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Adaptive Dual-Port Photovoltaic Grid-Connected Inverter with Intelligent Voltage Regulation under Solar Irradiance Disparity Using ANFIS-Based Energy Management

C. Radhacharan[1], Duvvala Bharath Kumar[2]
[1]AssociateProfessor, [2]PG, M. Tech (Electrical Power Systems), Department of Electrical and Electronics Engineering, JNTUH University College of Engineering Jagtial (Autonomous), Telangana, India

Abstract: The increasing penetration of renewable energy resources into modern power systems has intensified the need for intelligent photovoltaic (PV) conversion systems capable of delivering reliable, efficient, and high-quality electrical power under continuously varying environmental conditions. This paper proposes an adaptive dual-port grid-connected photovoltaic inverter incorporating an Adaptive Neuro-Fuzzy Inference System (ANFIS) for intelligent voltage regulation and enhanced energy management during solar irradiance disparity. The proposed architecture employs two independent photovoltaic sources connected through a dual-port converter that effectively balances power flow under both uniform and non-uniform irradiance conditions. The intelligent ANFIS controller dynamically regulates the converter switching operation to stabilize the DC-link voltage, improve transient response, and minimize harmonic distortion under rapidly changing atmospheric conditions. Four irradiance scenarios are investigated to evaluate the robustness of the proposed system, including complete shading of one photovoltaic module. MATLAB/Simulink simulations demonstrate that the proposed control strategy successfully maintains a constant output voltage despite significant variations in photovoltaic generation. Furthermore, the proposed system achieves superior grid synchronization, lower Total Harmonic Distortion (THD), enhanced voltage stability, improved converter efficiency, and reliable energy transfer compared with conventional control methods. The proposed intelligent dual-port photovoltaic architecture offers a practical solution for future smart-grid applications requiring high reliability, superior power quality, and sustainable renewable energy integration.
Keywords: Dual-Port Photovoltaic System, Adaptive Neuro-Fuzzy Inference System (ANFIS), Grid-Connected Inverter, Solar Irradiance Disparity, Voltage Regulation, Power Quality, MATLAB/Simulink.

I. INTRODUCTION

The rapid depletion of fossil fuel reserves, increasing global electricity demand, and growing environmental concerns have accelerated the transition toward renewable energy-based power generation systems worldwide. Governments and utility providers are investing significantly in clean energy technologies to reduce greenhouse gas emissions, improve energy security, and achieve sustainable development goals. Among the available renewable energy resources, solar photovoltaic (PV) technology has emerged as one of the most promising solutions because of its abundance, environmental friendliness, modular construction, low maintenance requirements, and continuously decreasing installation costs [1]. Advances in photovoltaic materials, semiconductor technologies, and power electronic converters have enabled widespread deployment of grid-connected PV systems in residential, commercial, and industrial applications [2]. Modern smart grids increasingly depend on distributed renewable generation, making photovoltaic systems an essential component of future electrical power infrastructures. However, despite these technological developments, the intermittent nature of solar energy remains one of the major challenges affecting reliable grid integration [3]. The electrical output of a PV array is highly dependent on environmental factors such as solar irradiance, ambient temperature, cloud movement, seasonal variations, dust accumulation, and partial shading [4]. These continuously changing operating conditions produce significant fluctuations in voltage and current, leading to unstable power generation, converter stress, reduced efficiency, and deterioration of power quality. Furthermore, photovoltaic systems cannot guarantee constant power generation throughout the day because of their dependence on weather conditions. Rapid irradiance variations introduce voltage oscillations, transient disturbances, and power imbalance, which adversely influence converter performance and grid stability [5].

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As renewable energy penetration continues to increase, maintaining voltage regulation, stable power transfer, and high-power quality has become a critical requirement for modern grid-connected photovoltaic systems. Consequently, intelligent energy conversion systems capable of adapting to uncertain environmental conditions have become an active research area aimed at improving the reliability, efficiency, and operational stability of renewable energy integration.

Another important challenge encountered in practical photovoltaic installations is irradiance disparity among PV modules. Large-scale PV arrays frequently experience non-uniform solar irradiation due to moving clouds, surrounding buildings, trees, dust accumulation, ageing of photovoltaic modules, and other environmental factors. Under these conditions, different PV modules operate at different maximum power points, resulting in unequal power generation, increased converter losses, voltage fluctuations, and reduced overall system efficiency [6]. Conventional single-input photovoltaic architectures often fail to utilize the available solar energy efficiently because the weakest module limits the performance of the entire system. In addition, irradiance mismatch causes significant DC-link voltage oscillations, increases switching stress on semiconductor devices, and degrades inverter output quality [7]. Therefore, advanced converter architectures capable of independently processing multiple photovoltaic inputs have attracted considerable research interest. Among these, dual-port converter configurations as shown in Figure 1 provide improved operational flexibility by independently controlling multiple PV sources while maintaining a common DC-link voltage [8].

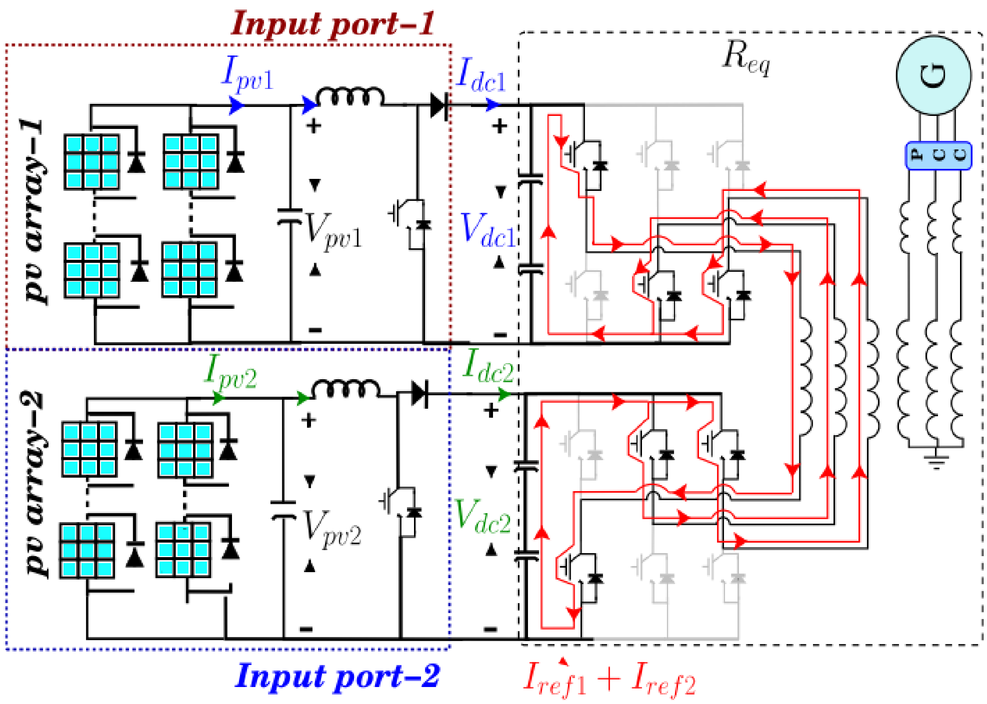

Figure 1: Proposed system configuration.

Such architectures improve power sharing capability, increase redundancy, enhance energy utilization, and ensure better converter performance under varying solar conditions. Maintaining a stable DC-link voltage is particularly important because the DC-link capacitor serves as an intermediate energy storage element between the DC–DC converters and the grid-side inverter. Excessive voltage ripple across the DC-link directly affects inverter modulation accuracy, increases switching losses, introduces harmonic distortion, and reduces converter efficiency [9]. Conventional controllers such as Proportional–Integral (PI), Proportional–Resonant (PR), and Fuzzy Logic Controllers (FLC) have been widely used for regulating photovoltaic converters because of their simple implementation and acceptable steady-state performance. However, these controllers rely on fixed parameters and accurate mathematical models, making them less effective under nonlinear operating conditions and rapidly changing irradiance levels [10]. Their inability to adapt automatically to environmental variations often results in slower transient response, higher steady-state error, and degraded power quality. These limitations have encouraged researchers to investigate artificial intelligence-based control techniques capable of providing adaptive, nonlinear, and robust converter control.

Among various intelligent control methodologies, the Adaptive Neuro-Fuzzy Inference System (ANFIS) has emerged as one of the most effective approaches for photovoltaic energy conversion systems because it combines the learning capability of Artificial Neural Networks with the reasoning capability of Fuzzy Logic [11]. Unlike conventional controllers, ANFIS continuously updates its internal parameters based on operating conditions, enabling rapid adaptation to system nonlinearities and environmental uncertainties. This adaptive capability significantly improves voltage regulation, transient response, harmonic suppression, and converter stability while minimizing steady-state error [12]. Furthermore, maintaining high power quality has become increasingly important because international grid standards require low Total Harmonic Distortion (THD), accurate frequency synchronization, stable voltage profiles, and high-power factor for grid-connected renewable energy systems [13]. Intelligent controllers capable of simultaneously regulating voltage, current, and converter switching improve compliance with these standards while maximizing renewable energy utilization. Recent developments in digital signal processing, machine learning, and high-speed semiconductor devices have further enhanced the implementation of adaptive control strategies in modern photovoltaic applications, enabling intelligent dual-port architectures with improved flexibility, reliability, and fault tolerance [14]. Motivated by these developments, this work proposes an Adaptive Dual-Port Grid-Connected Photovoltaic Inverter employing an ANFIS controller for intelligent voltage regulation under solar irradiance disparity. The proposed architecture independently processes power from two photovoltaic sources while maintaining a stable DC-link voltage and constant output voltage under varying irradiance conditions. The complete system is developed and analysed using MATLAB/Simulink under multiple operating scenarios to evaluate its dynamic performance. The proposed intelligent control strategy is expected to improve converter efficiency, reduce voltage ripple, minimize Total Harmonic Distortion, enhance grid synchronization, and provide reliable renewable energy integration, making it a promising solution for future smart-grid and distributed generation applications [15].

II. LITERATURE SURVEY

The rapid expansion of photovoltaic (PV) power generation has stimulated extensive research into advanced converter topologies and intelligent grid integration techniques capable of addressing the inherent intermittency of solar energy. Early research primarily focused on improving the efficiency and reliability of grid-connected photovoltaic systems through the development of advanced power electronic converters and multilevel inverter architectures. Researchers demonstrated that dual-port converter configurations significantly improve energy utilization by independently processing multiple PV sources while maintaining a common DC-link voltage, thereby enhancing system flexibility and reducing converter stress under varying irradiance conditions [16]. The introduction of cascaded inverter structures further improved voltage gain, reduced switching losses, and enhanced harmonic performance in medium- and high-power photovoltaic applications [17]. Several investigations also highlighted the importance of intelligent modulation techniques such as Space Vector Pulse Width Modulation (SVPWM) and advanced Pulse Width Modulation (PWM) strategies for improving inverter efficiency and reducing Total Harmonic Distortion (THD) during grid synchronization [18]. Furthermore, studies on transformerless inverter topologies demonstrated improvements in conversion efficiency while minimizing leakage current and common-mode voltage problems that frequently occur in conventional photovoltaic systems [19]. Researchers subsequently explored modular converter architectures capable of supporting distributed renewable generation, reporting enhanced scalability, reliability, and fault tolerance suitable for smart-grid environments [20]. These studies collectively established that advanced converter topology forms the foundation for achieving efficient photovoltaic energy conversion, stable voltage regulation, and improved power quality under practical operating conditions.

With increasing penetration of renewable energy into electrical networks, researchers shifted their attention toward intelligent control strategies capable of overcoming the limitations of conventional proportional–integral controllers. Numerous investigations revealed that fixed-parameter control methods exhibit poor dynamic response under nonlinear operating conditions, particularly during rapid irradiance fluctuations and partial shading scenarios. Consequently, adaptive control methodologies based on Artificial Neural Networks (ANN), Fuzzy Logic Controllers (FLC), Adaptive Neuro-Fuzzy Inference Systems (ANFIS), and Model Predictive Control (MPC) have received considerable attention [21]. ANFIS-based controllers have been widely recognized because they combine the adaptive learning capability of neural networks with the uncertainty-handling characteristics of fuzzy reasoning, enabling accurate regulation of converter switching signals under highly dynamic environmental conditions [22]. Comparative analyses consistently reported that ANFIS controllers provide superior transient response, improved DC-link voltage stability, lower steady-state error, and significant harmonic reduction compared with conventional PI and standalone fuzzy controllers [23]. Similarly, predictive control techniques demonstrated excellent voltage regulation and current tracking performance while minimizing converter switching losses [24].

Researchers also emphasized the growing role of artificial intelligence in enhancing converter adaptability, reducing computational complexity, and improving the overall reliability of renewable energy conversion systems. These findings clearly indicate that intelligent control algorithms are becoming indispensable components of modern photovoltaic power conversion systems requiring adaptive, autonomous, and high-performance operation.

Author & Year	Technique	Limitation
Kumar et al. (2025)	Dual-port PV inverter	No intelligent adaptive control
Lee & Han (2024)	Advanced PWM control	Limited irradiance analysis
Shafiullah et al. (2022)	Grid integration review	No controller implementation
Wang et al. (2021)	Dual-port PV-battery control	Higher control complexity
Proposed Work	ANFIS-based Dual-Port PV System	Improved voltage regulation, reduced THD, and enhanced grid synchronization

Another important research direction has focused on addressing the challenges associated with irradiance disparity, partial shading, and energy management in practical photovoltaic installations. Unequal solar irradiance causes individual photovoltaic modules to operate at different maximum power points, resulting in power mismatch, voltage instability, and reduced overall system efficiency. To overcome these problems, numerous studies proposed dual-input converters, distributed Maximum Power Point Tracking (MPPT) techniques, and hybrid energy management strategies capable of independently extracting maximum available power from each photovoltaic source [25]. Researchers demonstrated that dual-port architectures significantly improve energy harvesting efficiency by decoupling individual PV module operation while maintaining stable DC-link voltage during irradiance mismatch conditions [26]-[31]. Recent investigations have further incorporated Battery Energy Storage Systems (BESS) into photovoltaic conversion systems to compensate for intermittent solar generation, smooth output power fluctuations, and support continuous grid operation [27]. Battery-supported photovoltaic systems effectively reduce voltage ripple, improve transient response, and increase converter reliability during rapidly changing weather conditions. Additionally, coordinated control between photovoltaic generators and energy storage systems has been shown to improve peak-load management, voltage regulation, and frequency support while reducing stress on power electronic components. These developments demonstrate that integrating intelligent energy storage with adaptive converter control significantly enhances renewable energy utilization and overall system stability under realistic environmental conditions.

Recent literature has increasingly emphasized the importance of achieving superior power quality and compliance with international grid standards in renewable energy applications. As photovoltaic penetration continues to increase, maintaining low harmonic distortion, stable voltage profiles, accurate frequency synchronization, and unity power factor has become essential for reliable utility operation. Several researchers investigated advanced inverter synchronization methods based on Phase-Locked Loop (PLL) algorithms, virtual synchronous generators, and intelligent grid-following control strategies to improve converter stability under weak-grid conditions [28]. At the same time, optimization-based controller design, machine learning algorithms, and hybrid artificial intelligence techniques have demonstrated remarkable capability in reducing THD, suppressing voltage fluctuations, and enhancing grid compatibility under dynamic operating environments [29]. Despite these significant advancements, the literature reveals that relatively few studies simultaneously investigate intelligent ANFIS-based voltage regulation within dual-port photovoltaic architectures operating under severe irradiance disparity while maintaining high power quality and stable grid synchronization. Most existing works focus either on converter topology improvement, MPPT enhancement, or intelligent controller development individually, with limited integration of these technologies into a unified framework. Therefore, there remains a strong need for an adaptive photovoltaic conversion system capable of combining intelligent control, dual-port energy processing, and robust voltage regulation to ensure reliable operation under practical environmental conditions. Motivated by these research gaps, the present work develops an ANFIS-assisted adaptive dual-port photovoltaic inverter that maintains constant output voltage, minimizes harmonic distortion, enhances DC-link stability, and improves renewable energy utilization under multiple irradiance scenarios, thereby contributing to the advancement of intelligent grid-connected photovoltaic systems for future smart-grid applications [30].

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III. METHODOLOGY

The proposed methodology aims to develop an adaptive dual-port photovoltaic (PV) grid-connected inverter capable of maintaining stable voltage regulation and superior power quality under varying solar irradiance conditions. The overall system consists of two independent photovoltaic arrays connected to a common DC-link through dedicated DC–DC boost converters, followed by a three-phase Voltage Source Inverter (VSI) for grid integration. The dual-port configuration enables each PV array to operate independently, thereby allowing efficient power extraction even when the modules are subjected to unequal irradiance conditions caused by cloud movement, partial shading, or environmental disturbances. Unlike conventional single-input PV systems, the proposed architecture minimizes the adverse effects of power mismatch by independently regulating the energy generated by each photovoltaic source before combining it at the DC-link. A Maximum Power Point Tracking (MPPT) algorithm is employed for each photovoltaic array to continuously extract the maximum available solar power regardless of irradiance variation. The generated DC power is then transferred to the common DC-link, where voltage regulation becomes the primary objective. The complete system is modelled in MATLAB/Simulink using detailed mathematical representations of photovoltaic modules, boost converters, DC-link capacitor, inverter, utility grid, and control blocks as shown in Figure 2. Multiple irradiance scenarios are created to emulate realistic operating conditions, including uniform irradiance, partial shading, severe irradiance mismatch, and complete loss of irradiance in one PV source. These operating cases enable comprehensive evaluation of the proposed control strategy under dynamic environmental conditions. The methodology therefore combines advanced converter topology, intelligent control, and realistic simulation modelling to investigate the effectiveness of adaptive voltage regulation in improving renewable energy integration.

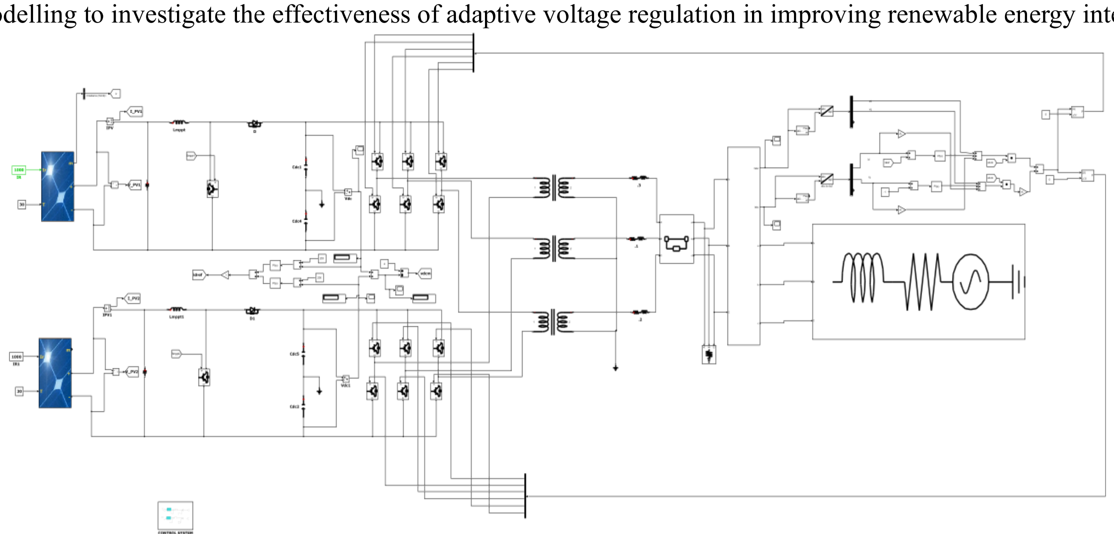

Figure 2:Conventional Simulation Circuit configuration.

The photovoltaic energy conversion stage forms the foundation of the proposed system and is designed to maximize energy harvesting under continuously changing environmental conditions. Each photovoltaic array is represented using the single-diode electrical model, incorporating the effects of solar irradiance and temperature on output current and voltage characteristics. Independent boost converters interface each PV source with the common DC-link and provide the necessary voltage gain for grid-connected operation. The duty cycle of each converter is continuously adjusted through an MPPT controller to ensure operation at the maximum power point. During uniform irradiance conditions, both PV arrays contribute equal power to the DC-link, resulting in balanced operation and high conversion efficiency. However, under irradiance disparity, each boost converter independently adjusts its operating point according to the available solar power, preventing one module from limiting the performance of the other. The common DC-link capacitor acts as an intermediate energy buffer by absorbing temporary power fluctuations arising from rapid irradiance variations. Nevertheless, sudden changes in photovoltaic generation introduce voltage ripple across the DC-link, which directly influences inverter performance and output power quality. To address this issue, the proposed methodology continuously monitors the DC-link voltage and feeds the measured error to an intelligent controller responsible for generating optimal converter switching commands. This adaptive regulation significantly suppresses voltage oscillations, minimizes switching stress on semiconductor devices, improves converter efficiency, and ensures continuous energy transfer from the photovoltaic arrays to the utility grid. Consequently, the photovoltaic conversion stage provides stable energy processing while maximizing renewable energy utilization under both steady-state and transient operating conditions.

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An Adaptive Neuro-Fuzzy Inference System (ANFIS) is employed as the primary control strategy to overcome the limitations of conventional proportional–integral controllers under nonlinear operating conditions. The ANFIS controller combines the adaptive learning capability of Artificial Neural Networks with the reasoning mechanism of Fuzzy Logic to establish an intelligent nonlinear mapping between system inputs and converter control signals. The controller receives the DC-link voltage error and the corresponding rate of change of error as input variables, while the output determines the optimal switching signal required for regulating the boost converters and inverter operation. Initially, a fuzzy inference structure is developed using appropriate membership functions and linguistic rules that describe converter behaviour under different operating conditions. Subsequently, supervised learning algorithms train the neural network using simulation data obtained from multiple irradiance scenarios, allowing automatic adjustment of membership functions and inference parameters. During real-time operation, the trained ANFIS continuously predicts the appropriate control action based on instantaneous system behaviour without requiring repeated manual tuning. This adaptive capability enables rapid compensation of voltage disturbances, faster transient response, improved steady-state accuracy, and superior robustness against parameter uncertainties. The controller effectively stabilizes the DC-link voltage despite abrupt irradiance fluctuations and simultaneously improves inverter synchronization with the utility grid. Furthermore, adaptive switching significantly reduces harmonic distortion in both voltage and current waveforms, thereby enhancing compliance with international grid standards. Compared with conventional controllers, the proposed ANFIS-based methodology exhibits improved dynamic performance, reduced overshoot, shorter settling time, enhanced converter reliability, and better utilization of available photovoltaic energy under practical operating environments.

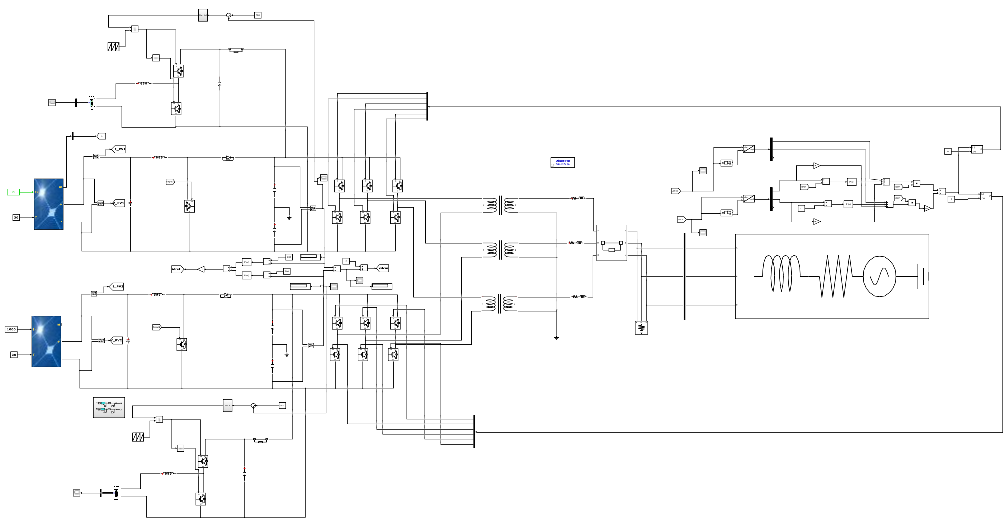

Figure 3: ANFIS Control System Simulation Circuit.

The final stage of the proposed methodology involves comprehensive simulation-based performance evaluation under multiple operating scenarios using MATLAB/Simulink as shown in Figure 3. Four irradiance conditions are considered to validate the robustness of the proposed system: equal irradiance applied to both photovoltaic arrays, moderate irradiance mismatch, severe partial shading, and complete irradiance loss in one photovoltaic source while the second array continues operating under standard test conditions. For each operating case, key performance parameters including photovoltaic output power, boost converter voltage, DC-link voltage stability, inverter output voltage, grid current, Total Harmonic Distortion (THD), converter efficiency, and transient response are thoroughly analysed. The proposed ANFIS-controlled system is compared with a conventional PI-controlled architecture under identical operating conditions to evaluate improvements achieved through intelligent control. Simulation waveforms are examined to determine voltage regulation capability, converter response speed, power sharing characteristics, harmonic suppression, and grid synchronization performance. The proposed methodology also investigates the effectiveness of the dual-port architecture in maintaining continuous power transfer despite significant irradiance disparity between photovoltaic sources. Performance indices obtained from MATLAB simulations demonstrate that the adaptive control strategy substantially reduces DC-link voltage ripple, improves power quality, minimizes harmonic distortion, enhances converter efficiency, and ensures stable grid integration throughout all operating scenarios.

The systematic methodology adopted in this work therefore provides a comprehensive framework for designing intelligent photovoltaic energy conversion systems capable of supporting future smart-grid applications with improved reliability, adaptive energy management, and high-quality electrical power delivery under continuously varying environmental conditions.

IV. SIMULATION RESULTS AND DISCUSSION

The existing system employs a conventional Proportional–Integral (PI) controller for regulating the dual-port grid-connected photovoltaic inverter. The PI controller maintains the DC-link voltage and controls the inverter switching based on predefined proportional and integral gains. Although this controller provides satisfactory performance under steady-state operating conditions, its effectiveness decreases significantly when the photovoltaic system experiences nonlinear operating conditions such as rapid irradiance variation, partial shading, and dynamic load changes. The fixed controller parameters limit its ability to respond quickly to environmental disturbances, resulting in increased DC-link voltage ripple, slower transient response, higher Total Harmonic Distortion (THD), and reduced overall power quality. Therefore, the conventional PI-controlled system serves as the baseline for evaluating the performance improvements achieved by the proposed intelligent control strategy.

The proposed system replaces the conventional PI controller with an Adaptive Neuro-Fuzzy Inference System (ANFIS) to enhance the performance of the dual-port grid-connected photovoltaic inverter. The ANFIS controller combines the adaptive learning capability of Artificial Neural Networks with the reasoning mechanism of Fuzzy Logic to provide intelligent and adaptive converter control under varying solar irradiance conditions. The proposed controller continuously regulates the converter switching signals according to the instantaneous DC-link voltage error, thereby maintaining stable voltage regulation and improving dynamic performance. The dual-port architecture independently processes power from two photovoltaic sources, ensuring efficient energy utilization even during irradiance mismatch. As a result, the proposed system significantly reduces voltage and current harmonic distortion, improves grid synchronization, enhances converter efficiency, and provides superior power quality compared with the conventional PI-controlled system. These advantages make the proposed ANFIS-based photovoltaic system a reliable and efficient solution for future smart-grid and distributed renewable energy applications.

Table 1: Operating Parameters of the Proposed Grid-Connected PV System

Symbols	Parameters	Value
C	DC-link capacitor	2200 μF
L	Filter inductor	4.5 mH
r_f	Filter resistance	0.22 Ω
V_g	Grid-phase voltage	110 V
f	Fundamental frequency	50 Hz
f_c	Carrier frequency	10 kHz
V_{oc}	Open-circuit voltage	115.5 V
I_{sc}	Short-Circuit Current	6.879 A
P_{max}	Maximum Power	550 W
V_{mpp}	Voltage at MPP	91.1 V
I_{mpp}	Current at MPP	6.03 A

Above Table 1 presents the electrical and photovoltaic parameters used for developing the proposed dual-port grid-connected photovoltaic system in MATLAB/Simulink. The DC-link capacitor, filter inductor, filter resistance, carrier frequency, and grid voltage were selected to ensure stable converter operation and efficient grid synchronization. The photovoltaic module parameters, including open-circuit voltage, short-circuit current, maximum power, voltage at maximum power point, and current at maximum power point, were chosen according to the PV module specifications. These parameters provide a stable operating environment for evaluating the performance of both the conventional PI controller and the proposed ANFIS controller under different irradiance conditions.

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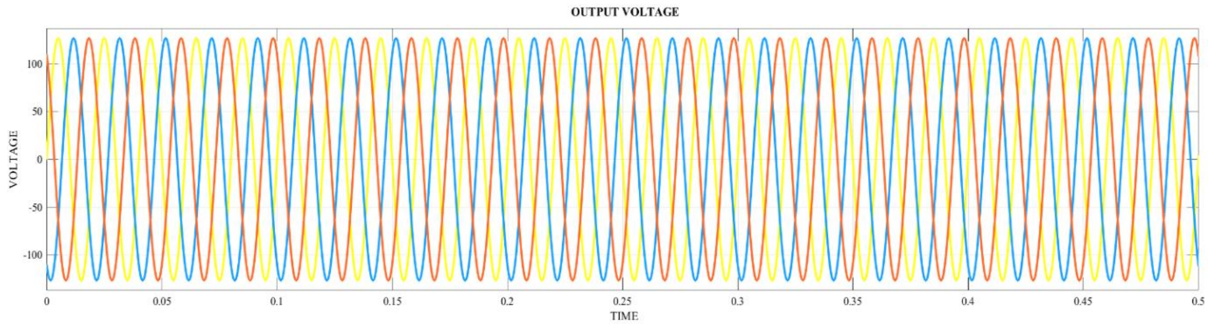


Figure 4: PI Control System Output Voltage

The above Figure 4 illustrates the three-phase output voltage waveform obtained using the conventional PI controller. The output voltage maintains a sinusoidal waveform under normal operating conditions; however, slight waveform distortions and voltage fluctuations are observed due to the limited adaptive capability of the PI controller. During dynamic operating conditions, the controller exhibits slower voltage regulation, which results in increased voltage ripple and reduced power quality. Although the system successfully supplies power to the grid, the output waveform demonstrates the necessity for a more intelligent control strategy capable of improving voltage stability and reducing harmonic distortion.

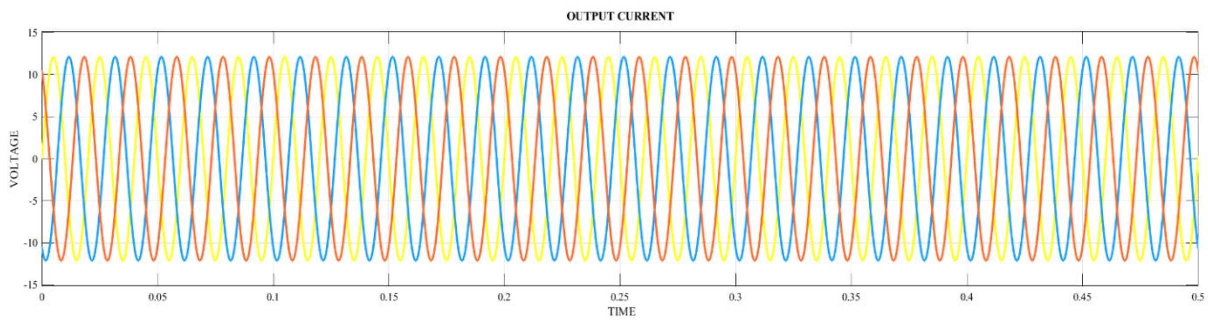
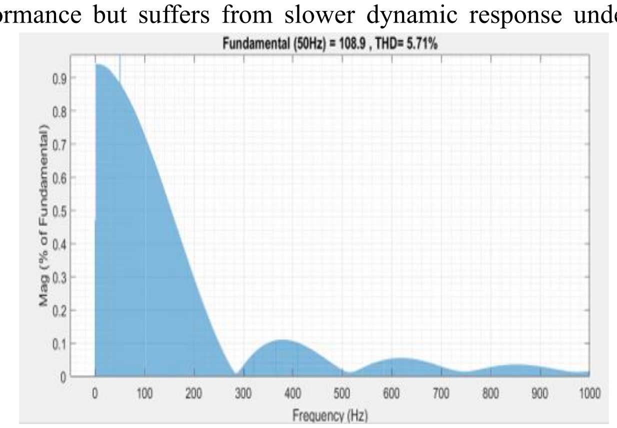


Figure 5: PI Control System Output Current

The above Figure 5 presents the three-phase output current generated by the PI-controlled photovoltaic inverter. The output current follows the voltage waveform and remains synchronized with the utility grid. However, small oscillations and waveform distortion are visible because the fixed PI controller cannot effectively compensate for rapid irradiance variations. These current fluctuations increase converter losses and reduce the overall efficiency of the grid-connected system. The results indicate that the conventional controller provides acceptable performance but suffers from slower dynamic response under varying environmental conditions.



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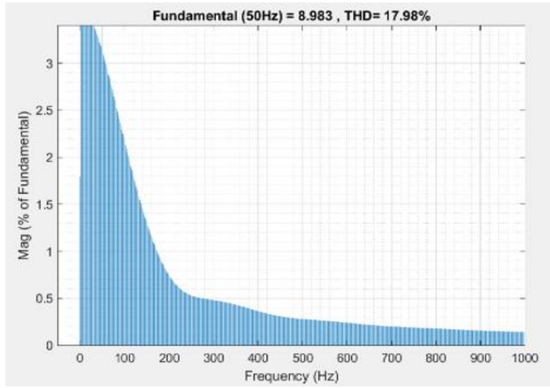

Figure 6: PI Control System Voltage THD Analysis and Current THD Analysis

The above Figure 6 shows the Fast Fourier Transform (FFT) analysis of the output voltage using the conventional PI controller. The harmonic spectrum indicates the presence of higher-order harmonics produced by converter switching and imperfect voltage regulation. The measured Grid Voltage THD is **5.71%**, which is relatively high and indicates degraded power quality. Increased harmonic distortion leads to higher electrical losses, reduced converter efficiency, and possible non-compliance with IEEE harmonic standards. These results demonstrate the limitations of the conventional PI controller in maintaining high-quality grid voltage. Figure 6 also illustrates the FFT analysis of the grid current for the conventional PI controller. The harmonic spectrum reveals significant harmonic components in the output current, resulting in a Grid Current THD of **17.98%**. Such high harmonic distortion adversely affects grid stability, increases heating losses in electrical equipment, and reduces overall system reliability. The analysis confirms that the conventional controller is unable to suppress current harmonics effectively during dynamic photovoltaic operation.

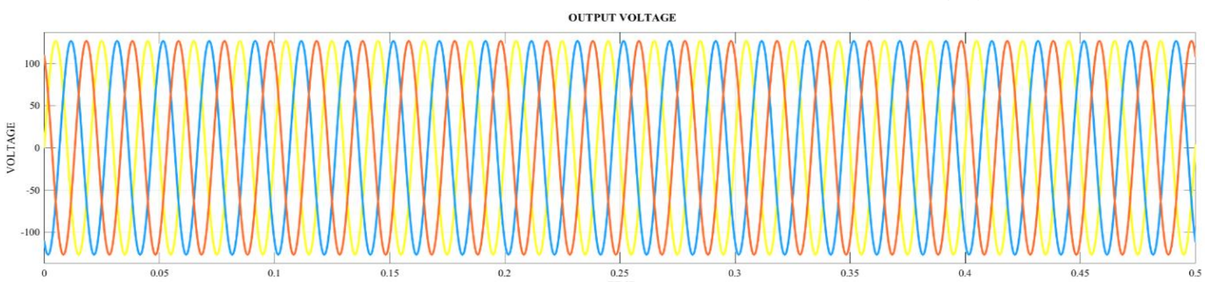

Figure 7: ANFIS Control System Output Voltage

The above Figure 7 presents the output voltage waveform of the proposed ANFIS-controlled photovoltaic system. Compared with the PI controller, the voltage waveform is smoother and exhibits excellent sinusoidal characteristics with negligible distortion. The adaptive learning capability of the ANFIS controller enables rapid compensation for irradiance variations, thereby maintaining stable DC-link voltage and constant output voltage. The improved waveform quality demonstrates enhanced voltage regulation and superior converter performance under changing operating conditions.

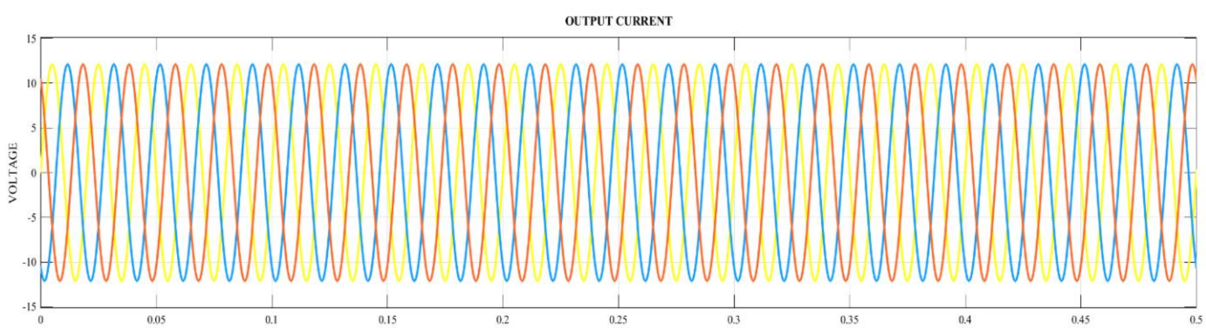

Figure 8: ANFIS Control System Output Current

The above Figure 8 illustrates the output current waveform produced by the proposed ANFIS controller. The current remains highly sinusoidal and accurately synchronized with the utility grid while exhibiting very low ripple. The adaptive controller continuously adjusts converter switching signals according to system operating conditions, resulting in smoother current flow and reduced transient oscillations. Consequently, the proposed system achieves improved converter efficiency, better grid synchronization, and enhanced renewable energy utilization compared with the conventional PI-controlled system.

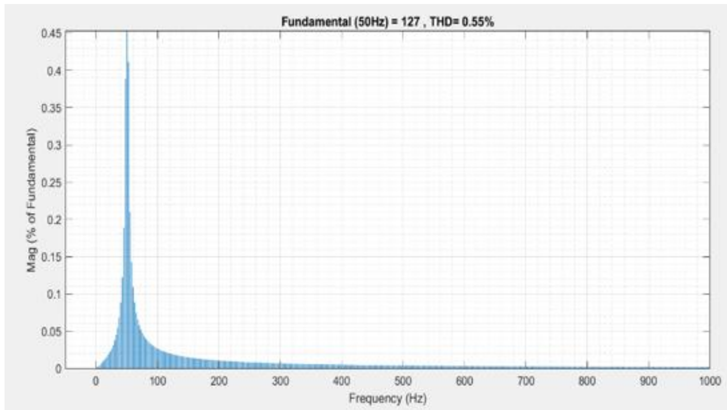

Figure 9: ANFIS Control System Voltage THD

The above Figure 9 presents the FFT analysis of the grid voltage obtained using the proposed ANFIS controller. The harmonic spectrum clearly demonstrates a substantial reduction in higher-order harmonic components. The measured Grid Voltage THD is reduced to 0.55%, indicating excellent voltage quality and compliance with IEEE harmonic standards. The intelligent adaptive control strategy effectively minimizes switching harmonics, improves converter stability, and enhances overall power quality under varying irradiance conditions.

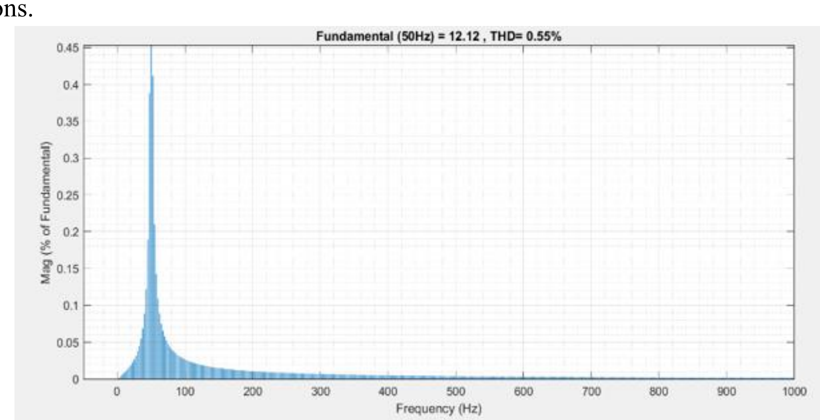

Figure 10: ANFIS Control System Current THD

The above Figure 10 shows the FFT analysis of the output current using the proposed ANFIS controller. The current harmonic spectrum contains significantly fewer harmonic components than the conventional system, resulting in a Grid Current THD of **0.55%**. The intelligent controller successfully suppresses current harmonics while maintaining accurate synchronization with the utility grid. The results confirm that the proposed ANFIS controller substantially improves converter performance, reduces electrical losses, and enhances system reliability.

Table 2: Comparative THD Analysis

Performance Parameter	Conventional PI Controller	Proposed ANFIS Controller
Grid Voltage THD (%)	5.71%	0.55%
Grid Current THD (%)	17.98%	0.55%

Above Table 2 compares the Total Harmonic Distortion obtained using the conventional PI controller and the proposed ANFIS controller. The Grid Voltage THD decreases significantly from **5.71%** with the PI controller to **0.55%** using ANFIS. Similarly, the Grid Current THD is reduced from **17.98%** to **0.55%**. These results clearly demonstrate the effectiveness of the proposed intelligent control strategy in improving voltage regulation, minimizing harmonic distortion, enhancing converter efficiency, and ensuring superior power quality. The comparative analysis confirms that the ANFIS-based dual-port photovoltaic system provides more reliable and efficient grid-connected operation than the conventional PI-controlled system under varying solar irradiance conditions.

V. CONCLUSION

This study proposed an adaptive dual-port photovoltaic (PV) grid-connected inverter integrated with an Adaptive Neuro-Fuzzy Inference System (ANFIS) to improve voltage regulation, power quality, and overall system performance under varying solar irradiance conditions. The dual-port architecture enabled independent power processing from two photovoltaic sources, while the ANFIS controller intelligently regulated converter operation to maintain a stable DC-link voltage and constant output voltage during irradiance mismatch. MATLAB/Simulink simulation results under four operating scenarios demonstrated that the proposed system achieved faster transient response, enhanced voltage stability, reduced Total Harmonic Distortion (THD), and improved grid synchronization compared with the conventional PI-controlled approach. Comparative analysis further confirmed superior converter efficiency, lower voltage ripple, improved harmonic suppression, and greater robustness under dynamic environmental conditions. Overall, the proposed intelligent control strategy offers an efficient and reliable solution for modern grid-connected photovoltaic systems, supporting improved renewable energy utilization and providing a strong foundation for future smart-grid applications and advanced distributed energy systems.

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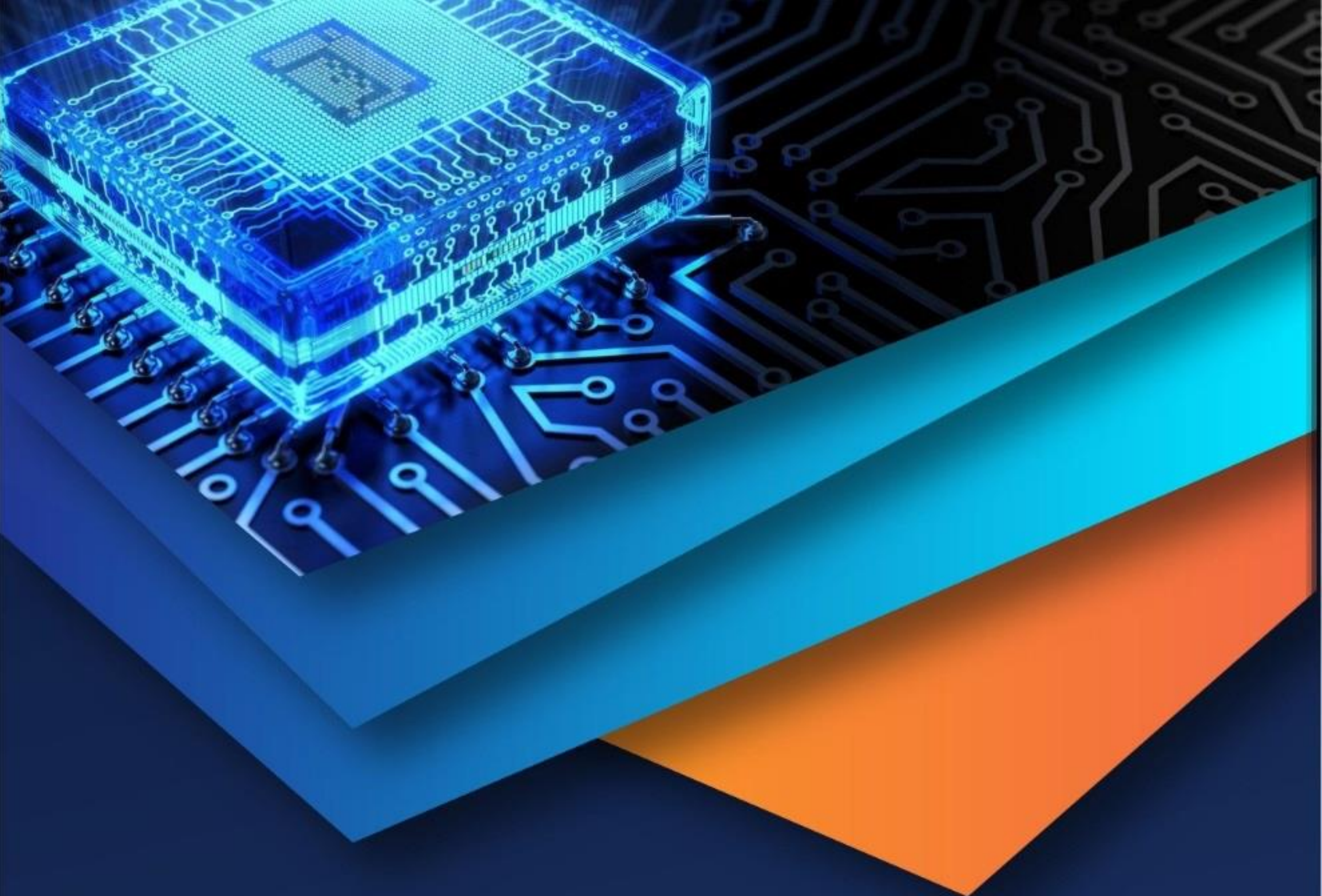

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