Performance Analysis of Grid-Connected Photovoltaic Inverter Based on the Total Harmonic Distortion

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Abstract: - The deployment of solar photovoltaic (PV) electricity along with associated technologies to promote sustainable growth in society is growing in popularity. Several concerns must be considered when PV systems are linked to the grid. One problem with power quality in PV systems, particularly when these systems are used widely, is harmonics. The purpose of this study is to lower harmonics in PV systems that are connected to the grid. The present investigation proposes the H5 inverter for grid-connected photovoltaic systems. Comparing the proposed H5 inverter to the conventional H4 inverter, the former effectively decreases the harmonics. The inverter is coupled to the grid over a simple LCL filter. For MPPT operation, the perturb and observe method is employed. MATLAB/Simulink is used in this paper to implement the Single-phase Grid-Connected Photovoltaic System. Total Harmonic Distortion is utilized as the performance metric in this comparison. The proposed technique's %THD value emphasizes its significance to put it into implementation.

Keywords— Harmonics, Inverters, Photovoltaic Systems (PV), Total Harmonic Distortion (THD).

1 Introduction

The demand for affordable, renewable, and environmentally friendly energy solutions is on the rise. Among these, photovoltaic (PV) energy stands out as a leading contender due to its widespread availability, ease of access, and eco-friendly operation. In the transition to sustainable energy sources, power inverters play a crucial role in converting photovoltaic electricity into the alternating current needed for grid integration—a trend gaining momentum [1]. Nevertheless, the connection of solar PV arrays to the grid through inverters brings about significant power quality (PQ) challenges. The main culprits behind these problems are harmonics in grid voltage and currents [2–3]. Harmonics, in particular, pose a considerable threat to power quality (PQ) as they manifest on the grid side [4-6]. Harmonic distortion, which displays the difference between the actual network voltage or load current and the ideal sinusoidal

K. R. Madhavi et al. (eds.), *Proceedings of the International Conference on Computational Innovations and Emerging Trends (ICCIET 2024)*, Advances in Computer Science Research 112,
https://doi.org/10.2991/978-94-6463-471-6_6

waveform, is the primary indicator of power quality. Some of the consequences that the harmonic could have on the setup, the equipment, or both are as follows:

- Higher efficiency losses in the system's equipment and electrical installation.
- Unexpected resonances.
- Electronic equipment disturbances that result in "logical" errors in digital circuits.
- Generator and motor failures.

The Total Harmonic Distortion is a commonly used metric for determining the accurate value of harmonic distortion. To calculate the total harmonic distortion of a signal, you add up all of the harmonic and divide them by the Fundamental frequency. THD is a measurement of how much distortion there is

$$THD = \sqrt{\frac{V_2^2+V_3^2+V_4^2+\cdots}{V_1}} \quad \text{----------1}$$

In the conventional PV system, the inverter uses generally an H4 inverter where the performance of the system is poor as per the harmonics are concerned. This paper presents an H5 grid-connected photovoltaic inverter which means the type of inverter used in this system is H5. This paper conducts an analysis of an H5 inverter based on the total harmonic distortion. The inverter delivers non-sinusoidal and demands filters to reduce harmonics from entering the grid [7]. therefore, a simple LCL filter has traditionally been utilized. The purpose of this research is to evaluate the impact of H-5 inverter topology on the overall working of the system where as the emphasis is on the harmonic content which is one of the performance systems of measurement to assess the power quality of the system.

2 System Configuration

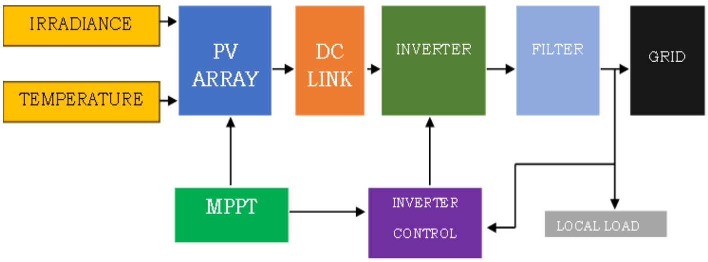


Fig 1. Block Diagram of Photovoltaic System connected to the grid

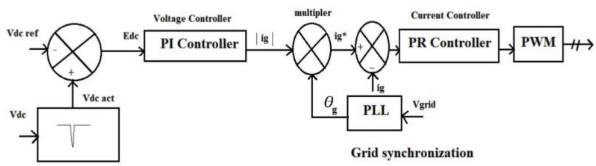


Fig.2. Control Structure of the system

2.1. Overall System Control and Operation

Starting with a solar panel that converts light energy into electrical energy is linked to the inverter via the DC link in the above block diagram. 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 process involves converting DC voltage into AC voltage through an inverter. A grid-connected device then receives the output of this inverter after passing through a filter. In a single-stage configuration, the photovoltaic inverter is vital for efficiently transmitting power generated by photovoltaic panels to the AC grid. To ensure the efficient collection of current from photovoltaic systems, the Maximum Power Point Tracking method such as perturbation and observation (P&O), is employed to control a reference DC-link voltage (Vdc*), which represents the photovoltaic voltage during operation. This voltage is then employed for control functions. For instance, a proportional-integral (PI) controller is utilized to standardize the amplitude of the grid current (ig), extracted from a phase-locked loop (PLL), thereby regulating the DC-link voltage (Vdc). The effectiveness of the control system for the photovoltaic setup is highlighted by employing an H5 inverter topology. The Total Harmonic Distortion (THD) percentage is observed to have changed, as evidenced by the simulation results. Moreover, the findings encompass a Fast Fourier Transform (FFT) spectrum analysis of the grid current. The transition from an H4 to an H5 inverter topology precipitates a discernible decrease in grid current harmonics.

2.2. 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 [10]. After a series of observations and perturbations, the operational point converges to the MPP. An algorithm is utilized to ascertain the temporal interval necessary to attain the Maximum Power Point (MPP) by amalgamating the power and voltage profiles over time (K) with samples from a preceding 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. Therefore, the MPP is discovered by minor perturbations of the PV curve, which increases the algorithm's response time.

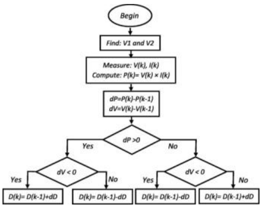
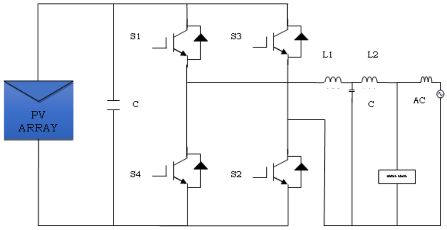


Fig.4. Flowchart of P & O Algorithm

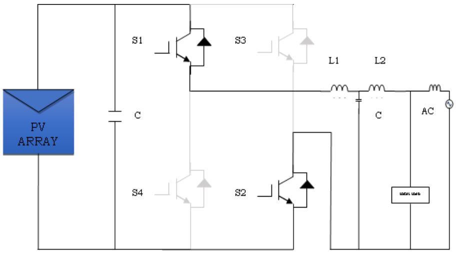
2.3. Single-phase full-bridge Inverter (H4/H-bridge)

AC power is produced with the conversion of DC power using an H-bridge inverter with a full-bridge topology. Four controlled switches with four diodes contribute to the circuit of a full-bridge inverter, as Figure 5 below illustrates. The switching sequence of an H-bridge inverter, which is also known as an H4 inverter, will vary depending on the type of the output waveform and the modulation used; e.g., sinusoidal PWM,

square-wave, etc. In generating a sine wave output utilizing a sinusoidal PWM method, the following is an example sequence:
Throughout the positive phase of the output waveform, switches S1 and S2 are actuated to create a connection between the positive terminal of the DC input and the load. Meanwhile, switches S4 and S3 remain deactivated to avoid any potential short circuit across the DC input.
In contrast, throughout the negative phase of the output waveform:
- Switches S3, and S4 are activated to link the negative terminal of the DC input to the load.
- Switches S1 and S2 are deactivated to avoid creating a short circuit across the DC input.
This alternating switching pattern, performed at a high frequency, effectively generates a sinusoidal output waveform across the load. The duty cycle of each switch is carefully adjusted to regulate the magnitude of the output voltage, thereby achieving the desired sinusoidal waveform.



(a)



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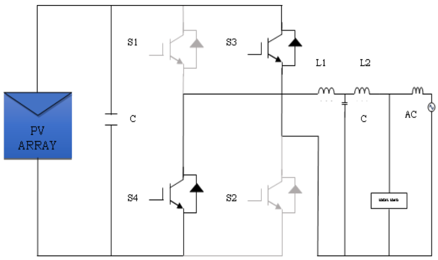


(c)

Figure 6 illustrates (a) the H4 inverter circuit, and (b) switches throughout the positive phase of the grid voltage. Panel (c) elucidates switches throughout the negative phase of the grid voltage.

2.4 Proposed H5 Converter

The H5 Transformerless inverter topology is depicted in Figure 7. This figure displays a standard H5 inverter linked to a solar panel via the fifth switch. Operating at the grid's frequency, this switch serves the purpose of disconnecting the PV system from the grid during zero conditions, effectively closing the path for leakage current.

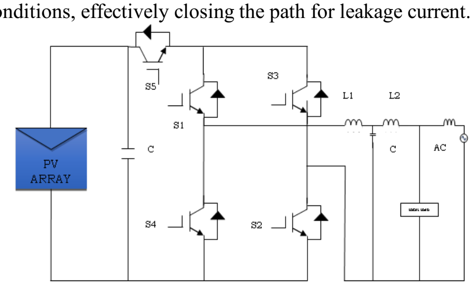
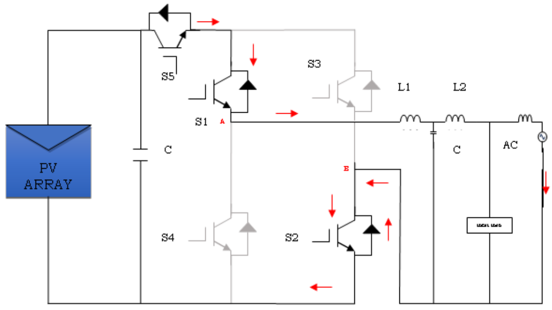


Fig.7. H5 inverter topology

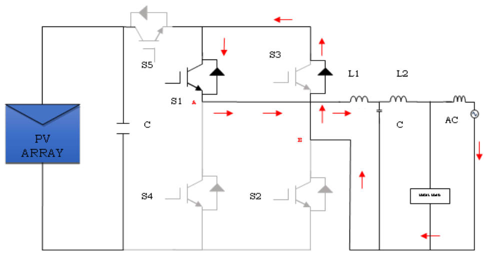
2.4.1 Proposed H5 Converter operation:-

The H5 inverter's operating principles are as follows:

The H5 inverter topology presents a significant evolution from the traditional full-bridge setup by incorporating an additional switch on the DC side. With a total of five switches, including switch S5 acting as a DC decoupling element, this configuration offers enhanced functionality. Figure 8a exemplifies the integration of the H5 inverter during the positive phase of the grid voltage. During this phase, switches S1, S2, and S5 are activated, with terminals A and B representing the inverter's output. Terminal A voltage (VAN) corresponds to the DC voltage from the PV panel (Vpv), while terminal B voltage (VBN) is zero, resulting in a common-mode voltage (Vcm) of Vpv/2. The direction of the current flow is indicated in Figure 8b with red arrows. During the freewheeling phase, the current traverses through switch S1 in opposition to the parallel diode of switch S3, as delineated in Figure 8c, resulting in VAN = VBN = 0 and Vcm = 0. Switch S5 serves a critical role in isolating the DC source from the grid throughout this phase, Thus, this maneuver serves to moderately diminish the outflow current. Moreover, switch S1 persists in its activation throughout the transmission and freewheeling phases of the positive phase of the grid voltage. In stark contrast, throughout the negative phase of the grid voltage, switches S5, S3, and S4 are engaged, culminating in VAN = 0 and VBN = VPV. Hence, Vcm = Vpv/2, as demonstrated in Figure 8d. Throughout the corresponding freewheeling phase, the current traverses across switch S3, the grid, and the antiparallel diode of switch S4.



(a)



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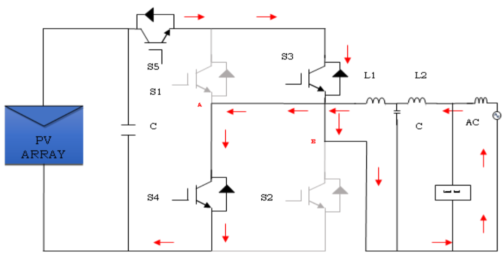

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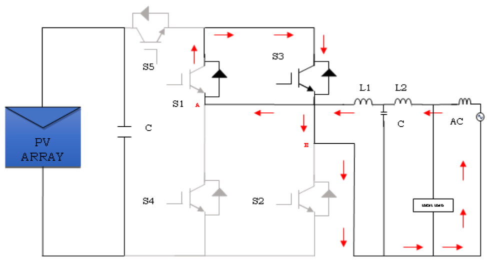

(d)

Fig.8. The H5 inverter encompasses four operational modes(a),(b),(c),(d)

2.5. Phase-locked loop (PLL): -

Aimed at grid operation, an inverter module must integrate a phase-locked loop (PLL). This essential component utilizes the measured grid AC voltage as a standard norm to compute both the operational period of the grid i.e.frequency and phase angle. These computed values are indispensable for precisely governing the phase of the signal output of the inverter. Through the implementation of a closed-loop design, Phase-Locked Loops (PLLs) adeptly mitigate discrepancies between the output and reference phase standards. Consequently, the performance of the inverter is directly influenced by the functioning of the PLL module [11].

2.6. Design of LCL filter (T filter)

Because of its substantial attenuation more than resonance frequency, the third-order LCL filter remains often used with grid-tied inverters. In comparison to the general filter, the LCL filter decouples the filter more effectively from the grid impedance [12]. Throughout the design phase, it's imperative to take into account the resonance of the LCL filter, along with the current ripple coursing through the inductors.

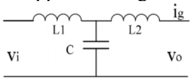

Fig.9.LCL Filter

An LCL-type filter was chosen based on the inverter filter study because of its better performance and simplicity. [13-15] 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 must be kept to a maximum of 20% of the esteemed current. There can't be too much or too little capacitance. A tiny value capacitance reduces the LCL filter's attenuation capability [16]. To guarantee acceptable system dynamics and avoid resonance difficulties, the T filter's resonance frequency should always be built within the range of equation (3). Grid fundamental frequency is fg in an equation, and sample frequency is fs. For optimal system stability, the grid-side inductance L2 must be meticulously aligned with the inverter-side inductance L2.

$$10fg < fres < 0.5fs \quad \text{-------(3)}$$

3 Specifications of the System

Table 1 Specifications of the System

Photovoltaic Rated Power	3.5 KW
Inverter input capacitor(DC link)	Cdc = 1100 uF
LCL Filter	Linv = 4.8 mH, Cf = 4.3 nF, Lg = 15 mH
Switching Frequency	fs= 10 kHz
DC link Voltage	Vdc = 513 V

Grid Nominal Voltage (RMS)	Vg = 230 V
Grid Nominal Frequency	fg = 50 Hz
Load	R=72.28 Ω L=220e-3 C=45e-6

MATLAB Simulation

4. Results and Discussion for H4 inverter in grid-connected photovoltaic system:

4.1 Current-Voltage & Power-Voltage characteristics of Photovoltaic module: -

According to Figure 10, the alternating current (Isc) exhibits a positive temperature coefficient, increasing with higher temperatures, while the voltage (Voc) shows a negative temperature coefficient, decreasing with rising temperatures. Additionally, the power, being the product of voltage and current, decreases with temperature, reflecting a negative temperature coefficient. The PV system plot corresponds to standard irradiance (1000 watts per square meter) and a standard temperature of 25°C.

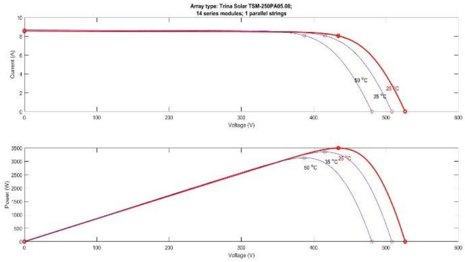

Fig.10. Characteristics of Photovoltaic panel

4.2. Grid Voltage and Grid Current Using H4 Inverter in a Grid-connected Photovoltaic System: -

The below figure gives the picture that when the PV system is coupled to the utility by activating the H4 inverter by giving pulses, There exists a distortion or manifestation of harmonics in both the grid voltage and grid current. Therefore, this has to be reduced by improving the current waveform by using a new inverter topology.

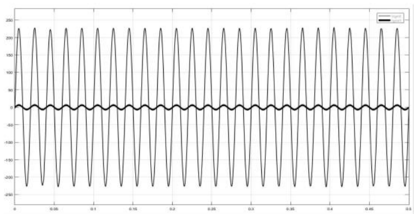

Fig.11. Grid Voltage and Grid Current using H4 inverter in a Grid-connected Photovoltaic System.

4.3. FFT spectrum Grid-connected Photovoltaic system using H4 inverter: -

The below figure 11 is the FFT spectrum using H4 inverter in Grid-connected Photovoltaic System. The FFT spectrum for the LC filter gives the %THD as 7.59% which is not the acceptable value in grid-connected photovoltaic systems where a modification has to be made to reduce the harmonic value.

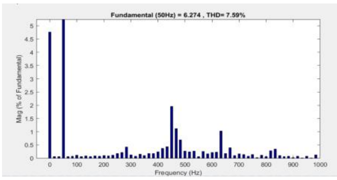

Fig.12.FFT spectrum using H4 inverter in Grid-connected Photovoltaic system

4.4 Simulink for H5 Inverter topology:-

4.5. Grid Voltage and Grid Current using H5 inverter in Grid-connected Photovoltaic System: - The below figure gives the picture that when the PV system is connected to the utility by activating the H5 inverter by giving pulses, there is less distortion and, the appearance of low harmonic compared to the H4 inverter. Therefore, the system has been improved by replacing the H4 inverter with the H5 inverter.

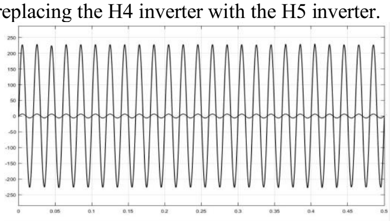

Fig.13. Grid Voltage and Grid Current using H5 inverter

4.6. FFT spectrum for an H5 Inverter:

Below Figure 13 is the FFT spectrum of a Grid-connected Photovoltaic System using an H5 inverter. The FFT spectrum for the H5 inverter gives the %THD as 7.00% which is better in performance in grid-connected photovoltaic systems when compared with the conventional H4 inverter

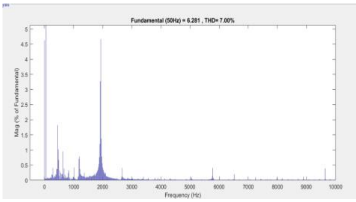

Fig.14.FFT spectrum using H5 inverter in a grid-connected Photovoltaic system

The following tabular column explains the percentage of THD for both H4 and H5 inverters at different switching frequencies. From the table, we can say that the H5 inverter topology has good performance when compared to the conventional H4 inverter by considering % THD as the measurement to analyze the functionality of the topologies.

Table 2. % THD for H4 and H5 inverter at Different frequencies

SNO	SWITCHING FREQUENCY	H4 INVERTER	H5 INVERTER

		(%Thd)	(%Thd)
1	5KHz	8.01%	7.30%
2	10KHz	7.59%	7%
3	20KHz	7.12%	6.89%

V Conclusion

There are various issues to take into account when photovoltaic systems are linked to the grid. Harmonics in PV systems present a problem, particularly when these systems are used extensively. The usage of inverters in PV systems to lower harmonics is addressed in this research.

MATLAB/Simulink was used to create a 1-phase grid-connected PV system for both the H4 and H5 inverters. Total Harmonic Distortion was utilized as the performance metric in this comparison (THD). This study presents the simulation results using the Harmonic spectrum. The H4 inverter has a percent THD of 7.59 percent for 1-phase grid-connected Photovoltaic systems, but the H5 inverter has a percent THD of 7.00 percent for 10KHz switching frequency. When compared to a system utilizing an H4 inverter, it is found that a 1-phase grid-connected Photovoltaic system for an H5 inverter has a lower harmonic spectrum. The THD is reduced with H5 when compared with the H4 inverter topology.

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