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

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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].

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].

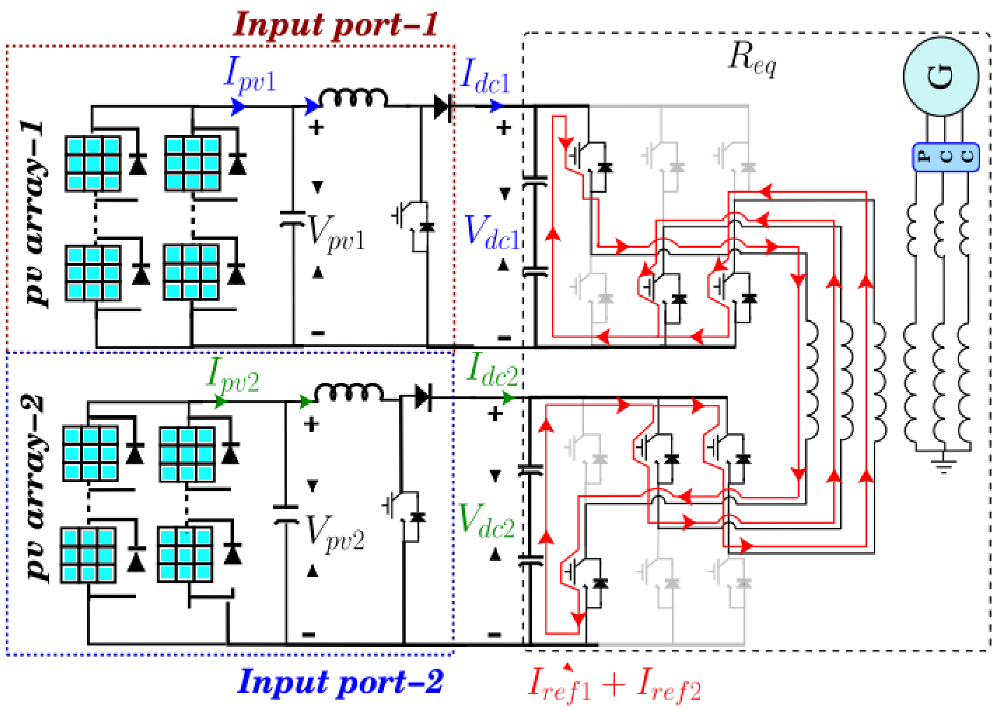


Figure 1: Proposed system configuration.

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].

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.

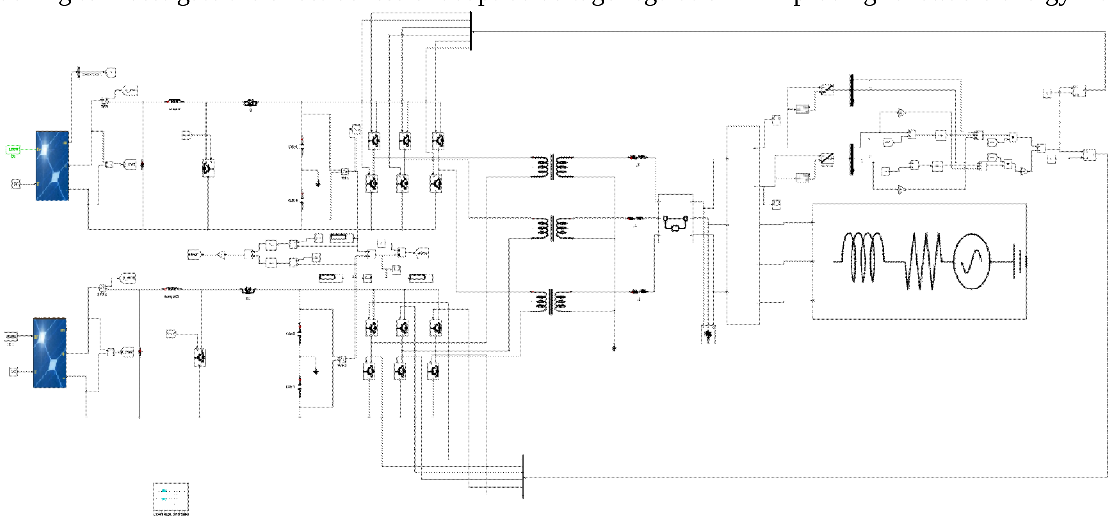
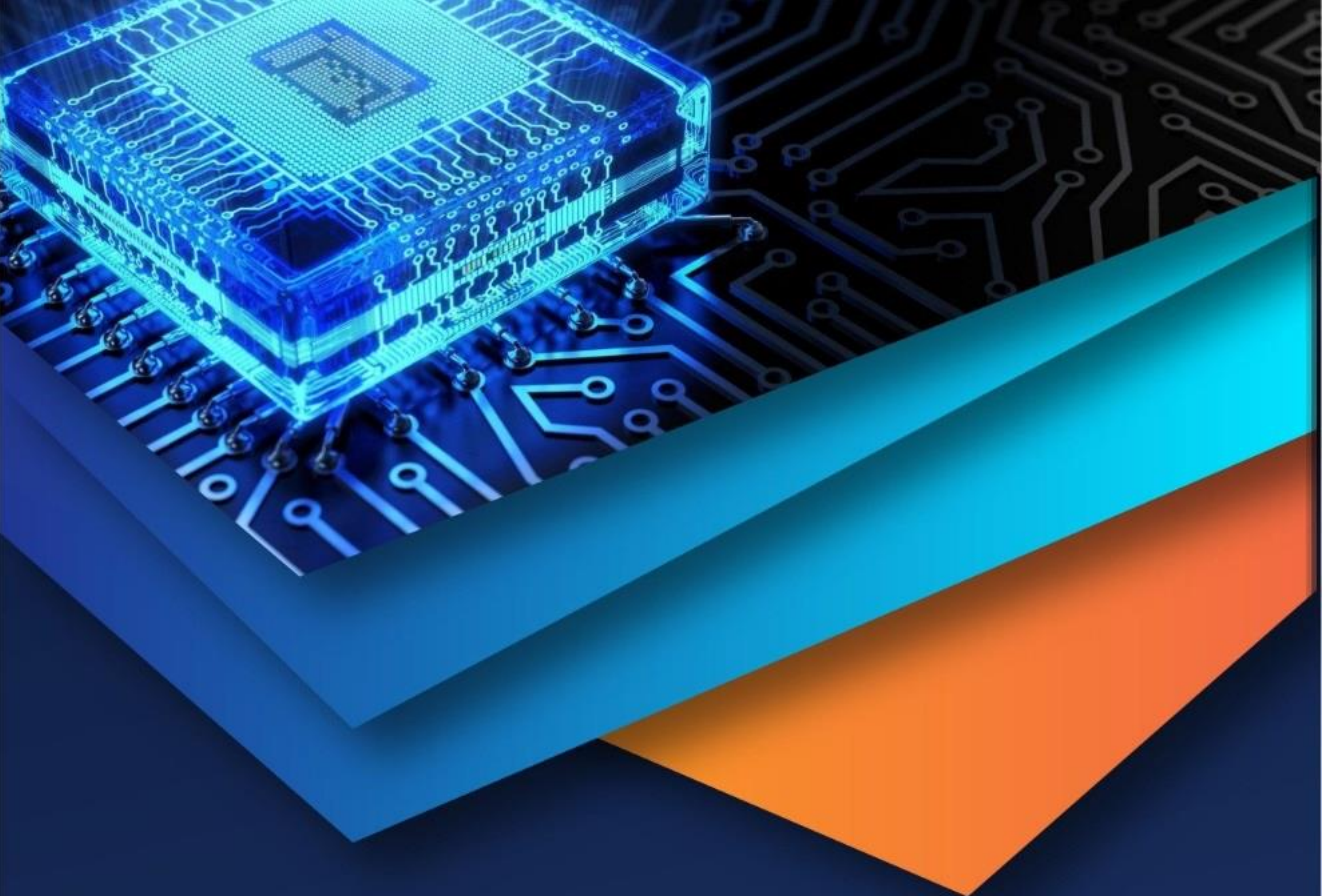


Figure 2:Conventional Simulation Circuit configuration.

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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