A Comprehensive Review on Modeling, Control, and Simulation of Grid-Connected PV Systems

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Abstract: *Grid-connected photovoltaic (PV) systems as sustainable energy-generation means for reducing dependence on conventional energy sources. This review considers the main areas of grid-connected PV systems, with emphasis on the complete design, modeling, and optimization of equipment on the AC side of the system. MPPT techniques, inverter control strategies, and grid synchronization are considered because these really have a bearing on system efficiency and system stability. The paper considers the classical methods of MPPT, such as Perturb & Observe and Incremental Conductance, as well as more advanced methods such as Variable Step-Size P&O and hybrid AI–fuzzy logic, stressing the fact that these latter methods improve tracking performance while reducing the steady-state oscillations. Inverter control methods are also analyzed and compared, with SVPWM showing clear advantages over SPWM in terms of THD reduction and maximizing the use of DC bus voltage together with grid voltage regulation improvement. PV system modeling using MATLAB/Simulink is discussed as a very modular system, giving possibilities for scalability and performance optimization under many different environmental and grid conditions. Challenges in current PV system simulation are discussed in the paper, including fast environmental variation, non-linearities, and computational load, while emerging trends such as hybrid modeling, digital twin integration, and cloud-based simulation frameworks are also discussed. The adoption of more advanced modeling and control strategies is, therefore, stated as a key component to enhance the effectiveness, reliability, and scalability of present-day grid-connected PV systems..*
Keywords: Grid-connected photovoltaic systems, Maximum Power Point Tracking (MPPT), Perturb and Observe (P&O), Incremental Conductance (INC), Space Vector PWM (SVPWM), MATLAB/Simulink, modular modeling, grid synchronization, photovoltaic system simulation.

I.INTRODUCTION

Given the facts, acceptance of renewable or alternate forms of energy will heavily shape the future. Being environmentally friendly, and thus easy to use, it is projected that with greater social acceptance, it will also become economically viable [1]. Renewable sources of energy are not known to produce slight amounts of greenhouse gases; wastes; or nearby pollutants, such as acid rain, urban or highway smog, or health hazards. These sources do not require expensive environmental cleanup laws. These energy sources can be utilized within all fields-from electricity generation to producing fuel for transportation to heat for domestic, commercial, and industrial processes [2].From among the various types of renewable technologies, solar photovoltaic (PV) systems represent one of the most commonly installed technologies; along with hydropower and wind power systems. Many photovoltaic systems are considered one of the greatest potential means of generating electricity because sunlight is abundantly available all over the Earth's surface, thus allowing for many applications [3]. The merits of photovoltaic technology are many. Clean energy, easy virtual maintenance, and silent operations all characterize this energy source, making it one of the most essential renewable energy sources.

Solar energy systems can generally be classified into two general categories: stand-alone systems and grid-connected photovoltaic (GPV) generation systems [4]. In the last two decades, GPV systems have gained greater importance as a quasi-reliable source of electricity supply and a bastion of the electrical grid. A GPV system is a decentralized generation system connected directly into the transmission and distribution network. Typically, it consists of two main controllers, namely, that of an MPPT and the inverter along with grid synchronization [5].

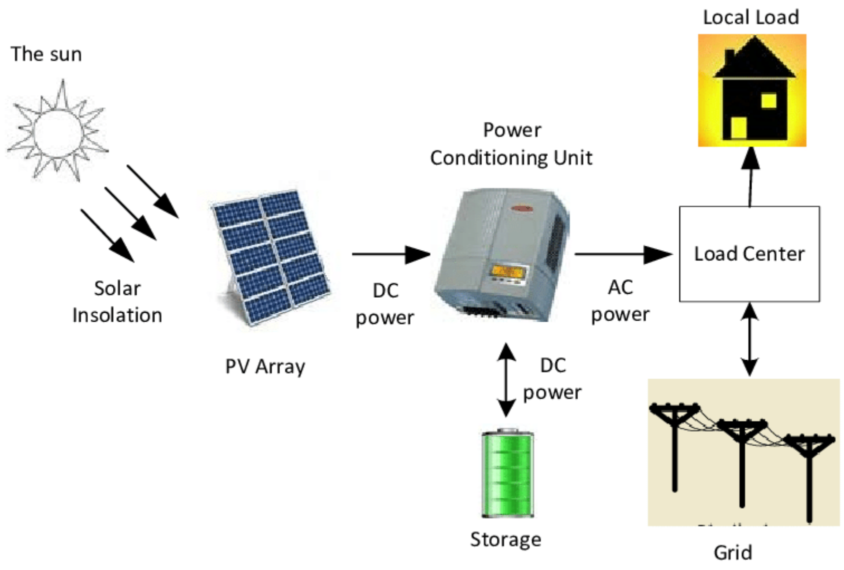

Figure 1 Main components of grid-connected photovoltaic systems [6].

The figure1 illustrates the operation of a grid-connected photovoltaic (GPV) system. Solar radiation (insolation) from the sun is captured by the photovoltaic (PV) array, which converts it into direct current (DC) power. This DC power is then sent to a power conditioning unit (PCU) that optimizes energy output through maximum power point tracking (MPPT) and converts the DC power into alternating current (AC) power using an inverter. The AC power is supplied to the load center, which distributes electricity to the local load (such as a household or building). Excess DC power generated can be stored in a battery storage system for later use. Additionally, any surplus electricity can be fed into the grid, while the system can also draw power from the grid when solar generation and storage are insufficient. This configuration ensures continuous and reliable energy supply.

Simulation plays a crucial role in the development of photovoltaic (PV) systems, as it provides accurate insights, is cost-effective, and reduces risks at all stages of project development—from initial planning to final operation [7]. It enables the assessment of project feasibility by analyzing solar resource availability at the site, assists in component sizing and selection, and predicts system performance in terms of energy yield, financial returns, profit margins, and levelized cost of energy (LCOE). Moreover, it facilitates the early detection of design flaws and energy loss factors such as shading, temperature variations, or component mismatches, allowing for timely corrective action [8]. Simulation also helps reduce initial development time and costs by eliminating the need for physical prototypes. By using simulation modelling, multiple configurations can be rapidly tested for performance suitability.

Additionally, simulation enables the study of system behaviour under various conditions, including grid integration, environmental influences, and long-term operational effects. It also provides a powerful tool for education and training through realistic modelling scenarios [9]. In PV systems, converters play an important role as inverters when connected to the grid, particularly in transformer-less configurations that are used with both renewable and non-renewable energy sources. In the case of solar PV modules, transformer-less inverters improve efficiency and reduce costs by minimizing leakage currents to the grid. Current inverter designs and simulations are often compared to conventional half-bridge and full-bridge topologies to evaluate their ability to step DC voltage up or down with respect to the load. These inverters utilize switches, capacitors, and free-wheeling diodes with PV modules, and their performance is assessed based on their ability to minimize common-mode leakage current. Comparative analyses between conventional and proposed inverter topologies are presented in this study [10].

MATLAB/Simulink plays a particularly vital role in the modeling and simulation of PV systems, offering a versatile platform for evaluating system behavior under a range of operating conditions. Its graphical user interface and extensive library of pre-defined blocks allow accurate representation of system components, including solar panels, inverters, maximum power point tracking (MPPT) controllers, and energy storage devices [11]. Furthermore, Simulink provides dynamic simulation capabilities, enabling researchers and engineers to study system performance during both steady-state and transient conditions, while testing control strategies that maximize power extraction and ensure effective grid integration [12]. In addition, MATLAB's robust computational tools support data analysis, optimization, and fault diagnosis, making it a comprehensive platform for design validation, performance enhancement, and complete integration into the PV system development process.

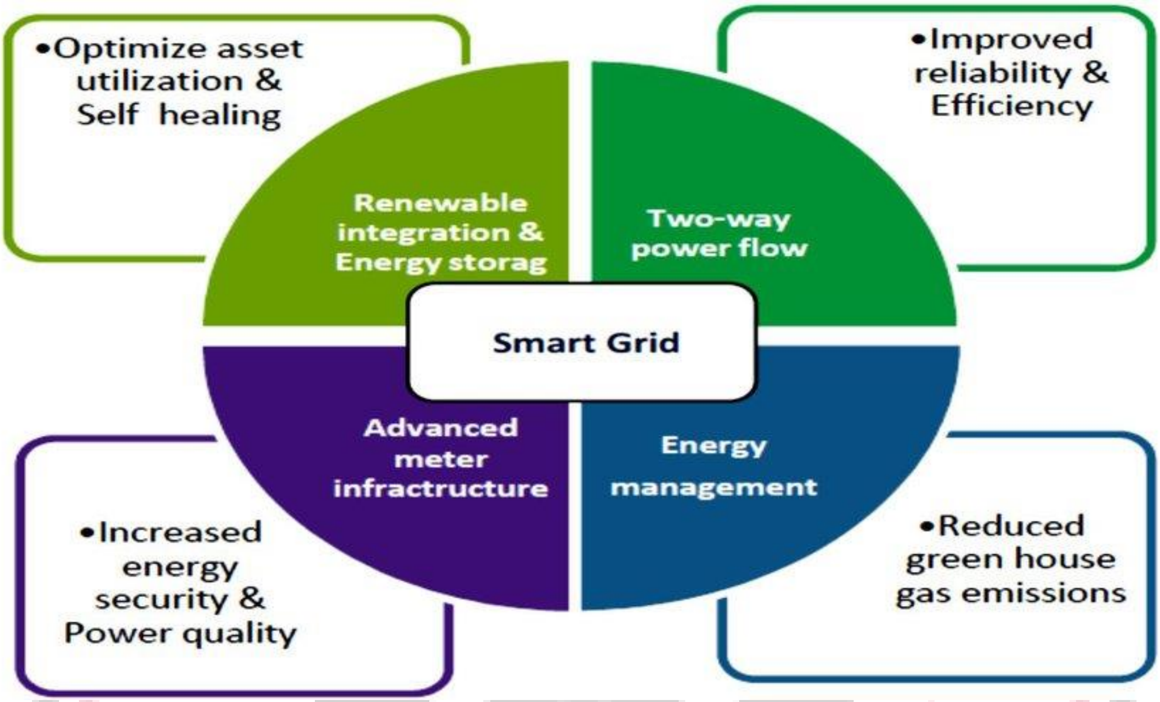

Figure 2 Smart Grid Challenges and Benefits.

The picture shows the components and benefits of a Smart Grid system. New forms of energy generation and storage, two-way power flow, energy management, and advanced meter infrastructure are the four major elements that the Smart Grid integrates at its core. Together, these elements facilitate better performance of the grid and sustainability.Renewable energy and storage integration bring flexibility in the utilization of assets and self-healing features to support the least flexible and most resilient grid. Two-way power flow thus creates high reliability and energy efficiency, energy flowing unconstrained between producers and consumers. Meanwhile, energy management in Smart Grid reduces greenhouse gas emissions by managing energy consumption and using cleaner energy sources. Advanced metering infrastructure improves energy security and power quality while providing real-time information for effective monitoring and control of grid operations.Hence, the Smart Grid implies a modernized grid, and in turn, this can very well imply energy efficiency, reliability, environmental sustainability, or all the three put together.

II.CONTROL STRATEGIES FOR GRID-CONNECTED PV SYSTEMS

Control strategies play a critical role in enhancing the efficiency, reliability, and power quality of grid-connected photovoltaic (PV) systems. These strategies are primarily focused on two key areas: Maximum Power Point Tracking (MPPT) and inverter control. MPPT techniques ensure that the PV array operates at its optimal power point under varying irradiance and temperature conditions, while inverter control maintains stable grid interaction by managing voltage regulation, harmonic distortion, and reactive power flow. The integration of intelligent MPPT algorithms with advanced inverter control methods, such as Space Vector Pulse Width Modulation (SVPWM), enables grid-tied PV systems to achieve superior energy yield, reduced losses, and improved overall stability even under dynamic environmental and load conditions[16]. These VSS-P&O and PD outputs were dramatically superior to standard INC method performance with relatively consistent outputs across trials. The P&O method is simpler as it requires sensors for the voltage and current only, and it is easier to be implemented [17]. INC is another method for tracking the MPP. This method is used to counter the weakness of the P&O method. The P&O method is not capable to compare the actual operating voltage at a maximum power point with the terminal voltage of the (PV) array. The INC method is easier to implement, it has a higher tracking speed, and better efficiency, this makes INC algorithm better than P&O [18]. Furthermore, hybrid ANN–fuzzy and INC–fuzzy approaches integrate the adaptability of machine learning with the uncertainty handling of fuzzy systems, delivering superior accuracy, faster convergence, and minimal steady-state oscillation across dynamic environments [19]. On the inverter side, comparative analyses between SPWM and SVPWM reveal SVPWM's clear superiority: SVPWM reduces THD from approximately 3.45% to 1.66% in 200 kVA systems and better utilizes DC bus voltage, while also lowering switching losses and improving harmonic suppression [20]. Advanced control frameworks combining SVPWM with dq0-frame PI or PR regulators, and further enhanced by harmonic and lead compensators, achieve exceptional grid voltage regulation, reactive power management, and THD mitigation in multilevel inverter configurations, especially under load changes and fault conditions [21]. Overall, integrating intelligent MPPT strategies and SVPWM-driven inverter control significantly enhances efficiency, stability, and power quality in grid-tied PV systems [22-23].

Table 1: Comparative Analysis of MPPT and Inverter Control Strategies for Grid-Connected PV Systems

Control Strategy	Key Features	Advantages	Limitations
P&O (Perturb & Observe)	Simple algorithm; adjusts voltage and current iteratively to find MPP	Easy implementation; requires only voltage and current sensors	Slow response to irradiance changes; oscillations around MPP
INC (Incremental Conductance)	Compares instantaneous and incremental conductance to track MPP	Higher accuracy and faster tracking than P&O; better under dynamic conditions	Slightly more complex implementation; requires accurate sensing
VSS-P&O (Variable Step-Size P&O)	Dynamically adjusts step size based on operating conditions	~30% faster tracking; ~80% reduction in power ripple; improved stability	More complex tuning; may require additional computation
Fuzzy Logic-based MPPT	Uses fuzzy inference for decision making	Very fast response (~25 ms); minimal voltage ripple (~1%); robust to environmental changes	Requires careful design of membership functions; computationally intensive
Hybrid ANN–Fuzzy / INC–Fuzzy MPPT	Combines machine learning adaptability with fuzzy uncertainty handling	Superior accuracy, faster convergence, minimal steady-state oscillations	High complexity; requires training data and more processing power
SPWM (Sinusoidal PWM) Inverter Control	Traditional modulation technique for inverters	Simple and well-understood; adequate performance in many applications	Higher Total Harmonic Distortion (THD); less efficient DC bus utilization
SVPWM (Space Vector PWM) Inverter Control	Uses space vector approach for improved inverter control	Lower THD (~1.66% vs 3.45% in SPWM); better DC bus voltage utilization; reduced switching losses	More complex implementation; requires advanced control hardware/software
SVPWM with PI/PR and Harmonic Compensators	Combines SVPWM with advanced regulators and compensators	Excellent grid voltage regulation; improved reactive power management; effective under faults	Highest complexity; requires precise tuning and computational resources

The table1 enlists some comparative features of the various MPPT methods and inverter control schemes used in grid-interactive PV plants, including their major features, advantages, and limitations. Such MPPT techniques as P&O and INC are very simple and popular; however, the implementation of P&O is easy, but the drawback is that it is slower and oscillates in steady state, while INC being more accurate is capable of tracking rapidly under dynamically changing scenarios. Therefore, more advanced MPPT techniques, namely VSS-P&O, fuzzy logic-based MPPT, and hybrid ANN–fuzzy or INC–fuzzy methods, enjoy fast transient response, less power ripple, and good stability at the expense of solution complexity and computer capacity. Meanwhile, in flipping the question, on the inverter control side, conventional SPWM is simple but less efficient, which produces high THD; meanwhile, SVPWM significantly reduces THD, optimizes DC bus utilization, and enhances harmonic suppression. Further advanced SVPWM methods together with PI/PR controllers and harmonic compensators present the best capabilities in regulating the grid voltage, managing reactive power, and handling faults in multilevel inverters, with intrinsic complexity for implementation and tuning.

III.PV SYSTEM COMPONENTS MODELING

Modeling of photovoltaic (PV) system components is essential for accurate analysis, design, and optimization of grid-connected systems. Each component—ranging from the PV module to the power converters, controllers, and energy storage units—must be mathematically represented to predict system behavior under varying environmental and load conditions. The PV module is typically modeled using the single-diode or double-diode equivalent circuit, which captures the effects of irradiance, temperature, and internal resistances on the I-V and P-V characteristics. Power electronic converters, such as DC-DC converters used for Maximum Power Point Tracking (MPPT) and DC-AC inverters for grid integration, are modeled to evaluate switching behavior, efficiency, and control dynamics. Controllers, including MPPT algorithms and grid synchronization mechanisms, are integrated into the models to ensure maximum power extraction and stable grid operation. Energy storage elements, if present, are modeled to analyze charging/discharging characteristics and their impact on system reliability. Such comprehensive modeling enables accurate simulation of the entire PV system, supports fault detection and mitigation studies, and allows optimization of component sizing, control strategies, and overall system performance

PV module modeling commonly employs single-diode mathematical models that are validated against industry-standard tools like PVSyst, ensuring accurate I–V/P–V characteristics under varying irradiance, temperature, and even wind conditions [24]. Comprehensive reviews highlight both deterministic and probabilistic parameter extraction methods, offering calibrated models to simulate realistic module behavior [25]. For DC–DC converter modeling, computationally efficient techniques use state-space representations combined with dynamic PV models, including steady-state detection to reduce simulation time while maintaining high accuracy [26]. Innovative three-port bidirectional converters integrating

PV modules with battery storage simplify topology and improve efficiency compared to dual-converter systems [27], particularly when using Simulink-based bidirectional control strategies [28]. Grid-interface modeling typically involves two-stage inverter setups where DC–DC converters regulated by MPPT feed voltage-controlled inverters with unity power factor; Simulink models include detailed filter and PLL dynamics for synchronization [29]. Dynamic state-space averaged models for three-phase inverters enhance understanding and support robust controller design [30]. Additionally, hybrid storage integration in microgrid simulations demonstrates MATLAB's versatility in modeling complex interactions between PV, battery, and grid-connected converters [31]. Advanced MATLAB/Simulink implementations include average-value models for DC–DC converters used in MPPT schemes (e.g., boost, buck-boost) that balance accuracy and simulation efficiency [32], as well as wide-input, high-gain DC–DC topologies tested with adaptive control (e.g., AGAO-RBFN) to minimize component stress and boost performance [33].

Table 2: Comparative Summary of Photovoltaic System Component Modeling

Component	Modeling Technique	Focus Area	Key Findings	Advantages	Reference No.
PV Module	Single-Diode Model	Accuracy under varying conditions	Validated against PVSyst; replicates I–V/P–V curves accurately	High fidelity, industry-validated	[24]
PV Module	Parameter Extraction (Deterministic & Prob.)	Calibration and realism	Uses Lambert W, LSTM, etc., for precise model fitting	Realistic behavior, adaptability	[25]
DC–DC Converter	State-Space Modeling	Speed and efficiency	Reduces simulation time with dynamic PV input and steady-state logic	Fast, accurate, low computational burden	[26]
DC–DC Converter + Storage	Three-Port Bidirectional Converter	Topological simplification	Combines PV and battery in single unit for efficiency	Fewer components, high integration	[27]
Converter Control	Simulink-Based Bidirectional Control	Power flow and efficiency	Enables dynamic bidirectional control in PV-battery setups	Improved system flexibility	[28]
Grid Interface	Two-Stage Inverter with MPPT	Grid Synchronization	Models filter/PLL for unity power factor operation	Effective for dynamic grid conditions	[29]
Inverter	State-Space Averaged Model	Transient behavior, control design	Captures dynamics of three-phase inverters	Robust controller tuning, analytical depth	[30]
Energy Storage Integration	Microgrid Simulation	Hybrid energy systems	Simulates interaction between PV, battery, and converters	Holistic view, stability testing	[31]

DC–DC Converter	Average-Value Model	MPPT efficiency, computational load	Maintains accuracy while simplifying computation	Optimized for large-scale or long-duration simulations	[32]
DC–DC Converter	High-Gain Converter with AGAO-RBFN Control	Component stress reduction	Adaptive control reduces stress and enhances gain	High performance, intelligent adaptation	[33]

Table 2 presents a comprehensive comparative summary of various modeling techniques applied to key components within a photovoltaic (PV) system, with a focus on enhancing accuracy, efficiency, and integration in a 6kW grid-connected setup. The table categorizes components such as PV modules, DC–DC converters, inverters, and energy storage systems, detailing the modeling methods used—ranging from single-diode models and state-space representations to intelligent control strategies like AGAO-RBFN. Each entry highlights the specific focus area, such as improving simulation speed, optimizing power flow, or ensuring realistic behavior under dynamic conditions. Key findings are summarized, showcasing how techniques like deterministic parameter extraction or bidirectional control enhance system performance. The table also outlines the advantages of each method, including computational efficiency, high fidelity, and adaptability. This comparative view serves as a valuable reference for researchers and designers seeking optimal modeling strategies tailored to individual system components within modern PV applications.

IV.SIMULATION AND VALIDATION OF THE GRID-CONNECTED PV SYSTEM

The grid-connected PV system was simulated and verified in Simulink, as a fast means of carrying out system-level simulations of the system (for a relatively larger system) [34]. The entire system was modelled and simulated on both the DC side (the PV modules, DC-DC converters) and AC side (interconnection inverters, filters, controllers) [35]. The system was implemented in a flexible modular design which facilitated hierarchical modelling, thus allowing re-use of the model and adapting for various system stages from small PV strings to large microgrids. The modular capability permits testing of different configurations and provides flexibility to switch around the scale seek to modify it [36]. Furthermore, the modular construction provided us the ability to see a variety of scenarios operating while in changing grid and weather conditions, while providing us some indication of system performance within other real challenges. This capability improves the optimization of the control strategy and adaptability towards operational demands and environmental considerations [37]. Also, it advances the design process as speaks to creation by permitting quick adaptation and validating specific component without having to re-work the whole system [38-40].
The simulation results indicate that the system can attain grid synchronization, effective power conversion, and accurate control of both active and reactive power [41]. The capabilities of real-time are, of course, also in the system, with interactions through Hardware-in-the-Loop (HIL) as a potentially robust way to test control strategy in a more realistic scenario; comprising environmental variations such as irradiance or for load variability to ensure the controller can be evaluated without the immediate need to be deployed physically [42]. There are further evaluations referred to as Software-in-the-Loop (SIL) and Processor-in-the-Loop (PIL) evaluations relevant from the initial design phase are also a valuable tool in the sense of determining the performance of the system and where the best way of optimizing the system can be approached [43]. Additional integration in this phase combined with modern enabling of high-performance platforms to enable faster simulation cycles and more precise evaluations, including complex grid variations and similarity of switch behavior [44]. This simulation and validation are powerful methods of maintenance of reducing development time, increasing the reliability of a system, and having a safer and more efficient grid-connected PV system implementation [45]. Also, catching things that may become an issue early will allow for an attempt at correcting those issues, smoothing the experience in moving to working conditions [46].

V.CHALLENGES AND TRENDS IN PV SIMULATION

There are several challenges that affect the accuracy, efficiency, and applicability of photovoltaic system models. One important issue is the almost impossible feat to capture ever-changing environmental conditions, such as rapid fluctuations in irradiance or temperature, which greatly affect system performance. It is also a difficulty to model nonlinearities relating to photovoltaic modules and converters as grid interactions, resulting in the solar plant behavior being not accurately predicted. Another limitation is computationally expensive, more so for large grid-connected systems or when analyzing advanced control strategies, fault analysis, or long-term performance evaluation. Further, integrating multi-physics phenomena, such as thermal effects, partial shade effects, and degradation mechanisms, into one simulation environment is a tough task.
On the brink of this transformation are modeling giants wrestling with day-to-day occurrences of this nature. Appropriate for modeling and simulation, intelligent modeling in the broad sense refers to methodological and algorithmic formulations with the highest levels of working methodologies-specific engineering knowledge. AI and scenarios of

machine learning algorithms are used increasingly for real-time parameter estimation, fault detection, and predictive modeling. Hybrid approaches that blend physics-based models with data-driven approaches are becoming more and more common while giving an upper hand on accuracy without a steep rise in computational load. Digital twin integration is a recent development, allowing continuous synchronization between simulation and respective real-time operational data for better performance monitoring and optimization. Efforts are underway to define standardized simulation frameworks that allow interoperability and consistency across a variety of tools and platforms. With greater computational power and cloud-based simulation platforms now at hand, the future of PV system simulation will surely be able to evolve into a more accurate, scalable simulation system with support for complex grid interaction and high penetration of renewable sources.

VI.CONCLUSION

In conclusion, grid-tied photovoltaic systems have become very central to the integration of renewable energy into modern power systems, and this in turns leads to a more sustainable environment by reducing the usage of such energy sources. This particular review stressed various elements to do with MPPT techniques, inverter control methods, and good grid synchronization strategies to ensure that the systems perform to the best of their capacities. Traditional MPPT methods, such as P&O and INC, are still favored because of their operational simplicity; however, advanced versions, such as VSS-P&O and the hybrid AI-fuzzy logic technique, offer an enormous advantage with respect to energy lessening, tracking speed, and output stability in rapidly varying conditions. Likewise, SVPWM-based inverter control strategies with the implementation of PI/PR controllers and harmonic compensators are far better than the traditional SPWM method in minimizing THD, suppressing harmonics, and reactive power compensation. Modular modeling of systems in MATLAB/Simulink is invaluable for designing, simulating, and validating PV systems such that it simultaneously offers provision for scaling from a very small system servicing one or two communities right through to a very large microgrid. However, despite challenges in fully capturing environmental variability, all system nonlinearities, and limiting computational complexity, new approaches such as digital twin incorporation, standardized simulation frameworks, and hybrid data-driven modeling methodologies appear promising in breaking these barriers. With these advancements, the innovative strategies must then be targeted to best deliver the grid-tied PV systems, which prove extremely efficient, highly reliable, and scalable to meet the ever-growing energy demands of future power grids.

References

[1] A. Papadaki, N. Savvakis, N. Sifakis, and G. Arampatzis, “Analysis of Hybrid Renewable Energy Systems for European islands: Market Dynamics, Opportunities and Challenges,” Sustain. Futur., vol. 9, p. 100601, 2025, doi: https://doi.org/10.1016/j.sftr.2025.100601.

[2] Y. F. Nassar, H. J. El-Khozondar, and M. A. Fakher, “The role of hybrid renewable energy systems in covering power shortages in public electricity grid: An economic, environmental and technical optimization analysis,” J. Energy Storage, vol. 108, p. 115224, 2025, doi: https://doi.org/10.1016/j.est.2024.115224.

[3] B. E. Escoto and M. L. S. Abundo, “Evaluating the feasibility and sustainability of hybrid renewable energy systems (HRES) for electric vessel charging applications: A case study in Donsol, Sorsogon, Philippines,” Results Eng., vol. 26, p. 105119, 2025, doi: https://doi.org/10.1016/j.rineng.2025.105119.

[4] P. H. Kumar et al., “Techno-economic optimization and sensitivity analysis of off-grid hybrid renewable energy systems: A case study for sustainable energy solutions in rural India,” Results Eng., vol. 25, p. 103674, 2025, doi: https://doi.org/10.1016/j.rineng.2024.103674.

[5] T. Tezer, “Multi-objective optimization of hybrid renewable energy systems with green hydrogen integration and hybrid storage strategies,” Int. J. Hydrogen Energy, vol. 142, pp. 1249–1271, 2025, doi: https://doi.org/10.1016/j.ijhydene.2025.03.006.

[6] M. S. Hossain Lipu et al., “Review of energy storage integration in off-grid and grid-connected hybrid renewable energy systems: Structures, optimizations, challenges and opportunities,” J. Energy Storage, vol. 122, p. 116629, 2025, doi: https://doi.org/10.1016/j.est.2025.116629

[7] Rehman, H. U., Yan, X., Abdelbaky, M. A., Jan, M. U., & Iqbal, S. (2021). An advanced virtual synchronous generator control technique for frequency regulation of grid-connected PV system. International Journal of Electrical Power & Energy Systems, 125, 106440. https://doi.org/10.1016/j.ijepes.2020.106440

[8] Kanwar, K., Vajpai, D.J. Performance Evaluation of Different Models of PV Panel in MATLAB/ Simulink Environment. Appl. Sol. Energy 58, 86–94 (2022). https://doi.org/10.3103/S0003701X22010078

[9] Badi, N., Khasim, S., Al-Ghamdi, S.A. et al. Accurate modeling and simulation of solar photovoltaic panels with simulink-MATLAB. J Comput Electron 20, 974–983 (2021). https://doi.org/10.1007/s10825-021-01656-0

[10] Swarupa, M. L., Kumar, E. V., & Sreelatha, K. (2021). Modeling and simulation of solar PV modules-based inverter in MATLAB-SIMULINK for domestic cooking. Materials Today: Proceedings, 38, 3414-3423. https://doi.org/10.1016/j.matpr.2020.10.835

[11] Banik, A., Shrivastava, A., Potdar, R. M., Jain, S. K., Nagpure, S. G., & Soni, M. (2022). Design, modelling, and analysis of novel solar PV system using MATLAB. Materials today: proceedings, 51, 756-763. https://doi.org/10.1016/j.matpr.2021.06.226

[12] Saitov, E. B., & Sodiqov, T. B. (2022, June). Modeling an autonomous photovoltaic system in the MATLAB Simulink software environment. In AIP Conference Proceedings (Vol. 2432, No. 1). AIP Publishing. https://doi.org/10.1063/5.0089914

[13] Singh, S., Saket, R. K., & Khan, B. (2023). A comprehensive review of reliability assessment methodologies for grid-connected photovoltaic systems. IET Renewable Power Generation, 17(7), 1859-1880. https://doi.org/10.1049/rpg2.12714

[14] Pavithra, C., & KB, S. A. (2024). Comparison of Solar P&O and FLC-based MPPT Controllers & Analysis under Dynamic Conditions. EAI Endorsed Transactions on the Energy Web, 11(1). https://doi.org/10.4108/ew.4988

[15] El Hamzaoui, F. Z., Abderrahime, T., & Taoufiq, B. D. (2024). Comparison Between Perturb & Observe, Fuzzy Logic MPPT Technique, and The Artificial Neural Network Techniques at Different Temperature Conditions. IFAC-PapersOnLine, 58(13), 599-604. https://doi.org/10.1016/j.ifacol.2024.07.548

[16] Kumar, Rajesh & Bhattacharya, Ananyo & Vardhan, Aanchal. (2024). Fuzzy Logic Controller and P&O-Based MPPT Techniques for Stand-Alone PV Systems: A Comparison. 10.21203/rs.3.rs-4926323/v1. http://dx.doi.org/10.21203/rs.3.rs-4926323/v1

[17] Singh, Shweta & Tiwari, Amar. (2017). Simulation and Comparison of SPWM and SVPWM Control for Two Level Inverter.

[18] Melhem, M. (2020, June). Analyzing and modeling pv with “p&o” mppt algorithm by matlab/simulink. In 2020 3rd international symposium on small-scale intelligent manufacturing systems (SIMS) (pp. 1-6). IEEE. https://doi.org/10.1109/SIMS49386.2020.9121579

[19] Abd Alhussain, H. M., & Yasin, N. (2020). Modeling and simulation of solar PV module for comparison of two MPPT algorithms (P&O & INC) in MATLAB/Simulink. Indonesian Journal of Electrical Engineering and Computer Science, 18(2), 666-677. DOI: 10.11591/ijeecs.v18.i2.pp666-677

[20] Nzoundja Fapi, C. B., Tchakounté, H., Ndje, M., Wira, P., Abdeslam, D. O., Louzazni, M., & Kamta, M. (2025). Fuzzy Logic-Based Maximum Power Point Tracking Control for Photovoltaic Systems: A Review and Experimental Applications. Archives of Computational Methods in Engineering, 1-24. https://doi.org/10.1007/s11831-024-10210-7

[21] Bouledroua, Adel & Tarek, Mesbah & Samia, Kelaiaia. (2025). Evaluation of pulse width modulation techniques to reduce total harmonic distortion in grid-connected PV systems. International Journal of Power Electronics and Drive Systems (IJPEDS). 16. 564. 10.11591/ijpeds.v16.i1.pp564-574. http://dx.doi.org/10.11591/ijpeds.v16.i1.pp564-574

[22] Shrestha, S., Subedi, R., Sharma, S., Phuyal, S., & Tamrakar, I. (2025). A Comparative Analysis of Transformer-less Inverter Topologies for Grid-Connected PV Systems: Minimizing Leakage Current and THD. arXiv preprint arXiv:2501.08103. https://doi.org/10.48550/arXiv.2501.08103

[23] Tawfiq, K. B., Sergeant, P., & Mansour, A. S. (2024). Comparative Analysis of Space Vector Pulse-Width Modulation Techniques of Three-Phase Inverter to Minimize Common Mode Voltage and/or Switching Losses. Mathematics, 12(18), 2832. https://doi.org/10.3390/math12182832

[24] Nfaoui, M., Ihfa, F.E., Bougtaib, A. et al. Comprehensive modeling and simulation of photovoltaic system performance by using matlab/simulink: integrating dynamic meteorological parameters for enhanced accuracy. J.Umm Al-Qura Univ. Appll. Sci. (2024). https://doi.org/10.1007/s43994-024-00175-5

[25] Fahim, S. R., Hasanien, H. M., Turky, R. A., Aleem, S. H. E. A., & Ćalasan, M. (2022). A Comprehensive Review of Photovoltaic Modules Models and Algorithms Used in Parameter Extraction. Energies, 15(23), 8941. https://doi.org/10.3390/en15238941

[26] Corti, F., Laudani, A., Lozito, G. M., & Reatti, A. (2020). Computationally Efficient Modeling of DC-DC Converters for PV Applications. Energies, 13(19), 5100. https://doi.org/10.3390/en13195100

[27] Ye, D., & Martinez, S. (2024). A Three-Port DC-DC Converter with Partial Power Regulation for a Photovoltaic Generator Integrated with Energy Storage. Electronics, 13(12), 2304. https://doi.org/10.3390/electronics13122304

[28] Kumar, V. H., Patel, R., Sahu, L. K., & Kishor, Y. (2024). Solar photovoltaic-integrated energy storage system with a power electronic interface for operating a brushless DC drive-coupled agricultural load. Energy Harvesting and Systems, 11(1), 20230127. https://doi.org/10.1515/EHS-2023-0127

[29] Farkas, I. & Seres, I. & Negash, Teklebrhan. (2021). MATLAB/SIMULINK BASED MODELING OF GRID-CONNECTED PV SYSTEMS. 21. 7.

[30] Esfandiari, A., & Hashemnia, M. N. (2022). A study on the dynamic model of a three-phase grid-connected inverter and an innovative method for its verification. International Journal of System Assurance Engineering and Management, 1-15. https://doi.org/10.48550/arXiv.2402.00132

[31] Muntaser, A., Saide, A., Ragb, H., & Elwarfalli, I. (2022). DC Microgrid Based on Battery, Photovoltaic, and Fuel Cells; Design and Control. arXiv preprint arXiv:2212.14803. https://doi.org/10.48550/arXiv.2212.14803

[32] Eze, Cornelius & Titus Obe, Chinedu & Ugbe, Oluchi & Victory, Madueme & Ejiofor, Oti. (2025). Evaluation of DC-DC Converters Using MATLAB Simulink. Ci-STEM Journal of Digital Technologies and Expert Systems. 02. 25-40. 10.55306/CJDTES.2025.020103. http://dx.doi.org/10.55306/CJDTES.2025.020103

[33] Dosa, M. (2022). A Soft-Switched Three-Port Dc-Dc Converter for a PV/Battery System. Minnesota State University, Mankato.

[34] Vasquez Plaza, Jesus David & Chavarro, Andres Felipe & Sanabria, Enrique & Patarroyo, Juan & Andrade, Fabio. (2022). Benchmarking Real-Time Control Platforms Using a Matlab/Simulink Coder with Applications in the Control of DC/AC Switched Power Converters. Energies. 15. 6940. 10.3390/en15196940. http://dx.doi.org/10.3390/en15196940

[35] Jaskolka, M., Pantelic, V., Wassyng, A., & Lawford, M. (2020). Supporting modularity in Simulink models. arXiv preprint arXiv:2007.10120. https://doi.org/10.48550/arXiv.2007.10120

[36] Samano-Ortega, V., Padilla-Medina, A., Bravo-Sanchez, M., Rodriguez-Segura, E., Jimenez-Garibay, A., & Martinez-Nolasco, J. (2020). Hardware in the loop platform for testing photovoltaic system control. Applied Sciences, 10(23), 8690. https://doi.org/10.3390/app10238690

[37] Ingalalli, Aravind & Satheesh, Hariram & Kande, Mallikarjun. (2016). Platform for Hardware In Loop Simulation. 41-46. 10.1109/SPEEDAM.2016.7525843. http://dx.doi.org/10.1109/SPEEDAM.2016.7525843

[38] Hutchinson, A. J., Harrison, C. M., Bryden, T. S., Alahyari, A., Hu, Y., Gladwin, D. T., ... & Forsyth, A. (2025). A comprehensive review of modeling approaches for grid-connected energy storage technologies. Journal of Energy Storage, 109, 115057. https://doi.org/10.1016/j.est.2024.115057

[39] Ahmed, Moiz & Behrends, Holger & Geißendörfer, Stefan & von Maydell, Karsten & Agert, Carsten. (2021). Power Hardware-in-the-Loop: Response of Power Components in Real-Time Grid Simulation Environment. Energies. 14. 593. 10.3390/en14030593. http://dx.doi.org/10.3390/en14030593

[40] Nebey, A. H. (2020). Energy management system for grid-connected solar photovoltaic with battery using MATLAB simulation tool. Cogent Engineering, 7(1), 1827702. https://doi.org/10.1080/23311916.2020.1827702

[41] Guingane, T. T., Bonkoungou, D., Korsaga, E., Simonguy, E., Koalaga, Z., & Zougmore, F. (2020, June). Modeling and Simulation of a Photovoltaic System Connected to the Electricity Grid with MALTAB/Simulink/Simpower Software. In 2020 8th International Conference on Smart Grid (icSmartGrid) (pp. 163-168). IEEE. https://doi.org/10.1109/icSmartGrid49881.2020.9144807

[42] M. A. Shobug, M. Alamgir Hossain, F. Yang, and J. Lu, "Dynamic Control of Isolated Network Microgrids: A Resilient Backpropagation Neural Network-Based Virtual Inertia Control Approach," IEEE Access, vol. 13, pp. 99939–99956, 2025, doi: 10.1109/ACCESS.2025.3576345.

[43] P. Samal, N. Nayak, A. Satapathy, and S. K. Bhuyan, "Load frequency control in renewable based micro grid with Deep Neural Network based controller," Results Eng., vol. 25, p. 103554, 2025, doi: https://doi.org/10.1016/j.rineng.2024.103554.

[44] C. Dardabi, S. C. Álvarez, and A. Djebli, "An Artificial-Neural-Network-Based Direct Power Control Approach for Doubly Fed Induction Generators in Wind Power Systems," Energies, vol. 18, no. 8, 2025, doi: 10.3390/en18081989.

[45] A. Kumar, D. Sharma, M. Pal, and S. Member, "Physics-Informed Neural Network-Based Control for Grid-Forming Converter's Stability Under Overload Conditions," 2025, [Online]. Available: https://arxiv.org/abs/2503.21529v1

[46] S. M. Thajeel and D. Ç. Atilla, "Reinforcement Neural Network-Based Grid-Integrated PV Control and Battery Management System," Energies, vol. 18, no. 3, 2025, doi: 10.3390/en18030637.

[47] A. M., S. K. V., and M. S. J., "A Novel Adaptive Recurrent Neural Network-Based Control Strategy for Type 3 WF to Mitigate Subsynchronous Interactions," IEEE Trans. Ind. Informatics, vol. 21, no. 6, pp. 4499–4510, 2025, doi: 10.1109/TII.2025.354