

A Review of Topologies and Control Methods for Single-Phase Grid-Connected Solar Inverters

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ABSTRACT

Since fossil fuels cannot keep up with the world's rising energy demands, solar photovoltaic (PV) systems offer a clean, pollution-free, and dependable alternative renewable energy source. So, the need for solar PV grid connected inverter systems are gaining more importance and emphasis is given to develop and design grid connected inverters with low cost, size, weight, highly reliable and efficient topologies. This review paper presents the evolution of inverter technologies, inverter topologies, with transformer or transformerless system. The key topologies, including H-bridge variants and multilevel structures, are compared based on parameters like efficiency, leakage current, and total harmonic distortion (THD). The various control strategies, encompassing maximum power point tracking (MPPT), pulse-width modulation (PWM), and current control methods like proportional resonant (PR) are presented for performance under varying grid conditions. A single phase full bridge inverter model is prepared and simulated in Matlab. The effect of variation of irradiance and temperature on the generated output power, voltage and current is measured. Also, the output current is of sinusoidal nature and the THD of 1.04% is analyzed using the FFT tool of Matlab.

KEYWORDS

Photovoltaic (PV) system, grid-connected inverter, transformerless inverter, SPWM, THD, etc.

1. Introduction

These days, solar photovoltaic energy is a recognised and reliable power generation technique that is classified as renewable energy. Since everyone is now aware of the advantages and significance of solar PV systems, they are widely used. However, solar energy is insufficient on its own to meet customers' growing energy demands. A solar PV grid connected inverter system is therefore the next potential emerging solution. Both the electrical grid and solar PV modules in this system supply the necessary amount of power. Consequently, solar PV grid-connected systems have experienced significant development and are currently the fastest-growing power electronics and power systems technology. The compact size, reduced weight, improved efficiency, reliability, and easy installation all contributed to the development, innovative and advanced inverter configurations.

These factors also impact the total cost of producing inverters. Because these systems are becoming more affordable, a large number of grid-connected PV systems have been constructed recently. Additionally, the governments create new policies and provide subsidies for these technologies. However, there is still pressure to further cut the costs [1]-[3].

The basic classification of PV systems is standalone (off grid) and grid connected (on grid). The standalone PV system is isolated from the grid and feeds power to ac or dc loads. On the other hand, PV systems coupled with grid are known as grid connected PV systems.

So, the grid-connected PV systems are now more often used in many real-world applications in comparison with standalone PV systems [4]. The following figure 1 shows the grid-connected photovoltaic system layout. It includes a photovoltaic system and many auxiliary modules, including transformers, converters and filters.

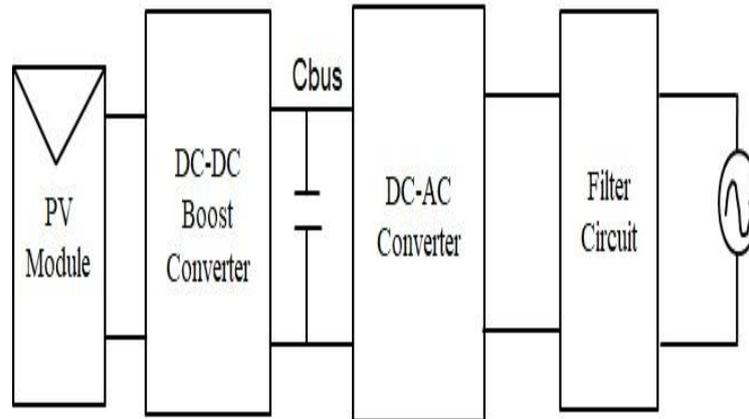


Figure 1: A structure of grid-connected PV system

Power conversion technologies include DC to DC (choppers) and DC to AC (inverters) based power electronic converters. The electric utility grid functions similarly to the grid-connected photovoltaic system, they do not require a storage system whereas the off-grid PV systems require an energy storage system. Additionally, when power generation is more as compared to the load demands, power is fed back into the electric utility grid. The solar PV systems are connected to the grid by a DC to DC converter and a current source inverter (CSI) or voltage source inverter (VSI). Grid-connected PV systems frequently use VSI in DC to AC conversion [5].

For residential applications, where power ratings usually range from 100 W to several kW, single-phase grid-connected inverters are crucial for converting DC power to AC power from PV modules synchronized with the utility grid. These inverters must ensure high efficiency, minimal harmonic distortion, and compliance with standards like IEEE 1547 and IEC 61727 to maintain grid stability and safety [6-10].

2. Objectives

A single phase full bridge inverter model is prepared and simulated in Matlab. The effect of variation of irradiance and temperature on the generated output power, voltage and current is measured. Also, the output current is of sinusoidal nature and the THD is analyzed using the FFT tool of Matlab. This review paper covers recent advancements in inverter topologies and control strategies, drawing from comparative studies and experimental validations. It addresses the shift toward transformerless designs to reduce size, weight, and cost, while mitigating issues like leakage currents caused by parasitic capacitances. The paper is structured to cover PV system classifications, detailed topology reviews, control methods, comparisons, challenges, and future directions.

3. Scope and Methodology

A Matlab software is used for the preparation and simulation of model of single phase inverter circuit under consideration. In Matlab R2020a, I developed a simulation module for a single phase grid-connected inverter depicted in figure 2. In this case, the MPPT algorithm aids in maximising the solar panels' power output. The following system specifications were taken into consideration:

Overall System (P_{out}) = 2 KW, open circuit voltage of PV (V_{oc}) = 309.5 V,

voltage at MPP (V_{mpp}) = 250-300 V, Inductor boost (L_{boost}) = 20 mH,

DC bus Capacitance (C_{bus}) = 3000 uF

Switching frequency of Boost Converter (F_{sw}) = 5 KHz,

Switching frequency of Inverter (F_{sw}) = 10 KHz,

LCL filter values: $L_1 = 4.06 \mu H$, $C = 6.23 \mu F$, $L_2 = 4.35 \mu H$

For this system, I have selected PV modules: 1Soltech 1STH-350-WH,

Series modules = 06 and parallel string = 01

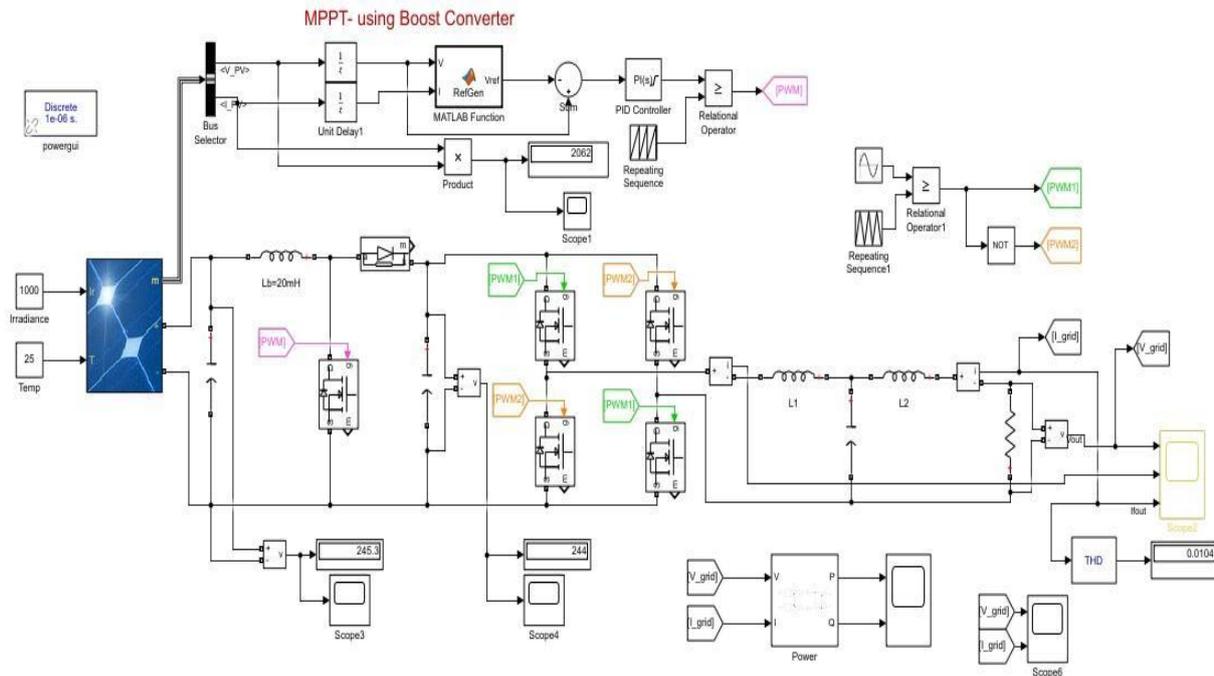


Figure 2: Simulink Model of Single Phase Double-Stage Grid connected Full Bridge inverter

4. Literature Review

4.1 System Classification

The grid connected PV inverter systems are divided into: Central Inverters: Used for large-scale plants (>100 kW), connecting multiple PV strings to a single inverter.

String Inverters: For medium-scale systems (1-100 kW), With specialized Maximum Power Point Tracking (MPPT), every string has its own inverter.

Multi String Inverters: Combine multiple strings with individual DC-DC converters feeding a common inverter.

Micro Inverters (AC Module): Module-level (100-400 W), providing per-panel MPPT to combat shading effects.

Single-phase configurations are prevalent in string and micro inverters for residential use, offering simplicity and cost-effectiveness.

The conversion of DC electricity from a grid-connected photovoltaic system requires careful adjustment of the voltage, frequency, and phase angle. An inverter is an important component of the system which converts DC power into AC power [11]-[13]. The figure 3 below illustrates the evolved grid-connected PV inverter systems. Line commutated inverters use power switching devices such as commutating thyristors, whose commutation process begins by reversing the polarity of AC voltage, when the utility grid requires it. The turn on process of these power semiconductor devices is controlled by applying appropriate gate signals to control terminals but for turn-off process auxiliary circuits known as commutation circuits are required. Self-commutated inverters facilitate precise current transmission between switching pairs, enabling gate signals to regulate the on and off operations of MOSFETs and Insulated Gate Bipolar Transistors (IGBTs). For medium to high power applications above 100 kW IGBTs are used, with a switching frequency restricted to 20 kHz. For low power applications, usually less than 10 kW, Power MOSFETs are used with a higher switching frequency of 20-800 kHz.

In grid-connected inverter systems, power semiconductor devices with higher switching frequencies are necessary so as to decrease the size of the magnetic filters, the harmonic content present in the inverter output current, and system's overall weight. Pulse Width Modulation (PWM) switching is used by self-commutated inverters to generate an AC output signal. Additionally, they are highly

resistant to disturbances in the utility grid and can regulate output voltage and output current of inverter, power factor, suppress output current harmonics, and adjust power factor all of which are desirable for PV systems connected to the grid. These days, self-commutated inverters are preferred over line-commutated inverters in the majority of PV inverter systems. CSI and VSI are the two types of self-commutated inverters. For a standalone PV inverter system, the voltage control mode is selected. The grid connected PV systems use both voltage and current management modes. It is common practice to use the current control method in grid connected PV systems to achieve a high value of power factor with a straightforward control circuit. The suppression of transient current is also achievable in the event of grid disturbances.

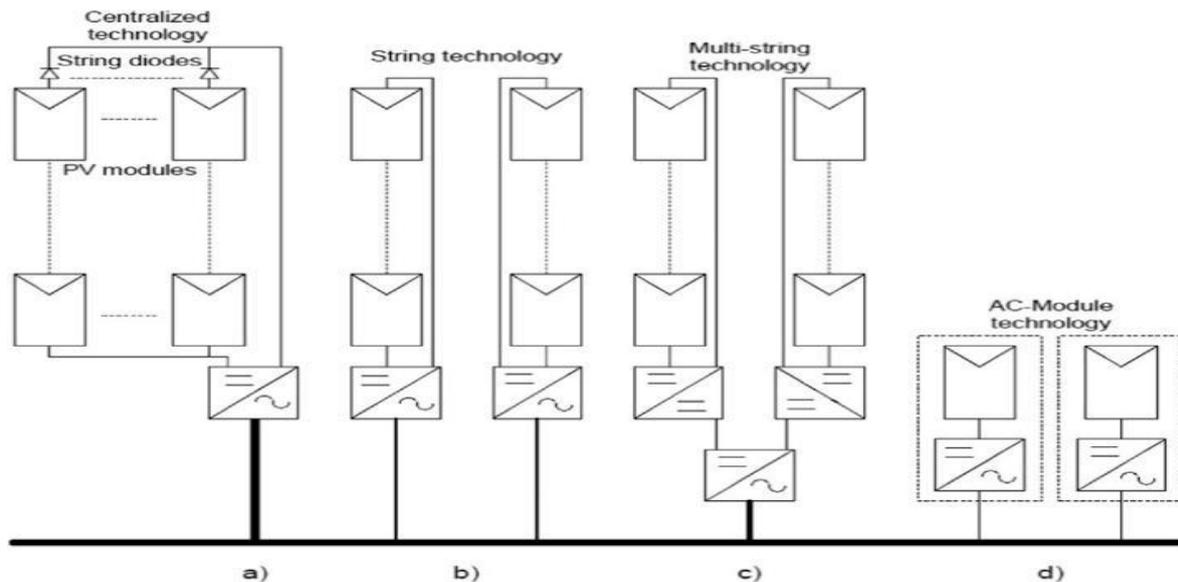


Figure 3: Grid Connected Inverters Evolution (a) Centralized Technology (b) String Technology (c) Multi-string Technology (d) AC-Module Integrated Micro Inverter Technology [1]

Centralized Inverter System: Line-commutated thyristor based inverters were used in the earlier grid-connected photovoltaic systems depicted in figure 3 (a) which had power ratings of more than a few kilowatts depending on the electrical drive system technology. These inverters were large, bulky, harsh for installation, unreliable, and their efficiency is up to 85-90%. Also they had issues like high harmonic content and poor power factor in the AC output current [14]-[15]. Nowadays, self-commutated inverters are preferred and used. Here, PV modules coupled in series are known as a string. Every string can generate an adequately high amount of voltage. For high output current requirement, strings are coupled parallelly through string diodes. This inverter is subject to the following stringent limitations. DC losses resulting from higher voltage DC connections, power losses resulting from centralised MPPT, and mismatch losses related to solar PV modules and string diode losses are the four main causes of power losses.

String Inverters System: Currently, the most widely used grid connected PV inverters are the string inverters depicted in figure 3 (b). The central inverter, in its smaller form, is coupled to one string of solar PV modules. Due to its connection to an inverter, a single string typically has a modest power range of roughly 5kW [16]. Additionally, because a single string is coupled to a single inverter and each string has a distinct MPPT, the string diode losses are decreased. When compared to a centralized inverter, this increases the string inverter's overall system efficiency by 1 to 3% [17].

Multi-string System: This architecture has developed to increase power levels while maintaining the characteristics of string inverters, such as overall efficiency, design flexibility, and dependability, as shown in figure 3 (c). Every PV string, or group of solar panels, has a low-power DC-DC converter attached to it. These converters have in-built MPPT, every string can run as efficiently as possible, independent of how well the other strings perform. A DC bus is used to combine the outputs of these

separate DC-DC converters. This bus acts as a central conduit for the combined DC power. The DC bus feeds into a single high-power inverter. The accumulated DC power is transformed into AC power by this converter and sent into the utility grid [12].

AC-Module Integrated Micro Inverter System: The AC-module integrated micro-inverter system is a compact and user-friendly photovoltaic (PV) technology designed to simplify installation and maximize efficiency at the module level, depicted in figure 3 (d). Because there is only one PV module in this system, mismatch losses between PV modules do not occur. The system is designed for easy installation. There is no need for additional inverters or complex wiring because each module has an integrated micro-inverter that allows it to be linked directly to the grid. This “plug-and-play” characteristic makes it user-friendly. Because every function—such as MPPT, DC to AC conversion, voltage amplification, etc. is carried out in a single stage, the circuit topologies get complicated.

4.2 Inverter Topologies

The inverter topologies are classified based on stages, isolation, and structure. Transformerless designs have gained prominence for efficiencies up to 98%, though they require strategies to minimize leakage currents.

Single-Stage vs. Multi-Stage Topologies

Single-Stage: Direct PV-to-grid conversion without intermediate DC-DC stages, simplifying design but limiting voltage regulation.

Multi-Stage: Include DC-DC boosters for MPPT and voltage amplification, common in micro inverters (e.g., boosting 40-60 V to higher levels).

Transformer vs. Transformerless

System with Transformer: Provide galvanic isolation via high-frequency (HF) or line-frequency (LF) transformers, enhancing safety but increasing size and losses [18]-[22].

Transformerless System: Use mid-point clamping or decoupling to manage common-mode (CM) voltages, achieving higher efficiency (up to 3% more) but prone to leakage currents.

The research and development of PV inverters is effectively carried out towards cost cutting, improvement in the overall efficiency, reliability and increasing the power density. The simplest way is to have less power processing stages to meet all these objectives. These inverter topologies are categorized by the power processing stages, the transformer or transformerless design, the locations of the power decoupling capacitors, and the kinds of grid interconnections [23]-[27].

Power Processing Stages: A single stage inverter handles all tasks, such as grid current control, voltage amplification, and MPPT is depicted in figure 4(a). This is typically centralized inverter configuration, having all drawbacks associated with it.

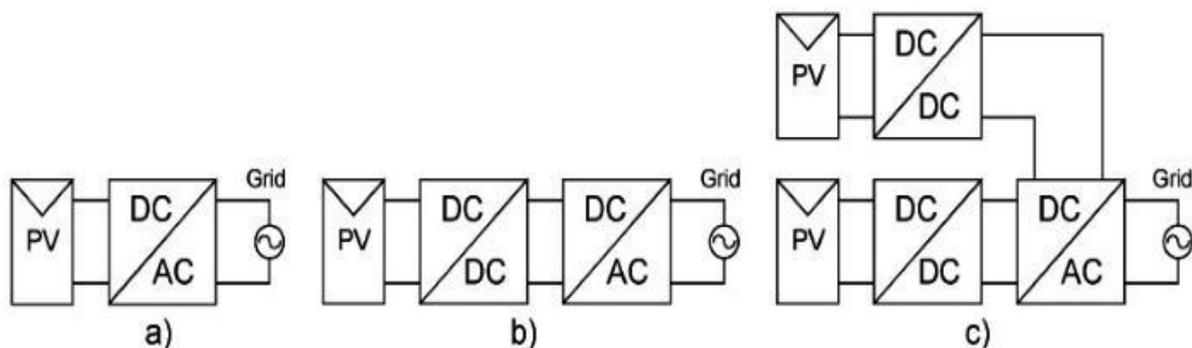


Figure 4: PV Inverters Types a) Single Stage Inverter System b) Dual Power Processing Inverter System c) Multistage Inverter System [1]

A dual stage inverter depicted in figure 4(b) having a dc to dc converter handles the MPPT whereas the grid current is controlled by the dc to ac inverter. In both stages, the voltage amplification can be incorporated. Pulse Width Modulation (PWM) is used in dc to ac inverters to regulate grid current. In dual power processing inverters, MPPT is managed by a dc to dc converter, while grid

current is handled by a dc to ac inverter. Voltage amplification can be used in both phases. Lastly, figure 4(c) shows the multi-string inverter. In this, every dc to dc converter has voltage amplification and possibly MPPT as well. The grid current is managed via a common dc-ac inverter. A dc link connects all dc to dc converters to this inverter. As a result, each PV module or string has improved control. It's possible that the common dc to ac inverter uses conventional Variable Speed Drives (VSD).

Power Decoupling in PV Systems: To filter voltage spikes and ensure that only DC element of the input power is passed through, capacitors are connected either in parallel with the PV modules or within the DC link of a multi-stage inverter. In such applications, electrolytic capacitors with large capacitance values are commonly used as depicted in figure 5. The high switching frequencies are frequently used by inverters to transform DC power into AC power. This high frequency operation can generate significant transients, which the DC link capacitor helps to manage by restricting their flow towards the input. However, electrolytic capacitors used in these applications face several challenges such as being relatively large and heavy, expensive due to their size and material requirements. Their lifespan is reduced at high operating temperatures. To address the issues associated with electrolytic capacitors, film capacitors are increasingly preferred for power decoupling in PV solar systems and inverter circuits [28]-[30].

Transformer Types and its Interconnections: Transformer-based and transformerless inverters are the two categories of inverters. LF transformers are used to lower the DC current that solar PV modules send into the grid. Additionally, it helps to provide galvanic separation between utility grids and solar PV modules.

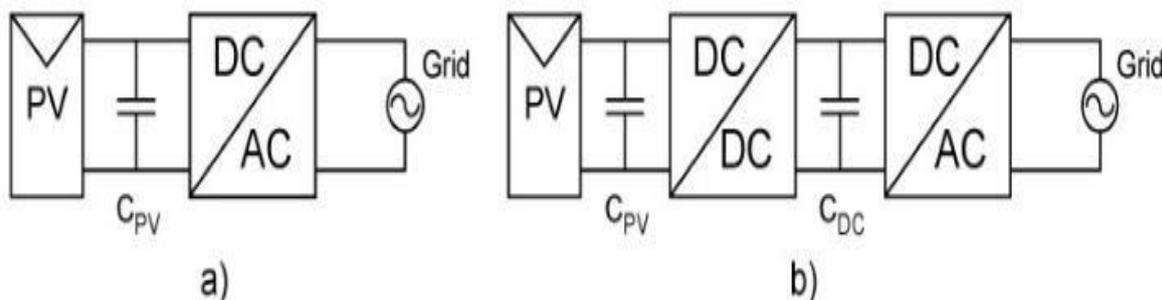


Figure 5: Power Decoupling Capacitor in Different Positions a) the PV modules in parallel with Capacitor used in Single Stage Inverter, b) In a multi-stage inverter, a capacitor is used in the DC link between the converter stages. [1]

The LF transformers are associated with numerous issues like large, bulky, costly and declines the overall efficiency of the inverter system. Alternatively, HF transformers or transformerless topology is cheaper, light in weight, offers higher efficiency as compared to transformer-based topology. The following figure 6 depicted the HF transformer designs.

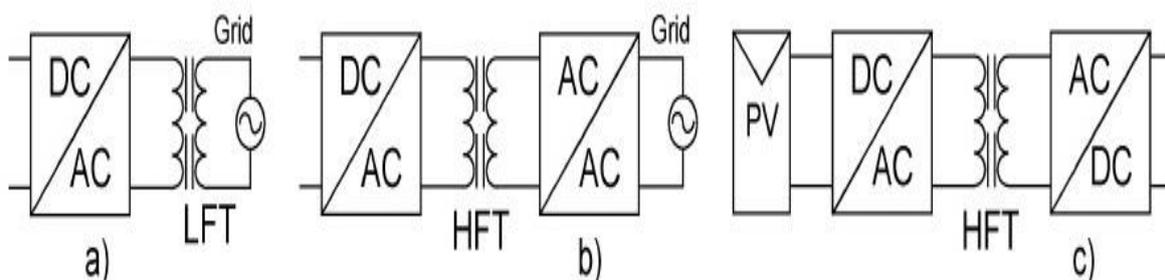


Figure 6: Inverters coupled with Transformer (a) Line Frequency (LF) Transformer between the grid and inverter (b) A HF Link Grid-Connected AC/AC Inverter Using A High Frequency (HF) Transformer (c) A Dc Link PV Model Connected To A DC To DC Converter Includes HFT [1]

4.3 Control Strategies

Control strategies ensure optimal power extraction, grid synchronization, and power quality. They include MPPT, PWM, and current/voltage controls.

MPPT Algorithms: PV arrays' maximum power point is tracked by MPPT as temperature and solar irradiation fluctuate. There are numerous methods available from conventional (e.g., perturb and observe) to advanced soft computing (e.g., swarm intelligence). Dedicated MPPT in string/micro inverters improves yield over centralized systems.

PWM Techniques: PWM generates switching signals for inverters. Unipolar and hybrid schemes produce three-level outputs with reduced losses but higher leakage; bipolar SPWM minimizes leakage and filter needs.

Current Control Methods: Current controllers regulate grid-injected current for low THD and harmonic mitigation. Classified as linear (e.g., PI, PR), non-linear (e.g., hysteresis), and predictive (e.g., dead-beat, MPC)

Proportional Integral (PI) are basic but limited in harmonic rejection. Proportional Resonant (PR) are excellent sinusoidal tracking, low steady-state error. Hysteresis control is simple, fast response, but variable switching frequency, whereas Dead-Beat control provides precise prediction, perfect steady-state tracking. Model Predictive (MPC) is an optimal performance, effective THD reduction. Comparisons for a 1 kW system show MPC with the best steady-state and harmonic mitigation, while PR and dead-beat excel in tracking.

Other Controls: Grid Synchronization uses phase-locked loops (PLL) for phase/frequency alignment. Anti-Islanding - detects grid disconnection to prevent unsafe operation. Voltage Control- Stabilizes DC-link and manages reactive power.

Controllers are further grouped as linear, non-linear, intelligent, robust, adaptive, and predictive, with selections based on grid conditions [31].

5. Result and Discussion

This section shows the results of the model prepared and simulated using matlab. The measured output voltage and current associated with the model is depicted in figure 7 a)

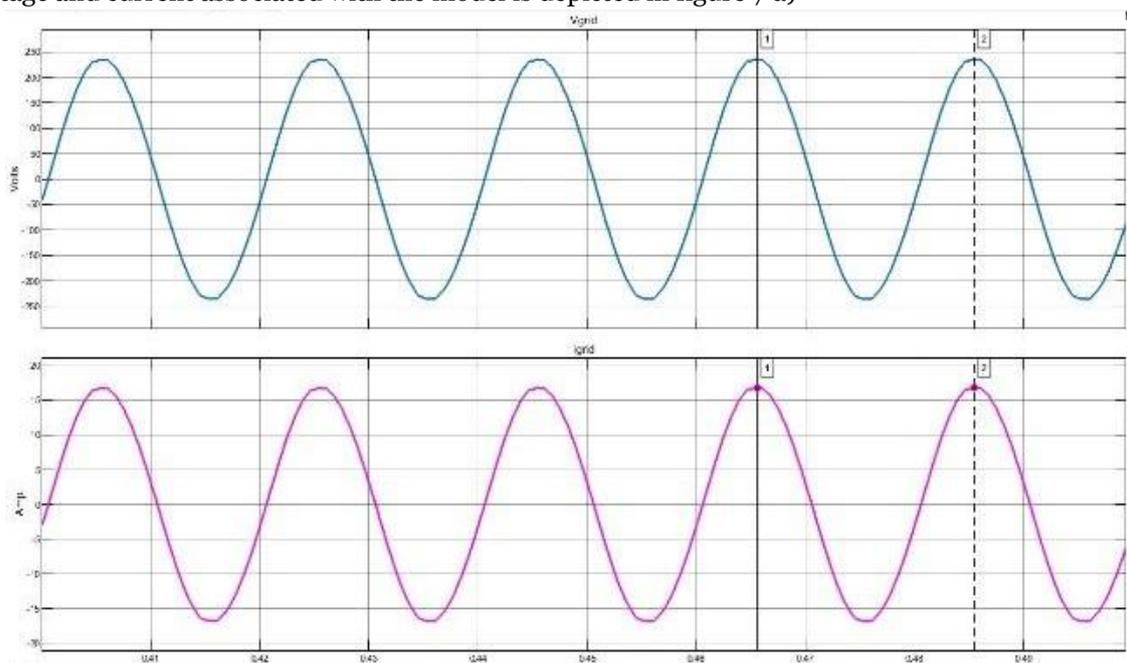


Figure 7 a): Output Voltage and Current waveform of simulated model

Additionally, as the temperature of PV modules and the amount of solar radiation change, the

associated output voltage, current and power data are recorded in the following table 1

Table 1

Effect of variation of solar irradiance and temperature on the MPPT, output voltage and current

Sr. No.	Solar Irradiance (W/m ²)	Temperature (°C)	MPPT Output (W)	Peak Output Voltage (V)	Peak Output Current (A)
1	1000	25	2061	235.7	16.84
2	1000	40	1988	232	16.57
3	1000	60	1833	222.7	15.91
4	700	25	1144	171.6	12.25
5	700	40	1173	176.2	12.39
6	700	60	1181	176.1	12.58
7	500	25	622	128	9.14
8	500	40	596.5	126.1	9.01
9	500	60	583.7	124.8	8.913

Using the FFT analysis tool, the study reveals that the Total Harmonic Distortion (THD) of grid's output current is 1.04%. and same is depicted in figure 7 b)

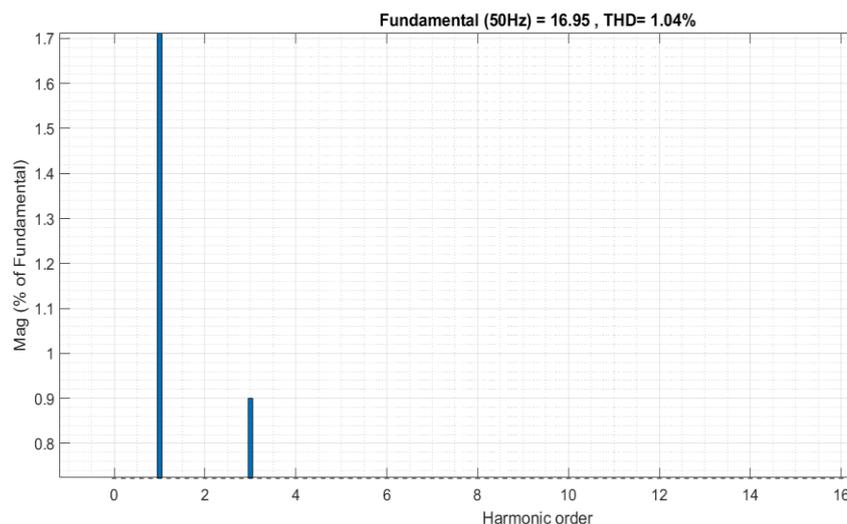


Figure 7 b): Total Harmonic Distortion (THD) of output current

6. Challenges and Future Trends

Challenges include leakage currents in transformerless grid codes. Future trends emphasize fault-tolerant topologies, advanced modulation for higher efficiency, and integration with smart grids using AI-based controls. AI is transforming single phase grid-connected solar inverter systems by enhancing efficiency, reliability, and adaptability. Its role spans MPPT, fault detection, control optimization, and grid integration.

7. Conclusion

Film capacitors are preferred over decoupling capacitors since they are expensive, bulkier, and have a shorter lifespan at high temperatures. LF transformers are large, bulky and costly and must be substituted by HF transformers or transformerless design to make compact, cheap, reliable and efficient inverter topologies. The solutions to the leakage current problem in transformerless inverters include H5, half bridge multilevel topologies, and the HERIC. For high power applications, the multilevel inverters are broadly used. PWM controllers are classified as linear and non-linear controllers. Due to its shortcomings, such as its inability to precisely track sinusoidal references, which could result in phase errors and inadequate disturbance rejection capabilities, PR controllers are recommended over PI. With the use of suitable controllers, like fuzzy logic or artificial neural networks, the inverter's output can be controlled. A simulation model of single phase full bridge inverter circuit is developed in Matlab R2020a. It is measured how changes in temperature and solar irradiance affect the output power, output voltage, and output current of solar modules. An incremental conductance approach is employed to guarantee the MPP of the PV module. The output current is sinusoidal, and Matlab's FFT tool is used to analyse the THD of 1.04%.

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