Intelligent fault detection of photovoltaic panel using neural networks

Detecção inteligente de falhas em painéis fotovoltaicos usando redes neurais

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ABSTRACT

This research primarily aims to leverage artificial neural network technology for diagnosing power output issues in photovoltaic (PV) panels stemming from fluctuations in solar irradiance and temperature. The proposed diagnostic approach relies on constructing a reference model that captures the expected normal operating behavior of the PV panel under fault-free conditions. This reference model is then compared against the actual power output, and the difference, known as the residual, is analyzed to detect potential faults. The neural network is trained using real-world data inputs like solar irradiance and temperature measurements, with the sole output being the power produced by the PV panel. Through training, the neural network learns to map the complex non-linear relationships between environmental inputs and expected power output, effectively modeling the PV system's intrinsic behavior under healthy conditions. Results demonstrate the neural network-based approach's remarkable ability to diagnose faults with high accuracy while avoiding potential non-linear complications. This intelligent monitoring system provides a reliable protocol for early fault detection through training on actual measurements, eliminating the need for complex mathematical models. Consequently, it streamlines
the maintenance process by negating intricate procedures to identify PV panel issues. The neural network effectively learns the mapping between environmental conditions and expected power output through exposure to real-world data during training. By analyzing deviations from this learned mapping, represented by the residual signal, the approach can reliably detect anomalies indicative of faults or performance degradation in the PV system. This data-driven nature allows the system to adapt to site-specific characteristics and capture non-linear effects without explicit modeling.

**Keywords:** PV panel, fault diagnosis, artificial neural networks, power faults, residual.

**RESUMO**

Esta pesquisa tem como objetivo principal aproveitar a tecnologia de rede neural artificial para diagnosticar problemas de saída de energia em painéis fotovoltaicos (PV) decorrentes de flutuações na irradiância solar e na temperatura. A abordagem de diagnóstico proposta baseia-se na construção de um modelo de referência que capta o comportamento operacional normal esperado do painel fotovoltaico em condições livres de falhas. Esse modelo de referência é então comparado com a saída de energia real, e a diferença, conhecida como residual, é analisada para detectar possíveis falhas. A rede neural é treinada usando entradas de dados do mundo real, como irradiância solar e medições de temperatura, com a única saída sendo a energia produzida pelo painel fotovoltaico. Por meio do treinamento, a rede neural aprende a mapear as complexas relações não lineares entre as entradas ambientais e a saída de energia esperada, modelando de forma eficaz o comportamento intrínseco do sistema fotovoltaico em condições saudáveis. Os resultados demonstram a notável capacidade da abordagem baseada em rede neural de diagnosticar falhas com alta precisão e, ao mesmo tempo, evitar possíveis complicações não lineares. Esse sistema de monitoramento inteligente fornece um protocolo confiável para a detecção precoce de falhas por meio de treinamento em medições reais, eliminando a necessidade de modelos matemáticos complexos. Consequentemente, ele agiliza o processo de manutenção ao eliminar procedimentos complexos para identificar problemas no painel fotovoltaico. A rede neural aprende de forma eficaz o mapeamento entre as condições ambientais e a produção de energia esperada por meio da exposição a dados do mundo real durante o treinamento. Ao analisar os desvios desse mapeamento aprendido, representado pelo sinal residual, a abordagem pode detectar com segurança anomalias indicativas de falhas ou degradação do desempenho do sistema fotovoltaico. Essa natureza orientada por dados permite que o sistema se adapte às características específicas do local e capture efeitos não lineares sem modelagem explícita.

**Palavras-chave:** painel fotovoltaico, diagnóstico de falhas, redes neurais artificiais, falhas de energia, resíduos.
1 INTRODUCTION

Recently, interest in renewable energy sources has increased, as they represent one of the most important main sources of global energy. Renewable energy is considered a clean energy source that does not pollute the environment, giving it great importance in achieving sustainable development. It constitutes essential supplies in driving production, achieving economic and social stability and growth, providing job opportunities, improving living standards, and reducing poverty. Therefore, most countries in the world are interested in developing this energy source and setting it as a goal to be achieved (Mohd Amiruddin et al., 2020a; Rahmoune et al., 2023).

Renewable energy is generated from natural sources that are continuously replenished, unlike finite non-renewable sources like fossil fuels. It is an environmentally friendly and sustainable form of energy with minimal impact compared to fossil fuels (Boyle, 2012; Farghali et al., 2023; Strielkowski et al., 2021). With traditional energy sources depleting and concerns over their long-term availability, the world faces a pressing need to transition towards renewable alternatives. Advanced nations have therefore adopted policies and strategies to promote the renewable energy sector in preparation for the post-petroleum era, while ensuring sustainable economic, social, and environmental development for future generations. This involves investing in the renewable resources available globally, such as solar, wind, hydroelectric etc., to harness clean energy sources that are crucial for achieving sustainable development goals (Bouznit et al., 2020; Olujobi et al., 2023).

On this basis, we must pay greater attention to this type of energy by becoming familiar with it in detail and highlighting the most important clean energy resources available in countries around the world. The benefits that can be obtained through solar energy are diverse; it can be used to generate electricity and heat, as well as for water desalination and powering satellites. Additionally, there is little need for maintenance, low costs, and a typical warranty period ranging from 20 to 25 years, except for the inverter, which is subject to change after 5 years or more of installation and operation. Furthermore, it has the potential for development and improvement to take advantage of its benefits in a better and
more efficient way, relying on quantum physics to multiply its outputs (Mohammed et al., 2023; Victoria et al., 2021).

Despite this, there are several obstacles that hinder the use of photovoltaic energy. One of the most prominent obstacles limiting the use of solar energy is the high initial installation costs, which include, for example, panels and storage batteries, although it is expected that these costs will decrease in the future. Additionally, solar panels are affected by weather conditions, with their efficiency decreasing in cloudy weather during winter due to reduced incoming radiation. There are also high energy storage costs, as this requires highly efficient batteries to store the energy generated during the day for use at night after sunset. Furthermore, there is a need for large installation areas, with the required area being directly proportional to the amount of energy to be generated; if the space does not allow for it, a number of panels must be dispensed with, and only a few can be used (Kavlak et al., 2018; “Solar Energy and the Global Energy Transition,” 2023; Soomar et al., 2022)

Artificial intelligence techniques, particularly neural networks, have been widely adopted for fault diagnosis in photovoltaic systems due to their precise reference behavior, self-learning capabilities, and data processing prowess. This neural network-based approach enables reliable monitoring and real-time detection of various faults affecting photovoltaic systems. Early fault detection in solar panels, the primary source of energy generation, is crucial to prevent disruptions, economic impacts, and component failures in photovoltaic plants (Elbachir; Ahmed, 2021; Mansouri et al., 2021).

This paper aims to leverage artificial neural network technology for diagnosing power output issues in photovoltaic (PV) panels caused by fluctuations in solar irradiance and temperature. The proposed diagnostic approach involves constructing a reference model that captures the expected normal operating behavior of the PV panel under fault-free conditions using a neural network trained on real-world environmental data inputs like solar irradiance and temperature measurements. The sole output of the neural network is the predicted power produced by the PV panel. By comparing the measured power output against this model's predictions, and analyzing the resulting residual signal, potential faults or anomalies can be reliably detected. This data-driven diagnostic method
demonstrates high accuracy in fault detection while inherently handling non-linear effects, providing a reliable and adaptable monitoring solution without requiring complex mathematical modeling of the PV system.

2 MODELING OF A PV PANEL

The mathematical model for the single-diode equivalent circuit of a photovoltaic cell can be expressed by the following equation (Mohd Amiruddin et al., 2020b; Rahmoune et al., 2023), (Bouzidi et al., 2021a, 2022a):

\[
I = I_{ph} - I_0 \left( e^{\frac{q(V+R_sI)}{a k T N_s}} - 1 \right) - \frac{V + R_sI}{R_{sh}}
\]  

(1)

Where:

- \(I\) is the cell output current (A), \(V\) is the cell output voltage (V), \(I_{ph}\) is the photocurrent (A), \(I_0\) is the reverse saturation current of the diode (A), \(R_s\) is the series resistance (\(\Omega\)), \(R_{sh}\) is the shunt resistance (\(\Omega\)) and \(a\) is the modified ideality factor.

The photocurrent \(I_{ph}\) is directly proportional to the solar irradiance and is given by (Olujobi et al., 2023; Strielkowski et al., 2021):

\[
I_{ph} = (I_{STC} + k_i(T - T_{STC})) \frac{G}{G_{STC}}
\]  

(2)

Where:

- \(I_{STC}\) is the cell short-circuit current at reference temperature and radiation (A), \(k_i\) is the short-circuit current temperature coefficient (A/°C) \(T\) is the cell operating temperature (°C), \(T_{STC}\) is the cell reference temperature (°C) and \(G\) is the solar irradiance (W/m²)

\[
I_0 = \frac{I_{STC} + k_i(T - T_{STC})}{e^{\frac{q(V_{OC} + k_p(T - T_{STC}))}{a k T N_s}} - 1}
\]  

(3)

The maximum power point of a solar module is determined by the product of its maximum power voltage and maximum power current. This can be expressed mathematically as (Elbachir; Ahmed, 2021; “Solar Energy and the Global Energy Transition,” 2023):
\[ P_{\text{max}} = I_{\text{mpp}} \cdot V_{\text{mpp}} \]  

(4)

Where:

\( P_{\text{max}} \) is the maximum power output of the module (W)  
\( V_{\text{mpp}} \) is the voltage at the maximum power point (V)  
\( I_{\text{mpp}} \) is the current at the maximum power point (A)

The maximum power point represents the operating condition at which the solar module delivers its highest possible power output for a given set of environmental conditions (solar irradiance and cell temperature). Identifying and operating the module at this point is crucial for maximizing energy extraction and overall system efficiency (Bouzidi et al., 2021b; Mansouri et al., 2021; Olujobi et al., 2023).

The efficiency of a photovoltaic module can be calculated using the following equation (Badran; Obeidat, 2022; Bouzidi et al., 2024, 2022b):

\[ \eta_{\text{pv}} = \frac{P_{\text{max}}}{S \cdot G} \]  

(5)

The (MSX 60 PV) solar panel is utilized, with key specifications listed in Table 1. It can directly power DC loads like 12V batteries for low-power applications or AC loads with an inverter. It comprises 36 series-connected multicrystalline silicon solar cells, rated at (60W) maximum power, (17.1V) maximum voltage, and (3.5A) maximum current. Figure 1 and 2 shows the P (Vph) characteristic curve of the photovoltaic panel module for self-consumption, varying with temperature and irradiance.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_{\text{max}} )</td>
<td>60 W</td>
</tr>
<tr>
<td>( V_{\text{max}} )</td>
<td>17.1 V</td>
</tr>
<tr>
<td>( I_{\text{max}} )</td>
<td>3.5 A</td>
</tr>
<tr>
<td>( I_{\text{sc}} )</td>
<td>3.8 A</td>
</tr>
<tr>
<td>( V_{co} )</td>
<td>21.1 V</td>
</tr>
</tbody>
</table>

Table 1. Parameters of the solar cell unit  
Source: (Bouzidi et al., 2022a)
The current-voltage (I-V) characteristics of the solar panel with varying temperature and irradiance levels are shown in Figures 3 and 4.
Photovoltaic (PV) systems are becoming increasingly popular for generating renewable and clean electricity. However, like any other system, PV panels and arrays can experience various faults that can reduce their efficiency and power output. Detecting and diagnosing these faults is crucial for maintaining optimal performance and preventing further damage or degradation (Al-Damook et al., 2022; Alonso-Garcia and Balenzategui, 2004).

Traditional fault diagnosis methods often rely on complex mathematical models or require extensive sensor data, which can be expensive and impractical for large-scale PV installations. Neural networks, a type of artificial intelligence technique, offer an attractive alternative for PV panel fault diagnosis (Gokmen et al., 2013; Osmani et al., 2023).

Neural networks are inspired by the human brain's ability to learn and recognize patterns. They consist of interconnected nodes (artificial neurons) that can process input data and learn to recognize specific patterns or relationships within that data.

By training a neural network on a diverse set of data representing different fault conditions, it can learn to accurately classify and identify various faults in PV panels. Figure 5.
The neural network collects real measurement data, split into training (70%), validation (15%), and testing (15%) sets Figure 6. It is a multilayer network with inputs of solar radiation and ambient temperature, and output of power produced. The hidden layer uses a sigmoid activation function, while the output layer is linear.

During operation, residuals are generated by comparing predicted and measured power outputs. Residual amplitude analysis against thresholds enables fault detection and isolation. This approach allows online monitoring and early fault detection without complex modeling.

The relationship to obtain the power error is given as follows:

\[ r(k) = Y_m(k) - \hat{Y}(k) \]  \hspace{1cm} (6)
\[ P = N.N \ (G, T) \] (7)

Figure 7 illustrates the algorithm used for training the neural network to detect errors at the level of the photovoltaic panel. This is done by relying on input data represented by the solar irradiance and temperature, and the output data represented by the power produced by the panel and the resulting current.

Figure 7. Neural network training algorithm

4 RESULTS AND DISCUSSION

This paper analyzes real-time data to detect and locate errors in a photovoltaic solar panel caused by temperature and irradiation variations on the cells, identifying failure cases. The diagnostic process compares to a healthy
reference model from normal operation data. Table 1 shows the panel characteristics used for simulation.

The neural network has 5 layers: adaptive layers 1 and 4, fixed layers 2, 3, and 5. Figures 8 and 9 show the actual and modeled P, I, V outputs match closely for the fault-free operating state, demonstrating the models accurately mimic the real system.

![Figure 8. Real and NN Model Power at (T=25C° and Irr = 1000W/m2)](source: The authors.)

In Figures 10 and 11, the faulty model shows lower outputs than the fault-free model. The residual between the models is measured for power, voltage, and current outputs.

![Figure 9. Real and NN Model Current at (T=25C° and Irr = 1000W/m2)](source: The authors.)
Furthermore, as shown in Figure 12 and 13, similarities can be observed in the (P-V) and (I-V) curves when irradiation defects occur.
Figure 13. Current system and NN Model at (T=25°C and Irr = 800W/m²)

Figure 14 illustrates the measured residual between the two models, namely the error-free PV model and the PV model with error, regarding the power produced by the PV panel end as a function of the voltage generated by said PV panel.

As a result of temperature change, power outputs exceeded the maximum. Comparing the actual system to the health model, the diagnostic output went from 0 to 1 in Figure 14, indicating precisely the existence of an error. The results demonstrated the effectiveness of the approach in detecting failures.

Figure 14. Residue Power PV at (T=41°C, Irr=1000 w/m²)

5 CONCLUSION

The results of this research, which employ artificial neural networks for diagnosing power reduction faults in photovoltaic (PV) panels caused by varying solar and temperature conditions, offer significant benefits to both society and academic communities. From an academic standpoint, this work advances fault
diagnosis and condition monitoring techniques for PV systems, contributing to the exploration of AI-based methods for modeling complex non-linear relationships in renewable energy applications. The data-driven nature of the approach fosters further research in adapting to diverse site and operating conditions.

In practical terms, the proposed neural network-based diagnostic system provides a reliable and efficient solution for early detection of power reduction issues in PV installations. This can lead to improved operational efficiency, cost savings, and enhanced reliability of PV systems, supporting the broader adoption of photovoltaic technology and the transition towards sustainable energy sources.

Overall, the successful implementation of this AI-based diagnostic technique addresses practical challenges in the renewable energy sector while advancing academic knowledge, benefiting both society through improved PV system performance and academics through further research opportunities in this field.
REFERENCES


