AI applications in maximum power point (MPP) tracking, power forecasting within PV systems

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Abstract:

The rapid evolution of artificial intelligence (AI) technologies has greatly improved the efficiency and effectiveness of photovoltaic (PV) systems, particularly in the areas of Maximum Power Point (MPP) tracking and power forecasting. MPP tracking is essential for optimizing solar energy extraction under fluctuating environmental conditions, different temperature and irradiance. AI algorithms, including neural networks and reinforcement learning, are increasingly utilized to dynamically adjust operating points in real-time. In this paper, the AI technology's offer enhanced adaptability and accuracy especially in the face of rapidly changing weather.

AI-driven power forecasting significantly enhances the ability to predict solar energy generation by utilizing historical data, meteorological information, and better grid management and energy resource allocation. The incorporation of AI in MPP tracking and power forecasting not only optimizes energy output and reliability but also promotes the sustainability and economic feasibility of solar energy systems. AI technology continues to advance, its applications within PV systems promise substantial improvements in energy efficiency and operational performance.

Key words: Artificial Intelligence (AI), Maximum Power Point (MPP) Tracking, Photovoltaic (PV) Systems, Solar Energy, Power Forecasting.

تطبيقات الدكاء الاصطناعي في تتبع نقاط الطاقة القصوى والتنبوبالطاقه داخل الأنظمة الكهروضوئية

الملخص

لقد أدى التطور السريع للدكاء الاصطناعي إلى تحسن بشكل كبير في كفاءة فعالية الأنظمة الكهروضوئية، على وجه الخصوص في مجالات تتبع الحد الأقصى لنقطة الطاقة والتنبؤ بالطاقة. يعد تتبع الحد الأقصى ضروريًا لتحسين استخراج الطاقة الشمسية في ظل تقلبات الظروف البيئية ودرجات الحرارة المختلفة والإشعاع. خوارزميات الذكاء الاصطناعي، بما في ذلك الشبكات العصبية والتعلم المعزز، يتم استخدامها بشكل متزايد لضبط نقاط التشغيل ديناميكيًا في الوقت الفعلي. في هذه الورقة، توفر تقنية الذكاء الاصطناعي قدرة معززة على التكيف والدقة خاصة في مواجهة التغير السريع في الطقس.

التنبؤ بالطاقة المعتمدة على الذكاء الاصطناعي بشكل ملحوظ يعزز القدرة على التنبؤ بتوليد الطاقة الشمسية من خلال استخدام البيانات التاريخية ومعلومات الأرصاد الجوية، وتحسين إدارة الشبكة وموارد الطاقة. دمج الذكاء الاصطناعي في تتبع الحد الاقصى والتنبؤ بالطاقة لا يؤدي إلى تحسن إنتاج الطاقة فحسب، ولكنه يعزز أيضًا الاستدامة والجدوى الاقتصادية لأنظمة الطاقة الشمسية.

تستمر تكنولوجيا الدكاء لاصطناعي وتطبيقاتها في التقدم في مجال الأنظمة الكهروضوئية مما يساهم بتحسينات كبيرة في كفاءة الطاقة والأداء التشغيلي.

الكلمات المفتاحية: الذكاء الاصطناعي، القوة القصوى تتبع النقاط الأنظمة الكهروضوئية، الطاقة الشمسية.

I. Introduction

AI an increasingly important role in the renewable energy sector is played. It has the potential to optimize various aspects of renewable energy systems. Energy generation efficiency is improved, and enable better integration of renewable sources into the grid. Artificial intelligence in renewable energy offers tremendous potential to facilitate the transition to a clean energy future. By harnessing AI technologies, renewable energy systems can become more efficient, reliable, and economically viable, ultimately speeding up the global move towards sustainable energy sources [1]. The main sources of renewable energy generation can be categorized into several primary types; hydrogen energy, wind energy, solar energy, hydro energy, geothermal energy, bioenergy, and ocean energy [2].

AI techniques can assess large volumes of data, including satellite imagery, weather patterns, and historical energy production information, to pinpoint ideal sites for renewable energy projects. This analysis aids in optimizing energy generation potential and minimizing initial costs [3]. The forecast renewable energy generation based on historical data by using AI algorithms, weather forecasts, and real-time sensor data. Precise energy forecasting is essential for integrating renewables into the grid and managing the variability associated with sources such as solar and wind [4]. AI enables real-time monitoring and control of renewable energy systems and operations of grid. In addition, the scheduling of power generation, storage, and demand response systems to ensure efficient and stable operation of the grid are optimized [5]. Prediction of equipment failures in renewable energy systems can analyze sensor data and identify patterns with AI. By identifying potential issues early on, maintenance can be scheduled proactively, which helps minimize downtime and lower maintenance costs. In [6], AI algorithms can examine market data, energy prices, and demand patterns to enhance energy trading strategies. Additionally, they can aid in market analysis by forecasting future price trends, uncovering market inefficiencies, and optimizing energy portfolios.

The integration of renewable energy sources into the current power grid by managing bidirectional energy flows are enhanced by AI, optimizing energy routing, and balancing supply and demand in real-time. [7]. Also, energy storage systems by analyzing historical data and real-time energy demand and supply is optimized. It helps in enhancing grid stability, identification of the optimal charging and discharging schedules of energy storage devices, and decreasing the costs [8]. AI algorithms of energy demand patterns is predicted, allowing utilities for optimizing load forecasting and implement demand response. This helps in balancing supply and demand, reducing peak loads, and optimizing energy utilization [9]. Energy consumption patterns in buildings and industrial processes to identify energy-saving opportunities is analyzed by AI. Also, provide insights to optimize energy consumption, energy efficiency improvement, and carbon footprints reducment [10].

Significant role in renewable energy generation is effected with the Weather conditions. Integrating weather with AI of renewable energy systems for real-time monitoring of weather parameters; solar radiation, wind speed, and temperature are detected. This data, combined with historical weather can be used for accurate weather forecasting, which is essential to optimize generation unit and grid integration [11]. AI utilizes the communication and interaction between renewable energy systems and the smart grid. Smart electric meters; enable bidirectional communication, providing real-time information on energy consumption and allowing for demand response all programs. The integration of grid stability, load balancing, and energy management are optimized [12].

AI enable remote monitoring and control of renewable energy systems, capability allows operators and maintenance teams to monitor system performance, detect anomalies, and remotely control equipment, reducing the need for physical site visits. In [13] Remote monitoring and control improve operational efficiency, minimize downtime, and allow for quick responses to any issues that arise. AI can consolidate data from various sources within a renewable energy system, such as sensors, controllers, and other devices. Data aggregation facilitates a comprehensive view of system performance and enables cross-analysis of different parameters. Integration with data management systems and cloud platforms allows for centralized storage, processing, and analysis of data from various sources [14]. AI can be readily deployed and adjusted in scale according to the specific needs of a renewable energy system. It provides flexibility in terms of sensor types, communication protocols, and data collection frequencies, enabling customization to meet system requirements [15].

The size of hybrid power generation systems is optimized; a particle swarm optimization algorithm is employed due to its efficiency and ability to converge on optimal solutions. The algorithm proved to be more effective than the traditional genetic algorithms in [16]. The simulated annealing algorithm proved to be more effective at reducing the overall cost of the hybrid power generation system, delivering better results than the response surface methodology [17]. In this paper, AI systems can predict energy demand, facilitating a better alignment of power generation from photovoltaic (PV) systems with consumption patterns, which in turn improves grid stability in response to changing conditions.

II. VOLTAGE –CURRENT CHARACTERISTIC OF SOLAR ARRAY

The algorithm creates a model that mimics the behavior of the solar panels and their power output in Fig. 1. AI is designed to learn how the power output of the panels changes with varying conditions, irradiance and temperature. The parameters of the neural network to optimize its accuracy in predicting the maximum power point where the panels generate the most energy and the efficiency of the MPPT process are improved [18].

AI can adapt to changing environmental factors, leading to better energy capture from the solar panels. This can result in increased overall energy output from the PV system, contributing to more efficient and effective utilization of solar energy. Fig. 2, V-I and V-P characteristics of a solar panel under different irradiance levels, it is important to understand how these parameters are affected by changes in irradiance. At higher levels of irradiance, the solar panel will produce more current and voltage, resulting in increased power output. This is because higher irradiance levels provide more energy for the solar cells to convert into electricity. Fig. 3, the I-V and V-P characteristics of a solar panel at temperature increases, the efficiency of solar panels decreases, leading to lower power output. This is because higher temperatures cause solar cells to operate less efficiently [19].

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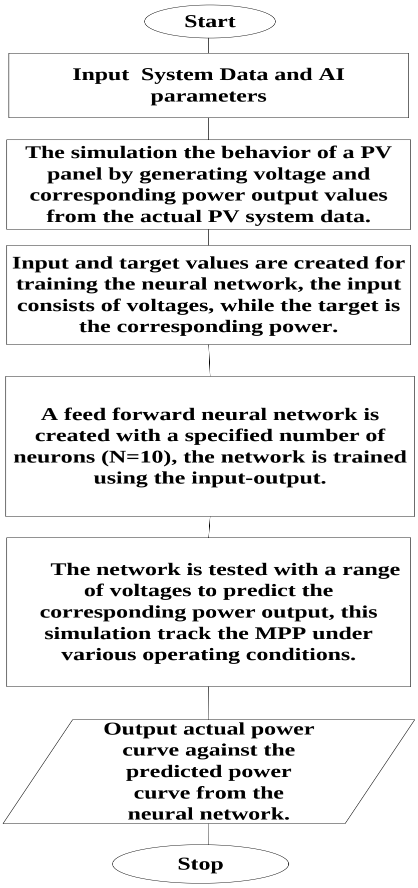

Fig.1 flow chart of power forecasting PV systems using AI

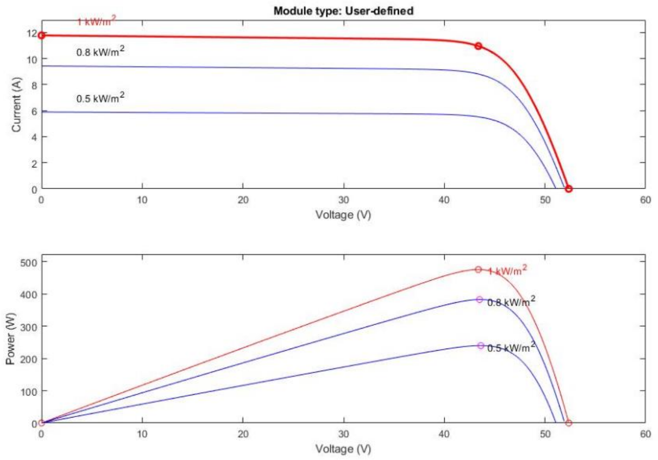

Fig. 2 V/I & V/P characteristics under different irradiance

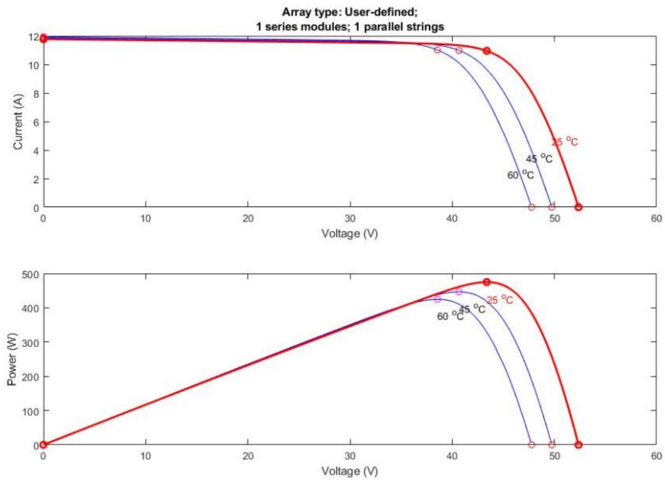

Fig.3 V/I & V/P characteristics under different temperature

III. ARTIFICIAL INTELLIGENT DESIGN OF POWER FORECASTING

AI is a comprehensive term commonly used alongside deep learning and machine learning. Fundamentally, AI refers to a computer system's capacity to carry out tasks that usually necessitate human intelligence, including decision-making. This definition includes a broad array of capabilities that are perceived as requiring human intellect. AI is classified into several categories: narrow AI, general AI, and super AI. Narrow AI is created for specific tasks and functions within a limited context, whereas general AI seeks to mimic human intelligence and behavior, enabling it to learn and tackle a variety of problems. Super AI, in contrast, refers to the theoretical capability of machines to not only solve any problem but also exceed human performance and possess self-awareness [20]. ANNs represent a critical and powerful methodology within the broader field of AI, enabling various applications energy systems; photovoltaic technology. Their ability to learn from data and identify patterns makes them particularly well suited for tasks such as MPP tracking and power forecasting.

Artificial Neural Networks (ANNs) are models of artificial intelligence that simulate neural network structures. These models are paired with a learning algorithm or learning rule. ANN can be seen as a function that is refined by modifying parameters, connection weights, or design elements like the number of neurons and their interconnections. Essentially, a neural network model reflects our current understanding of how neurons operate and interact with one another. Feedforward networks, which do not contain loops, can be structured into layers, allowing them to create memoryless or dynamic input-to-output mappings. A multilayer perceptron (MLP) is a specific type of feedforward neural network in which each layer is fully connected, and in some configurations, the number of nodes in each layer remains constant. Also, the activation function used across the hidden layers is often uniform in several configurations [21]. This is illustrated in Fig. 4, where it is evident that each layer connects to all nodes in the subsequent layer.

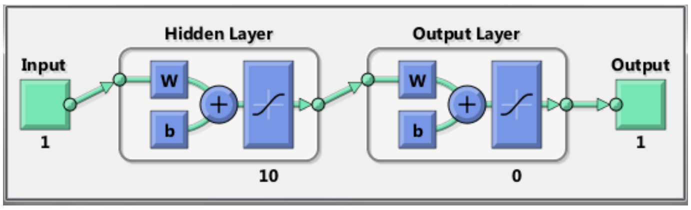

Fig. 4 Multilayer network

In Fig. 5, training an ANN is depicted as an iterative process in which the network receives training data examples one at a time, adjusting the weights after each input. The input variables supplied to the ANN in dq coordinates consist of the current, output voltage, DC link voltage, reference current, and the angle from the Phase-Locked Loop (PLL).

The neural network processes both the real and imaginary components of these variables, yielding two input features. The output of the ANN is the maximum power, represented as an optimal modulation signal, which is applied to the PWM at each sampling instance.

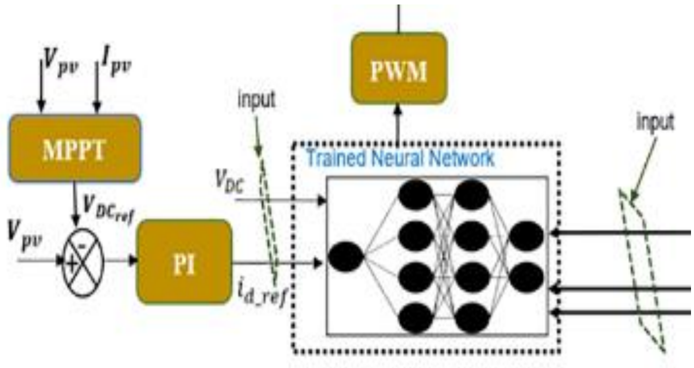

Fig.5 training of Artificial Neural Networks

IV. Simulation Results And Discussion

The simulation was conducted using the parameters Open-circuit voltage (VOC) equal 50.24V, Isc (Short Circuit Current) equal 10.77A, Vmp (Voltage at Maximum Power Point) equal 43.38V, Imp (Current at Maximum Power Point) equal 10.95A. The training process was conducted multiple times using the Levenberg-Marquardt algorithm. The network accepts two inputs, features ten hidden neurons, and generates a modulating signal with a single output. The results will be analyzed in the subsequent sections to evaluate the performance of the ANN controller for solar PV systems.

The proposed controller successfully ensures high power quality extraction across different irradiance levels, even in the face of abrupt changes in irradiation. The performance of the ANN controller can be evaluated based on the results, which demonstrate how well the Vdc and output current align with the MPP tracking profile in fig. 6. Error histograms are essential for visualizing and understanding the error distribution of a predictive model, enabling more informed decisions for model refinement and selection in fig. 7. The training state is crucial for understanding the performance and progress of a neural network during the learning process in Fig. 9. Monitoring these aspects allows for adjustments and optimizations to improve the model's accuracy and efficiency.

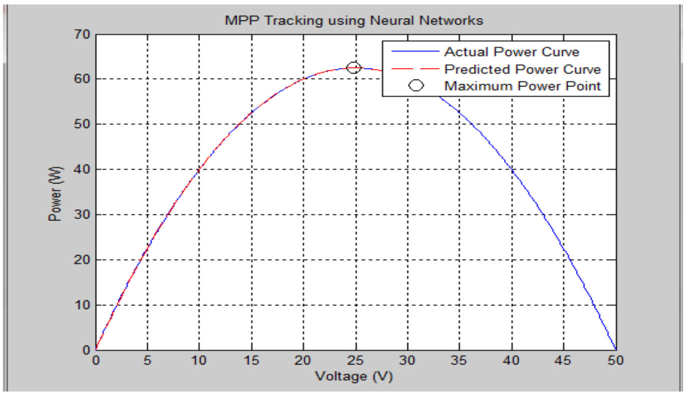

Fig.6 Predict power for test voltage

Fig.7 Best Validation Performance

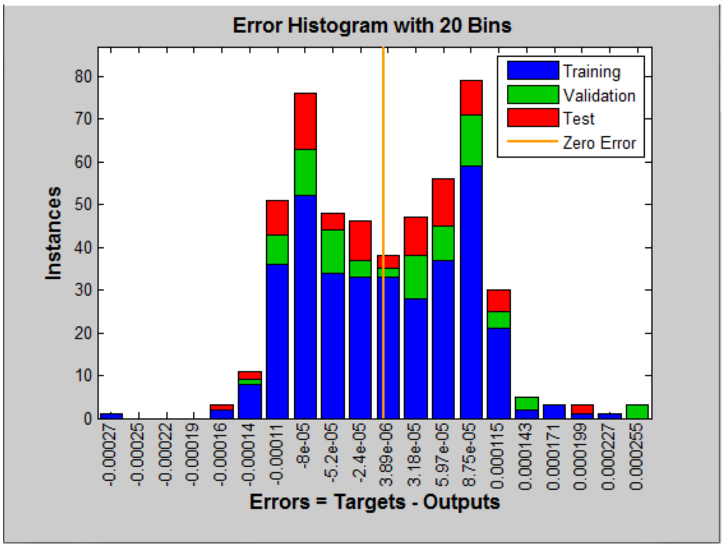

Fig.8 Errors in a dataset or model predictions

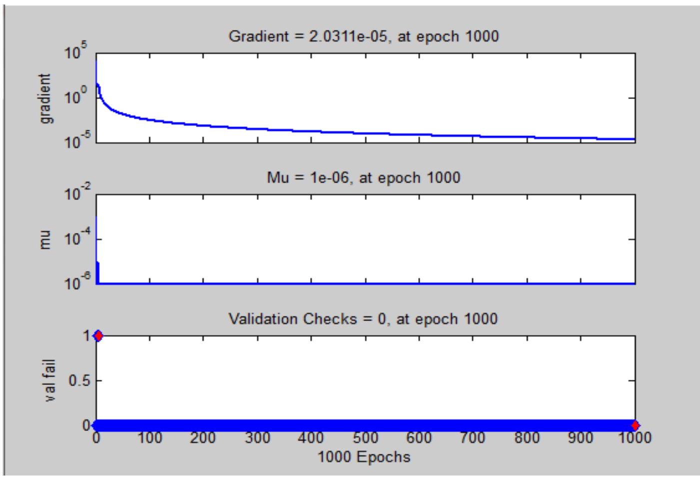

Fig.9 Neural Network Training State

The simulation results shown in Figs. 10 and 11 demonstrate that the proposed ANN performs exceptionally well under different conditions. It successfully tracks the current reference in accordance with the applied irradiance profile, while both the MPP and DC voltage effectively follow their respective references.

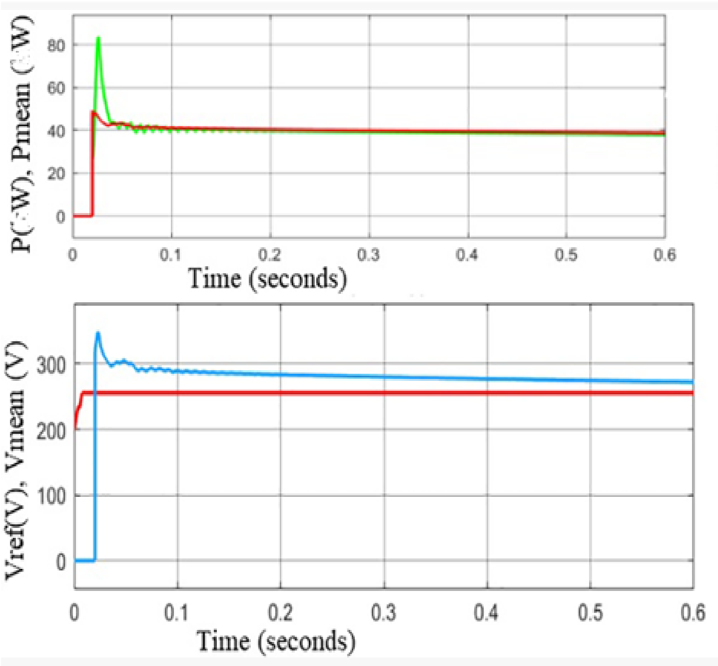

Fig.10 Mean Voltage and Power under different conditions

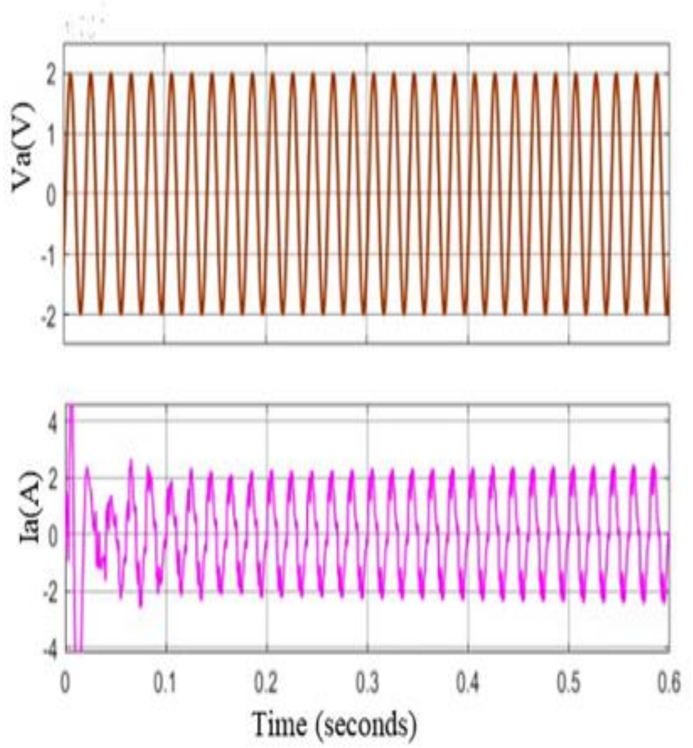

Fig.11 Current and Voltage under different conditions

CONCLUSION

AI has the potential to revolutionize the industry by optimizing energy generation, distribution, and consumption, leading to increased efficiency, cost savings, and environmental sustainability. AI in renewable energy holds tremendous promise. The technologies of AI can enhance renewable energy forecasting and optimization, improve smart grid management, optimize energy efficiency and demand-side management, and facilitate the integration of renewable energy sources into the existing power grid.

The advanced controller implemented in the MATLAB/SIMULINK environment is depend on ANN. The proposed controller, the maximum power point tracking (MPPT) technique is employed. Maximum Power Point (MPP) tracking and power forecasting are calculated. MPP tracking is essential to optimize solar energy extraction under fluctuating environmental conditions, different temperature and irradiance.

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