Revolutionizing Solar PV Systems: AI-Driven Advances in Maximum Power Point Tracking

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Abstract: *The increasing global demand for energy, alongside the diminishing availability of fossil fuel reserves, underscores the urgent need to transition towards sustainable energy sources, notably photovoltaic (PV) systems. This study focuses on the integration of artificial intelligence (AI) methodologies into Maximum Power Point Tracking (MPPT) for solar PV systems, aiming to optimize energy generation and efficiency.AI-enhanced MPPT techniques harness cognitive computing capabilities to overcome inherent limitations of traditional MPPT methods. These AI-driven approaches enable precise tracking of the maximum power point (MPP) on the complex P-V curve of solar panels, thereby enhancing energy extraction efficiency under varying environmental conditions such as sunlight intensity fluctuations and temperature changes. The study provides comprehensive insights into the development, performance, and comparative analysis of various AI algorithms utilized in MPPT. It evaluates the efficacy of AI techniques such as machine learning algorithms (e.g., neural networks), evolutionary algorithms (e.g., genetic algorithms, particle swarm optimization), and fuzzy logic systems in improving MPPT performance metrics. Through rigorous evaluation criteria and comparative studies, the research highlights the advantages of AI-based MPPT over traditional heuristic or rule-based approaches. These benefits include enhanced accuracy in MPP tracking, faster adaptation to changing environmental parameters, increased energy yield, and improved robustness against fluctuating conditions.*

Keywords: *Artificial Intelligence, Maximum Power Point Tracking (MPPT), Photovoltaic Systems, Renewable Energy, Computational Intelligence, Solar Energy, AI Algorithms.*

I. INTRODUCTION

Generation of electricity has seen a significant growth in demand throughout the last decade. However, due to the depletion of fossil fuel supplies, power plants that rely on them are unable to supply the demand for power. It is imperative to use alternative energy sources, such as energy from renewable sources. PV-based generating is becoming more and more necessary for both standalone applications and systems connected to the grid. [1]. One of the most crucial demands for individuals in showing is power. In addition does solar energy contribute to the power era, but it also lessens the pollution that comes from burning fossil fuels. The primary motivation behind the Endeavour's utilization of many renewable energy resources is the persistent increase in both fuel expenses and nursery gas outflow levels. Solar energy is a sustainable energy source that can be used since it is easy to convert into power using a photovoltaic (PV) framework, clean, and emits no emissions. The creation of PV control has proven to have significant promise in supplying energy demands. [2] whereas due to its high initial cost, PV frameworks are not commonly used. Once more, there is no evidence that the energy transmitted by photovoltaic cells (PV) consistently yields anything as it is totally reliant on the sun's sunlight exposure, the surrounding temperature of the PV modules, the location on the solar cells, and other factors.

II. ARTIFICIAL INTELLIGENCE IN SOLAR SYSTEM OPTIMIZATION BY MPPT TECHNIQUES

The GMPP is often predicted and estimated by the current artificial intelligence (AI) MPPT approaches using sensory data such as sunlight irradiance, the electrical inputs of the photovoltaic system, and current- input measures along the non-linear P-V curve. Because MPPT is a complicated, reliable, self-learning, digitalized system, integrating AI speeds up convergence and transient response. Conventional HC MPPT and AI-based MPPT are the two primary forms of MPPT approaches [3]. The terms bio-inspired MPPT, bio-computing MPPT, bio-based MPPT, and computational intelligence (CI) based MPPT are used to describe AI-based MPPT. The components that make up this system are mostly artificial neural networks (ANN), genetic algorithms (GA), fuzzy logic controlling (FLC), genetic evolution (DE), Tabu search (TS), Cuckoo search (CS), firefly algorithms (FA), particle swarm optimization, or (PSO), and hybrid algorithms such as The current-voltage (I-V) curve is tracked and scanned using conventional HC MPPT techniques, which also include Fibo nacci searching, global MPPT (GMPPT) segmentation searching, HC, constant voltage, fractional short-circuit current, fractional open-circuit voltage, and extremum seeking controlling. For every kind of MPPT, there are several many sources of a comparative literature evaluation. Only AI-based and hybrid MPPT approaches have been covered in the literature to yet.

Particularly for AI-based MPPT approaches, there have been remarkably few study comparisons [4]–[5]. The contributions of this paper are as follows:

The applicability and utilizations of AI in MPPT for solar power system are reviewed;

- A summary of the research and development areas for AI in MPPT is given;

- Each AI algorithm's performance is evaluated and compared across MPPT methodologies. Popular AI-based MPPT approaches are examined and assessed in this research. This paper offers a thorough understanding of the most recent developments and advancements in artificial intelligence (AI) as they relate to MPPT for solar power systems. Generally speaking, every traditional MPPT method has the same drawbacks, such as power fluctuations, the inability to function properly in PSC and abrupt variations in irradiance, trapping at a local maximum power point, and oscillation around the maximum power point. AI is therefore used to get around these problems [6], [7]. Figure. 1 displays a typical MPPT block diagram, where PWM stands for width of pulse modulation.

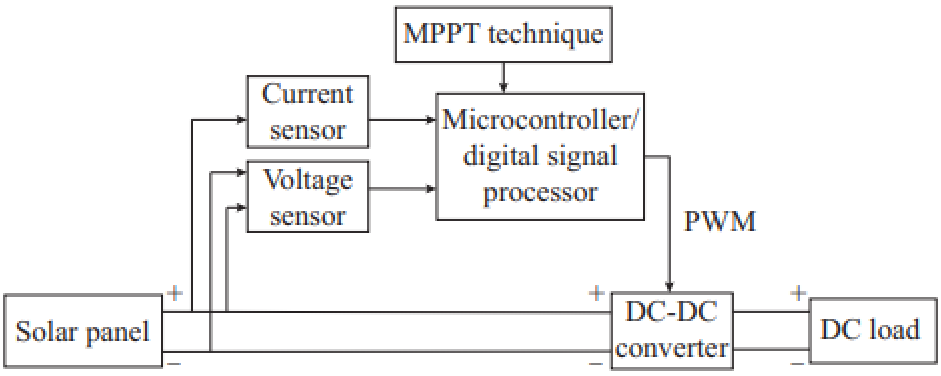

Figure 1. Block diagram of typical MPPT.[7]

III. MODELING OF STANDALONE PV SYSTEM

A solar cell generates very little electricity between 1 and 3 W due to its thinness. In order to create a photovoltaic module and generate the required power, we assemble solar panels in parallel or series configurations or combination to enhance the energy. A series cell layout raises the module's voltage, whereas a parallel cell arrangement permits the resultant generator current to be increased. The equivalent circuit of the PV module is shown in Figure. 2.

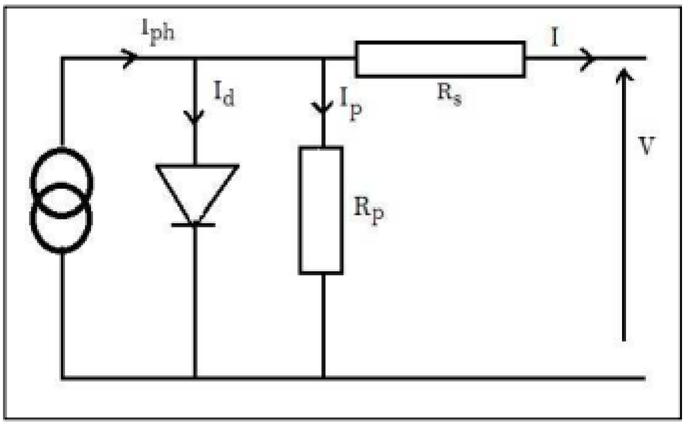

Figure. 2. Model of the photovoltaic module

The voltage-current characteristic is a complex and nonlinear function. Its equation is given as follows:

$$\mathbf{I} = \boldsymbol{I_{ph}} - \boldsymbol{I_o}\left[\boldsymbol{exp}\left(\frac{\boldsymbol{q}}{\boldsymbol{akT}}(\boldsymbol{V}+\boldsymbol{IRs})\right)-\mathbf{1}\right]-\frac{\boldsymbol{V}+\boldsymbol{IRs}}{\boldsymbol{R_p}})$$

Where, Iph is the light-generated current or photocurrent, I0 is the reverse saturation current of diode, q is the electron charge (1.60217646*10-19 C), k is the Boltzmann constant (1.3806503*10-23 J/K), and T is the temperature of the p-n junction in K. a is the diode ideality factor, It depends on recombination mechanisms in the space charge zone. In the ideal case, Rs tends towards 0 and Rp to infinity. And in the real case, these resistors provide an assessment of the imperfections of the diode. [8]

IV. PV-BATTERY SYSTEM TOPOLOGIES

A typical PV generator, power electronic components, a battery device, and a control unit make up a Photovoltaic-battery system. The market is currently filled with a wide range of industrial PV-battery installations designed for use in residential structures [9]. The kind of connection between the battery storage and the PV system is one of these goods' primary distinguishing features. The system layouts of the most common topologies are illustrated in Figure 1. The photovoltaic inverter and a charging equipment with a bilateral charge converting are connected to the home's AC-bus in AC-coupled systems. On the other hand, the battery can also be connected to the DC-side of the PV inverter[10]. The battery in a DC-coupled photovoltaic system can only be charged by DC-bus electricity. Bidirectional converters that convert AC to DC are a feature of AC/DC-coupled networks, allowing for further battery charging using the AC-bus power source in the home. [11] A DC/DC charge regulator may be utilized as well to connect the battery pack straight onto the Photovoltaic generator. These battery systems with generator coupling feed the loads through a single Photovoltaic inverter. In order to provide a better understanding of the different system topologies, the relevant paths of energy flow are shown in Figure 3. The path that that power transfers across the three different locations of reference on the PV generator side (PV), battery side (BAT), and AC side (AC) is taken into consideration while choosing the nomenclature of the pathways. All network topologies have the path PV2AC, which defines the transformation of DC electricity from the PV generator to AC power. Depending on the topology, either PV2BAT or AC2BAT describes the charging path. The discharging pathways are BAT2AC and BAT2PV. It is necessary to have specified energy circulation channels in order to properly characterize integrated systems and modular components of systems.[12]

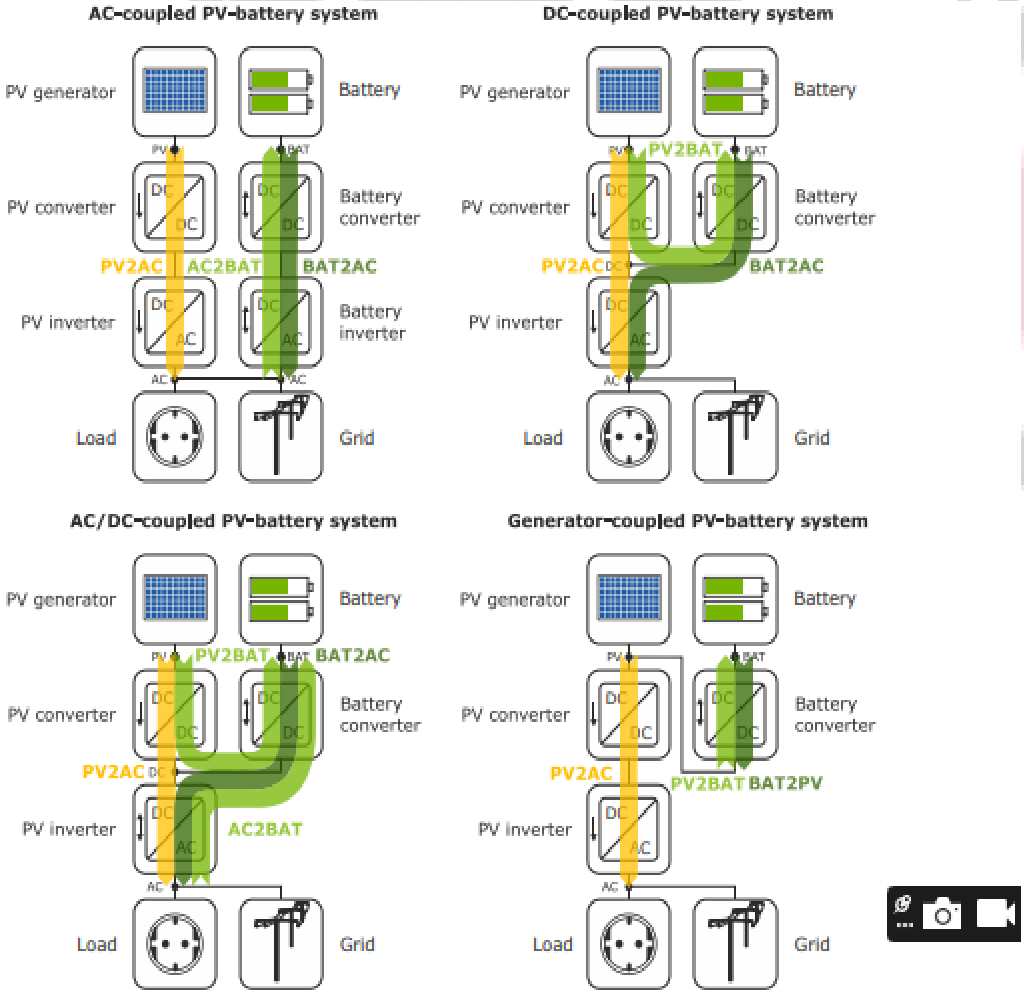

Figure 3 Schematic system configuration and relevant power flows of different topologies of PV-battery systems[12].

V.APPLICATION OF ARTIFICIAL INTELLIGENCE FOR POWER SYSTEM.

AI aims to execute an electrical system's layout [13], forecasting [14], control, optimizing, maintenance, and security [8], as shown in Figure 1. The features of design, forecasting, control, and maintenance are among the highlighted fields of AI application that have received the most attention in the literature. Cybersecurity components are evolving and were thought to be the upcoming developments for AI applications in PV power systems.[15] AI is being developed to help the system develop knowledge in the layout, control, and maintenance aspects for increasing efficiency and decreasing response time. This is made possible by an abundance of data in the performance of PV power systems. This strategy promoted data-driven research efforts to examine the intricate and difficult issues in electricity systems.

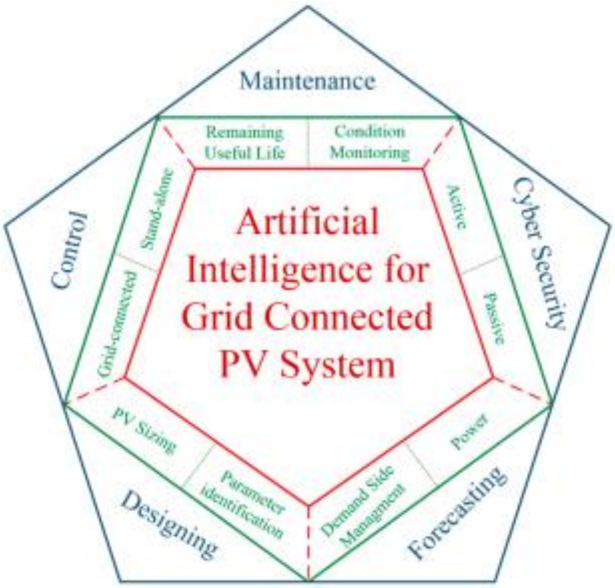

Figure 4. Application of artificial intelligence for power system.

A layout identifying the techniques between the function and application of AI in power systems is mapped as shown in Figure 5.[16]

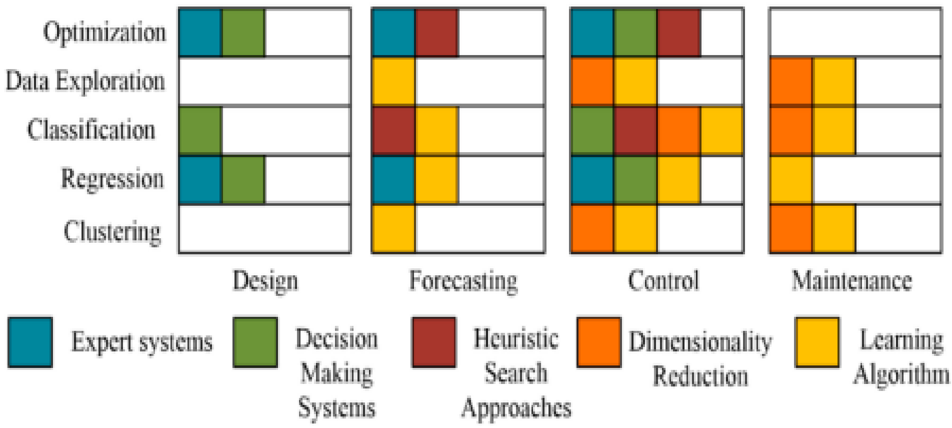

Figure 5. Generalization of different AI applications for the design, control, forecasting and maintenance of grid-tied PV systems.[17]

As the application of AI in solar PV is rather extensive, and several papers have reported good results, it must be noted that many of the proposed methods were performed in narrow case studies. These studies indicate that the relative degree of generalization of the models is low and does not produce similar results if applied to a different environment. In the given settings, the AI techniques in Figure 5 were deployed, and most of the results proved to outperform conventional methods in every applicable section[18].

V. CONCLUSION

The study underscores the pivotal role that artificial intelligence (AI) plays in advancing Maximum Power Point Tracking (MPPT) technology for solar photovoltaic (PV) systems. By harnessing AI's capabilities, particularly machine learning and optimization algorithms, significant strides have been achieved in enhancing productivity, response times, and ecological adaptability within solar energy generation. AI-based MPPT methods enable more precise and rapid tracking of the maximum power point (MPP) on the non-linear P-V curve of solar panels. This capability ensures that PV systems operate at peak efficiency under varying environmental conditions, such as changes in solar irradiance and temperature. Traditional MPPT techniques often struggle with these dynamic conditions, leading to suboptimal performance and reduced energy harvest. The comparative evaluation presented in the study highlights the clear advantages of AI-based MPPT over conventional methods. AI techniques exhibit superior performance in terms of efficiency, stability, and robustness, thereby demonstrating their potential to revolutionize the effectiveness of solar PV systems. These advancements not only contribute to maximizing energy output but also support sustainability goals by reducing reliance on fossil fuels and minimizing environmental impact.

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