Review on AC Stage Design and Modelling Techniques in 6kW Grid-Connected Photovoltaic Systems

Diwakar Sharma[1], Sarvesh Pratap Singh[2]
[1]M. tech Scholar, Department of Electrical Engineering, School of Research and Technology, People's University, Bhopal
[2] Assistant Professor, Department of Electrical Engineering, School of Research and Technology, People's University Bhopal
diwakar0810sharma@gmail.com[1] , sarvesh_pratap@peoplesuniversity.edu.in [2]

Abstract: Grid-connected photovoltaic (PV) systems are increasingly recognized as a sustainable solution to reduce reliance on conventional energy sources. This paper reviews several key aspects of 6kW grid-connected PV systems, with a focus on AC stage design and modeling methodologies. The primary objective is to examine the crucial elements involved in optimizing system performance, particularly maximum power point tracking (MPPT), inverter control, and grid synchronization. The review delves into the advancements in MPPT techniques, including Perturb and Observe (P&O) and Incremental Conductance (INC), along with more sophisticated control methodologies to enhance system performance under varying operational conditions. The study also highlights the advantages of modular PV system designs, which enable hierarchical modeling to evaluate system behavior under dynamic grid conditions, considering factors like fluctuating weather and irradiance. This design flexibility is instrumental in addressing challenges related to power conversion, synchronization, and system stability under changing environmental conditions. The outcomes suggest that modular PV systems offer scalability, from small-scale installations suited for community use to larger microgrids, making them adaptable for a wide range of real-world applications. The paper emphasizes that such systems not only improve operational performance but also provide a pathway to integrating PV systems into more extensive energy networks, thereby contributing to the development of more resilient and sustainable energy infrastructure.

Keywords: Grid-connected PV system, AC stage design, MPPT, inverter control, grid synchronization, system simulation, performance optimization.

I INTRODUCTION

It is recognized and acknowledged that renewable and non–conventional forms of energy will play a crucial role in the future as they are environmentally friendly, easy to use and are bound to become economically more feasible with increased usage [1]. RE sources generate little if any greenhouse gases, waste, or pollutants that contribute to acid rain, urban smog, and health problems and do not require an environmental cleanup cost. In addition, these resources can be used to produce electricity for all economic sectors, fuels for transportation, heat for building and industrial processes [2]. Among all the various RE technologies, solar photovoltaic or precisely PV is the most exploited RE source alongside with hydro and wind power in terms of the pace of deployments and as it is considered a very promising source of future electrical power generation due to the abundance of sunlight over a large area of the earth surface thus giving rise to several applications of PV systems [3]. PV exhibits numerous merits such as cleanness, low maintenance, no noise and regarded as one of the most essential RE sources. There are two classes of the solar energy system, namely stand-alone and grid-connected PV (GPV) generation systems [4]. Recently the GPV system is playing an increasingly significant role as an electrical supply resource as well as an integral part of the electrical grid generation network. A GPV system is an independent decentralized power system that is connected to an electricity transmission and distribution system. GPV system comprises two controllers as one is for MPPT and the other for inverter controls and grid synchronization [5].

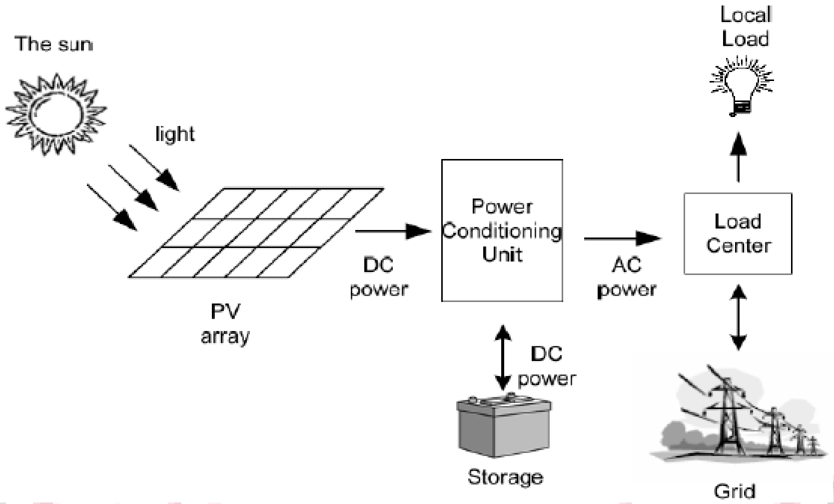

Figure 1 Main components of grid-connected photovoltaic systems [6].

Figure 1 illustrates the main components of a grid-connected photovoltaic (PV) system. Sunlight is captured by the PV array, which converts solar energy into direct current (DC) electricity. This DC power is then sent to a power conditioning unit, typically an inverter, which converts it into alternating current (AC) suitable for household or grid use. Some of the DC power can also be stored in batteries for later use. The AC power is then routed through a load center, where it powers local electrical loads such as appliances or lighting. Any excess electricity can be fed into the utility grid, enabling energy sharing or credit accumulation, enhancing system efficiency and reliability.

Simulation is critical during the development of a photovoltaic (PV) system, because it provides insights that are accurate, cost effective, and reduces risk, at any level of project development from early planning to the final operational stage [7]. It allows for the analysis of the feasibility of a project including the availability of solar resources at a site, it assists with the sizing and selection of components, predictions of system performance such as energy yield, financial returns, profit margins, and levelized cost of energy (LCOE), and assists with early identification of design shortcomings and energy loss possibilities, such as from shading, temperature effects, or mismatched components, which allows for early corrective action [8]. Simulation further reduces initial development costs and time of a PV system by providing an alternative to and eliminating the need for physical prototypes, employing simulation modeling methods allows multiple configurations to be tested against performance suitability quickly. In addition, they provide an opportunity to study effects on system behavior due to grid integration, the environment, or effects of long-term behavior, while also providing useful education and training methods through realistic modeling scenarios [9]. Converters which are used as inverters when connected to grid and with Transformer-less which are mainly considered with different sources like non-renewable and renewable. In renewable sources solar PV (Photo voltaic) cells in module are considered for improving efficiency and reducing the cost by neglecting leakage current in the grid. Present inverters designed and simulated are compared with half-bridge and full bridgefor increasing or decreasing DC voltage w.r.t. load. The inverter is connected and disconnected with the switches and capacitors with the variation of the DC output voltage. The overall analysis is to minimize leakage current in common mode. The free-wheeling diodes and switches are used with PV modules. The comparison made with respect to conventional and proposed topologies is presented in this study [10]. The role of MATLAB/Simulink is especially important in the modeling and simulation of photovoltaic (PV) systems, as it is both a broad and flexible platform to examine how systems react under different operating conditions. It utilizes a graphical interface and has a library of pre-defined blocks that allow for adequate representation of a PV system's components including solar panels, inverters, maximum power point tracking (MPPT) controllers, and energy storage systems [11]. Additionally, with Simulink, a dynamic simulation is available so researchers and engineers can examine the functionality of the PV system during steady- state and transient events, while also implementing control strategies that maximize power extraction, and interface with the grid [12]. In addition, MATLAB's computational abilities support data analysis, optimization algorithms, and other algorithms, providing a useful platform to support design validation, fault analyses, and performance optimization, and can be completely integrated into the development of PV systems.

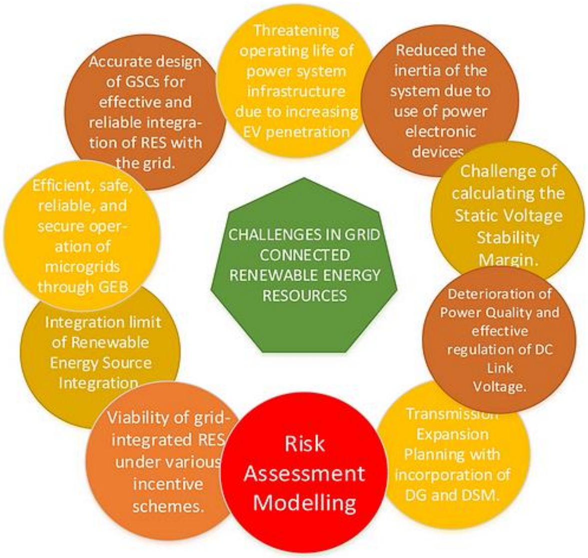

Figure 2 Challenges of grid-integrated renewable energy systems [13].

The figure 2 illustrates the challenges of grid-integrated renewable energy systems, highlighting various factors that impact the efficiency and reliability of such systems. At the center, the key challenge is the integration of renewable energy resources (RES) into the grid, which requires addressing issues like accurate design of Grid Synchronization Controllers (GSCs), deterioration of power quality, and effective regulation of DC link voltage. Surrounding this central challenge are different related aspects, such as the threatening operating life of power systems due to increasing electric vehicle penetration, the viability of grid-integrated RES under energy source integration schemes, and increased complexity in managing microgrids. Additionally, the figure highlights issues like reduced system inertia, the challenge of calculating the static voltage stability margin, and the need for effective transmission expansion planning to incorporate distributed generation (DG) and demand-side management (DSM). All these factors must be carefully managed through risk assessment modeling to ensure a reliable and stable integration of renewable energy into the power grid.

II Control Strategies for Grid-Connected PV Systems

Grid-connected PV systems rely on strong control techniques to maximize performance. Specifically, MPPT and inverter control are essential. MPPT methods such as Perturb & Observe (P&O) and Incremental Conductance (INC) offer a simple-but-slow response time, resulting in oscillating performance during rapidly changing irradiance [14]. PV systems with increasing sophistication will utilize more advanced MPPT techniques to optimize performance. A variable step-size version of P&O (VSS-P&O), was reported to improve tracking time by ~30% and power ripple by ~80% and increased output stability for VSS-P&O [15]. Outputs with the incorporation of fuzzy logic in the P&O showed a similar rapid response time of ~25 ms to previous optimization trials along with only ~1% of voltage ripple [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

MPPT/Inverter Strategy	Technique	Improvement Focus	Key Findings	System Impact	Comparison With	Reference No.
Overall Control Strategy	MPPT & Inverter Control	Performance Optimization	Emphasizes role of control in grid-tied PV performance	Enhances efficiency and quality	General Overview	[14]
MPPT	P&O, INC	Dynamic Performance	Suffer from oscillation and slow response	Sub-optimal tracking under transients	Modern methods	[15]
MPPT	VSS-P&O	Convergence Speed, Ripple Reduction	~30% faster response, ~80% less ripple	Better tracking efficiency	Conventional P&O	[16]
MPPT	Fuzzy-enhanced P&O	Stability and Ripple	~25 ms stabilization, ~1% voltage ripple	Superior to INC in ripple control	INC	[17]
MPPT	P&O	Simplicity, Implementation	Requires only voltage and current sensors	Simple and widely used	INC	[18]
MPPT	INC	Tracking Accuracy, Speed	Easier to implement, faster tracking, higher efficiency	More accurate than P&O	P&O	[19]
MPPT	ANN–Fuzzy, INC–Fuzzy	Hybrid Intelligence	High accuracy, fast convergence, low oscillations	Most robust under dynamic conditions	Fuzzy, INC	[20]
Inverter Control	SVPWM vs SPWM	THD, DC Bus Utilization	SVPWM lowers THD to ~1.66%, better DC bus use	Superior harmonic and efficiency control	SPWM	[21]
Inverter Control	SVPWM + dq0 PI/PR + HC/LC	Grid Compliance, Power Quality	Strong voltage and reactive power control in multilevel setup	Ideal for fault/load variation conditions	Basic PI/dq0	[22]

Integrated Control Strategies	MPPT + Inverter Control	System Optimization	Smart MPPT + SVPWM yields optimal system efficiency	Holistic PV system enhancement	Conventional combined control	[23]

Table 1 provides a concise comparison of key MPPT and inverter control strategies used in grid-connected PV systems, highlighting their technical focus, performance improvements, and system impact. It shows that while conventional methods like P&O and INC are simple and widely used, they are less effective under dynamic conditions. Enhanced methods such as VSS-P&O, fuzzy logic, and hybrid ANN–Fuzzy improve tracking speed, accuracy, and stability. In inverter control, SVPWM combined with advanced PI/PR regulators outperforms SPWM by reducing THD and enhancing voltage regulation. The table emphasizes that combining intelligent MPPT with advanced inverter control yields superior overall system performance.

III PV System Components Modeling

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

The paper highlights several key challenges in current simulation models for grid-connected PV systems, notably the limited ability to represent real-world uncertainties, nonlinear behaviors, and environmental variations such as partial shading, temperature fluctuations, and dynamic load profiles. Many existing models are rigid and lack adaptability to rapidly changing grid and weather conditions, which restricts their application in advanced grid scenarios. Furthermore, integrating hybrid energy storage systems and multi-level inverter topologies can be complicated in practice but simplified in a simulation due to their uncontrolled nature causing simulated performance to differ from real-world performance. In some cases, especially with high-resolution (or real-time) simulations, computational limitation is still a barrier.
The paper reaffirms recent trends in the incorporation and utilization of intelligent control systems and AI into integrating and managing energy systems. Fuzzy logic, artificial neural networks (ANN), and adaptive neuro-fuzzy inference systems (ANFIS) are increasingly used in MPPT, fault detection, and dynamic load management in photovoltaic systems because of their ability to handle nonlinearities and adapt to situations in real-time.20 The use of machine learning algorithms for causal relationships to optimize systems, predictive maintenance, and controller tuning. Both of these trends attempt to reduce the gap between behavior exhibited in the simulation and actual performance in the field, therefore, making smart, more resilient and efficient future PV systems.

VI Conclusion

In summary, grid-tied photovoltaic systems are essential for enhancing renewable energy integration, boosting sustainability, and lessening reliance on traditional power sources. This review underscores the vital significance of effective MPPT methods, strong inverter management, and grid alignment to guarantee peak performance in PV systems. The integration of advanced MPPT algorithms greatly improves system efficiency, power conversion, and overall reliability of the system. The modular design strategy outlined in this paper offers versatility for scaling and modifying PV systems from small setups to extensive microgrids, ensuring they fulfill the increasing requirements of contemporary energy systems. The study highlights significant obstacles, such as grid integration and system stability, and offers insights into methods for addressing these challenges. With the increasing demand for renewable energy, embracing these innovative modeling, simulation, and control strategies will be crucial for optimizing grid-connected PV systems, guaranteeing their efficiency, stability, and long-term operational success.

References

[1] Hamid, A. K., Mbungu, N. T., Elnady, A., Bansal, R. C., Ismail, A. A., & AlShabi, M. A. (2023). A systematic review of grid-connected photovoltaic and photovoltaic/thermal systems: Benefits, challenges and mitigation. Energy & Environment, 34(7), 2775-2814. https://doi.org/10.1177/0958305X221117617

[2] Morey, M., Gupta, N., Garg, M. M., & Kumar, A. (2023). A comprehensive review of grid-connected solar photovoltaic system: Architecture, control, and ancillary services. Renewable Energy Focus, 45, 307-330. https://doi.org/10.1016/j.ref.2023.04.009

[3] Nyamathulla, S., & Chittathuru, D. (2023). A review of multilevel inverter topologies for grid-connected sustainable solar photovoltaic systems. Sustainability, 15(18), 13376. https://doi.org/10.3390/su151813376

[4] Zidane, T. E. K., Aziz, A. S., Zahraoui, Y., Kotb, H., AboRas, K. M., & Jember, Y. B. (2023). Grid-connected Solar PV power plants optimization: A review. IEEE Access, 11, 79588-79608. https://doi.org/10.1109/ACCESS.2023.3299815

[5] Bisoyi, S.K., Maurya, S., Binod, S., Srivastava, A., Baluni, A. (2022). Performance of Grid-Connected Photovoltaic and Its Impact: A Review. In: Nagar, A.K., Jat, D.S., Marín-Raventós, G., Mishra, D.K. (eds) Intelligent Sustainable Systems. Lecture Notes in Networks and Systems, vol 334. Springer, Singapore. https://doi.org/10.1007/978-981-16-6369-7_29

[6] Ahmad, Zameer. (2013). Control of Grid Connected Solar Photovoltaic System. 10.13140/RG.2.1.1253.2969. http://dx.doi.org/10.13140/RG.2.1.1253.2969

[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] Cirak, B. E. K. I. R. (2023). Modelling and simulation of photovoltaic systems using MATLAB/simulink. WSEAS Transactions on Power Systems, 18, 49-56. DOI: 10.37394/232016.2023.18.6

[43] Roy, R. B., Rokonuzzaman, M., Amin, N., Mishu, M. K., Alahakoon, S., Rahman, S., ... & Pasupuleti, J. (2021). A comparative performance analysis of ANN algorithms for MPPT energy harvesting in solar PV system. IEEE Access, 9, 102137-102152. https://doi.org/10.1109/ACCESS.2021.3096864

[44] Hussain, M. T., Sarwar, A., Tariq, M., Urooj, S., BaQais, A., & Hossain, M. A. (2023). An Evaluation of ANN Algorithm Performance for MPPT Energy Harvesting in Solar PV Systems. Sustainability, 15(14), 11144. https://doi.org/10.3390/su151411144

[45] Sadick, A. (2023). Maximum power point tracking simulation for photovoltaic systems using perturb and observe algorithm. DOI: 10.5772/intechopen.111632

[46] Ali, S., El Iysaouy, L., Lahbabi, M., Boujoudar, Y., Alharbi, S. J., Azeroual, M., ... & Ness, S. (2023). A matlab-based modelling to study and enhance the performance of photovoltaic panel configurations during partial shading conditions. Frontiers in Energy Research, 11, 1169172. https://doi.org/10.3389/fenrg.2023.1169172