Development and Validation of a MATLAB/Simulink Framework for Grid-Connected PV System Performance Analysis

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Abstract
Modeling and simulation of a grid-connected hybrid solar-wind energy system was prepared with MATLAB/Simulink to investigate the behavior of the system under different environmental conditions, with two Maximum Power Point Tracking (MPPT) controllers: standard Perturb and Observe (P&O) algorithm and Artificial Neural Network (ANN)-based. The hybrid energy system consisted of photovoltaic (PV) modules and a wind turbine with a Permanent Magnet Synchronous Generator (PMSG), DC-DC boost converters along with MPPT controllers, and a three-phase inverter, with Sine Pulse Width Modulation (SPWM) and dq0-based PI control to synchronize with the grid. The simulation process simulated a hybrid energy system for two scenarios, i.e. constant and time-varying solar irradiance, compared the performance of the system; power output, voltage stability, dynamic response, and Total Harmonic Distortion (THD). The results clearly showed that the P&O method was simple and manageable under steady-state conditions, however the ANN-based controller was better in terms of accuracy, adaptability and efficiency to the overall system performance under dynamic and fast changing environmental conditions. In addition, the ANN controller was optimal in maintaining a fixed DC link voltage and achieving low THD that is required for the high quality and reliable operation of hybrid renewable energy systems.

Keywords: Hybrid solar-wind system, MPPT, ANN controller, P&O algorithm, inverter control, MATLAB/Simulink, THD, grid integration, renewable energy optimization.

I INTRODUCTION

Energy is an essential component of human development, serving a fundamental component of growth in economies, society and technology, and quality of life. As populations increase and urban areas expand, energy consumption has significantly increased too [1]. This increase in energy consumption has also come with elevated concerns for climate change and environmental sustainability, leading to a push for clean, renewable alternatives to fossil fuel sources. Of all the renewable technologies, solar energy - especially through photovoltaic (PV) systems - is emerging as a leading technology due to its scalability, sustainability, and reduced costs [2]. In the context of developing constructive renewable energy solutions, grid-connected PV systems, in particular, have emerged as a practical and widely adopted approach to integrating renewable energy solutions in the power supply framework. These systems provide a self-consumption grid working hybrid which allows users to generate free energy from the sun while using the grid to support their energy usage and sending surplus energy to the grid at peak times. The challenge is to create accurate, complete and reliable models of these systems to optimise their performance, economic feasibility and grid stability [3]. The modelling and simulation of grid-connected photovoltaic systems needs a validated simulation framework with a model, as in tools such as MATLAB/Simulink, to reduce uncertainties in actual energy output, evaluate the dynamic nature of the system, and optimise design parameters before the hardware is deployed [4].

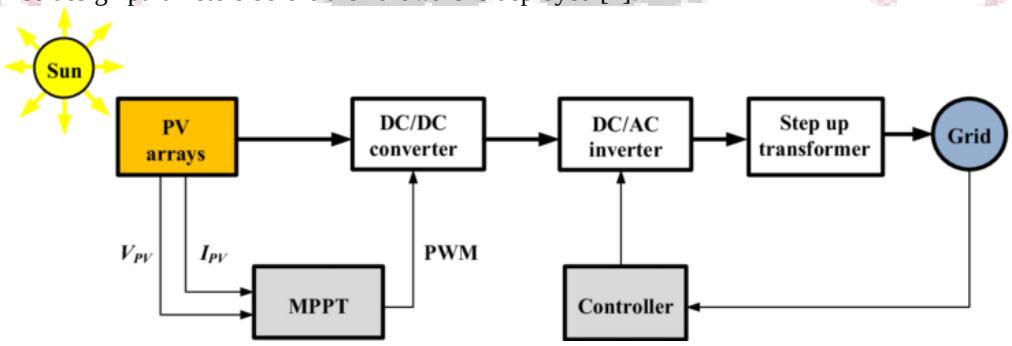

Fig. 1 Block diagram of grid-connected PV system [5]

Figure 1 contains a block diagram depicting a simple grid connected PV system, showing functional parts involved in the conversion of solar energy to grid usable electricity. The system starts with the PV arrays that collect the sun's energy and produce direct current (DC) electricity. The DC electricity is regulated by a maximum power point tracking unit in order to efficiently extract maximum data turbine life from the PV arrays, regardless of environmental conditions. The MPPT stage provides a regulated DC voltage to a DC-DC converter which, in turn, utilizes pulse width modulation (PWM) to regulate the DC voltage levels to desired levels for inverter conversion. Following the operational DC power conditioning, the conditioned DC power is sent to a DC-AC inverter which converts the DC signal into alternating current (AC) power for grid application. The inverter output is then processed through a step-up transformer to achieve the required voltage output for grid application. The inverter

is controlled by a controller unit which monitors inverter synchronization and quality of power delivered to the grid interface. Therefore, the presented architecture can be viewed as a typical representation of modern grid-tied PV systems with regards to energy conversion, control and grid interface.

Grid-connected PV systems have experienced many technical challenges that prevent them from being an optimum resource integrated with the power grid. As illustrated in Figure 1.5, these technical challenges can be grouped into two general areas, namely the grid side and the PV side. Grid side technical challenges are power quality disturbances (including voltage fluctuations, harmonics, etc.), limited grid capacity, and diminished grid reliability. On the PV side, energy conversion efficiency and losses are tremendously limiting factors [6]. As PV systems proliferate in complexity, as well as in the dynamism of the grid environment, new modeling frameworks need to be flexible and accurate. These flexible models allow researchers and engineers to assess system performance as it would behave under real-world, nonlinear, and time-varying situations. Ultimately, these designed models would allow for the further design and optimization of reliable and efficient grid-connected PV systems which have been designed with grid compliancy [7]. To reach the goals and lessen the technical and operational challenges confronted by grid-tied photovoltaic (PV) systems, such as such as voltage fluctuations, harmonic distortion, synchronization, and conversion inefficiencies, enable students, researchers, and engineers to catch up, MATLAB/Simulink presents a modular and dynamic way to perform simulation and validation. This platform enables researchers and engineers to build, modify, and simulate individual components of a system such as PV arrays, MPPT controllers, DC-DC converters, inverters, and synchronization units in isolation from the rest of the model [8]. Modular capabilities are especially valuable in order to test different control strategies or hardware configurations in different environments and grid conditions. Additionally, libraries such as Simscape Electrical have built-in resources for creating realistic behaviors (e.g., temperature variability and non-linear I-V characteristics) that increase the accuracy and fidelity of simulations [9].

In addition to this, MATLAB / Simulink features advanced system analysis tools, allowing for rapid prototyping, automated code generation, and real-time hardware-in-the-loop analysis (HIL). Fault injection also allows researchers to playback grid disturbances - like voltage sags, loss of synchronization, and inverter faults - in simulation while assessing the robustness of the system without any physical risk [10]. MATLAB/Simulink can simulate VA representation of voltage source inverter (VSI) with dq-frame control, use Phase Locked Loops (PLLs) for precise and accurate grid synchronization, and LCL filters for harmonic mitigation to produce fully orthogonal AC output while interacting safely and stably with the grid. These great capabilities position MATLAB/Simulink as the ideal platform for the central performance and reliability issues at the heart of grid-connected PV systems, providing a scalable solution for all academics and industrial applications [11].

II LITERATURE REVIEW

Shrestha et al. (2025) [12] drew attention to the shift from grid-connected transformer-based inverters (GBTIs) to transformer-less grid-connected inverters (GLTIs) in photovoltaic (PV) systems. This shift occurs, in part, because GBTIs provide galvanic isolation to minimize leakage current but higher costs, efficiency, and physical size are all drawbacks. TLGIs are capable of minimizing these shortcomings and several common transformer-less inverters were analyzed in terms of common-mode voltage (CMV), differential-mode voltage (DMV), total harmonic distortion (THD), and leakage current. During the simulation with MATLAB/Simulink, one of the main findings was that the H5 topology provides a valid compromise in balancing leakage current, THD, and operational efficiency for grid-connected PV.

Jäger-Waldau et al. (2025) [13] reported a significant global increase in clean energy investments, with solar PV leading at a 20.5% annual growth rate. Investments in PV reached USD 514 billion in 2024, contributing to the installation of nearly 600 GWp of new capacity and bringing global installed capacity beyond 2.2 TWp. It was noted that 36 countries exceeded 1 GWp of annual PV installations, indicating broad market maturity. Despite cost reductions in PV hardware and battery systems, the authors cautioned that the current pace of deployment remains inadequate to meet the 1.5 °C climate target, signaling a pressing need for accelerated integration of renewable technologies.

Dora et al. (2025) [14] emphasized the intermittent nature of renewable energy and its impact on reliability when used independently. It was stated that combining renewables with conventional thermal generators has traditionally been the approach for achieving a stable energy supply. The authors introduced the concept of a globally interconnected electricity grid, where renewable energy could be transmitted across regions to enhance supply security and sustainability. Despite the theoretical advantages—such as improved efficiency, emission reduction, and energy balancing—the economic, technical, and environmental implications of such large-scale interconnection require deeper investigation.

Kamal et al. (2025) [15] mentioned that renewable energy sources, though clean and increasingly adopted, suffer from intermittency which affects supply reliability. The integration of energy storage, particularly batteries, was presented as a solution to bridge the gap between generation and demand. A case was referenced involving a hybrid PV-battery system implemented in a hilly region of rural India, where simulations and resource assessments confirmed the system's technical and economic viability. The findings support the role of PV-battery hybrids in ensuring energy security and efficient electricity delivery in off-grid or remote locations.

Ahmed et al. (2025) [16] traced the evolution of PV technology through three generations: crystalline silicon, thin-film, and emerging technologies like perovskite and organic solar cells. It was highlighted that solar PV has become increasingly vital across sectors such as agriculture, telecommunications, and transportation. The study identified strong growth in installed capacity across Europe, with Italy showing notable progress. World-wide, China, the U.S. and India were identified as global leaders in capacity expansion. Energizing results were emerging but challenges such as regulatory bodies in the way, price limitations and system compatibility remained. The authors proposed helpful policy reforms, off-grid development, continued subsidy reductions, and more advanced inverter technologies for grid integration.

Table 1 Comparative Summary of Recent Literature on Photovoltaic (PV) Systems

Author(s) (Ref. No.)	Main Focus	Key Technologies	Challenges Addressed	Methodology
Shashwot Shrestha et al. (2025) [12]	Grid-connected inverters for PV	Transformer-less inverters (TLGI), H4/H5/HERIC topologies	Leakage current due to lack of galvanic isolation	MATLAB/Simulink simulations
Arnulf Jäger-Waldau et al. (2025) [13]	Global clean energy investment trends	PV system deployment and investment	Cost fluctuations, insufficient deployment vs. 1.5 °C goal	Market trend analysis, LCOE metrics
Kumar Dora et al. (2025) [14]	Integration of multiple RES and global grid concept	Hybrid systems, global electricity grid	Intermittency, regional viability	Strategic analysis, global initiatives review
Md Mustafa Kamal et al. (2025) [15]	Solar PV + battery storage in remote regions	PV-battery hybrid systems	Reliability in rural, hilly areas	Techno-economic analysis, load-sharing study
Shoaib Ahmed et al. (2025) [16]	Evolution and deployment of PV tech	1st–3rd gen PV, applications, policy impacts	Regulatory barriers, integration, cost	Review of tech, regional studies (e.g., Italy)

III OBJECTIVES

- To implement a hybrid solar-wind energy system with control from a neural-network-type controller to optimize energy generation and improve reliability.
- To study the system performance, both steady state and dynamic, and allow for adaptive response through training the model.
- To reduce harmonics and keep output voltage and frequency stable to meet grid criteria.

IV METHODOLOGY

The study uses a structured modeling and simulation framework as a basis for designing and investigating a hybrid solar-wind energy systems using MATLAB/Simulink. The hybrid system uses two main mechanisms to control the system power flow from renewable sources, namely, using Perturb and Observe (P&O) and an Artificial Neural Network (ANN). MATLAB/Simulink is a high-level matrix-based programming language with object-oriented features that facilitates scientific and engineering calculations, iterative designs, visualization of quantitative data, and investigation of real-time control systems. The modeling and simulation environment includes several system features including, power electronic converters, inverters, loads, and optional grid connection features. The platform offers additional features including, toolboxes that can be adjusted for application development and deployment, further offering flexibility and application in modeling advanced and complex energy systems.

Designing of Hybrid Energy System

The hybrid solar-wind energy system is developed to provide better reliability through the use of solar or wind resources as able. The system as displayed in Figure 2, consists of a PV module and a wind turbine. The PV

module generates DC power as regulated by a boost converter, utilizing MPPT (P&O or ANN) while the wind turbine, equipped with a permanent magnet synchronous generator (PMSG), produces AC power which is rectified to DC. The total DC is converted to AC by an inverter to provide power to loads or export to the grid. PV systems generate clean energy and can be connected to the grid as stand alone or grid integrated systems. In the grid-tied configurations, a power conditioning unit (PCU) converts power from DC to AC that is synchronized to the grid AC voltage and is disconnected during an outage. PV cells/modules always operate at a maximum power point (MPP), which can be modeled as a circuit to resemble the electrical behavior.

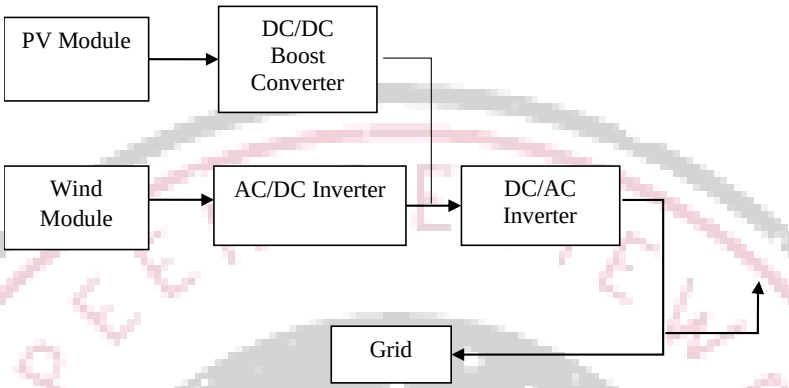

Figure 2 Hybrid energy system topology

Photovoltaic (PV) systems are a clean, renewable energy source with output influenced by geographic location. They are categorized as stand-alone or grid-tied based on their design and operational requirements. Grid-tied systems connect to the utility grid via a power conditioning unit (PCU), which converts DC output from the PV array into grid-compliant AC power. The PCU also ensures disconnection during grid outages for safety. PV cells operate at a maximum power point (MPP), defined by the optimal combination of current and voltage, and are typically modeled using a simple equivalent circuit for accurate performance analysis.

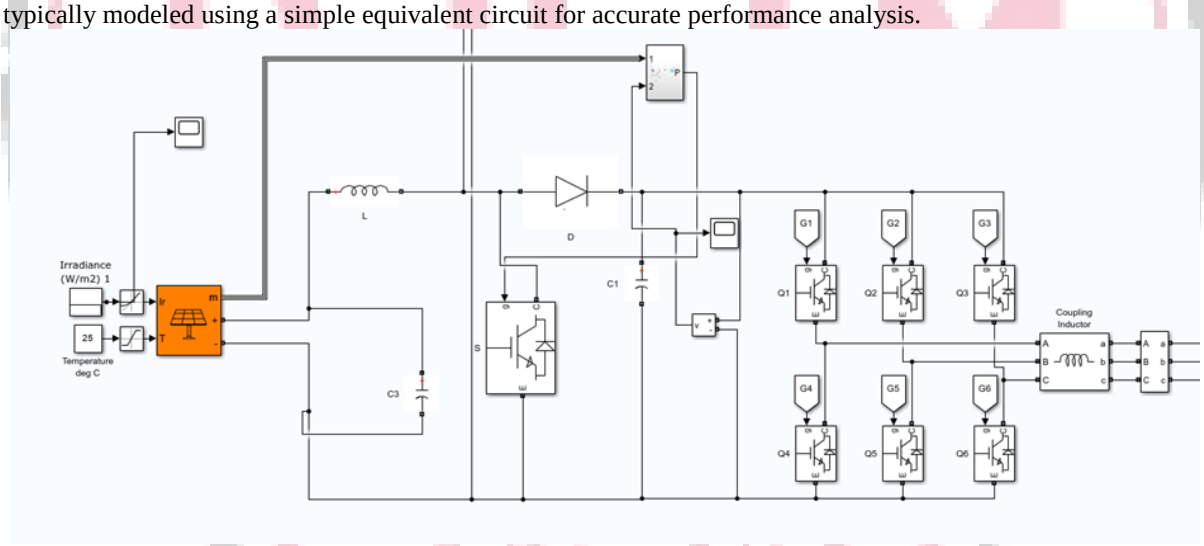

Figure 3 PV system in MATLAB/SIMULINK designing

A series resistance of the cell (Rs) is attached in series with the parallel configuration of cell photocurrent (Iph), an exponential diode (D), and a shunt resistance (Rsh). The current and voltage of the cells are represented by Ipv and Vpv, respectively

$$I_{pv} = I_{ph} - I_s\left(e^{q(V_{pv}+I_{pv}*R_s)/nKT} - 1\right) - (V_{pv} + I_{pv} * R_s)/R_{sh}$$

Where:

I_{ph}- Solar-induced current

I_s - Diode saturation current

q - Electron charge (l.6e^{-19}C)

K - Boltzmann constant (l.38e^{-23}J/K)

n - Ideality factor (l~2)

T - Temperature ^{0}K

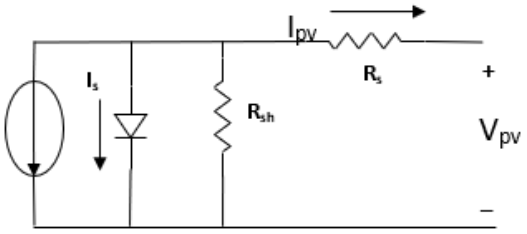

Figure 4 Equivalent circuit of solar PV cell

The current generated by the solar PV cell due to solar energy relies on the level of solar irradiation and the operating temperature, which can be articulated as:

$$I_{ph} = I_{sc} - k_i(T_c - T_r) * \frac{I_r}{1000}$$

Where:

I_{SC} Short-circuit current of cell at STC

K_i Cellshort-circuit current/temperature coefficient(A/K)

I_r *Irradiance* in w/m^2

$T_{c,\ Tr}$ Cell working and reference temperature at STC

A PV cell exhibits an exponential connection between voltage and current, with the maximum power point (MPP) situated at the curve's knee, as illustrated in Fig 5

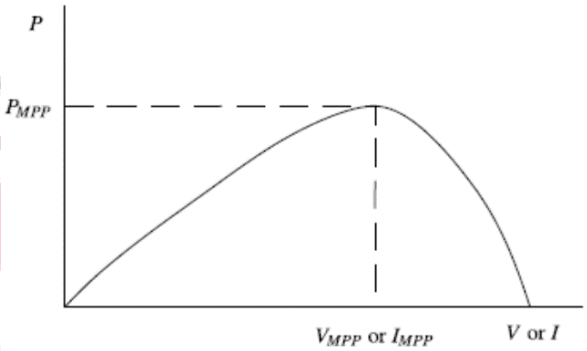

Figure 5 Characteristic PV array power curve

Table 2 Parameters used in Designing of PV system

Sno.	Parameters	Values
1	Model	SunPower
2	Maximum Power (Array)	6 KWatts
3	Open circuit voltage	64.6 Volts
4	Shot circuit current	6.14 Ampere
5	Irradiation	200 to 1000 wb/m^2
6	Temperature	25^{0}C

Wind Energy System Modeling

Wind energy is a clean, abundant resource whose power generation depends on the wind potential of the installation site. For a techno-economically viable system, sites with high average wind speeds are preferred. Wind system models assess turbine performance based on feasibility, cost, energy security, and ability to meet load demands. Wind turbines convert wind's kinetic energy into mechanical rotation via rotor blades, which then drive a generator to produce electricity. Typically, Permanent Magnet Synchronous Generators (PMSG) are used, though turbines cannot extract all wind energy. The turbine's behavior is modeled mathematically to optimize performance based on aerodynamic, mechanical, and electrical parameters.

Output aerodynamic power of the wind-turbine is expressed as:

$$P_{Turbine} = \frac{1}{2}\rho A C_p(\lambda, \beta) v^3$$

where, ρ is the air density (typically 1.225 kg/m3), *A* is the area swept by the rotor blades (in m2), *CP* is the coefficient of power conversion and *v* is the wind speed (in m/s)

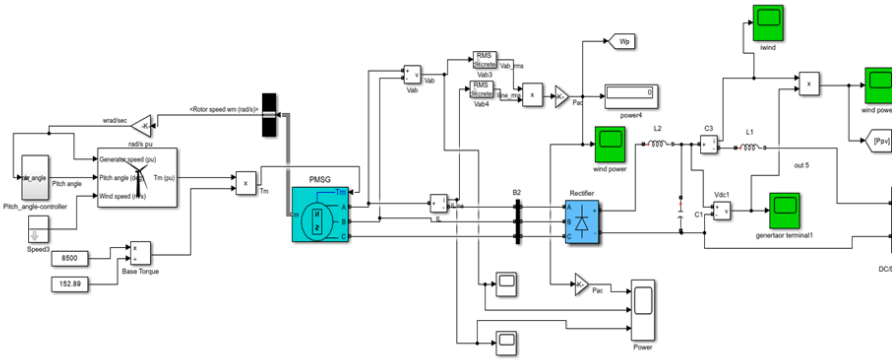

Figure 4.5: Simulink design of wind energy system

This mechanism utilizes the varying torque output wm and aims to enhance the current and voltage waveform to reach its peak value.

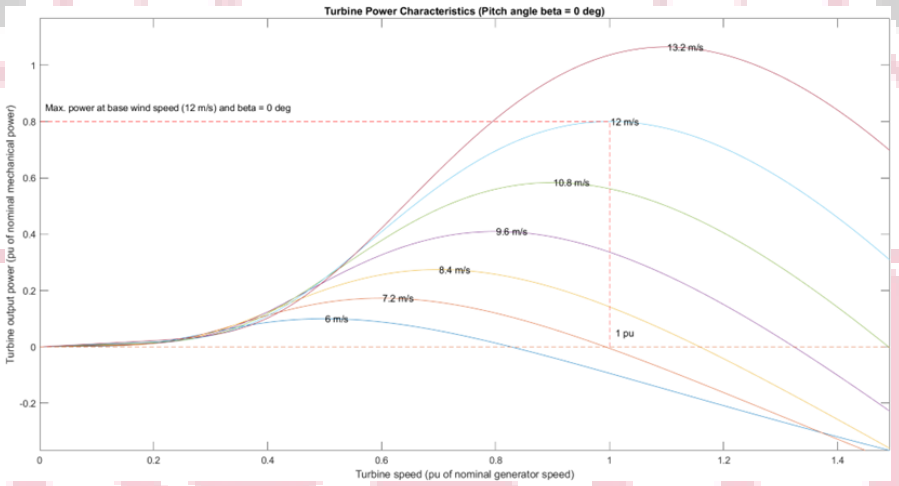

Figure 4.6: Wind turbine Characteristics used in simulation

Converter Modeling and Control Design

Two control strategies—Perturb and Observe (P&O) and Artificial Neural Network (ANN)—are used to manage power conversion in hybrid solar-wind systems. P&O offers a simple, conventional MPPT approach by adjusting voltage to track maximum power, while ANN provides an adaptive, intelligent solution capable of responding to changing environmental conditions. Their performance is compared under constant and variable irradiance levels, evaluating output power, voltage and current quality, THD, and dynamic response. Results demonstrate ANN's superiority in efficiency and stability over traditional methods.

A. P&O driven method for converters

Among the various MPPT algorithms—such as Incremental Conductance (IC) and fuzzy logic-based methods—the Perturb and Observe (P&O) technique is one of the most widely used due to its simplicity and cost-effectiveness. It is particularly suitable for low-power applications like residential and small commercial PV systems. The method works by periodically adjusting the duty cycle of the DC-DC converter and comparing the resulting voltage and power values with previous measurements to determine the direction toward the Maximum Power Point (MPP). This iterative process helps shift the operating point toward optimal power output. Figure 4.7 illustrates the working principle of the P&O algorithm, showing how voltage perturbations and corresponding power changes guide the controller to track the MPP effectively.

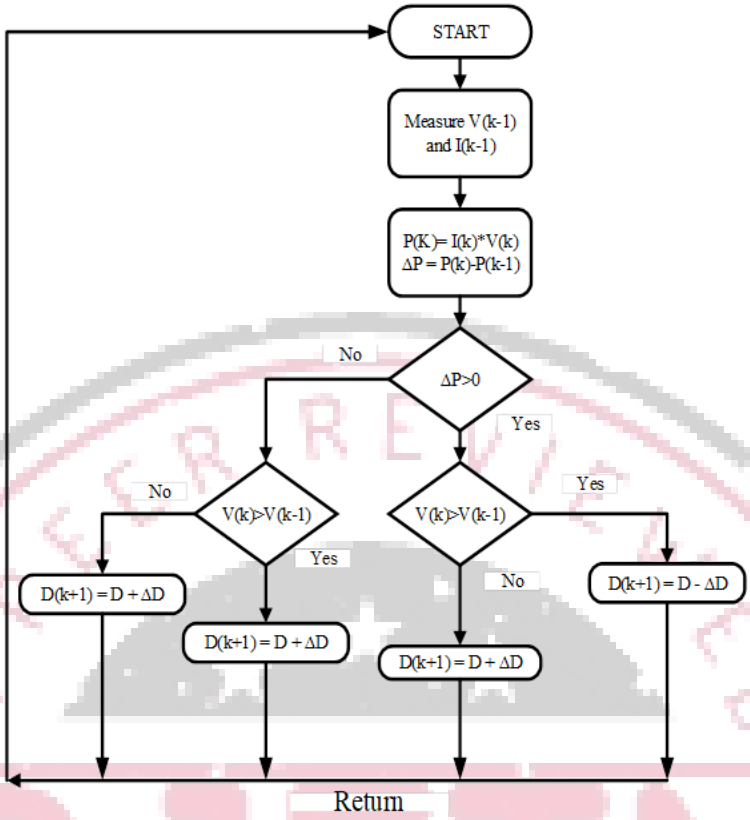

Figure 4.7: Perturb and Observe (P&O) scheme for driving the converters in hybrid system

B. ANN based control system design for converters

Artificial Neural Networks (ANNs) are intelligent systems that replicate human cognitive behavior to process information and make real-time decisions, even in the presence of noise. Composed of input, hidden, and output layers, ANNs use weighted connections and transfer functions to map inputs to outputs. In this study, a feedforward multilayer perceptron (MLP) trained via supervised learning and backpropagation is used to control the DC-DC converter in a hybrid solar-wind system. The ANN processes inputs like irradiance, temperature, and electrical values to generate optimal control signals for tracking the maximum power point (MPP). Unlike traditional P&O methods, ANN offers faster response and better adaptability to changing environmental conditions. Figure 4.9 illustrates the ANN controller technique used to drive the converter in the proposed system.

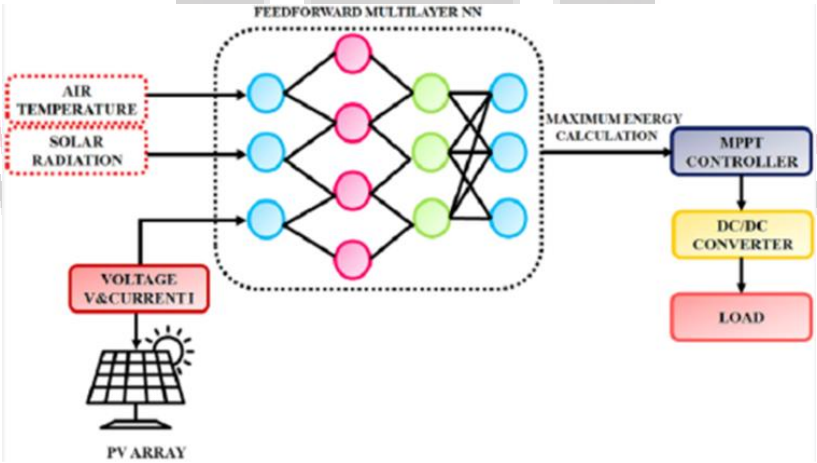

Figure 4.9: NN controller Technique for driving converter

C. DC-AC Converter/Inverter Modeling

An inverter is a key component in hybrid solar-wind systems, converting DC power into high-quality three-phase AC suitable for grid or load connection. The system uses a three-phase inverter with Sine Wave Pulse Width Modulation (SPWM) and IGBT-based switches for fast, efficient operation. Inverter performance depends on parameters like DC voltage, grid voltage, and switching frequency. Figure 4.11 illustrates the inverter control implementation in SIMULINK, which employs a dq0 synchronous reference frame and PI controller to regulate

voltage and shape current. This setup compares DC link voltage with a reference, processes the error through PI control, and generates modulation signals to drive the IGBT gates, ensuring effective power delivery and enhanced voltage regulation, particularly when paired with ANN-based control.

V RESULTS AND DISCUSSION

The growing demand for sustainable energy has increased interest in hybrid systems that combine solar and wind sources to enhance reliability and efficiency. Their complementary nature makes solar-wind systems highly effective, though efficient energy extraction under varying conditions remains a challenge. This study models a hybrid solar-wind system in MATLAB/Simulink, comparing two converter control strategies: the widely used Perturb and Observe (P&O) MPPT algorithm and an adaptive Artificial Neural Network (ANN)-based method suited for dynamic, non-linear environments. The systems are evaluated under two test scenarios—Case 1 with constant solar irradiation and Case 2 with variable levels—to simulate real-world conditions. In Case 1, the hybrid system's performance is assessed under stable solar input, mimicking clear weather conditions. This scenario enables an accurate comparison of the control strategies' steady-state behavior, including efficiency, response time, and tracking accuracy. The consistent environment allows both algorithms to be tested in ideal conditions, providing a clear view of their inherent performance capabilities.

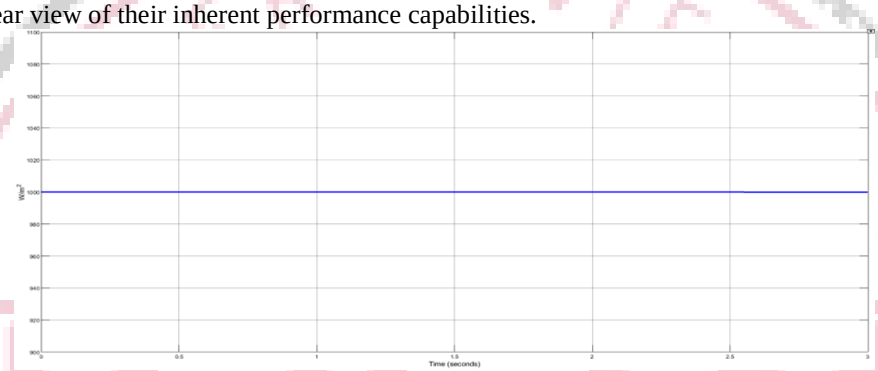

Figure:4 input irradiation of 1000W/m2 to solar system

The solar irradiance is maintained at a constant 1000 W/m² as shown in Figure 4, which represents standard test conditions (STC) typically used in PV system evaluation. This level of irradiance is equivalent to full sunlight and is commonly used as a benchmark for assessing the maximum power output of solar panels.

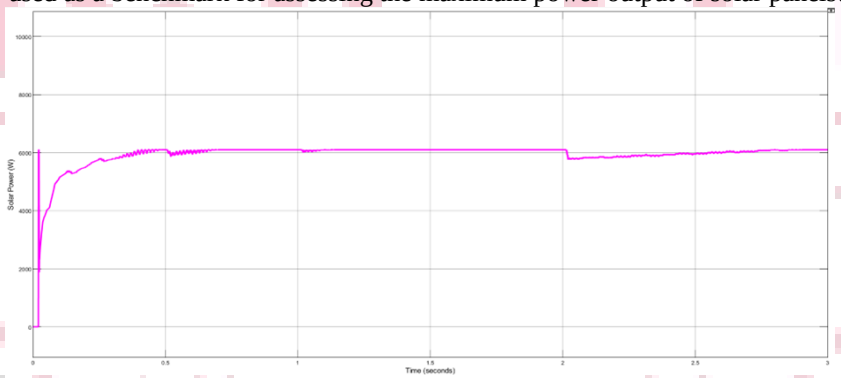

Figure:5 Power output from the solar system with constant input irradiation level

This figure 5 presents the solar power output (approximately 6000W) over a simulation period of 0 to 3 seconds, with a constant solar irradiance of 1000 W/m² for case 1 scenario.

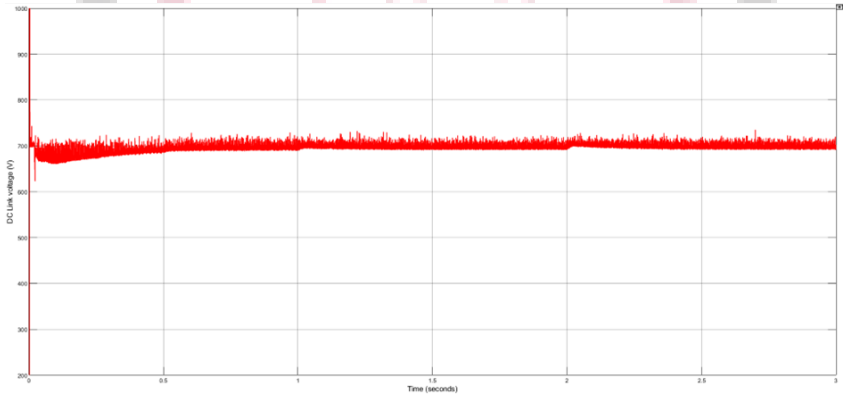

Figure:6 DC link voltage of system 1 with constant input irradiation level

The figure 6 displays the DC link voltage of System 1, which uses a Perturb and Observe (P&O) based converter control, under a constant solar irradiance level of 1000 W/m². Once the initial transient is over, the voltage fluctuates around the 700 V mark. The small ripples and noise-like variations observed are typical in DC link voltages due to switching actions in the power electronic converters.

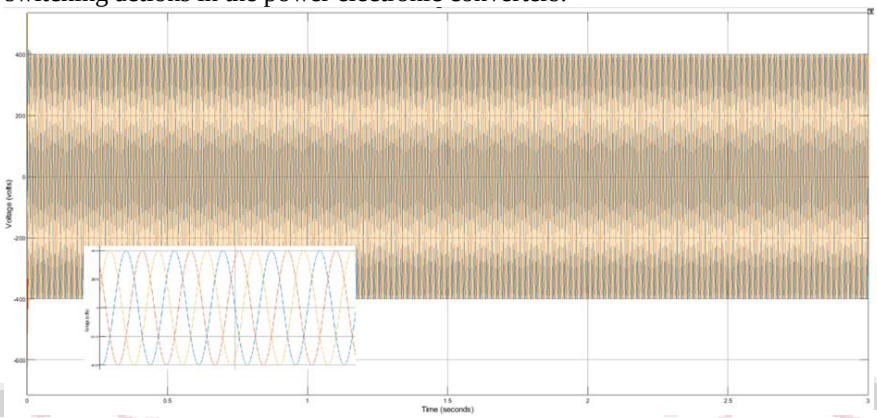

Figure:7 Three phase AC voltage in the system 1 with constant input irradiation level

The figure represents the three-phase AC voltage output of 400 V from System 1, which uses a P&O-based converter control, under a constant solar irradiation level of 1000 W/m². The graph shows three sinusoidal waveforms (phases A, B, and C), each 120° out of phase with the others

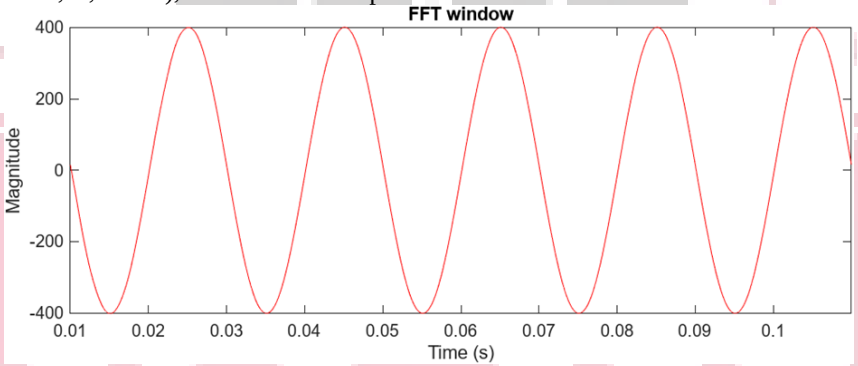

Figure:8 FFT analysis of voltage in the system 1 with constant input irradiation level

The figure 8 shows the Fast Fourier Transform (FFT) analysis for the output voltage waveform from System 1 at steady-state conditions with fixed solar irradiance (1000 W/m²). The FFT is important for analyzing the harmonic content of a waveform, most importantly in power electronic systems where inverter switching creates unwanted frequency components.

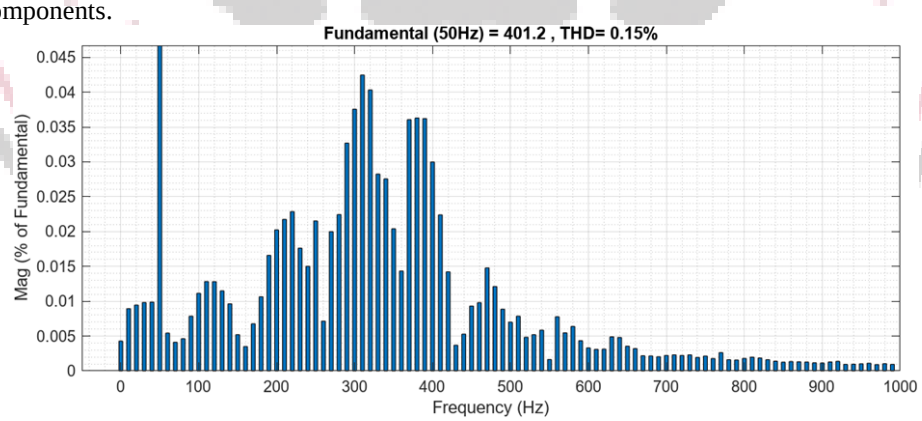

Figure:9 THD% of voltage in the system 1 with constant input irradiation level

The figure 9 shows the THD% spectrum of the AC output voltage from System 1, which uses a Perturb & Observe (P&O)-based converter control, under a constant solar irradiance of 1000 W/m². The main goal of this analysis is to assess the Total Harmonic Distortion (THD) and thus the power quality of the output voltage which in this case was found to be 0.15%

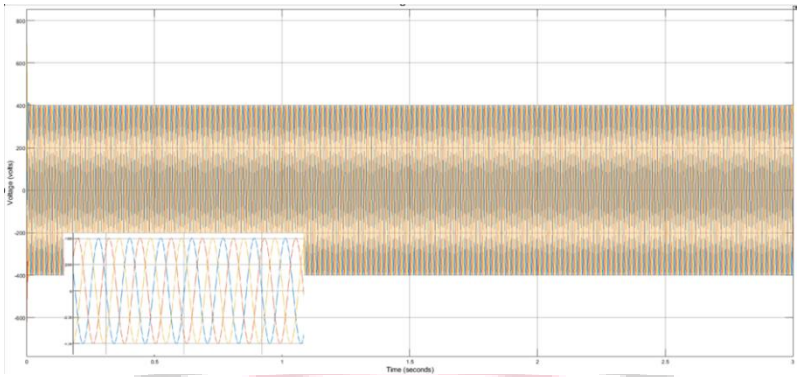

Figure:10 Three phase AC voltage in the system 2 with constant input irradiation level

The figure 10 illustrates the three-phase AC voltage waveforms generated at the output of System 2, which uses an Artificial Neural Network (ANN)-based control strategy, under constant solar irradiance conditions (1000 W/m²)

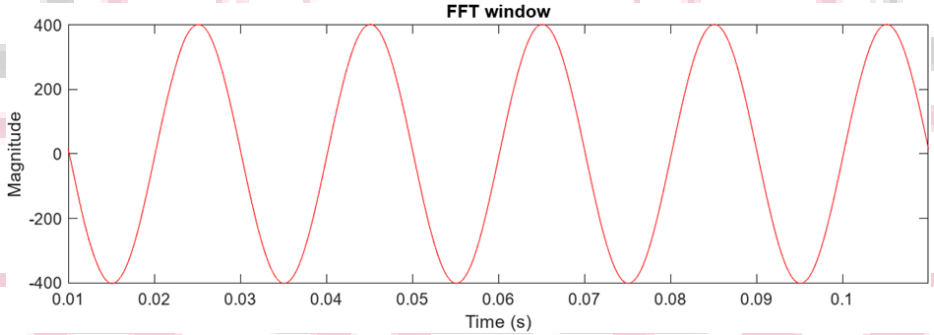

Figure:11 FFT analysis of voltage in the system 2 with constant input irradiation level

The Figure 11 presents the Fast Fourier Transform (FFT) analysis of the three-phase output voltage from System 2, which is controlled using an Artificial Neural Network (ANN), under constant solar irradiation (1000 W/m²). The FFT decomposes the voltage waveform into its frequency components.

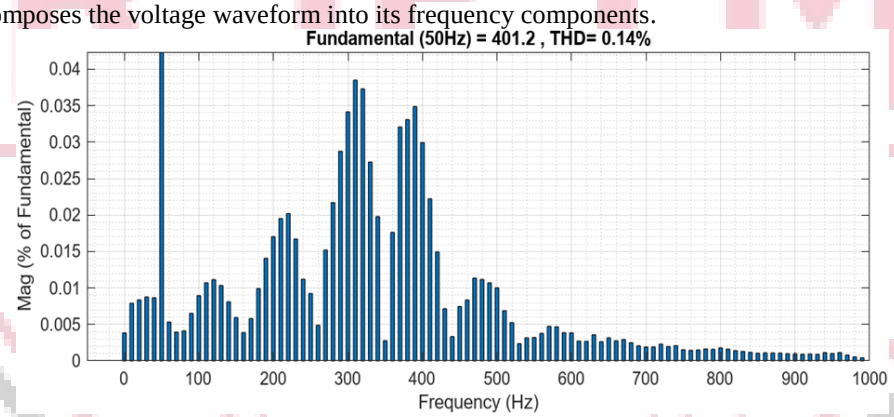

Figure:12 THD% of voltage in the system 2 with constant input irradiation level

The Figure 12 shows the Total Harmonic Distortion (THD%) which was found to be 0.14% of the AC voltage waveform in System 2, which uses an Artificial Neural Network (ANN)-based converter control, under constant solar irradiance (1000 W/m²)

A. Case 1: Constant Irradiation

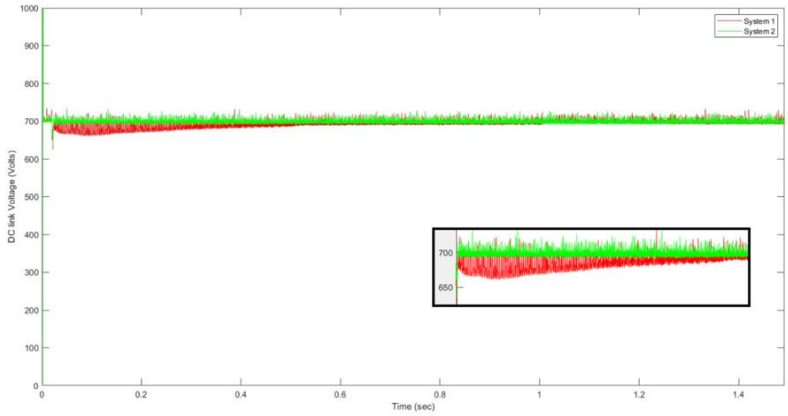

Figure:13 Comparative assessment of DC link voltage controllers in system 1 and 2 in case 1

The figure 13 compares the DC link voltage profiles of System 1 (P&O-based control) and System 2 (ANN-based control) under a constant solar irradiance of 1000 W/m². The red curve indicates System 1, and the green curve is System 2. System 1 (red) has larger fluctuations and slower settlement behavior thus has a larger degree of ripple or noise in the DC link voltage. System 2 (green) showed tighter regulation and less ripple demonstrating more stability in the DC link, this is likely due to the ANN controller's preciseness to adapt to changing conditions. The purpose of comparing the two-system performance on each other is to highlight the difference in control strategy between DC link voltage stability in System 1 and System 2 when irradiance is held constant for each system.

Table 5.1: Comparative assessment of different parameters in case 1

Parameters	**Units**	**System 1**	**System 2**
Voltage	Volts (V)	400	400
THD% in voltage	Percentage (%)	0.15	0.14
Current	Ampere (A)	75	75
THD% in current	Percentage (%)	2.45	2.10
Active Power	Kilowatts (KW)	47.23	49.62
Reactive Power	KVar	21.52	15.23
Power factor	-	0.91	0.956

B. Case 2: Variable Irradiation

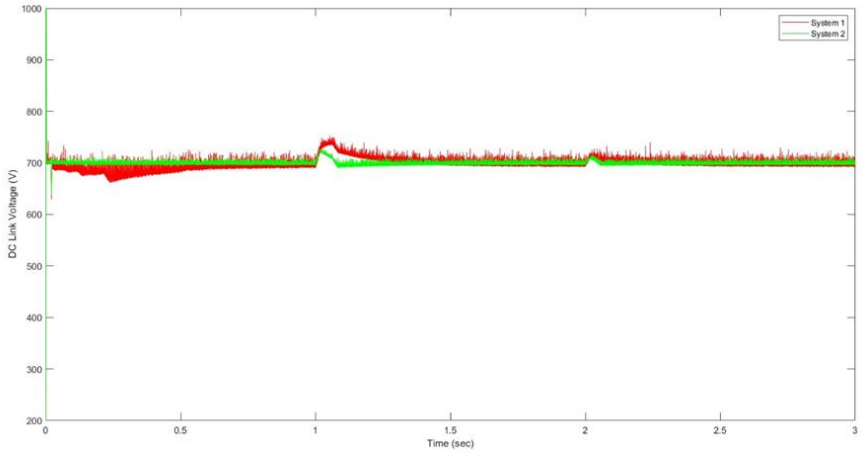

Figure:14 Comparative assessment of DC link voltage controllers in system 1 and 2 in case 2

This figure 14 compares the DC link voltage behavior of System 1 (in red, P&O-based control) and System 2 (in green, ANN-based control) under variable solar irradiance conditions over a 3-second simulation. At 0 to 1 second, during constant high irradiance (1000 W/m²), both systems stabilize around 700 V, but System 1 shows more voltage ripple, whereas System 2 maintains a smoother and more stable profile. At 1 second, when irradiance drops to 500 W/m², System 1 experiences a noticeable voltage spike and oscillation, while System 2 shows a faster and more controlled adjustment. At 2 seconds, following another drop in irradiance to 200 W/m², System 1 again displays larger fluctuations, whereas System 2 demonstrates better damping and voltage stability.

Table 5.2: Comparative assessment of different parameters in case 2

Parameters	**Unit**	**System 1**	**System 2**
THD% of current at 1 sec	%	1.18	1.10
THD% of current at 2 sec	%	1.15	1.07

VI Conclusion

MATLAB/Simulink was effectively used to simulate a hybrid renewable energy system, showcasing the operational benefits of intelligent control methods. While the P&O algorithm proved functional for stable conditions, the ANN-based control strategy delivered significantly improved dynamic response, voltage stability, and power quality. These outcomes support the use of ANN controllers in real-time applications where environmental variability is a factor, emphasizing their role in enhancing the reliability and efficiency of hybrid solar-wind energy systems.

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