grid Voltage(Vg)	Grid Current(Ig)	Power Factor	%THD For Grid Current
100	228.2	4.135	0.980	8.03
80	228.2	5.965	0.981	7.29
60	228.3	6.239	0.982	6.58
40	227.8	8.987	0.990	5.98
20	228.1	15.45	0.991	5.00

The following is the figure 15 that explains the value of %THD for various loading conditions from 20% to 100% for the both conventional LC Filter and proposed grid-connected photovoltaic systems using the LCL filter

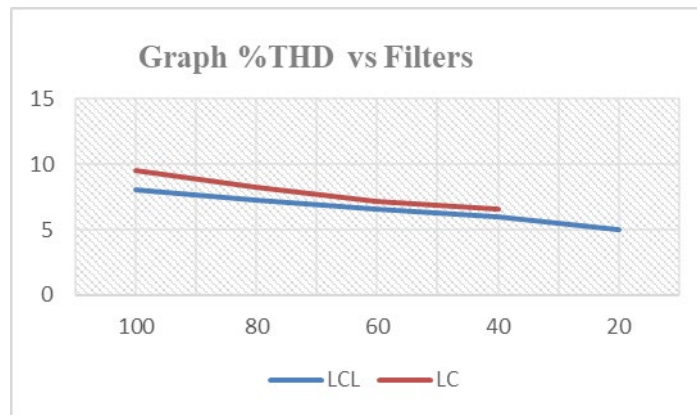


Fig. 15 The graph between %THD and loading conditions for grid-connected photovoltaic systems using LC and LCL filters

9. Conclusion

When Photovoltaic systems are connected to the grid, there are several challenges to consider. One of the challenges, specifically with the large-scale use of PV systems, is harmonics in PV systems. This paper investigates the use of well-known filters to reduce harmonics in PV systems.

MATLAB/Simulink was used to create a 1-Phase grid-connected PV system for both the LC and LCL filters. Total Harmonic Distortion was utilized as the performance metric in this comparison (THD). This study presents the simulation results using the Harmonic spectrum. LCL Filter has a percent THD of 8.03 percent for 1-Phase grid-connected Photovoltaic systems, but LC Filter has a percent THD of 9.54 percent for 100% Loading conditions. When compared to a system utilizing LC Filter, it is found that a 1-phase grid-connected Photovoltaic system for LCL Filter has a lower harmonic spectrum. the THD is reduced with LCL when compared with the LC filter. The paper will provide support to the study of LC and LCL filter designs in grid-connected Photovoltaic systems at different loading conditions. The values of grid voltage, grid current, and power factor in grid-connected Photovoltaic Systems using LCL filter point out the place of its application.

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Conflict of Interest

The authors declare that there is no conflict of interest.

Author Contributions

All authors made an equal contribution to the original draft's conception, formal analysis, research, methodology, writing, and editing. The final version of the manuscript has been read and approved by all authors.

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