

Designing of Efficient MLI for MPPT Based Solar PV Micro-Grid for Indian Telecomm Networks BS: Challenges and Constraints

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Abstract – The study explores eco-friendly power supply alternatives for Indian telecommunication networks (ITN), focusing on challenges of renewable energy solutions like solar PV systems design. The Design of renewable energy system for telecommunication networks is a recent open field of research. It is required to investigate the distortion less solar photovoltaic (PV) system performance. This paper presents a comprehensive investigation of proposed design and performance of a 31-level inverter for solar PV systems with Maximum Power Point Tracking (MPPT) for TN. The proposed inverter employs a cascaded H-bridge topology with 12 switches, enabling the generation of 31 distinct voltage levels ranging from -15Vdc to +15Vdc. The system is designed to optimize energy extraction from solar PV panels while minimizing Total Harmonic Distortion (THD) to ensure high power quality. Comparative analyses of various MPPT techniques, including Perturb and Observe (P&O), Incremental Conductance, and Constant Voltage, reveal that P&O and Incremental Conductance achieve superior average power output of 8.00 W, while Constant Voltage underperforms at 2.02 W. Simulation results demonstrate that the proposed 31-level inverter effectively reduces THD, with values of 3.20% and 2.05% over 2 and 10 seconds, respectively, outperforming lower-level inverter configurations and satisfying the IEEE 519 standard limit of 5%. The study highlights the significance of advanced modulation strategies, such as Sinusoidal Pulse Width Modulation (SPWM) and fuzzy logic control, in mitigating harmonic distortion. The proposed 31-level inverter outperforms and have achieved lowest THD level of 2.05 % which offered nearly 60 % improvement over the 15 level existing inverters.

Key Words: Telecommunication Network, Solar PV Systems, Renewable Energy, Maximum Power Point Tracking, FFT Analysis, Total Harmonic Distortion (THD),

1. INTRODUCTION

The integration of solar photovoltaic (PV) systems into Indian telecommunication networks (TN) faces a variety of challenges, including space constraints, intermittent power availability, high initial costs, power tracking, grid compatibility, and the most essentially the inverter designs. There are certain remote Base stations) BS) where it is advantageous to deeply

the micro-grid connected solar PV systems for local power demands. This paper explores sustainable power supply alternatives for telecom towers, highlighting the limitations of traditional energy sources like grid electricity and diesel generators. It investigates various challenges of renewable energy solutions, especially solar PV systems in the context of TN. The prime concern of study is to address the major challenge of mitigating the distortion and generation of stable approximation of pure sine wave at the inverter output of PV systems operations. This research has aimed to investigate and design an efficient multi-level inverter (MLI) for hybrid systems that combine multiple renewable resources with conventional power options to offer reliable and cost-effective energy solutions for telecommunication infrastructure.

In this context, the research assesses the performance of three-level inverters, five-level H-bridge inverters, and five-level H-bridge inverters with LC filters to achieve near-sinusoidal waveforms and minimize Total Harmonic Distortion (THD), which is crucial for enhancing energy efficiency within telecommunication networks. The initial phase of the paper has reviews Maximum Power Point Tracking (MPPT)-based solar PV systems and off-grid solar PV systems. The focus is to discuss their advantages and challenges. Furthermore, it addresses the stability of solar PV systems in TN, emphasizing the influence of THD on system performance and the necessity for advanced control strategies and harmonic mitigation techniques. The findings reveal that reducing THD remains a critical challenge for telecommunications inverters, primarily due to their design limitations at lower inverter levels. Thus, as a novel contribution a modified 31 level optimal MLI design is proposed to reduce the distortion below the IEEE standard limits.

The challenges that must be overcome for solar PV systems efficient energy operations in Indian TN (ITN) include, limited space, sporadic power generation, high initial costs, grid integration, maintenance needs, fluctuating energy demands, regulatory obstacles, battery storage limitations, environmental factors, a lack of skilled workers, security concerns, and obsolescence of technology. The telecom and renewable energy sectors must work together, prepare carefully, and come up with creative solutions to overcome these obstacles. Stakeholder cooperation, creative problem-solving, and meticulous preparation are necessary to meet these hurdles. The usage of MLIs within the ITN's is critical due to their ability to improve power quality, increase efficiency, and facilitate the integration of renewable energy sources. MLIs reduce total harmonic distortion, which is critical for sensitive telecommunications equipment. Furthermore, its modular architecture allows for a smaller size and weight, making them perfect for space-constrained installations. MLIs help to more effective operations by improving dependability, lowering electromagnetic interference, and saving long-term costs. They also align with India's aspirations for sustainable and smart grid projects, ensuring robust and uninterrupted communication services.

Telecom networks power distribution and consumption can be optimized with the use of sophisticated energy management systems. The creation of smaller, more effective solar panels can solve the issue of limited space while enhancing system performance as a whole. Enhancing security protocols and funding workforce training initiatives can also help address the skilled labour shortage and safeguard vital infrastructure from possible dangers. This dissertation investigates eco-friendly power supply alternatives for telecom towers, emphasizing the shortcomings of conventional methods, such as grid power and diesel-powered generators, owing to their substantial carbon emissions and lack of reliability. This study explores renewable energy solutions, such as solar PV systems, wind energy, and fuel cell technology, as feasible options to minimize dependence on fossil fuels and lower emissions. They proposed that hybrid systems, which integrate multiple renewable sources with traditional power options, provide reliable and cost-effective solutions for powering telecommunication towers. Additionally, the study advocates

for the implementation of regulatory measures and financial incentives to promote the adoption of renewable energy-based power systems within the telecommunications industry.

A. Contribution of Work

In this study, we conducted a thorough investigation of Multilevel Inverter (MLI) designs for MPPT-based solar PV systems. The work aimed to achieve near-sinusoidal waveforms while analyzing THD in various inverter topologies, specifically three-level inverters, five-level H-bridge inverters, and five-level H-bridge inverters with LC filters. The novel part of this study is the investigation of cascaded H-bridge inverters to successfully reduce THD, thereby improving the energy efficiency in telecommunications networks (TN). The major contribution of this study focuses on comparing single-phase and three-phase inverter designs. Finally, to improve the performance, this study suggests a 31-level controlled inverter as a novel technique for decreasing harmonic distortions. Notably, the results show that the five-level Cascaded H-Bridge (CHB) inverter has the lowest observed THD, exhibiting significant gains over previous technologies. Furthermore, the proposed 31-level inverter design demonstrated a significant reduction in THD while surpassing the previously established 15-level inverters. This innovation not only demonstrates the effectiveness of higher-level inverters in increasing power quality but also their potential for wider use in telecommunications infrastructure. The novelty of this work lies in its focus on optimizing (lowering) higher-level inverter design complexity specifically for TN, answering the important need for efficient energy solutions in a period when the need for dependable communication services is rapidly increasing.

2. CHALLENGE OF SOLAR PV SYSTEM DESIGN IN TN

This paper aimed to address or introduce the description of challenges for solar PV system design and integration to Indian telecommunication networks could address the following key points as illustrated in the Figure 1 for specific application to TN. These TN rely heavily on solar PV systems because of their substantial energy requirements, need for power dependability, limited space, environmental considerations, integration with current infrastructure, remote site locations, financial aspects, regulatory adherence, and potential for growth. These systems must fulfil power requirements, endure harsh conditions, seamlessly integrate with existing setups, and operate independently in isolated areas. A significant challenge lies in striking a balance between upfront costs and long-term operational advantages, and complying with local and national regulations adds complexity.

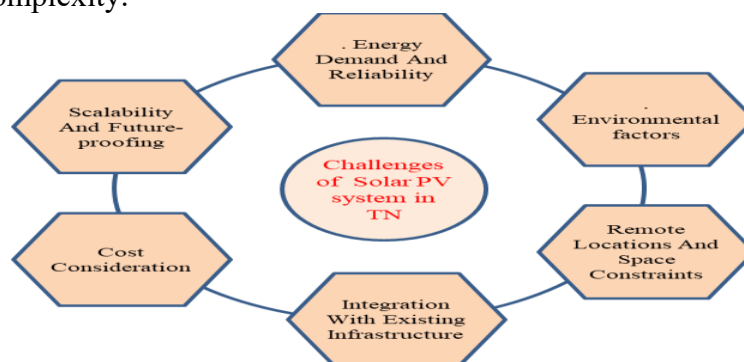


Fig. 1 Challenges Of Solar PV System Design In TN

To ensure long-term viability, it is crucial to design systems capable of accommodating future network expansion and technological progress. Implementing or installing solar PV systems with integration into existing TN requires meticulous planning and specialized knowledge to address these multifaceted challenges. Professionals must consider factors such as ideal panel positioning, energy storage solutions, and efficient power management systems to maximize the benefits of solar technology. Furthermore, continuous maintenance and monitoring are essential to guarantee sustained performance and reliability of these systems in diverse and often severe environments.

Cutting-edge solutions, including sophisticated energy-management algorithms and smart grid integration, are being developed to enhance the efficiency of solar PV systems in telecommunication networks. These innovations aim to boost energy efficiency, lower operational expenses, and improve the overall system dependability. Moreover, the incorporation of emerging technologies, such as artificial intelligence and machine learning, enables the predictive maintenance and real-time optimization of solar PV systems, further increasing their effectiveness in supporting telecommunication infrastructure.

A. Motivation for Solar PV system in TN

The primary drivers for implementing Solar PV systems in telecommunication networks are shown in Figure 2. These motivations include the sector's swift expansion, shortcomings in traditional power sources, environmental considerations, and the practicality of renewable energy technologies such as solar PV, wind turbines, and fuel cells.

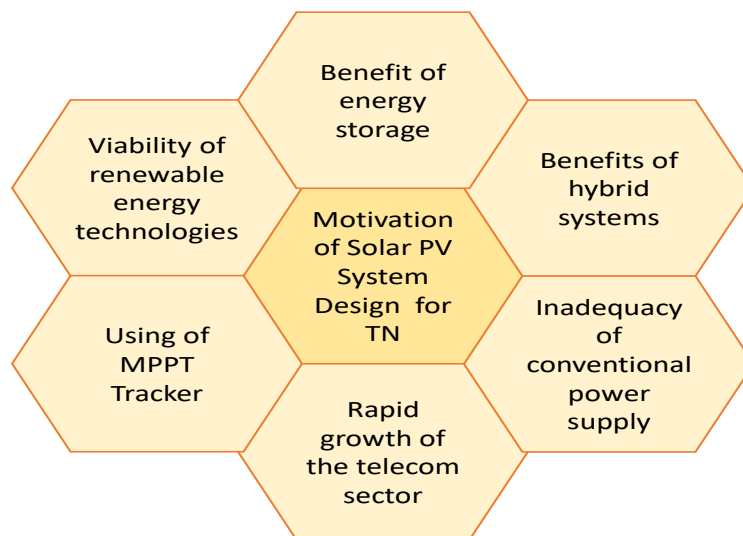


Fig. 2 Major Motivations To Work On Solar PV Systems In TN

Combining multiple energy sources in hybrid systems offers dependable and economic power supply solutions. To ensure continuous power provision, energy storage plays a vital role. The adoption of renewable energy-based systems can be significantly influenced by policy measures and instruments. The research assumes worldwide applicability, technological progress, and economic viability, making its findings relevant across various regions and scenarios.

3.1. CLASSIFICATION OF SOLAR PV SYSTEM DESIGN

Classification of Solar PV systems architectures used for TN are illustrated in the Figure. The broadly systems are classified as on grid and off grid systems. the inverter design is an essential part for operation of the Solar PV system. The board category of the inverter design is classified as Multi level Inverter (MLI) and the PWM controlled Inverter designs as in Figure 3.

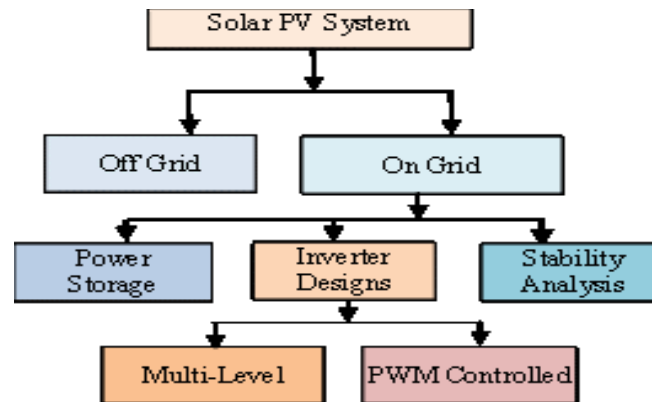


Fig. 3 Classification Of Solar PV Systems Architectures Used For TN

There are some hybrid designs which integrates the both MLI and PWM control to improve the efficiency. This paper is also focused to investigate and validate the such MLI based inverter designs.

3.2. GENERAL CHALLENGES OF TN- SOLAR PV SYSTEM

The given context offers limited explicit information about the solar PV system installation challenges specific to Indian telecommunication networks. Nevertheless, we can deduce certain general obstacles that may be applicable. A major hurdle for solar PV system deployment in rural India is substantial upfront investment and extended return periods (Pal et al., 2023). This could pose difficulties for telecom networks that aim to implement solar power, particularly in isolated regions. Furthermore, Pal et al. (2023) identified storage-device obstacles and policy/regulatory concerns as crucial impediments. The integration of distributed PV systems into existing networks can present technical difficulties. Drawing parallels from remote Australian networks, issues such as diminished power quality, insufficient spinning reserves, heightened operational complexities, and potential system failures can arise with increased PV penetration (Jamal et al., 2017). Similar challenges may be encountered by Indian telecom networks that adopt solar PV systems.

Another factor that can notably affect system efficiency is the accumulation of dust on PV panels, particularly in certain geographical areas (Mani & Pillai, 2010). This may necessitate an additional upkeep for PV installations in telecom towers. In conclusion, while the context lacks specific information on Indian telecom networks, we can extrapolate that financial constraints, technical integration challenges, and environmental factors, such as dust buildup, are likely to be primary obstacles for solar PV adoption in this sector. For a successful implementation, it is crucial

to develop robust control mechanisms, incorporate forecasting technology, and ensure proper maintenance (Jamal et al., 2017).

Pal, M., et al. (2023) identifies barriers to solar PV systems in Indian dairy farming, including high initial cost, storage device issues, policy, education, affordability, and long payback periods, with a roadmap for overcoming these. The challenges of grid integration of PV systems are addressed by Shafiullah et al (2022). In a study by Tang et al. (2023), researchers evaluated China's technical capacity for solar photovoltaic (PV) electricity production. Their assessment employed a solar PV electricity generation model and incorporated data from more than 2400 monitoring stations but study was specific for China.

4.1. REVIEW OF MPPT BASED SOLAR PV SYSTEM FOR TN

Because they allow for effective energy capture in the face of changing environmental circumstances, Maximum Power Point Tracking (MPPT) approaches are crucial for improving the operation of solar photovoltaic (PV) systems in communications networks. Khan, O. et al. (2016) reported a hardware-based panel enhancement for MPPT-based trackers, proposing to use gallium-nitride for panel design. An excellent evaluation of the THD analysis in solar PV systems was published by A. A. Sarhan et al. (2020). For MPPT-based PV systems, they presented a number of control techniques, such as fuzzy control and PSO-based P&O systems. In partial shadowing situations (PSCs), when there are several local maximum power points, the MPPT algorithms are essential for optimizing power extraction from PV systems (Li et al., 2019). Conventional MPPT techniques frequently encounter difficulties such steady-state oscillations and inefficient monitoring of maximum power during PSCs and abrupt changes in irradiance (Subramanian & Raman, 2020). Numerous sophisticated MPPT approaches have been developed to address these problems.

When compared to other artificial intelligence MPPT methods, using Overall Distribution (OD) MPPT algorithm used in conjunction with Particle Swarm Optimization (PSO) has proven to be more accurate and efficient (Li et al., 2019). Similarly, compared to Perturb and Observe (P&O) and PSO-based MPPT algorithms, the Grasshopper Optimization Algorithm (GOA)-tuned MPPT approach performs better in both steady-state and dynamic scenarios (Subramanian & Raman, 2020). Innovative technologies like Internet of Things (IoT)-enabled MPPT solar chargers can be beneficial for communications networks that need reliable power sources. During the performance testing, this system achieved 99.74% efficiency, allowing for remote control and monitoring (Rokonuzzaman et al., 2020). Additionally, at a switching frequency of 400 kHz, distributed MPPT systems that use sub module integrated converters (subMICs) using Gallium Nitride (GaN) field-effect transistors demonstrate peak efficiencies surpassing 99% (Khan et al., 2016). To sum up, innovative MPPT methods including OD-PSO, GOA, and IoT-enabled systems offer viable ways to maximize solar PV systems in telecom networks. Maintaining a steady power supply in the telecommunications infrastructure requires improved efficiency, dependability, and flexibility to shifting environmental circumstances, all of which are provided by these techniques.

4.2. Review of off Grid Solar PV system for TN

The usage of off-grid solar photovoltaic (PV) systems to power telecom tower base stations has become increasingly popular in telecommunication networks, particularly in rural areas. When compared to conventional diesel generators, these systems offer a number of advantages, including

lower operating costs and a less carbon footprint (Kaur et al., 2019). Usually, hybrid renewable energy systems (HRES) that integrate solar panels, wind turbines, and battery storage are used to integrate solar PV systems into telecom networks. By addressing the intermittent nature of the renewable energy sources, this approach guarantees a more reliable power supply. However, the HRES components must be sized optimally to achieve both economic viability and a dependable power supply.

Researchers have developed complex optimization algorithms to address this issue, such as discrete multiple-purpose grey wolf optimization (DMGWO), which considers variables like the likelihood of a power supply outage, the cost of electricity, and the generation of excess energy (Kaur et al., 2019). Notably, off-grid solar PV systems are used in telecom networks for purposes other than only producing electricity. These freestanding PV systems may now be remotely monitored, which enhances their effectiveness and maintenance capabilities thanks to the incorporation of Internet of Things (IoT) technology. According to Lopez-Vargas et al. (2019), this is especially beneficial in areas without traditional wired telecommunication infrastructure. In conclusion, off-grid solar PV systems have proven to be sustainable and viable for supplying electricity to distant telecommunications networks. These systems are now more dependable and economical for telecom applications because to the integration of solar PV with other renewable energy sources and energy storage systems, as well as sophisticated optimization strategies and remote monitoring features.

4.3. Stability Analyses Of Solar PV System For TN

Total Harmonic Distortion (THD) presents significant challenges for MPPT-based solar PV systems in Tennessee. The non-linear power electronic converters used by the MPPT algorithms have the potential to introduce harmonics into the system, lowering efficiency and compromising power quality. Sensitive telecom equipment may be impacted by these harmonics' potential to produce voltage distortions, increased power losses, as well as electromagnetic interference. Moreover, the variable nature of temperature and solar irradiation can exacerbate THD problems, making it difficult to maintain a steady power output. Sophisticated control tactics, like enhanced MPPT algorithms with adaptive filtering approaches, must be used to address these problems. Furthermore, in order to guarantee compliance with power quality regulations and preserve the dependability for telecommunication networks powered with solar PV systems, it could be necessary to integrate harmonic reduction devices, such as active power filters.

There is little precise information regarding THD comparisons of solar PV systems in telecommunication networks, according to the survey that was provided. Nonetheless, we can infer several pertinent conclusions about THD in grid-connected solar PV systems from the facts currently available: THD levels have decreased and power quality has improved with grid-connected solar PV systems. According to Ahsan et al. (2021), THDi and THDv at the point of common connection were 10.2% and 5.2%, respectively, for 50% PV penetration. These values are within IEEE criteria for low voltage networks (Ahsan et al., 2021). This implies that when connected to the grid, solar PV systems may sustain acceptable THD levels. In order to further lower THD in solar PV systems, sophisticated modulation techniques have been developed. For example, when compared to conventional modulation techniques, the "triangle saturated common mode pulse width modulation (TSCMPWM)" control suggested for a 3-phase 5-level modular multilevel cascaded (MMC) inverter-based grid-tied PV system provides the lowest voltage THD (Haq et al., 2021).

For a 3-phase, 5-level MMC inverter-based grid-connected PV system, an additional sophisticated PWM technique met IEEE-519 grid integration standards by achieving output line voltage THDs of 12.49% (without filter) and 0.96% (with filter) and output current THDs of 4.64% (Haq, Hosain, et al., 2021). These results imply that solar PV systems can be planned and managed to maintain low THD levels, which would be advantageous for sensitive equipment in telecommunication networks, even though they do not directly address telecommunication networks.

Table. 1 Summary Of Survey On Solar PV System For TN

Author	System Design	Methodology / Performance
Kaur et al [13]	The usage of off-grid photovoltaic (PV) solar energy systems to power telecom tower bases has become increasingly popular in communications networks, particularly in rural areas.	Have developed complex optimization techniques, such discontinuous multi-objective gray-wolf optimization (DMGWO), to address this problem.
Lopez-Vargas et al [14]	These freestanding PV systems may now be remotely monitored, which enhances their efficiency maintenance capabilities thanks to the incorporation of the Internet of Things (IoT) technology.	In isolated areas, off-grid photovoltaic (PV) panels have shown to be a viable and sustainable way to power telecommunications networks.
Ahsan et al [15]	Furthermore, it might be challenging to maintain a constant power output due to THD issues being made worse by the unpredictable nature of environment and solar radiation.	Overall harmonic interference (THD) values have been shown to drop and electricity quality to rise with grid-dependent solar PV systems. At 50% PV penetration, THDi & THDv were 10.2% & 5.2%, respectively, with a point of common connection.
Haq et al [16]	Triangle saturation common mode pulse width variation control suggested for a 3-phase 5-level (MMC) inverter-based grid-tied PV system provides the lowest voltage THD.	This implies that when connected to the grid, solar PV systems may sustain tolerable THD levels.
Haq, Hosain, et al [17]	THD levels, that might be advantageous for telecommunication networks' sensitive equipment	The PWM approach produced output voltage line THDs of 12.49% (with out filtering) and 0.96% (with filter) and current flow THDs of 4.64% for a 3-phase, 5-level MMC inverter-based a grid-connected PV system.

Table 1 displays an overview of the survey's main findings. Because telecommunications inverters are designed at lower inverter levels, the survey's findings show that lowering Total

Harmonic Distortion (THD) is still a major difficulty. The potential integration of solar PV systems into communications networks without sacrificing power quality is indicated by the ability to reach THD levels within IEEE standards. For solar photovoltaic (PV) systems to continue operating at their best in terms of efficiency, power quality, and performance, harmonic distortion must be reduced. Power quality problems, equipment deterioration, and reduced system efficiency may result from harmonics produced by the power electronic converters used in photovoltaic systems.

Energy losses are decreased, clean power output is maintained, and system component longevity is increased by reducing harmonic distortion. Furthermore, this guarantees compliance with grid interconnection policies and procedures, which makes it easier to integrate solar PV systems into current electricity networks. Higher energy production, better grid stability, and increased system reliability can all be achieved by successfully reducing harmonic distortions through the use of advanced control and filtering techniques. Advanced power quality monitoring systems can detect and analyse harmonic distortion in real time, enabling prompt corrective action. Using multiple inverters and active harmonic filters can significantly lower the output waveform's harmonic content. Furthermore, integrating advanced forecasting algorithms with smart grid technologies can help anticipate and proactively address future harmonic issues, guaranteeing that solar PV systems function at their best within bigger power networks.

Table. 2 Summary And Merits And Demerits Of The Various Methods

Reference	Methodology	Merits	Demerits
[1] Amal et al. (2017)	Review of PV deployment challenges in remote areas	Comprehensive overview of challenges	Lacks specific case studies
[2] Mani & Pillai (2010)	Impact analysis of dust on PV performance	Identifies critical factors affecting efficiency	Limited empirical data
[3] Pal et al. (2023)	ISM-MICMAC approach for barrier identification	Systematic barrier prioritization	Focused on a specific context (dairy farming)
[4] Hossain et al. (2020)	Energy-aware cellular networks with load balancing	Integrates renewable energy into cellular networks	Not specifically focused on PV systems
[5] Pal et al. (2023)	Barrier identification for solar PV in dairy farming	Highlights deployment challenges	Context-specific; may not be generalizable
[6] Shafiullah et al. (2022)	Review of grid integration challenges for PV	Comprehensive overview of solutions	Lack of experimental validation
[7] Tang et al. (2023)	Assessment of solar PV potential	Provides dense station-based assessment	Geographic limitations in scope
[8] Khan et al. (2016)	Development of GaN-based converters for PV	High efficiency in MPPT applications	Technology-specific; may have cost implications

[9] Sarhan et al. (2020)	Comparative study of MPPT controllers	Evaluates multiple MPPT strategies	Limited to MPPT controller comparison
[10] Li et al. (2019)	Particle swarm optimization for MPPT	Effective under partial shading conditions	Complexity in implementation
[11] Rokonuzzaman et al. (2020)	IoT-enabled smart solar charge controller	Enhances efficiency with IoT integration	Hardware implementation challenges
[12] Subramanian & Raman (2020)	Grasshopper optimization for MPPT	Novel optimization algorithm application	Requires tuning of parameters
[13] Kaur et al. (2019)	Grey Wolf algorithm for optimal sizing	Multi-objective optimization approach	Limited to PV-wind-battery systems
[14] Lopez-Vargas et al. (2019)	IoT application for real-time monitoring	Real-time data monitoring capabilities	Dependent on connectivity
[15] Ahsan et al. (2021)	Harmonic analysis of grid-connected PV	Focus on harmonic distortion impacts	Limited to low voltage networks

5.1. Proposed MPPT based Solar PV Microgrid Design Systems

As illustrated in Figure 4, solar PV systems based on Maximum Power Point Tracking (MPPT) consist of solar panels, an MPPT controller, the DC-DC converter, an inverter, a bank of batteries, a charging controller, a monitoring system, protection devices, cabling and connections, a mounting structure, and a grounding system. When combined, these components maximize energy collection and provide power to the specified load or grid connection. For MPPT-based solar photovoltaic (PV) systems to maintain power quality and maximize system performance, THD evaluation is essential. A grid-connected single-phase H-bridge micro inverter with sine pulse width modulation (SPWM) control produces better power quality results with lower THD, according to research on THD analysis in MPPT-based PV systems.

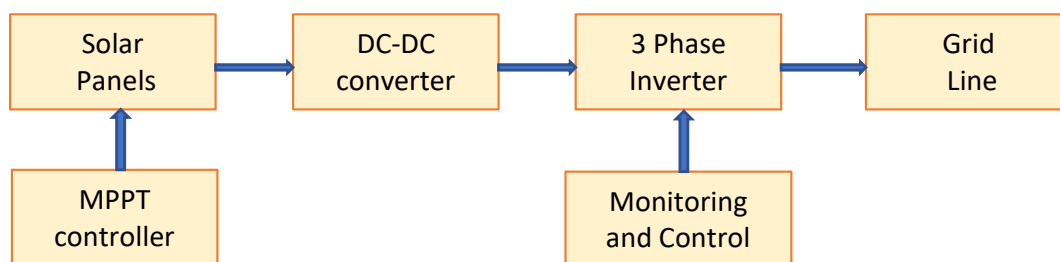


Fig. 4 System Diagram Of The MPPT Based Solar PV Systems

Figure 4 presents a layout of a solar PV system integrated with MPPT for enhanced energy efficiency. The system initiates with solar panels that capture solar irradiance and generate DC electricity. This output is fed into an MPPT controller, which continuously adjusts the operating point of the PV array to extract maximum power under varying environmental conditions. The

optimized DC power is then processed by a DC-DC converter, which regulates the voltage to suit the inverter input requirements. A three-phase inverter subsequently converts the DC power into AC, making it compatible for grid integration. The AC output is supplied to the grid line, enabling distributed energy contribution. Additionally, a monitoring and control unit is interfaced with the inverter to supervise system performance, ensure operational stability by minimizing THD. therefore this work emphasizing its role in maximizing power extraction and grid compatibility. The mathematical formulation for the nth harmonics THD is given as

$$THD = \sqrt{\frac{\sum_{k=2}^n V_k^2}{V_1^2}} \quad (1)$$

5.2. 5 level H bridge Inverter

This section has presented the first two inverter architectures as validated and investigated for the THD performance for Indian telecon networks utilizations. These designs are based on the multi-level H bridge-based inverters designs. Figure 5 have presented the validation of the models of inverter with the 3 and 5 level H bridge as validated in the work in early phase. A three-level Sinusoidal Pulse Width Modulation (SPWM) inverter typically employs a Neutral Point Clamped (NPC) topology, utilizing twelve switches for a three-phase configuration. This structure enables the generation of three distinct voltage levels, which effectively reduces harmonic distortion and enhances overall efficiency compared to conventional two-level inverters. In contrast, the four-level J-Bridge inverter—an extension of the cascaded H-Bridge topology—introduces an additional voltage level, requiring a greater number of switches and independent DC sources. This results in higher waveform resolution and improved harmonic performance. However, these benefits come with increased system complexity and greater control effort, making the J-Bridge inverter more suitable for advanced applications requiring superior output quality.

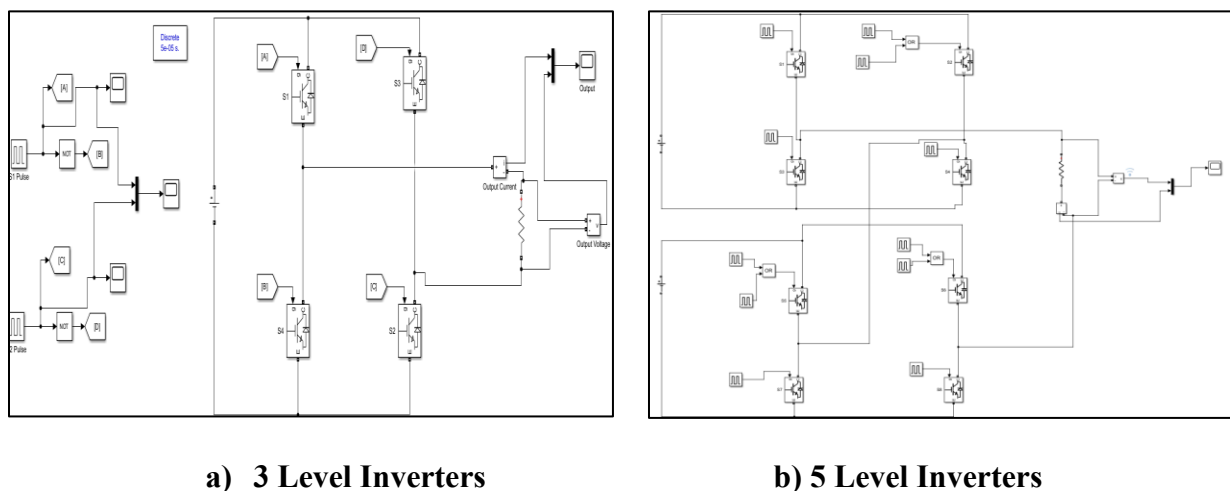


Fig. 5 Inverter With The 5 Level H Bridge As Validated In The Work In Early Phase

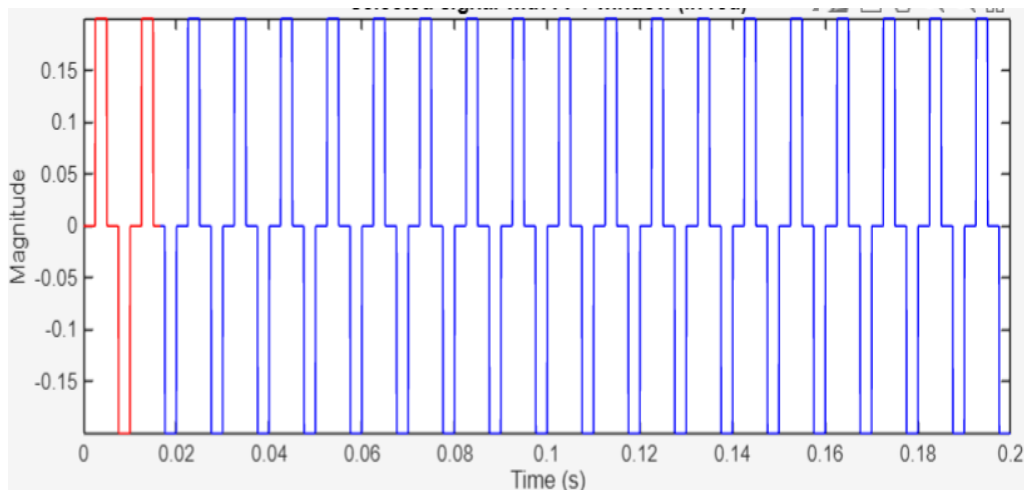
Table 3 outlines the component requirements for two MLI topologies: the three-level SPWM inverter and the five-level H-bridge inverter. For the three-level SPWM configuration, a

total of 12 insulated-gate bipolar transistors (IGBTs) is employed, with four switches allocated per phase.

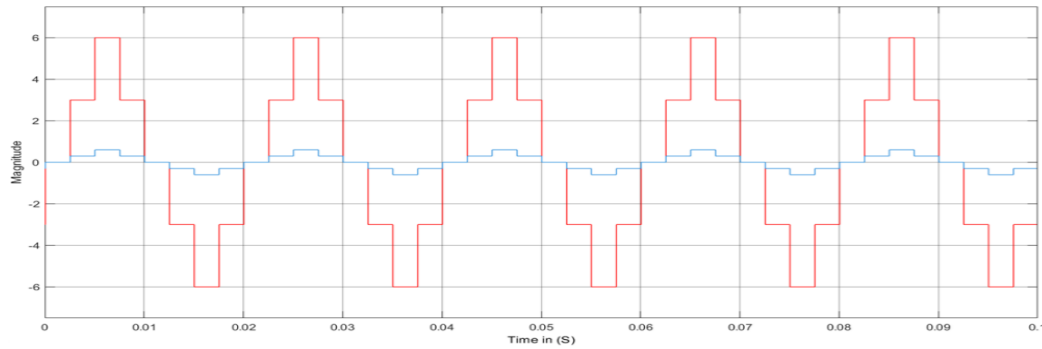
Table. 3 Component Used For 3 Level Inverter

MLI	Component	Quantity
3 level SPWM	IGBTs (Switches)	12 (4 per phase)
	Diodes	6 (2 per phase)
	DC Link Capacitors	2
5 level H bridge	H-Bridge Cells	6 (2 per phase)
	Switches	24 (Total)
	DC Sources	6 (one per cell)

Additionally, six diodes are integrated into the circuit, distributed as two per phase, to facilitate bidirectional current flow and enhance switching performance. The DC link is stabilized using two capacitors, which serve to maintain voltage balance across the inverter levels. In contrast, the five-level H-bridge inverter as in Table 3 utilizes a modular structure comprising six H-bridge cells, with two cells assigned per phase. Each cell is powered by an independent DC source, resulting in a total of six DC sources. The switching operation is managed by 24 switches, reflecting the increased complexity and control granularity required for higher-level modulation. This comparative component analysis highlights the trade-offs between inverter topologies in terms of hardware complexity, scalability, and control requirements, which are critical considerations in the design of efficient multilevel power conversion systems.



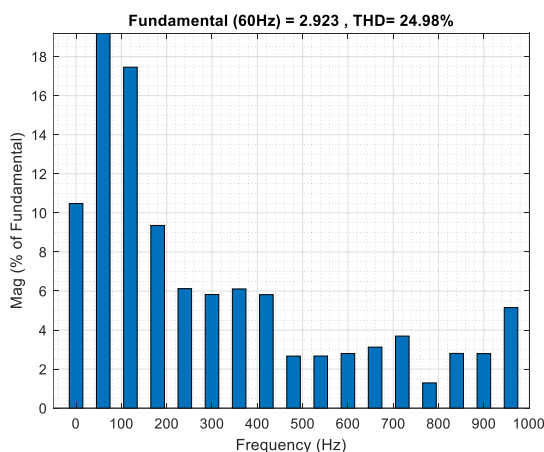
a) Validated Waveform For 3 Level Inverter Design



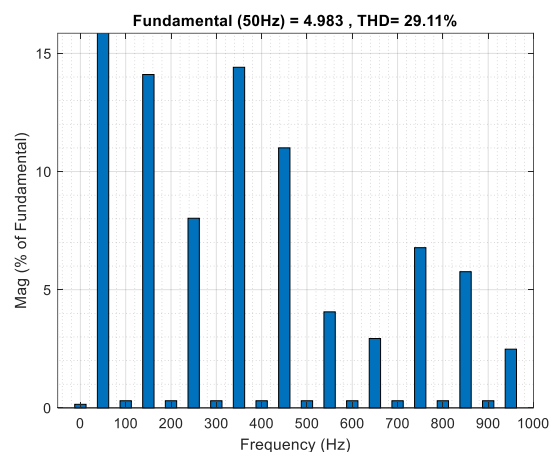
b) Validated Waveform For 5 Level Inverter Design
Fig. 6 The 3-Phase Voltage Waveform

Figure 6 presents the validated output voltage waveforms for both the three-level and five-level inverter designs. The Figure 6 a), waveform corresponding to the three-level inverter exhibits a relatively smooth and symmetrical profile with a voltage range of ± 0.15 V over a 0.2-second interval, indicating effective modulation and phase balance but not the pure sine wave. In contrast, Figure 6 b), waveform for the five-level inverter, which demonstrates a more intricate stepped structure with a significantly higher voltage range of ± 6 V over a shorter duration of 0.1 seconds. The increased resolution and voltage levels in the five-level design reflect its enhanced capability for finer control and reduced harmonic distortion, validating its suitability for high-performance power conversion applications.

Figure 7 presents a comparative analysis of Total Harmonic Distortion (THD) for two inverter topologies: the three-level SPWM inverter and the five-level H-bridge inverter. The results indicate that the three-level SPWM inverter achieves a lower THD of 24.98% with a fundamental frequency of 60 Hz and a magnitude of 2.923, suggesting superior harmonic performance and cleaner output. In contrast, the five-level H-bridge inverter exhibits a higher THD of 29.11% at a fundamental frequency of 50 Hz and a magnitude of 4.983, reflecting increased harmonic content.



a) 3 Level Inverter SPWM



b) For 5 Level B Bridge Inverter

Fig. 7 THD Validation And FFT Analysis a) 3 Level b) 5 Level H Bridge Inverter

Although the five-level design offers higher voltage levels, the elevated THD implies a trade-off in power quality. Overall, the three-level SPWM inverter demonstrates better harmonic suppression, making it more favorable for applications requiring high-quality voltage output. This initial validation makes it clear that although increasing levels may improve voltage level but THD minimization is a big challenge.

5.3. Proposed 31 level Inverter Design

This paper proposed to design a 31-level controlled MLI architecture with optimal compact design. The proposed 31-level inverter is generally composed of several H-bridge cells arranged in a cascaded configuration. Each H-bridge has the capability to produce three distinct voltage levels: +V_{dc}, 0, and -V_{dc}. Consequently, the total output voltage V_{out} of a 31-level inverter can be mathematically represented as:

$$V_{out}(t) = \sum_{i=1}^n V_i(t) \quad (2)$$

In this context, n denotes the number of H-bridges, while $V_i(t)$ signifies the output voltage of each individual H-bridge.

$$V_{out}(t) = K \cdot V_{DC} \quad \text{for} \quad k = -15, -14, \dots, 0, \dots, 14, 15 \quad (3)$$

For a 31-level inverter, the output voltage levels can be represented as kk , which takes on values ranging from -15 to +15. The output voltage for MLI is expressed as;

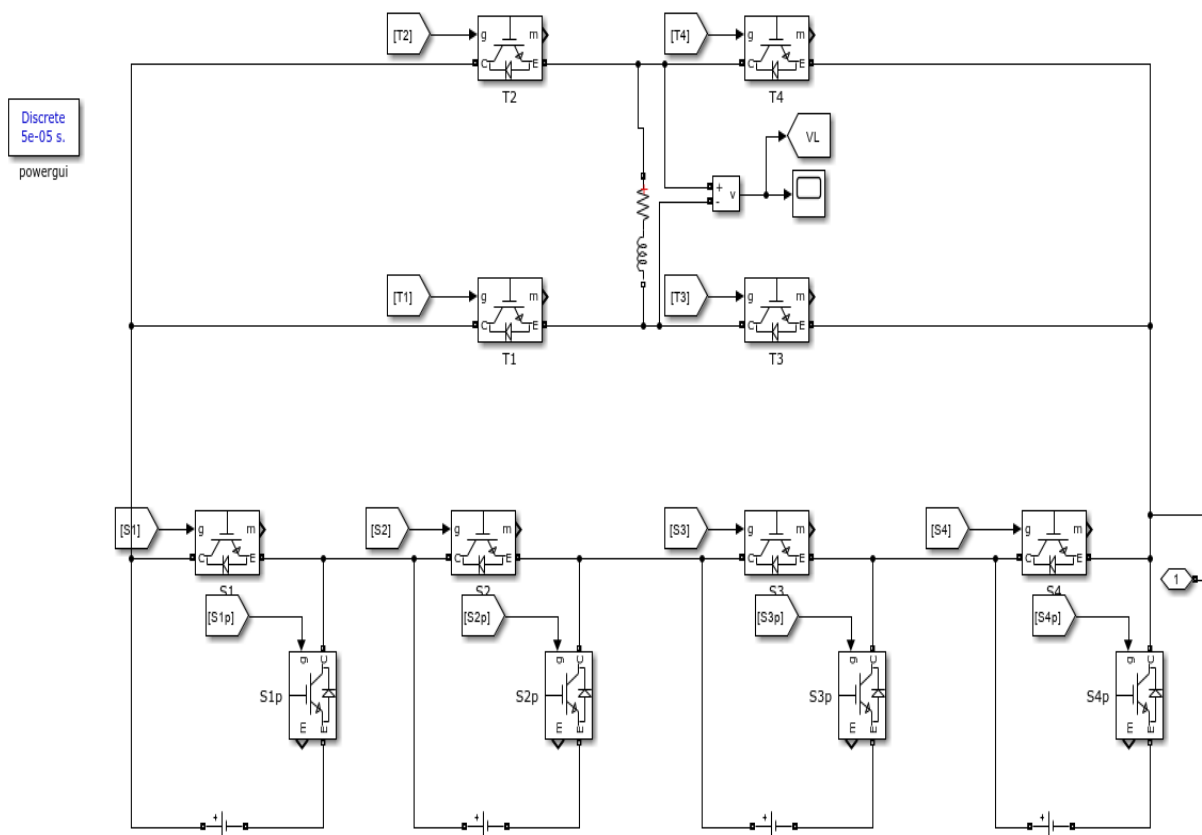


Fig. 8 Proposed 31 Level Inverter Model

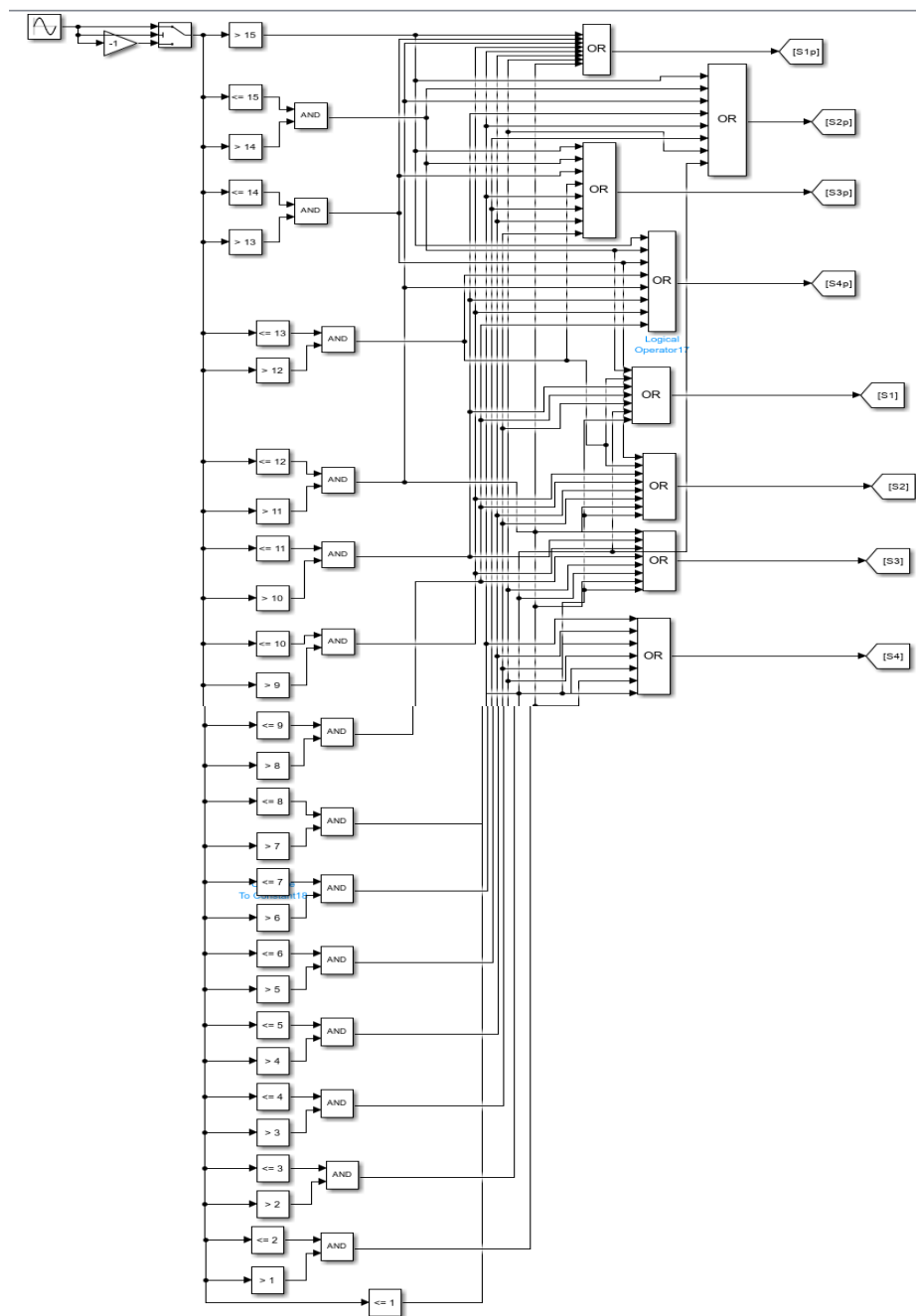


Fig. 9 31 Level-Controlled Logic For Inverter

$$V_{out} = \frac{k}{15} V_{DC} \quad (4)$$

This paper proposed to use the common modulation technique for multi-level inverters is the phase-shifted PWM. The modulation index m can be defined as:

$$m = \frac{V_{out}}{V_{DC}} \quad (5)$$

To assess the harmonic content of the inverter's output, the Fourier series can be employed. The output voltage can be expressed in terms of its fundamental frequency and the associated harmonic components. The proposed 31 level MLI design for the solar PV systems is illustrated in the Figure 8. the respective logic control system is given in Figure 9. it is clear from the Figures that proposed design consist of 12 switches of total.

The above presented mathematical modeling framework provides a comprehensive understanding of the operation of a 31-level inverter.

$$V_{out}(t) = V_1 \sin(\omega t) + \sum_{n=2}^{\infty} V_n \sin(n\omega t + \varphi_n) \quad (6)$$

In this formulation, V_1 represents the amplitude of the fundamental frequency component, V_n denotes the amplitudes of the harmonic components, and φ_n indicates the phase shifts associated with each harmonic.

The 31-level inverter operates using a cascaded H-bridge topology comprising four H-bridges and auxiliary switches (T1–T4) to synthesize stepped voltage levels from $-15V_{dc}$ to $+15V_{dc}$ in $1V_{dc}$ increments. Each H-bridge (S1–S4) contributes either $+V_{dc}$, $0V$, or $-V_{dc}$ based on its switch configuration (p/n pairs). By strategically turning on/off these switches, the system produces additive or subtractive voltages. Additional switches (T1–T4) allow finer control and redundancy to optimize switching performance and device stress. The digitally switching logic for the all 12 switches for 31 level inverters are given in the Table 3.

Table. 3 Switching Logic Table (31-Level Inverter)

Level	S1p	S1n	S2p	S2n	S3p	S3n	S4p	S4n	T1	T2	T3	T4	Output Voltage
0	0	0	0	0	0	0	0	0	0	0	0	0	0V
1	1	0	0	0	0	0	0	0	0	0	0	0	+Vdc
2	0	1	0	0	0	0	0	0	0	0	0	0	-Vdc
3	1	0	1	0	0	0	0	0	0	0	0	0	+2Vdc
4	0	1	0	1	0	0	0	0	0	0	0	0	-2Vdc
5	1	0	0	0	1	0	0	0	0	0	0	0	+2Vdc
6	0	1	0	0	0	1	0	0	0	0	0	0	-2Vdc
7	1	0	1	0	1	0	0	0	0	0	0	0	+3Vdc
8	0	1	0	1	0	1	0	0	0	0	0	0	-3Vdc
9	1	0	1	0	1	0	1	0	0	0	0	0	+4Vdc
10	0	1	0	1	0	1	0	1	0	0	0	0	-4Vdc
11	1	0	1	0	1	0	1	0	1	0	0	0	+5Vdc
12	0	1	0	1	0	1	0	1	0	1	0	0	-5Vdc
13	1	0	1	0	1	0	1	0	1	1	0	0	+6Vdc
14	0	1	0	1	0	1	0	1	0	1	1	0	-6Vdc
15	1	0	1	0	1	0	1	0	1	1	1	0	+7Vdc
16	0	1	0	1	0	1	0	1	0	1	1	1	-7Vdc
17	1	0	1	0	1	0	1	0	1	1	1	1	+8Vdc
18	0	1	0	1	0	1	0	1	1	1	1	0	-8Vdc
19	1	0	1	0	1	0	1	0	1	1	1	0	+9Vdc

20	0	1	0	1	0	1	0	1	1	1	0	1	-9Vdc
21	1	0	1	0	1	0	1	0	1	0	1	1	+10Vdc
22	0	1	0	1	0	1	0	1	0	1	1	1	-10Vdc
23	1	0	1	0	1	0	1	0	1	1	0	1	+11Vdc
24	0	1	0	1	0	1	0	1	1	0	1	1	-11Vdc
25	1	0	1	0	1	0	1	0	0	1	1	1	+12Vdc
26	0	1	0	1	0	1	0	1	1	1	0	1	-12Vdc
27	1	0	1	0	1	0	1	0	0	0	1	1	+13Vdc
28	0	1	0	1	0	1	0	1	1	0	0	1	-13Vdc
29	0	1	0	1	0	1	0	1	1	1	1	1	-15Vdc
30	1	0	1	0	1	0	1	0	1	1	1	1	+15Vdc

As clear from the Figure above that proposed inverter design employs 4 cascaded H-bridge cells, each capable of generating three distinct voltage levels: +Vdc, 00, and -Vdc. By combining these cells, the inverter achieves a highly granular output waveform. With a total of 15 discrete voltage steps in both positive and negative directions, the system produces

$$2N + 1 = 2(15) + 1 = 31 \quad 2N + 1 = 2(15) + 1 = 31 \quad (7)$$

It concluded to 31 distinct voltage levels, allowing for smoother waveforms and improved harmonic performance compared to lower-level configurations. The total output voltage $V_o(t)$ at time t is the sum of voltages generated by each H-bridge cell:

$$V_o(t) = V_1(t) + V_2(t) + V_3(t) + V_4(t) \quad (8)$$

Each cell output $V_i(t)$ is modeled as:

$$V_i(t) = S_{ip}(t) \cdot V_{dc} - S_{in}(t) \cdot V_{dc} \quad (9)$$

Where: $S_{ip}(t)$ --- status of "positive" switch (1 = ON, 0 = OFF)

$S_{in}(t)$ --- {status of "negative" switch (1 = ON, 0 = OFF)}

This creates possible outputs of +Vdc, 0, -Vdc per cell, and combinations create levels from -15Vdc - 15Vdc. The PWM Control algorithms periodically adjust switching to equalize stress and maintain voltage integrity.

6.1. Results and Discussions

This section has presented the various experimental results of the ML based Solar PV system MLI investigation. Figure 10 compares the average power output of solar PV systems over the range of solar irradiance levels for the three different MPPT techniques as Perturb and Observe (P&O), Incremental Conductance, and Constant Voltage. The results clearly demonstrate that the P&O method yields the highest power output throughout the irradiance spectrum, reaching up to 8 W at 1000 W/m², indicating superior tracking efficiency. The Incremental Conductance method performs comparably, with slightly lower output, suggesting robust adaptability under dynamic conditions. In contrast, the Constant Voltage method consistently underperforms, delivering significantly lower power—approximately 2 W at 1000 W/m²—highlighting its limited responsiveness to irradiance fluctuations. Overall, the figure underscores the advantage of adaptive MPPT algorithms in maximizing energy extraction from solar PV systems.

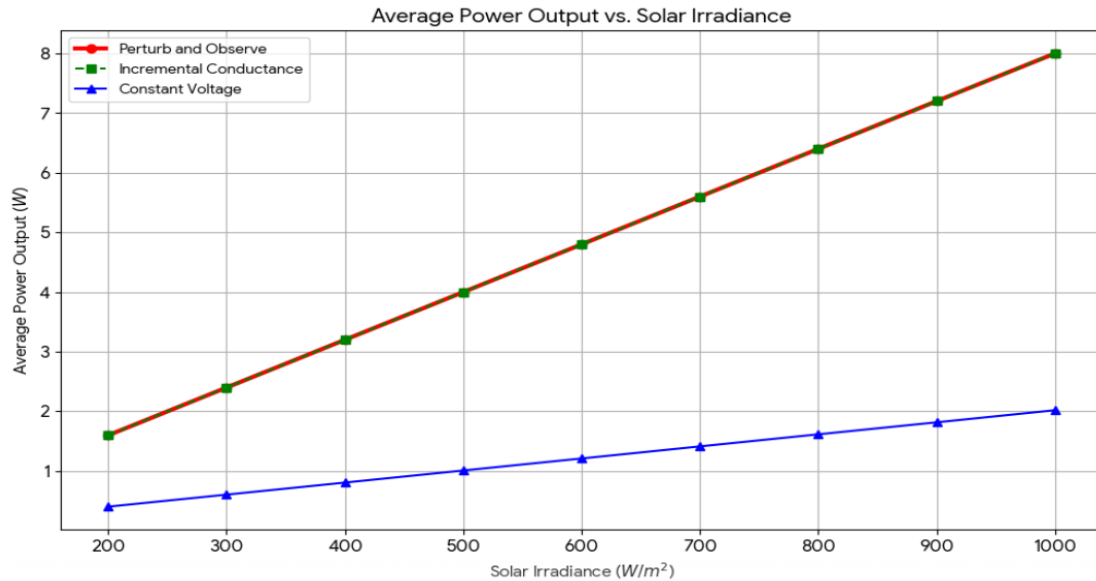


Fig. 10 Results Of Average Power Output For Different MPPT Tracker Based Solar PV Systems

Figure 11 provides a clear comparative analysis of the simulated average power output for three distinct MPPT techniques. The results reveal that both the P&O and incremental conductance methods achieve an identical and notably high average power output of 8.00 W, underscoring their effectiveness in accurately tracking the maximum power point under varying conditions. In stark contrast, the Constant Voltage method delivers a significantly lower output of 2.02 W, indicating its limited capability in adapting to dynamic irradiance and temperature variations. This performance gap emphasizes the critical role of adaptive MPPT algorithms in optimizing energy harvest from solar PV systems, with Perturb & Observe and Incremental Conductance emerging as the most efficient strategies in this simulation.

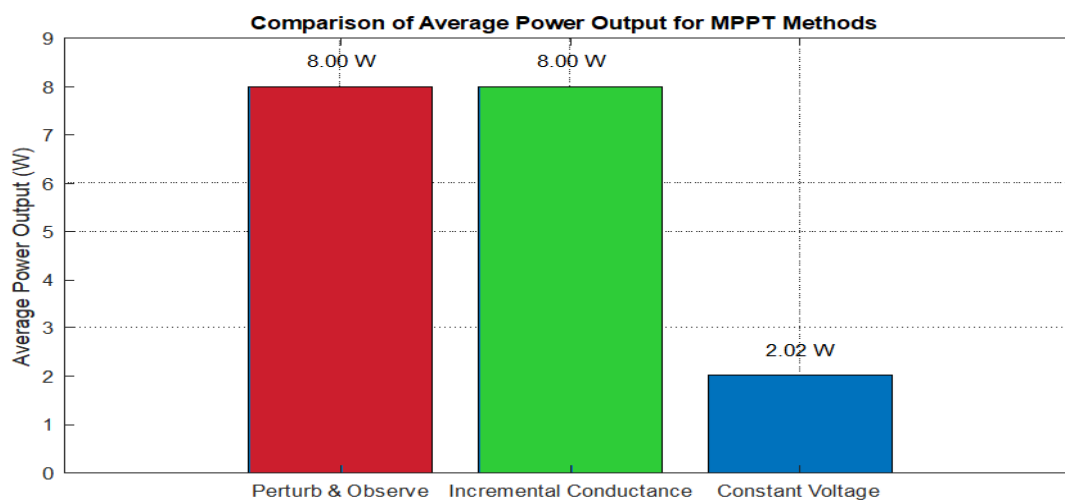


Fig. 11 Comparison Of Simulated Average Power Output For Three Different MPPT Methods

6.2. Simulation Time Comparison

Figure 12 presents a comparative analysis of the average execution time for three MPPT algorithms: Perturb & Observe, Incremental Conductance, and Constant Voltage. The results, depicted in a bar chart, indicate that the Constant Voltage method exhibits the shortest execution time at 2.44×10^{-5} seconds, reflecting its computational simplicity. In contrast, Perturb & Observe and Incremental Conductance require longer execution times of 2.64×10^{-4} seconds and 2.69×10^{-4} seconds, respectively, due to their iterative and adaptive nature. While the Constant Voltage method is computationally efficient, its lower tracking accuracy.

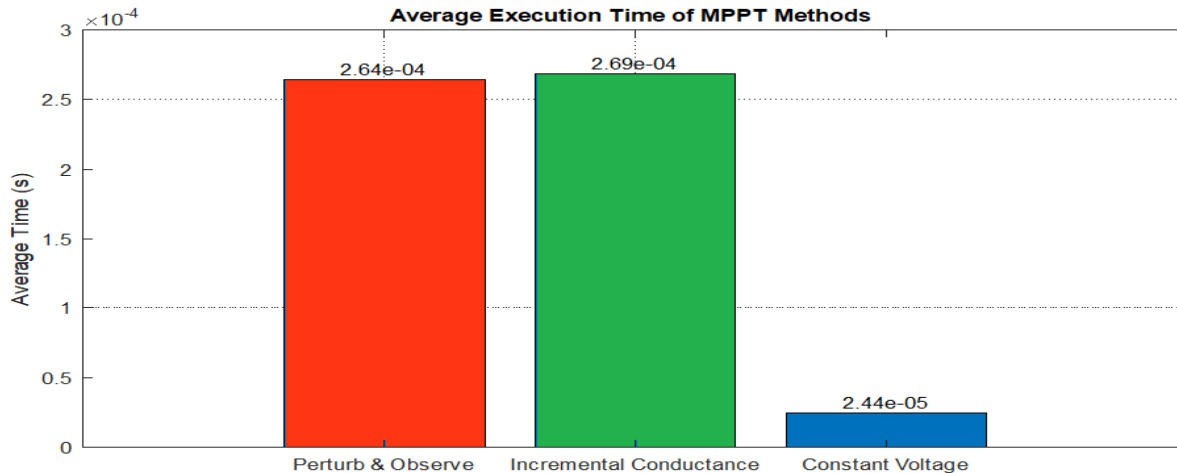
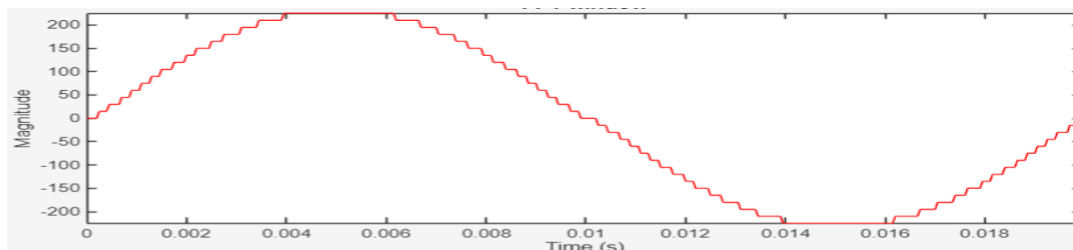


Fig. 12 Comparison Of The Average Execution Time Performance For Different MPPT Methods

This suggests a trade-off between speed and performance. This comparison underscores the importance of balancing execution time with tracking precision when selecting MPPT strategies for real-time solar PV applications.

6.3. THD Performance Results

The detailed waveform simulation and FFT analysis results for THD calculation for proposed 15 level inverters are illustrated in the Figure 13 below. the 31-level inverter stepped output waveform is shown in Figure 13 a). it is clear the it's a good approximation of pure sine wave.



a) Output Voltage Wave For 31 Level Inverters

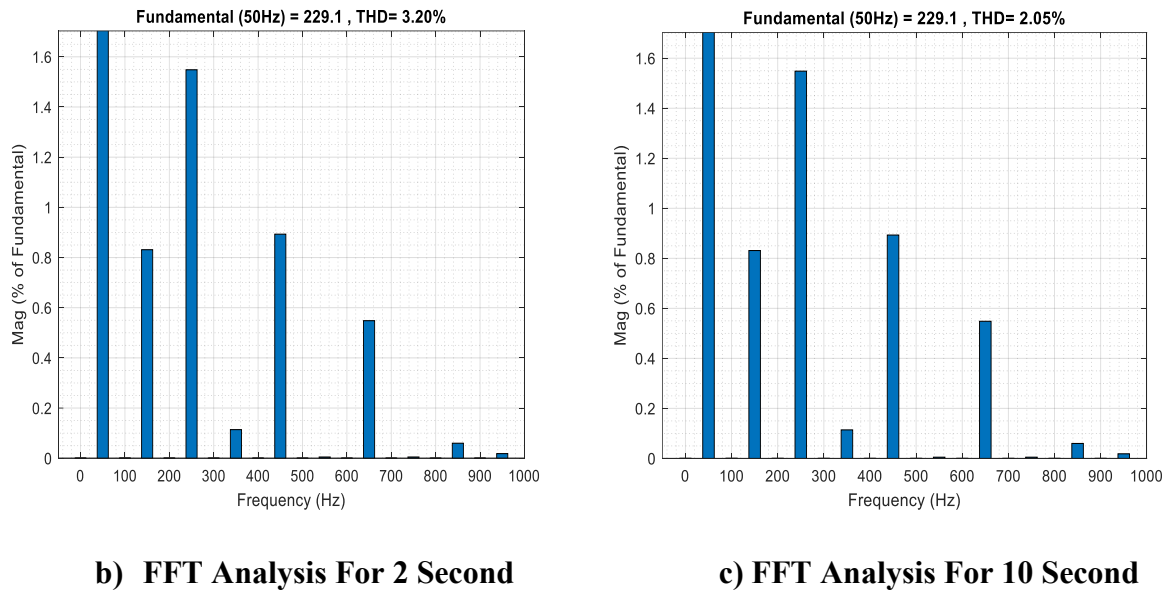


Fig. 13 Proposed FFT Evaluation For The 31-Level Inverter Design

Figure 13 b) and c) presents the FFT-based THD analysis for the proposed 31-level inverter design over two distinct time intervals—2 seconds and 10 seconds. In both cases, the fundamental frequency remains constant at 50 Hz with a magnitude of 229.1, allowing for a direct comparison of harmonic performance. The results reveal a notable reduction in THD from 3.20% at 2 seconds to 2.05% at 10 seconds, indicating improved waveform purity and reduced harmonic content over extended operation. This decline in THD suggests that the inverter stabilizes and delivers cleaner output as the system settles, enhancing its suitability for high-quality power applications. The analysis underscores the effectiveness of the 31-level design in minimizing harmonic distortion, thereby contributing to greater efficiency and reliability in multilevel inverter systems.

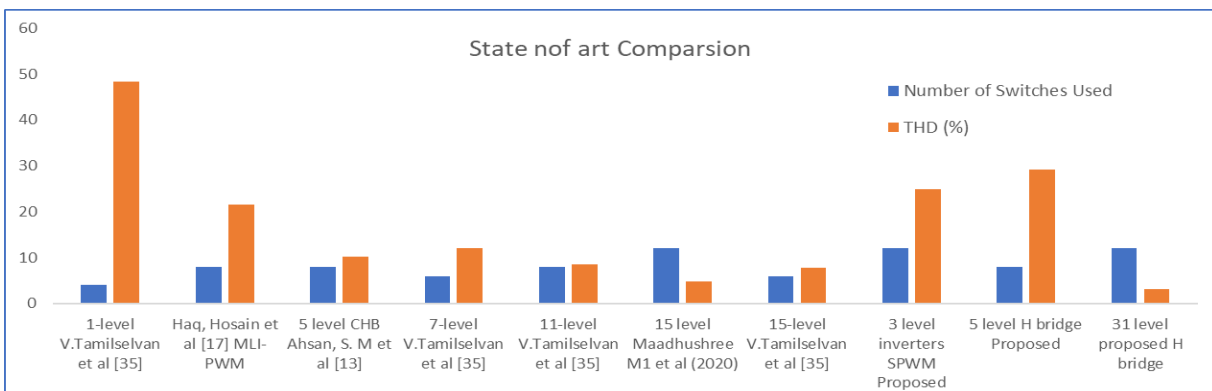
6.4. State of art Comparison

According to experimental findings, the Total Harmonic Distortion (THD) of grid voltage and current consistently remained below the IEEE 519 standard threshold of 5%, thereby validating the efficacy of Sinusoidal Pulse Width Modulation (SPWM) in mitigating lower-order harmonics (Priyadarshi et al., 2023). Notably, the choice of Maximum Power Point Tracking (MPPT) strategy significantly influences THD performance. Comparative analyses indicate that intelligent MPPT techniques—particularly those employing fuzzy logic control—are more suitable for photovoltaic (PV) systems than conventional algorithms. In one study, a closed-loop fuzzy logic-based inverter integrated with a low-pass filter was implemented to suppress harmonic distortion. The results demonstrated superior THD reduction and effective MPPT tracking using fuzzy logic algorithms (Hassan et al., 2020). These findings underscore the critical role of THD analysis in MPPT-driven solar PV systems. Advanced control methodologies, such as fuzzy logic-based MPPT and SPWM, have shown considerable potential in enhancing power quality by minimizing harmonic content. Future investigations should explore the comparative THD performance of diverse MPPT strategies to establish optimal approaches for harmonic mitigation in PV applications.

Table. 4 state-of-the-art THD levels comparison using various MLI techniques

Output Voltage Level	Number of Switches Used	THD (%)	IEEE 519 limit of 5%	Improvement required
1-level V.Tamilselvan et al [35]	4	48.34	5	43.34
Haq, Hosain et al [17] MLI-PWM	8	21.49	5	16.49
5 level CHB Ahsan, S. M et al [13]	8	10.2	5	5.2
7-level V.Tamilselvan et al [35]	6	12.00	5	7.0
11-level V.Tamilselvan et al [35]	8	8.53	5	3.33
15 level Maadhushree M1 et al (2020)	12	4.71	5	-0.29
15-level V.Tamilselvan et al [35]	6	7.80	5	2.8
Proposed 3 level inverters SPWM	12	24.98	5	19.98
Proposed 5 level H bridge	8	29.11	5	24.11
Proposed 31 level proposed H bridge 2 s	12	3.20	5	-1.8
Proposed 31 level proposed H bridge 10 s	12	2.05	5	-2.95

Table 4 presents a comparative stat of art THD levels achieved using various MLI techniques relative to the IEEE 519 standard limit of 5%. The results highlight that lower-level inverter configurations, such as 1-level and conventional PWM-based MLIs, exhibit significantly high THD values, indicating substantial room for improvement. In contrast, higher-level designs—particularly the proposed 31-level H-bridge inverter—demonstrate superior harmonic performance, with THD values of 3.20% and 2.05% over 2 and 10 seconds respectively, both well below the IEEE threshold. Notably, the 15-level inverter by Maadhushree M1 et al. also meets the standard with a THD of 4.71%. These findings confirm that increasing the output voltage levels and employing advanced modulation strategies such as SPWM and fuzzy logic control can effectively reduce harmonic distortion and enhance power quality in solar PV systems.

**Fig. 14 Performance Comparison For Reference Study**

These results are also much clearly presented as a bar graph in the Figure 14, it is clear that the proposed 31 level inverter design makes it clear that significant lower THD level is reported which also satisfies the requirement of IEEE 519 standard limit. the number of switches are also remains same to previous designs comparatively.

7. CONCLUSIONS AND FUTURE SCOPES

Integrating solar PV systems into Indian TN faces challenges such as space constraints, high initial costs, grid compatibility, maintenance demands, and limited skilled labor. Addressing these requires strategic planning and collaboration between telecom and renewable energy sectors. The paper aimed to design the comparative ML code for comparing the optimal performance of various MPPT tracker methods. This study introduces a novel 31-level inverter architecture for solar photovoltaic (PV) systems integrated with MPPT for TN base stations for THD minimization. Utilizing 12 switches in a cascaded H-bridge configuration, the inverter generates stepped output voltages ranging from -15 Vdc to $+15\text{ Vdc}$. Simulation analyses reveal that the P&O and Incremental Conductance MPPT algorithms deliver superior average power output compared to the Constant Voltage method. The proposed inverter achieves THD levels of 3.20% over 2 seconds and 2.05% over 10 seconds, significantly outperforming conventional multilevel inverter (MLI) designs and complying with the IEEE 519 standard threshold of 5%. These findings underscore the advantages of high-level inverter topologies and advanced modulation techniques in enhancing power quality and minimizing harmonic distortion in solar PV applications.

Future telecommunication network solar PV system designs include advanced energy management systems, compact solar panels, improved energy storage solutions, smart grid integration, hybrid renewable systems, IoT and remote monitoring, adaptive MPPT algorithms, and distortion analysis

8. Declaration

The authors hereby declare that this research is entirely original and has not been copied or reproduced from any other source. No financial support or funding was received for the conduct of this study. Furthermore, the authors confirm that there are no conflicts of interest associated with this research.

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