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Adaptive Control Based Multi-Level Inverter for Solar PV Applications

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Abstract- — There has been an increased use of MLIs in renewable energy generation because of their ability to provide good output voltages while minimizing harmonic distortion. On the other hand, traditional inverter systems face issues with distorted waveforms, high total harmonic distortion (THD), and poor adaptability to changing dynamics. This paper proposes an adaptive control based five-level multilevel inverter for a grid-connected photovoltaic (PV) system. A PV array, an MPPT technique, a five-level inverter configuration, and an adaptive Proportional-Integral (PI) controller make up the proposed system. Simulations were performed on the system using MATLAB/Simulink under different loading conditions. The PI control scheme adjusts the control parameters to regulate the voltage and synchronize with the grid. The simulation results show that the system effectively minimizes the THD and improves waveform quality when compared to conventional two-level inverters. Besides, the system operates optimally in transient conditions and varying loads.

Keywords : multilevel inverter, solar PV, adaptive control, MPPT, THD, grid synchronization.

I. INTRODUCTION

The growing demand for clean and sustainable energy has led to increased adoption of renewable energy sources across the world. Among these, solar photovoltaic (PV) systems have gained significant importance due to their availability, scalability, and environmentally friendly nature. Solar PV systems convert sunlight directly into electrical energy in the form of direct current (DC). However, since most electrical loads and utility grids operate using alternating current (AC), efficient power conversion is essential for practical utilization of solar energy. As a result, power electronic converters, particularly inverters, play a vital role in enabling the integration of solar PV systems with the electrical grid.

Inverters are responsible for converting DC power generated by PV panels into usable AC power. Conventional two-level inverters are commonly used due to their simple structure and ease of control. However, with increasing power ratings and higher grid penetration of solar PV systems, these inverters face several drawbacks. Poor power quality, high harmonic distortion, excessive switching losses, overheating, and difficulties in grid synchronization are some of the major challenges associated with two-level inverters. Moreover, their limited scalability makes them less suitable for high-power grid-connected applications where stringent power quality standards must be met.

Multilevel inverters (MLIs) provide an effective solution to overcome the limitations of conventional inverters. By generating output voltage with multiple discrete levels, MLIs significantly reduce harmonic distortion, improve waveform quality, and lower voltage stress on power electronic devices. These features make multilevel inverters highly suitable for high-power and grid-connected solar PV applications. However, inverter performance can vary under changing load and operating conditions. To address this issue, adaptive control techniques are incorporated into the multilevel inverter system. Adaptive control enables real-time adjustment of control parameters, ensuring improved voltage regulation, enhanced grid synchronization, and better overall system performance. This project focuses on developing an adaptive control–based multilevel inverter for solar PV applications to achieve improved power quality and reliable grid integration.

II. RELATED WORKS

The development of inverter technologies has gained significant attention due to the increasing integration of renewable energy systems, particularly solar photovoltaic (PV) applications. Conventional two-level inverters have been widely used because of their simple design and ease of implementation. However, they are known to produce square wave outputs with high harmonic distortion, which affects power quality and limits their suitability for high-power applications.

To address these limitations, researchers have extensively explored the concept of Multilevel Inverter topologies. These inverters generate output voltage using multiple discrete levels, resulting in a waveform that closely resembles a sinusoidal signal. Various configurations such as cascaded H-bridge, neutral-point clamped, and flying capacitor inverters have been proposed in the literature. Among these, cascaded H-bridge structures are preferred for modularity and ease of control. Studies have shown that increasing the number of voltage levels significantly reduces harmonic distortion and switching stress on power electronic devices.

In addition to topology improvements, modulation techniques have also been investigated to enhance inverter performance. Pulse width modulation (PWM) strategies, including sinusoidal PWM and carrier-based PWM, are commonly used to control switching operations. These methods help in achieving better voltage regulation and reducing harmonic components, but their performance is still dependent on operating conditions and system parameters.

Recent research has focused on advanced control strategies to further improve system performance. Adaptive control techniques have gained attention due to their ability to adjust controller parameters in real time. Unlike conventional controllers with fixed gains, adaptive controllers respond dynamically to variations in load and system conditions, thereby improving stability and transient response. Several studies demonstrate that adaptive control can effectively reduce overshoot, minimize steady-state error, and enhance voltage regulation in inverter-based systems.

Furthermore, the performance of inverter systems under different load conditions has been an important area of investigation. Linear loads exhibit predictable behavior, whereas nonlinear loads introduce harmonics and distort the current waveform. Research indicates that multilevel inverters perform better than conventional inverters under nonlinear load conditions due to their improved voltage profile. When combined with adaptive control, the system can maintain stable operation even in the presence of disturbances.

Despite significant advancements, many existing studies focus either on inverter topology or control strategy independently. Limited work has been done on integrating multilevel inverter design with adaptive control and evaluating their combined performance under both linear and nonlinear loads. This paper aims to address this gap by providing a comprehensive comparative analysis of conventional and multilevel inverters with and without adaptive control.

III. METHODOLOGY

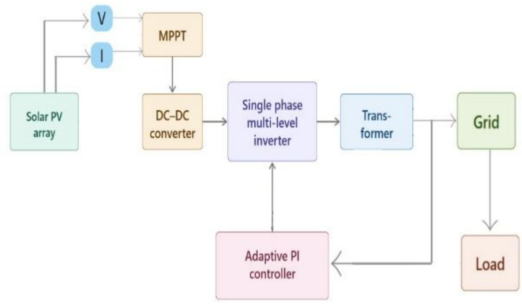


Fig. 1. Block Diagram of the Proposed Adaptive Control Based Multilevel Inverter System

The proposed system represents a grid-connected solar photovoltaic (PV) power generation system integrated with an adaptive control–based multilevel inverter. The system consists of a solar PV array, maximum power point tracking (MPPT) unit, multilevel inverter, adaptive controller, grid, and load. Each block plays a vital role in ensuring efficient power conversion, improved power quality, and stable grid synchronization.

The solar PV array serves as the primary energy source and converts solar irradiance into direct current (DC) electrical power. Due to variations in sunlight intensity and temperature, the output power of the PV array is not constant. To ensure maximum extraction of available solar power, a Maximum Power Point Tracking (MPPT) unit is incorporated. The MPPT continuously monitors PV voltage and current and generates appropriate reference signals so that the PV array operates at its maximum power point under varying environmental conditions.

The DC output from the PV array is fed to the multilevel inverter, which converts the DC power into alternating current (AC) suitable for grid connection and load supply. The multilevel inverter generates output voltage with multiple discrete levels, thereby reducing harmonic distortion, improving waveform quality, and lowering stress on power electronic switches compared to conventional two-level inverters. The inverter output is supplied to both the grid and the load, enabling grid-connected operation while meeting load demand.

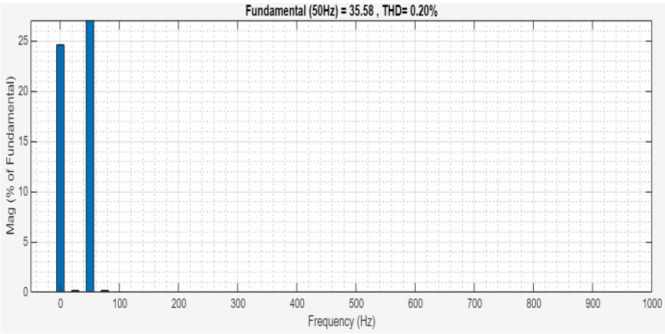
An adaptive controller, consisting of a conventional PI controller combined with adaptive control logic, is employed to regulate the inverter operation. The controller receives feedback signals from the AC side, such as voltage and current, and dynamically adjusts control parameters in response to load and grid variations. This adaptive action ensures effective grid synchronization, improved voltage regulation, and reduced total harmonic distortion. Overall, the proposed block diagram illustrates a robust and efficient solar PV system capable of delivering high-quality power to the grid and connected loads under varying operating conditions.

IV. RESULTS AND DISCUSSION

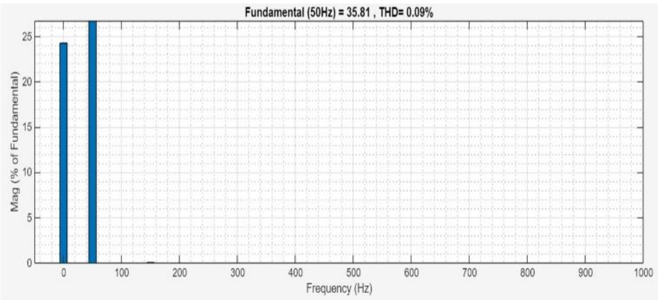
THD Under Varying Load Conditions

1.LOAD – 1kW (Linear load-0.5kW, Non-Linear Load - 0.5kW)

(a) Conventional Inverter

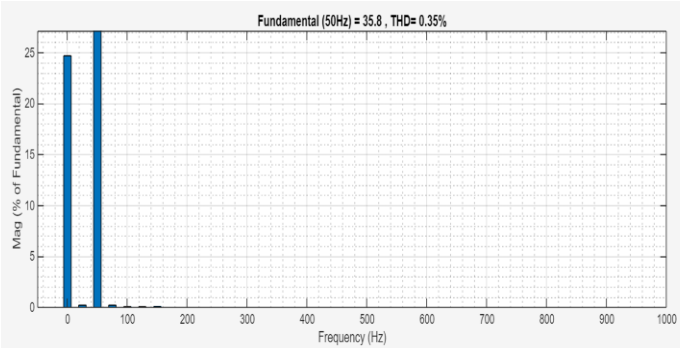


(b) 5 – Level Inverter

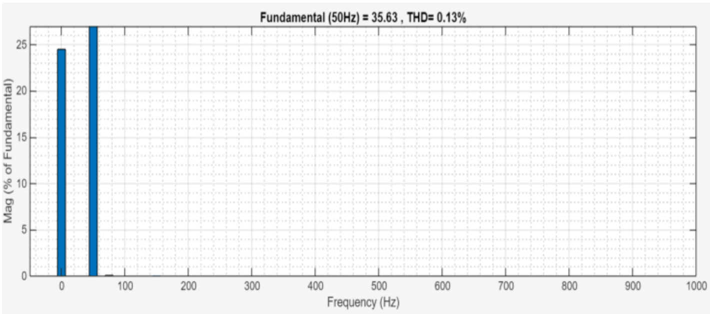


2. LOAD – 2kW (Linear load-1kW, Non-Linear Load - 1kW)

(a) Conventional Inverter

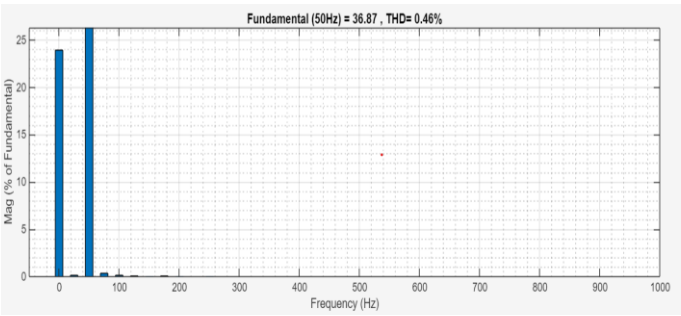


(b) 5 – Level Inverter



3. LOAD – 4kW (Linear load-2kW, Non-Linear Load - 2kW)

(a) Conventional Inverter



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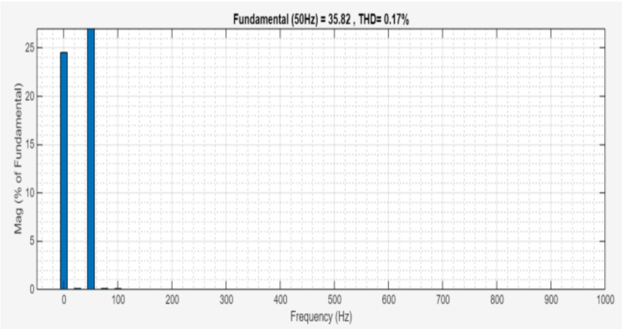
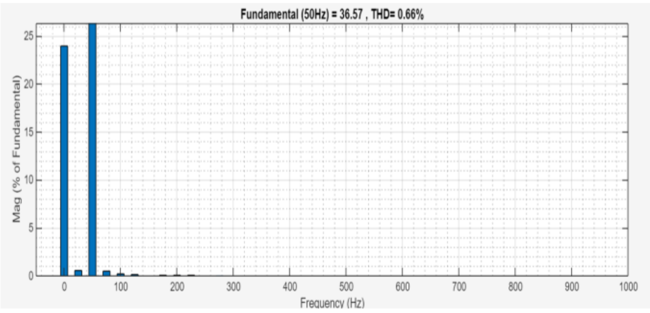
(b) 5 – Level Inverter

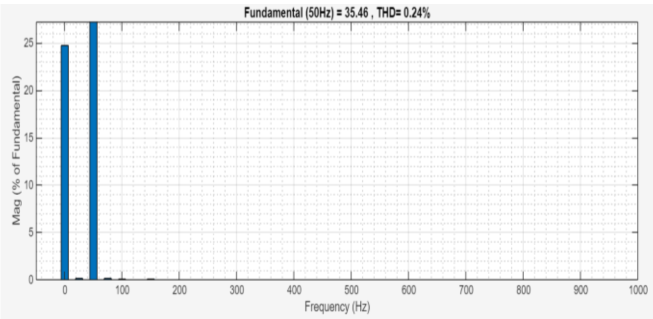


4. LOAD – 6kW (Linear load-3kW, Non-Linear Load - 3kW)

(a) Conventional Inverter

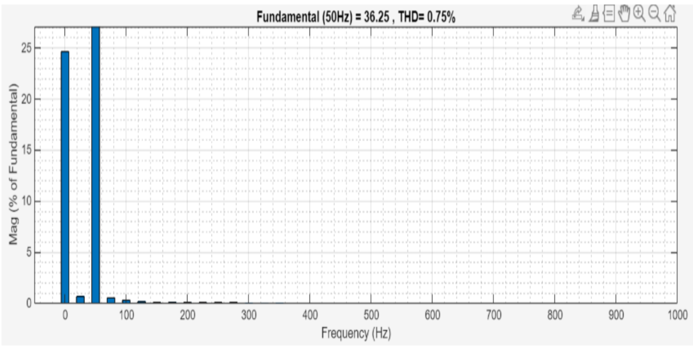


(b) 5 – Level Inverter

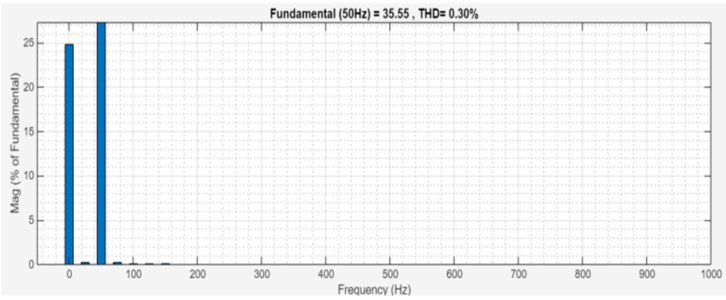


5. LOAD – 8kW (Linear load-4kW, Non-Linear Load - 4kW)

(a) Conventional Inverter

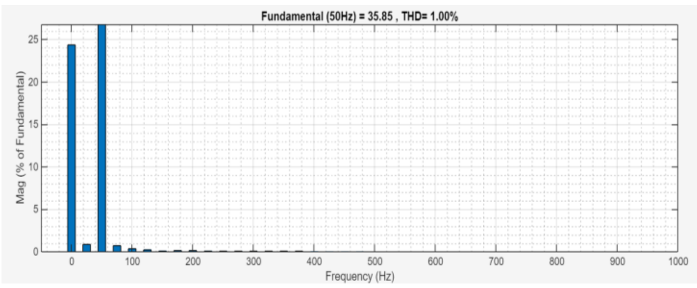


(b) 5 Level Inverter



6. LOAD – 10kW (Linear load-5kW, Non-Linear Load - 5kW)

(a) Conventional Inverter



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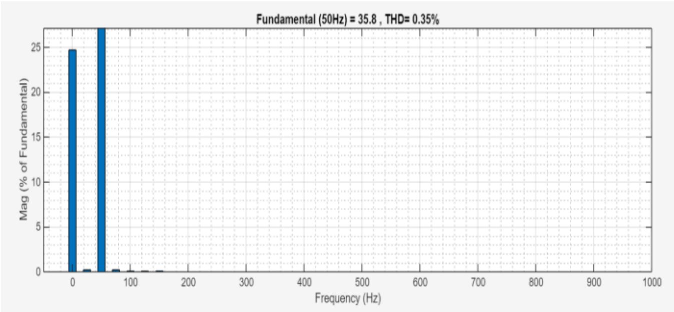
(b) 5 – Level Inverter



Comparative Analysis

LOAD	Two-Level Inverter THD	Five-Level Inverter THD
1kW	0.20	0.09
2kW	0.35	0.13
4kW	0.46	0.17
6kW	0.66	0.24
8kW	0.75	0.30
10kW	1.00	0.36

The harmonic performance of the proposed system is analyzed by comparing the Total Harmonic Distortion (THD) of the grid current for both the conventional two-level inverter and the proposed five-level multilevel inverter under different load conditions ranging from 0.5 kW to 5 kW. The obtained results clearly indicate that the five-level multilevel inverter provides significantly lower THD compared to the conventional inverter for all loading conditions.

In the conventional two-level inverter, the grid current THD is comparatively higher due to abrupt switching between positive and negative voltage levels. This sudden switching action introduces higher harmonic components into the output current waveform, thereby affecting the overall power quality. At lower load conditions, the conventional inverter exhibits higher distortion levels, and although the THD gradually decreases with increase in load, the harmonic content remains comparatively higher than the multilevel inverter system.

On the other hand, the five-level Cascaded H-Bridge multilevel inverter generates a stepped output waveform that closely resembles a sinusoidal waveform. Due to the presence of multiple voltage levels, the switching stress and harmonic content are considerably reduced. As a result, the grid current waveform becomes smoother with improved waveform quality and lower distortion.

From the observed results, the five-level inverter achieves very low THD values under all loading conditions. Even though the THD slightly increases with increase in load, the obtained values remain significantly lower than those of the conventional inverter. This demonstrates the superior harmonic reduction capability of the proposed multilevel inverter system.

The reduction in THD confirms that the proposed multilevel inverter improves power quality, reduces harmonic injection into the grid, and enhances the overall performance of the solar PV system. The obtained results also verify that the multilevel inverter is more suitable for grid-connected renewable energy applications where low harmonic distortion and stable operation are essential requirements.

Therefore, the comparative analysis clearly proves that the proposed five-level multilevel inverter provides better harmonic performance and improved grid current quality compared to the conventional two-level inverter under varying load conditions.

Overall Comparative Analysis of Conventional Inverter and Proposed Multilevel Inverter System

Parameter	Conventional Inverter	Multi-Level Inverter + Adaptive PI-Controller
Voltage waveform quality	Poor	Improved
Current distortion	High	Reduced
THD	High	Low
Stability	Moderate	Better

The overall performance comparison between the conventional two-level inverter and the proposed five-level multilevel inverter with adaptive control is presented based on important performance parameters such as voltage waveform quality, current distortion, Total Harmonic Distortion (THD), and system stability. The comparative analysis clearly demonstrates the improved performance of the proposed multilevel inverter system over the conventional inverter system.

In the conventional inverter, the output voltage waveform quality is comparatively poor due to abrupt switching between positive and negative voltage levels. This results in distorted output waveforms with higher harmonic components. In contrast, the proposed five-level multilevel inverter generates multiple stepped voltage levels that closely approximate a sinusoidal waveform, thereby significantly improving the waveform quality.

Similarly, the conventional inverter exhibits higher current distortion because of increased switching harmonics and limited voltage levels. The distorted current waveform negatively affects power quality and overall system efficiency. However, in the proposed multilevel inverter with adaptive control, the current distortion is considerably reduced due to improved switching operation and harmonic suppression capability.

The comparison of Total Harmonic Distortion (THD) further confirms the effectiveness of the proposed system. The conventional inverter produces higher THD values because of large voltage transitions and switching harmonics. On the other hand, the multilevel inverter with adaptive control achieves lower THD values by generating smoother output waveforms and improving harmonic elimination. The adaptive controller further enhances the dynamic response and maintains stable operation under varying load conditions.

In terms of stability, the conventional inverter provides only moderate performance during load variations and dynamic operating conditions. The proposed multilevel inverter integrated with adaptive control offers better system stability, improved voltage regulation, and enhanced dynamic response. The controller continuously monitors the system output and adjusts the control action accordingly, thereby maintaining stable inverter performance.

Therefore, the overall comparison clearly indicates that the proposed five-level multilevel inverter with adaptive control provides superior performance in terms of waveform quality, harmonic reduction, current distortion, and operational stability when compared to the conventional two-level inverter system. These improvements make the proposed system more suitable for modern solar PV and grid-connected renewable energy applications.

V. CONCLUSION

This work presented a comparative evaluation of a conventional inverter and a multilevel inverter enhanced with an adaptive control approach under both linear and nonlinear loading conditions. The study was carried out using simulations in MATLAB/Simulink, with emphasis on output voltage characteristics, current behavior, and Total Harmonic Distortion (THD).

From the analysis, it is observed that the conventional inverter produces a two-level output waveform with noticeable distortion, which negatively impacts power quality. In comparison, the Multilevel Inverter generates multiple voltage levels, resulting in a waveform that is much closer to a sinusoidal profile. This leads to a considerable reduction in harmonic content and improved overall output quality.

In addition, the inclusion of Adaptive Control contributes to better dynamic performance of the system. The controller continuously adjusts its parameters based on operating conditions, which helps in minimizing fluctuations, improving voltage regulation, and achieving quicker stabilization. These advantages are more evident under nonlinear load conditions, where system disturbances are higher.

In summary, the results confirm that the integration of multilevel inverter topology with adaptive control provides a more effective solution compared to conventional inverter systems. The approach ensures improved waveform quality, lower harmonic distortion, and enhanced stability, making it suitable for modern power conversion applications.

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