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Exploiting PV System Performance: A Combined Approach Using MPPT, IoT, Cleaning, Cooling, and Neural Networks

Alaa Younus Rawdhan[1*] and Mohammed Sh Ahmed[2]

[1]*Department of the Electrical Engineering, College of Engineering, University of Tikrit, Iraq; alaa.y.rodhan44349@st.tu.edu.iq*
[2]*Tikrit University/ College of Petroleum Process Engineering Tikrit, Saladin Governorate, Iraq; mohammed.shwash@tu.edu.iq*

[*]**Correspondence:** Alaa Younus Rawdhan; *alaa.y.rodhan44349@st.tu.edu.iq*

ABSTRACT- This paper investigates the effects of three foremost methodologies—Maximum Power Point Tracking (MPPT), Internet of Things (IoT)-driven cleaning and cooling, and Neural Network Training (NNT)—on improving the efficacy of solar photovoltaic (PV) systems. Solar photovoltaic systems have considerable complications in sustaining maximum performance due to environmental conditions such as dust collection, temperature variations, and an insufficient energy management. A new control method is presented to challenge these difficulties, including MPPT, IoT-based cleaning and cooling, and NNT for the real-time optimization of PV systems. The simulation findings indicate a substantial increase in power production when both technologies are used together. Power generation is improved throughout a 24-hour period, especially during periods of low solar irradiation, by the coordinated use of MPPT, IoT, cleaning, and cooling techniques. The IoT-controlled technology enhances power production by 7–9% across many operating situations, especially in advantageous geographic settings, while simultaneously decreasing energy consumption. NNT dynamically modifies system settings in real-time, exceeding conventional optimization methods. The results underscore the potential of MPPT, IoT, cleaning, cooling, and NNT to markedly enhance the efficiency and productivity of solar PV systems, tackling the primary concerns of dust collection, elevated temperatures, and suboptimal energy management.

Keywords: PV system, IOT, MMPT, NNT, power composition.

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1. INTRODUCTION

Renewable energy sources, such as solar power, are supplanting finite resources like oil and coal, impacting the global energy sector. Photovoltaic systems are often used for collecting solar energy, rendering it a favored renewable option. Solar photovoltaic systems provide advantages compared to other renewable energy sources; yet, they also encounter challenges. Photovoltaic modules with series or parallel cells generate energy in sunshine. Temperature, wind, and precipitation influence the effectiveness and reliability of these systems. Dust may significantly impede solar panel efficiency in dry environments.

Solar photovoltaic systems have emerged as a fundamental component of renewable energy solutions, owing to its capacity to incarceration plentiful solar energy with no environmental repercussions. Notwithstanding their extensive use, photovoltaic systems encounter intrinsic constraints like energy losses due to soiling, overheating, and inefficiencies in power conversion under variable sun irradiation. These issues emphasize the need for sophisticated optimization methods to enhance energy output, especially during times of low irradiance and under adverse climatic circumstances. This work is motivated by the possibility to integrate MPPT, IoT-based cleaning and cooling systems, and NNT to dynamically improve PV system performance in real-time. This study is significant as it illustrates how an integrated strategy may alleviate prevalent inefficiencies, resulting in considerable enhancements in power production, system dependability, and overall operating efficiency.

Dust accumulation can reduce solar panel efficiency by up to 20% daily, particularly in summer months. This significant loss has a direct impact on the overall efficiency of solar power systems. Alamri et al. [1] applied hydrophobic SiO_2 nanomaterial to solar PV panels, showing that manual cleaning improved panel efficiency by 15% for dust-covered panels and by 5% for already clean ones. The study suggests that incorporating nanoparticles can enhance solar panel performance. However, daily cleaning remains essential for maintaining efficiency, even though it may be costly and time-consuming.

M. Altıntaş and S. Arslan [2] explored the effectiveness of electrostatic cleaning devices for removing dust from solar panels. Their work examined modern cleaning techniques, the chemical composition of dust, and its effects on solar panels. By comparing a newly designed electrostatic cleaning device with traditional methods, they evaluated its cleaning efficiency and the associated electrical losses under varying operational

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conditions, highlighting how different cleaning techniques can enhance solar system efficiency.

Nasser and Younis [3] investigated advanced management systems such as cleaning, cooling, and auto-tracking to improve solar panel efficiency. They emphasized the importance of better Maximum Power Point Tracking (MPPT) and neural networks to optimize system performance. Their study highlighted the role of MPPT, cleaning, and cooling in significantly affecting solar panel output.

Chellal et al. [4] focused on advanced robotic technology for solar panel cleaning, emphasizing the importance of frequent maintenance for optimal performance. Their research discussed the potential of artificial intelligence, particularly neural networks, in automating cleaning and cooling processes to boost efficiency. Similarly, King et al. [5] developed a mathematical model for a compressed air system used to clean and cool PV panels, further reinforcing the need for efficient cleaning and cooling techniques to enhance panel output.

Biswas [6] proposed an IoT-based smart system for solar panel cleaning and monitoring. This approach uses microcontrollers and sensors to eliminate dust and grime that hinder power output, thus ensuring the sustainability of solar energy systems. In a related study, Noh et al. [7] developed a waterless, fully automated cleaning system for solar panels, improving performance through enhanced MPPT, cleaning, and cooling processes.

Badhoutiya (2023) also emphasized the need for regular cleaning and maintenance of solar panels to maximize production, highlighting the importance of MPPT, cleaning, and cooling systems for increased efficiency and sustainability. Bhandari [9] studied a semi-automatic cleaning system and advocated for neural networks in reducing maintenance costs and promoting the growth of solar energy.

Samuel and Rajagopal [10] supported the use of an IoT-based cleaning system for PV panels, stating that dust control, intelligent analysis, and system control can boost efficiency. Their method integrates neural networks to enhance MPPT, cleaning, and cooling for optimized solar conversion, underscoring the importance of predictive maintenance and new technologies in maximizing solar energy use.

Ramalingam [11] proposed using IoT technology to regulate cleaning, improving the efficiency of photovoltaic systems for intelligent solar maintenance. This study emphasized the benefits of enhanced cleaning for improving both the effectiveness and durability of PV panels. Similarly, SUBRAMANIAN, Amin et al. [12] developed a robotic system to reduce dust accumulation on PV panels, showing that automated cleaning processes improve power generation and reduce maintenance costs by eliminating the need for human intervention.

The study by Chadly [13] introduced an AI-powered cleaning robot that uses a convolutional neural network (CNN) model to remove dirt and bird droppings from solar panels, demonstrating improvements in panel efficiency, power output, and lifespan. Vinoth et al. [14] echoed the necessity of regular cleaning to maintain solar panel efficiency and longevity, noting that routine maintenance extends the life of solar panels while maximizing power output.

Finally, Chadly [15] suggested better management of solar PV system administrators to account for weather-related efficiency losses. The research concluded that effective cleaning techniques derived from literature can substantially improve solar panel cleaning and overall system efficiency.

2. OBJECTIVES

In general, this study focuses on enhancing the effectiveness of various aspects of solar panels; these include a control system for MPPT, automated cleaning, and cooling using a neural network.

1. To create and apply the maximum power point tracking technique of the photovoltaic panels using the proposed neural network-based optimization algorithm for increasing the MPPT efficiency and hence the power generated.
2. Relative to this aim, the following objectives are proposed: The development of a novel automatic cleaning and cooling control system for photovoltaic systems with the use of neural networks for efficiency enhancement under different climate climates.
3. The purpose of this study is to determine the actual enhancement in the sun power conversion and the decrease in the power consumption through the application of optimized MPPT accompanied by cleaning and cooling systems through neural network techniques.

3. MATHEMATICAL MODEL

This mathematical model provides a foundation for designing and implementing a neural network to improve the maximum power point tracking (MPPT), cleaning, and cooling capabilities of solar panel systems. The model integrates data collection, training of neural networks, control methods for cleaning and cooling based on real-time environmental data from the Internet of Things (IoT), and optimization of maximum power point tracking (MPPT).

a. MPPT Optimization

1. Initial Setup:
   - Initial angle: $\theta = 35^o$
   - Initial conditions: $E_o = 1000\ \frac{W}{m^2}$
   - $T0 = 25^oC$
   - $H0 = 50\%$
   - Previous power: $P_{prev} = 0$

b. Irradiation Simulation

- At each time step t, simulate the change in irradiation

$$E_t = E_{t-1} + \Delta E \qquad (1)$$

where ΔE *a random step change within* $[-100{,}100]\ W/m^2$.

c. Voltage and Current Simulation

- Open-circuit voltage V_{oc} and short-circuit current I_{sc}:

$$V_{oc,t} = E_t \times 0.01\ \ (volts) \qquad (2)$$

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$$I_{sc,t} = E_t \times 0.05 \ (amps) \quad (3)$$

- Voltage and current at maximum power point (MPP):

$$V_{mpp,t} = V_{oc,t} \times 0.8 \quad (4)$$

$$I_{mpp,t} = I_{sc,t} \times 0.9 \quad (5)$$

d. Cleaning and Cooling Control

Linear temperature increment $T_t = T_{strat} + t \times \left(\frac{T_{end} - T_{start}}{time\_steps}\right)$ (6)

Cleaning control based on irradiation: $L_t = \begin{cases} 1 & \text{if } E_t < 500\ W/m^2 \\ 0 & \text{otherwise} \end{cases}$ (7)

Cooling control based on $Irr\ (E_t)$ and T_t :

$$C_t = \begin{cases} 1 & if\ E_t > 1000\ or\ T_t > 40 \\ 0 & otherwise \end{cases} \quad (8)$$

e. ***Logging Data*****: Log the optimal angle, power, voltage, current, irradiation, temperature, humidity, and control signals at each time step.**

Performance Analysis: average power for each θ :

$$avg\_power(\theta) = \frac{1}{|\{t:\theta_t=\theta\}|}\sum_{t:\theta_t=\theta} P_t \quad (9)$$

f. IoT-Enabled Cooling System

Use IoT sensors to monitor temperature. When temperatures reach specific limitations, activate the cooling system. Improve cooling with predictive maintenance. Thus, Integrating of IoT enabled cleaning and cooling devices along with MPPT technology might enhance the efficiency of solar PV system. Cleaning devices can detect the level of dust and/or debris on solar panels and clean them on its own through IoT. IoT-based cooling devices may also regulate temperatures of solar panels to reduce on heat-based efficiency losses. It is discussed in the paper that MPPT, IoT based cleaning and cooling could increase the efficiency of the solar PV systems.

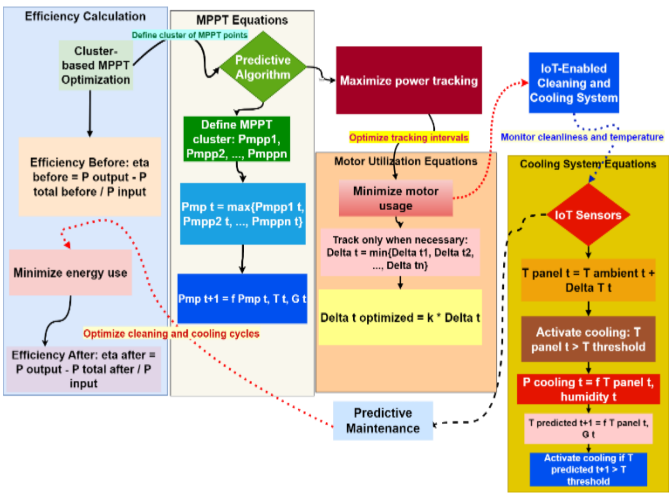
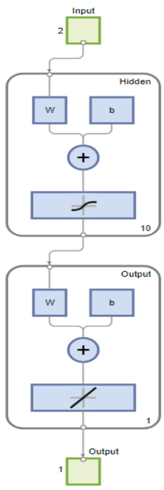


Figure 1. Diagram explanation details describe how the proposed MPPT solution is integrated with the IoT-based cleaning and cooling systems for the further increase in the efficiency of the solar PV systems in details, where all the mathematical equations and efficiency coefficients introduced are provided.

Enhancing the efficiency of photovoltaic (PV) systems plays a crucial role in increasing renewable electricity production while minimizing environmental impact. This study aims to improve energy generation in PV systems by integrating Maximum Power Point Tracking (MPPT), cooling, cleaning, and Internet of Things (IoT) technologies. The proposed approach seeks to optimize power management, reduce energy consumption, and mitigate negative effects on the environment [16]. The efficiency of a photovoltaic energy conversion system is largely influenced by the quality of the modules and their compatibility with the load [17], [18]. Achieving system-wide optimization requires real-time, accurate, and large-scale sensing [19]. Effective system design strategies capture environmental energy and make it accessible for conversion and storage [20]. This research also investigates power management solutions that account for fluctuations in energy supply and demand within the system and its network [21]. The article outlines the design and implementation of a complex domestic energy system consisting of PV modules, energy storage banks, and grid-connected converter circuits. One of the primary challenges addressed is daily energy flow control, aimed at maximizing cost savings while optimizing the specifications of PV modules and energy storage (EES) bank capacity. Daily optimization results are analyzed to determine the best system configurations within a given budget [22]. The proposed strategy optimizes power management across renewable energy sources, storage technologies, and varying load demands. In addition to covering its initial investment, the system is projected to deliver an annual return of up to 8% [23]. By incorporating a network architecture that integrates MPPT, cooling, cleaning, and IoT systems, solar energy efficiency is significantly improved. This method enhances power control, storage, and overall solar power utilization, while reducing costs and minimizing environmental impact.

g. Neural Network Design

Figure 2 depicts the feedforward neural network with input layer, hidden layer and output layer of the network. These are the input parameters; the beginning angle, the current irradiance, the temperature, and the humidity. Output parameters consist of; Optimum angle of cleaning signal and cooling signal.



(a)

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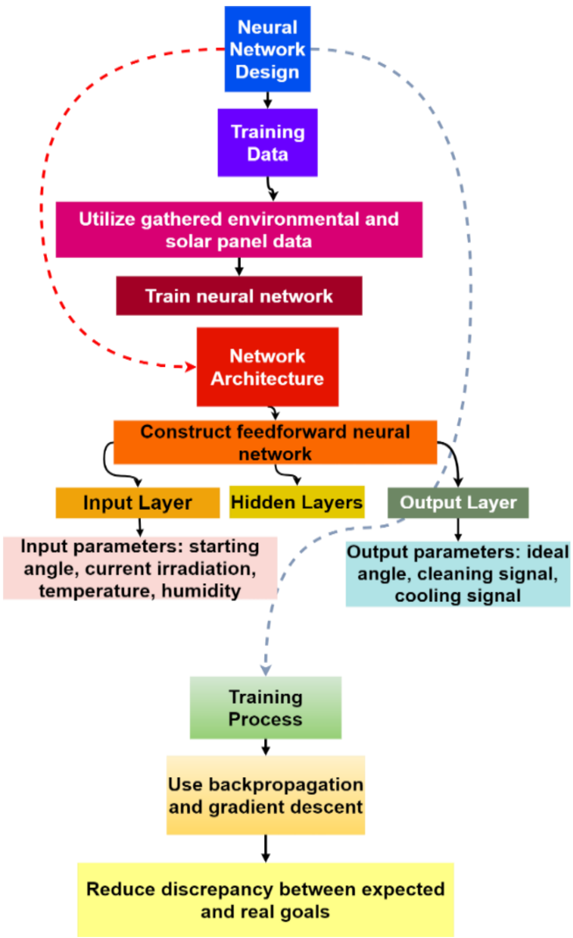

(b)

Figure 2. ***(a)*** Block Diagram and ***(b)*** flowchart of NNT Using in PV system

Training Data

In this case we want to train a neural network using the environmental and solar panel data. According to the gathered data, this network pursues the optimal angle, cleaning, and cooling.

Backpropagation with gradient descent is used to train the neural network. The intention is to reduce the difference that exists between expected and achieved goals.

Network Architecture

- Let $x = [\theta, E, T, H]$ be the input vector where:
  - o θ is the initial angle of the solar panel,
  - o E is the current irradiation,
  - o T is the temperature,
  - o H is the humidity.

- The neural network $f(x; w)$ has parameters w (weights and biases) and outputs $y = [\theta_{opt}, C, L]$ where:
  - o θ_{opt} is the optimal angle,
  - o C is the cooling signal,
  - o L is the cleaning signal.

Training Data

Inputs $x_i = [\theta_i, E_i, T_i, H_i]$ for $i = 1,2,\dots,N$ (10)

Targets: $y_i = [\theta_{opt}, C_i, L_i]$ for $i = 1,2,\dots,N$ (11)

Training Process

The loss functions $\mathcal{L}$ you should use is the mean squared error(MSE), which is the average of the squared differences of the expected and real targets.

$$\mathcal{L} = \frac{1}{2}\sum_{i=1}^{N}\|f(x_i; w) - y_i\|^2 \quad (12)$$

Minimize the loss function using back propagation which adjusts the parameters w by using gradient descent algorithm.

$$w \leftarrow w - \eta\nabla_w\mathcal{L} \quad (13)$$

where η is the learning rate.

4. NEURAL NETWORK OPTIMIZATION

Neural network optimization entails enhancing the efficacy of neural networks by the modification of parameters, including weights, biases, and learning rates. This procedure often employs optimization methods such as gradient descent, which systematically reduces the loss function to enhance model accuracy. Advanced methods, such as Adam or RMSprop, are often used to expedite convergence and mitigate problems like as disappearing or ballooning gradients. In the realm of solar PV systems, neural network optimization may provide real-time adjustments of operational parameters to enhance energy output. Utilizing extensive information, neural networks may adeptly discern patterns and provide accurate predictions that improve overall system performance.

- Input to the neural network: $x_t = [\theta_t, E_t, T_t, H_t]$ (14)
- Neural network output: $y_t = f(x_t; w) = [\theta_{opt,t}, C_t, L_t]$ (15)
- Update the angle: $\theta_{opt,t} = y_{t,1}$ (16)
- Ensure $\theta_{opt,t}$ stays within [35^o , 65^o]: $\theta_{opt,t} = \max(35, min(\theta_{opt,t}, 65))$ (17)

5. SIMULATION RESULTS

In the simulation studies the effectiveness of MPPT in combination with IoT based cleaning and cooling has been analyzed which showed the improvement in the performance of the solar photovoltaic (PV) systems. This, in turn, increases the supply of renewable energy hence improving environmental management. *Figure 3* illustrate the power produced by a photovoltaic (PV) system where different improvement aspects have been applied as well as where they have not been applied. These approaches include Maximum Power Point Tracking (MPPT), Internet of Things (IoT) optimization, cleaning, and cooling. This *figure* portrays four separate curves.

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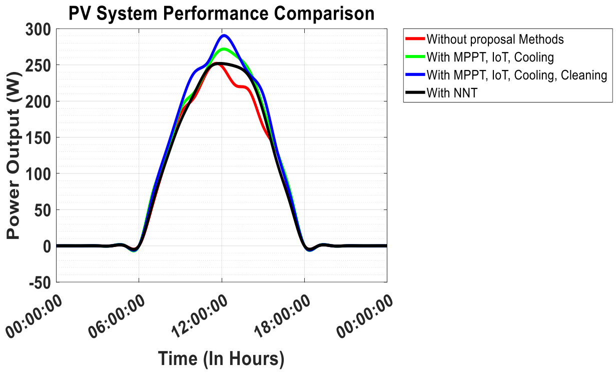

Figure 3. Illustrates the power production of a photovoltaic (PV) system under several circumstances.

The red curve represents the original power production without any improvement. Conversely, the green curve illustrates the power output achieved after employing these improvement IOT and cooling system, the blue curve represents the system with improving MPPT, using IOT, Clean system, and cooling system. It emphasizes the ways in which these strategies enhance the efficiency of power generation throughout the day, especially during the hours of lowest solar irradiation, resulting in improved performance. *Figure 4* demonstrates the effect of using (IoT) technology to regulate the motor's motion for (MPPT) in a photovoltaic (PV) system. This figure illustrates a significant rise in power generation, with enhancements of 7% and 9% seen across different circumstances. The IoT system uses dynamic motor positioning to continually monitor and optimize the operating point of the PV panel. This ensures that the panel runs at its maximum power output, considering prevailing environmental factors such as irradiance and temperature. Through the efficient use of IoT for controlling the (MPPT) process, *figure 4* provides visual proof of how IoT-driven MPPT improves the performance of PV systems, it illustrates the use of IoT technology to enhance MPPT, leading to substantial improvements in power generation. It also offers vital information on the advantages of smart control systems in renewable energy applications. The significant increase in power output, with improvements of 7% and 9% seen in distinct circumstances. The enhancement demonstrates that the (IoT) enables immediate modifications, leading to optimal consumption of solar energy and enhancing the efficiency of the photovoltaic (PV) system. The Bar charts illustrate these enhancements. Usually, that display the power output with and without IoT-controlled MPPT. These bar plot emphasize the percentage gain obtained in each scenario. It is essential to comprehend the conditions in which the 7% and 9% enhancements take place. The reported power production improvements would be influenced by factors such as solar irradiance levels, temperature fluctuations, and the efficacy of IoT algorithms in adjusting to these variables. *Figure 5* presents hourly energy generation in a simulation. The baseline production rate is set at fifty units per hour, with minor fluctuations. The energy consumed by the motor for continuous tracking remains constant throughout each hour. The IoT system's power consumption during continuous operation is referred to as "IoT used." The "Optimized IoT Consumed" metric quantifies the reduced power consumption achieved by the IoT system under optimal operation. The *figure* also depicts intermittent energy monitoring and production alongside continuous monitoring, highlighting hourly energy generation rates.

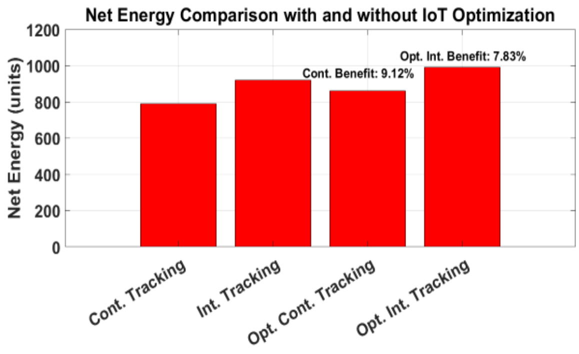

Figure 4. Illustration the bar plot for Power generation using IOT

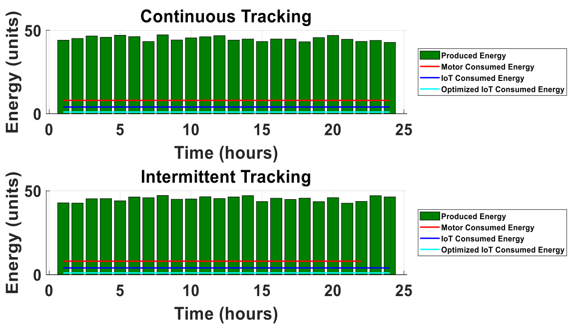

Figure 5. Illustration the continuous and intermittent MPPT

5.1 Effects of Neural Network Training (NNT)

The performance of the PV system is boosted via Neural Network Training (NNT), surpassing traditional methods. Increased Power Output helps. *Figure 4* shows how NNT boosts power. NNT easily outperforms other methods in real-time forecasting and optimizing operational parameters. A detailed analysis of the data shows that MPPT, IoT, cleaning, cooling, and NNT increase PV system efficiency and productivity *figure 6*. *Figure 6a* shows the neural network model's training, validation, and test results. The total of the square of the difference between anticipated and actual values, or mean squared error (MSE), is shown at each epoch. The histogram in *figure 6b* shows the distribution of training errors, or variations between anticipated and actual values. This helps measure model accuracy and bias. *Figure 6c* shows a regression analysis histogram comparing the mean of predicted and actual power output. Key elements of simple regression are shown to show the regression line, degree of fit, and quality of fit. The Training State Plot (*Figure 6d*) plots Training Gradient, Learning Rate, Validation Checkpoint, etc. vs epochs. This *figure* provides crucial neural network training information.

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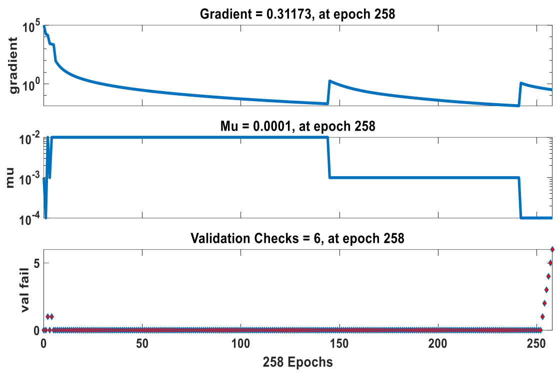

Figure 6a. Performance Plot

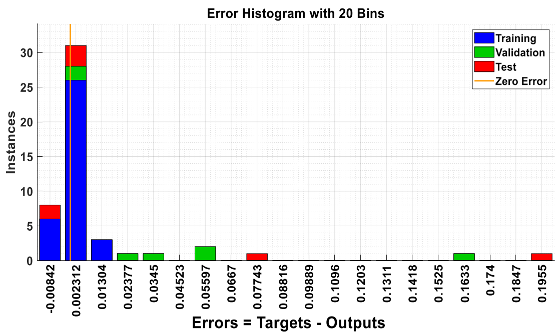

Figure 6b. Error Histogram

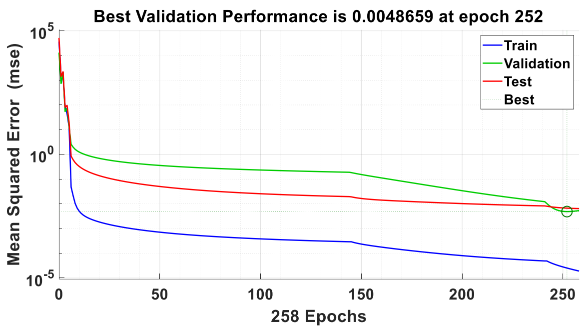

Figure 6c. Regression Plot

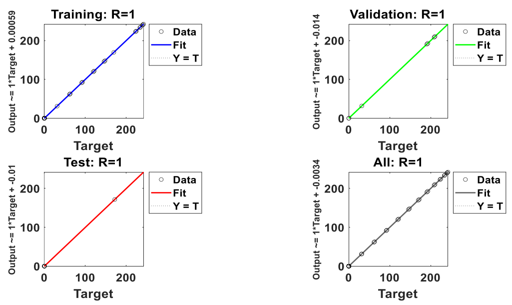

Figure 6d. Training State Plot

5. CONCLUSIONS

The simulation findings indicate that the incorporation of Maximum Power Point Tracking (MPPT) with IoT-based cleaning and cooling systems yields a little improvement in solar photovoltaic (PV) performance. This integration facilitates renewable energy production and aids in environmental conservation. The integration of optimization methods, such as MPPT, IoT, cleaning, and cooling, improves power production efficiency, especially in conditions of low solar irradiation. The integration of IoT in motor control for MPPT systems enhances power production, yielding gains of 7% and 9% under varying situations. The IoT system enables the ongoing modification of the motor constant, enhancing the placement of the PV panel to optimize power output in response to external variables such as irradiance and temperature. Examples of hourly power output demonstrate consistent consumption under continuous monitoring and decreased power use under optimum IoT management.

This paper indicates that regular energy monitoring and production improve system efficiency. Furthermore, the integration of Neural Network Training (NNT) significantly enhances photovoltaic (PV) system performance, effectively double the advantages realized by traditional approaches. NNT dynamically modifies the system's operating settings in real-time to guarantee optimum performance. The amalgamation of MPPT, IoT, cleaning, cooling, and NNT significantly improves the efficiency and productivity of photovoltaic systems, hence augmenting solar energy use and total power output. Future works should investigate sophisticated machine learning methods beyond NNT to enhance energy generation and achieve superior performance gains. Furthermore, exploring hybrid methodologies that integrate various optimization strategies, such as fuzzy logic control or deep learning models, with IoT-enabled photovoltaic systems may provide superior outcomes. Enhancing the system's scalability for bigger photovoltaic farms and assessing the economic viability of these technologies will be essential for widespread implementation. Finally, examining the long-term impacts of IoT-controlled cleaning and cooling systems on panel longevity and maintenance expenses may provide significant insights into system durability and sustainability.

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