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Learning of Maximum Power Point Tracking Architecture with Various Algorithms for Photovoltaic Systems: A Review

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Abstract

Currently, as the requirement on the Earth for ever more electricity grows, so too accordingly must demands upon renewable energy. These days, with the growth of renewable energy on all fronts, countries everywhere watch its development. Since demand for power generation goes up again, fossil fuels become less and less available, and expense is not coming down. When there is a rapidly changing irradiance, temperature, or partial shading, the output power from PV systems varies dramatically. In contrast, conventional MPPT techniques like P&O and INC have slow convergence rates. They are prone to steady-state oscillations, adapting poorly as the environment changes rapidly. For this reason, advanced AI-based MPPT approaches bring an improved level of tracking, most are based on a static neural network structure. Under complicated operating situations, these techniques provide improved capacity to determine the maximum global power point. When handling extremely dynamic environmental variables, their performance could still be constrained. As a result, intelligent and adaptable MPPT frameworks that can make decisions in real time and learn continuously are crucial. These methods may greatly enhance tracking accuracy, lower power losses, boost energy conversion efficiency, and guarantee steady PV system operation, all of which help meet the world's expanding need for dependable and sustainable renewable energy production. Under complicated operating situations, these techniques provide improved capacity to determine the maximum global power point. When handling extremely dynamic environmental variables, their performance could still be constrained. As a result, intelligent and adaptable MPPT frameworks that can make decisions in real time and learn continuously are crucial. These methods may greatly enhance tracking accuracy, lower power losses, boost energy conversion efficiency, and guarantee steady PV system operation, all of which help meet the world's expanding need for dependable and sustainable renewable energy production.

Keywords: Efficiency, maximum-power point tracking, Perturb and Observe, partial shading conditions, photovoltaic systems

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INTRODUCTION

Day or night Solar energy is an averting source at Earth's end output, and it often finalizes a nightmare but helps somewhat in averting the disaster. The present figure is a mere 1.7 % of the world's energy consumption. However, if everyone is going to use these new fuel sources as their primary source of electricity, it is estimated that as many as 950 million people will get on the bandwagon by 2040. It may then surpass 1TW for realized solar power capacity in 2025 as well [1–5]. Therefore, it can be said that solar PV power can contribute to the eco-environment. Its popularity is growing, especially in terms of renewable energy choices. Although PV power modules have the advantage of being waterproof, this method has its drawbacks. For example, the cost of PV panels is very high and their efficiency is low, and they degrade over time. Building a solar power plant is very expensive. Nevertheless, wind power systems only need to make some minor adjustments and they'll be able to generate electricity with reasonable efficiency across most of the country [6–11].

The efficiency of solar radiation-generated electricity by a solar PV module is usually below 17 percent, and the weather in the area where it is sited has a notable impact on this outcome. In solar PV, maximum power point tracking (MPPT) technology is used to extract as much power as possible from the PV panel. In solar PV MPPT, environmental and electrical inputs are the two basic system input parameters. Various algorithm-based MPPT approaches have already been developed to reach the maximum power point (MPP). Perturbation and observation (P&O) along with incremental conductance (based on the dQ/dV ratio) are two classical MPPT methods that are used most frequently because they are simple to implement and easy to understand. Installing photovoltaic (PV) systems has become an essential part of renewable energy because the world needs cleaner and environmentally friendly power [12–17]. Environmental circumstances, such as temperature and irradiance differences, in general or partial shading, fundamentally influence an actual r system. Although PV systems are widely used, environmental circumstances such as temperature and irradiance variations or partial shadowing still have a significant impact on the system's true efficiency [18–23].

Moreover, the current-voltage (I-V) and power-voltage (P-V) characteristics of the nonlinearity of the PV array shift according to these variable conditions. However, this is sometimes insufficient. To stabilize dependable energy harvesting, maximum power point monitoring (MPPT) has become essential [8]. In other words, solar power generation is a significant ecological issue. The means of transforming to power is a great ecological challenge. Photovoltaic systems (PVGS) are used to convert sunlight into energy. To measure the apparent conversion efficiency, the PVGS requires an MPP.So as to maintain the PVGS at the maximum power point (MPP) we will concentrate on a manipulation point called maximum power point tracking (MPPT). The MPPT employs an algorithm to ensure that the PVGS always operates at the MPP. Many MPPT techniques have been proposed. Each has unique advantages and disadvantages, as well as a unique MPP-tracking mechanism [9]. Because maximum power point tracking (MPPT) systems require a technique to maximize efficiency, proportional-integral-derivative (PID) controllers are typically used because of their flexibility and ease of use. [10]. Despite this, the simple design of the product often fails to meet the desired MPPT standards. As a result of their straightforward programming, traditional methods such as Perturb and Observe (PSO) and Incremental Conductance (INC) [12] have become widely accepted techniques. However, they cannot adapt to changes in their surroundings [11]. This paper considers only considered MPPT in PV. To reach the MPP, the MPPT controller is usually connected to the converter.

The DC-DC Boost converter was selected for several reasons to do this work. In the presence of a converter, this topology of the regulated current is physically more obvious because the switch losses and inductance are lower, and the current ripples are smaller under full-load conditions. If the power-voltage (P-V) curve has more than one peak, then those controllers are all discarded. Particle Swarm Optimizers (PSOs) and artificial neural network (ANNs) optimization techniques are better than traditional MPPT algorithms in medium-scale solar power stations; therefore, researchers are searching for more sophisticated algorithms to tackle these problems. Fuzzy Logic Controllers (FLCs) are drawing attention because they perform better than optimized artificial techniques such as ANN and PSO and can deal with nonlinearities and uncertainties within the system [24–26].

(11) Fuzzy logic controllers are especially suited to dynamic situations because they require experience and skill rather than exact system parameters or complicated models. For large-scale solar power plants, where external conditions can change dramatically over long periods, this is a now-or-never opportunity to use machine learning in MPPT. By automating the optimization process and allowing the MPPT controller to constantly adapt to different situations, machine learning may provide

high levels of tracking efficiency but with far lower computational costs. Automation still requires large datasets, and the complexity of Auto ML optimization techniques makes it very difficult to sufficiently reduce the training time for real-time implementation. However, doctrine holds out hope: one day, when new data become available and time has passed, ML will eventually allow fine-tuning possibilities to increase.

LITERATURE REVIEW

A new technique for creating a sliding mode maximum power point tracking (MPPT) controller for photovoltaic (PV) systems operating under rapidly changing atmospheric conditions was proposed [27]. Additionally, the optimum sliding mode controller (SLMC) gains, which are found using the genetic approach (GAO), drive the variable step of the typical perturb and observe (Pb&O) approach. For the best power control in the EV charging station, a PI controller, a grid using current-controlling topology, and an efficient charging station built with GAO-optimized Sliding Mode-based reconfigurable step size Pb&O as an MPPT controller were also implemented and evaluated. The primary contribution of this study is to improve the tracking performance of the developed controller to reach the maximum power point (MPP) with minimal oscillation, low overshoot, minimal ripple, and excellent speed in rapidly changing air turbulence conditions, as well as to guarantee supply continuity to the EV. The GAO-optimized sliding mode MPPT ensures fast, stable, and ripple-free tracking with reliable EV charging under variable weather conditions. However, its disadvantages include high computational complexity, dependence on accurate GA parameter tuning, increased implementation difficulty owing to hybrid controller design, and limited real-world validation for large-scale PV–grid–EV systems.

This study presents the modeling and control of an Off-grid Photovoltaic (PV) system consisting of a monocrystalline PV module, DC load, a DC-DC boost converter, and maximum power point tracking (MPPT) block. The output characteristics is nonlinear and vary with temperature and sun irradiation. Therefore, for given climatic conditions, the PV module output power is maximal when its voltage is equal to a certain value. When the temperature and solar irradiance change, the duty cycle of the converter, which is considered as the control law, is continuously adjusted to track the maximum power point (MPP) of the module. This study highlights the non-linear backstepping controller to extract the maximum power from the PV system. Lyapunov stability analysis was used to confirm the asymptotic stability of the system [28]. The proposed controller offers fast and accurate tracking of the MPP, regardless of changes in climatic conditions. The nonlinear Backstepping MPPT controller ensures fast and accurate tracking with proven stability; however, its disadvantage is that the tracking efficiency may decline under parameter uncertainties or modeling errors, and its design complexity makes real-time implementation more difficult compared to simpler MPPT methods.

A novel Flexible Power Point Tracking (FPPT) algorithm based on Genetic Algorithms (GAs) was presented in this study [29]. The algorithm was designed to effectively handle fluctuating solar irradiation levels and partial shading scenarios. The main objective was to enhance the power output and tracking accuracy under dynamic environmental conditions based on extensive simulations. The results showed superior performance in terms of power output, tracking accuracy, and convergence speed compared to traditional techniques. Its adaptability to changing environmental conditions renders it suitable for real-time implementation, thereby contributing to efficient power generation in PV systems.

The comparative analyses underscore the superiority of the GA-based FPPT algorithm, highlighting its potential to significantly improve power-point tracking in photovoltaic systems. This highlights the significance of adaptive algorithms in modern PV systems, particularly for reducing the effects of partial shading on energy yield. The GA-based FPPT algorithm provides high tracking accuracy, fast convergence, and adaptability under partial shading; however, its disadvantages include a higher computational load, potential slower response under very rapid irradiance changes, and dependence on proper GA parameter tuning for optimal real-time performance [30]. This study proposes a fast and accurate algorithm for global maximum power point tracking (GMPP) based on the sine-cosine algorithm (SCA) of a photovoltaic (PV) system for various weather changes. The performance of the proposed SCA algorithm demonstrates the superiority and efficiency of the PV system managed by the SCA algorithm. It has very low initial oscillation, very low MPP steady-state oscillation, fast response time, accelerated convergence speed, fast and accurate GMPP tracking, and PV system efficiency that increases under various weather conditions. Additionally, the resulting embedded software was integrated on an onboard "Arduino MKR ZERO board," which serves as a digital platform for implementing the suggested SCA algorithm, to validate it using the V-cycle validation and verification procedure. The Sine-Cosine Algorithm (SCA) MPPT achieves fast and accurate GMPP tracking with low oscillations and high efficiency; however, its disadvantages include increased computational complexity, sensitivity to algorithm parameter settings, and potentially slower adaptation under extremely rapid irradiance fluctuations compared to simpler heuristic methods.

This investigation presents a Corona-Virus Optimization (CVO) algorithm to harvest maximum power against seven well-known conventional and bio-inspired MPPT algorithms. The suggested method was calculated under conditions of Partial Shading (PS), Complex Partial Shading (CPS), and Uniform Irradiance (UI) [31]. Furthermore, the comparative analysis between seven already implemented and proposed techniques shows that the CVO algorithm lessens the unwanted oscillation and enables a quicker search for the GM. Moreover, a numerical analysis was conducted to evaluate the stability, robustness, performance, and sensitivity of the CVO algorithm. The proposed technique provides the highest efficiency. The Corona-Virus Optimization (CVO) MPPT achieves high efficiency, fast global maximum tracking, and reduced oscillations; however, its disadvantages include higher computational demand, complex implementation, and potentially slower real-time response under extremely rapid irradiance changes compared to simpler MPPT methods.

This study presents a new adaptive control framework to enhance the performance of MPPT, which minimizes the complexity of system control and efficiently manages uncertainties and disruptions in the environment and PV system. Here, the MPPT algorithm is decoupled from model reference adaptive control (MRAC) techniques, and the system gains MPPT with overall system stability [32]. Moreover, a mathematical model was formulated, and an efficient MRAC was designed for MPPT. The simulation outcomes indicate that the proposed controller exhibits excellent tracking under varying circumstances, such as solar radiation and temperature. The MRAC-based adaptive MPPT provides stable and efficient tracking under varying conditions; however, its disadvantages include a slower convergence speed compared to metaheuristic algorithms, sensitivity to model inaccuracies, and increased design complexity for real-time implementation.

This study proposes that the particular input for the photovoltaic module capable of generating the highest possible output power is called the maximum power point (MPP) or highest voltage. The maximum power changes with the Sun's energy parameter of the required temperature of the PV module [33]. This is in contrast to the dissimilar tracking techniques, such as the P-O methods. Furthermore, several components were used to compute the input parameters, which had their own uncertainties. This uncertainty was removed by using devices equipped with sensors comprising Industry 4.0 techniques. The values were delivered back by sensors, enabling error-free solar energy estimation. This delivers admirable outcomes; hence, they are employed. This system can be developed as a charge controller by employing a microcontroller-based circuit for the DC-DC buck converter and introducing MPPT.

A hybrid Maximum Power Point Tracking (MPPT) approach that can quickly adapt to fast-changing weather conditions is proposed. The proposed method entails the combination of a Perturb and Observe (P&O) MPPT technique with a Look-Up Table (LUT) algorithm [34]. The algorithm operates through a series of stages to attain the MPP with improved speed and accuracy in response to the observed variations in the input(s). The efficacy of the proposed approach in terms of MPP tracking performance was assessed through comprehensive simulation studies and experimental testing across diverse input conditions. The evaluation of the proposed two-stage algorithm involved an assessment of its tracking response, reliability, and accuracy in relation to other established methodologies. The proposed algorithm exhibits a satisfactory level of overall efficiency, as evidenced by excellent tracking efficiency even under frequently changing weather conditions. The hybrid P&O–LUT MPPT achieves fast and accurate tracking under rapidly changing weather with high efficiency; however, its disadvantages include increased algorithm complexity, dependence on accurate LUT data, and slightly slower convergence compared to purely heuristic or metaheuristic MPPT methods under extreme irradiance fluctuations.

To improve the tracking performance during abrupt changes in solar irradiation, this study suggests integrating a neural network (NN) with the P&O algorithm. When abrupt changes are detected, the suggested neural network modifies the duty cycle. Even with a small dataset used for training, it accurately forecasts the duty cycle change. Compared with the traditional P&O method, the combination of the NN with P&O greatly enhanced the tracking performance, particularly during abrupt changes in irradiance. The NN–P&O MPPT improves tracking performance under sudden irradiance changes and requires a small training dataset; however, its disadvantages include higher computational complexity, dependence on NN training quality, and potentially slower real-time response when processing rapid fluctuations compared to simpler P&O methods [35]. This study presents fault classification and optimized maximum power point tracking (MPPT) in solar photovoltaic (PV) systems. This study evaluates the tracking efficiency (TE) of solar PV systems using the nature-inspired dragonfly algorithm (DA), moth flame optimization algorithm (MFOA), grasshopper optimization algorithm (GOA), and salp swarm optimization algorithm (SSOA) to determine the optimal optimization model for MPPT under PSC. According to the simulation results, SSOA outperformed DA, GOA, and MFOA in terms of tracking efficiency. Random forest (RF), artificial neural network (ANN), support vector machine (SVM), and convolutional neural network (CNN) models are used to further categorize defects in solar PV systems. The SSOA-based MPPT achieves superior tracking efficiency under partial shading, and CNN enables high-accuracy fault classification; however, its disadvantages include high computational complexity, longer convergence time compared to simpler MPPT algorithms, and dependence on extensive training data for accurate fault detection [36].

This study investigates the state-of-the-art architecture of photovoltaic systems (PVS) by evaluating the performance of a developed maximum power point tracking (MPPT) algorithm based on fuzzy particle swarm optimization (FPSO) for temperate continental latitudes. The material of this study provides an evaluation of traditional MPPT algorithms in relation to the state-of-the-art FPSO algorithm. This study summarizes the problems of On-Grid PV systems and analyzes methods for solving them by combining them with hydrogen technologies. The effectiveness of the FPSO algorithm under the conditions of the inverter distance from the common point of the DC switching cabinet (DCCC) was confirmed. Effectiveness of the MPPT algorithm based on FPSO under partial shading conditions. The FPSO-based MPPT achieves robust tracking under partial shading and inverter distance variations; however, its disadvantages include high computational complexity, sensitivity to particle swarm and fuzzy parameter tuning, and longer convergence time compared to simpler MPPT methods, which may limit real-time responsiveness in rapidly changing irradiance conditions [37].

An intelligent nonlinear proportional-integral-derivative (NPID) controller coupled with a hybrid salp particle swarm optimization algorithm (SPSOA) was used to successfully harvest the GMP of a PV system. The performance of the SPSOA-NPID controller was measured in terms of the settling time, rising time, overshooting, peak time, undershoot, rotor rotation speed, and GMP under various realistic irradiation and temperature profiles. In this study, the optimum parameter settings for the proposed NPID and basic PID controllers were obtained using the hybrid genetic algorithm and PSO (GA-PSO) techniques. The proposed SPSOA-NPID performance was analyzed based on efficiency, the lowest average ripples, and the fastest average tracking time. Finally, a hardware-in-the-loop (HIL) experiment was conducted to confirm that the proposed SPSOA-NPID control can be practically implemented. Consequently, the proposed SPSOA-NPID-based GA-PSO control system is determined to be a potential MPPT approach. The SPSOA–NPID MPPT achieves fast tracking, low ripples, and high efficiency under varying conditions; however, its disadvantages include high computational complexity, dependence on accurate hybrid SPSOA parameter tuning, and challenging real-time implementation for large-scale PV systems owing to the combined optimization and nonlinear control design. An improved marine predator algorithm (IMPA) was proposed [38, 39] to extract the highest power point of a photovoltaic system under complicated sun irradiation circumstances. The opposition-based learning (OBL) technique was developed in IMPA to address the problems with the conventional marine predator algorithm (MPA), and the sine cosine algorithm (SCA) was incorporated into the iteration stage to improve the system's search capability [40–46].

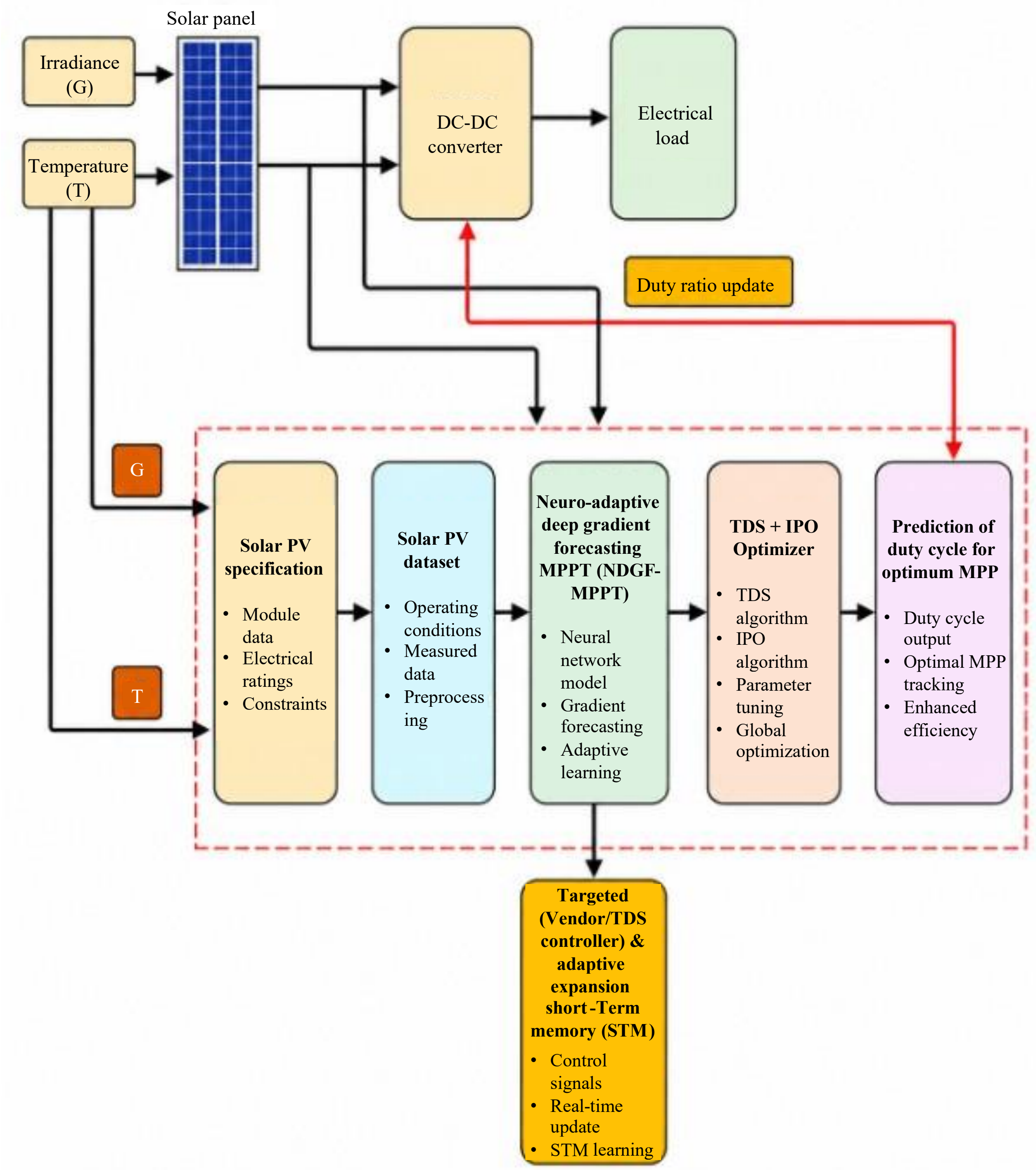

Figure 1. Proposed neuro-adaptive deep gradient forecasting MPPT (NDGF-MPPT) framework for solar PV systems.

CONCLUSION

This review examines the evolution of Maximum Power Point Tracking (MPPT) techniques for photovoltaic (PV) systems and highlights the limitations of conventional approaches under dynamic environmental conditions. Conventional techniques such as Incremental Conductance (INC) and Perturb and Observe (P&O) are straightforward and popular; however, they perform poorly in situations with partial shading and abrupt changes in irradiance. Recent advancements in artificial intelligence, machine learning, metaheuristic optimization, and adaptive control strategies have significantly improved the tracking accuracy, convergence speed, and energy extraction efficiency. Based on this analysis, the proposed Neuro-Adaptive Deep Gradient Forecasting MPPT (NDGF-MPPT) framework combines forecasting, adaptive learning, and intelligent optimization to enhance the performance of PV systems. The integration of the TDS-IPO optimizer further improves the duty-cycle selection for an efficient maximum power point operation. The proposed architecture is expected to reduce power losses, improve system stability, and ensure reliable operation under varying weather conditions. Future work will focus on real-time hardware implementation, computational optimization, and validation under large-scale PV installations to demonstrate the practical effectiveness and scalability of the proposed method for next-generation renewable energy systems.

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