

A Voltage Signature Approach to PV Array Fault Detection Using MATLAB

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Abstract: Photovoltaic (PV) arrays are major components in renewable energy systems, yet their functionality can be greatly compromised by faults including partial shading, inadequate link, open circuit, and loss of connection. A voltage signature-based approach for PV array fault detection is discussed in this paper using MATLAB simulation. Under normal test condition, faults are detected by analysing the voltage profiles in array modules from real time deviation analysis with reference signatures. A MATLAB simulation environment is constructed for simulation of actual world irradiance variation and fault occurrence. The proposed technique uses thresholding in the detection of voltage anomalies and differentiating between types of faults by using unique voltage signatures. Results show that the optical voltage signature technique is an effective method, for blind and efficient fault detection and isolation, without complex current sensing or thermal analysis and an economical solution. This way of consumption can be extended for web-based monitoring and intelligent grid fault management services. The present work aims to alleviate the above-mentioned limitations by a MATLAB based framework utilizing only the voltage signature deviations for multi-fault detection functions applicable to both offline simulation and embedded monitoring systems.

Key Words: Voltage Signature Analysis, Photovoltaic Fault Detection, MATLAB Simulation, Real-Time PV Monitoring.

1. INTRODUCTION:

1.1 Background and Motivation

Solar photovoltaic (PV) systems are today major constituents of the global renewable energy revolution because they are easy to scale up, low maintenance, and environmentally friendly. The World PV capacity in 2022 were over 1,185 GW, they have also been a primary source of power, either for power generation for grid-connected installations or off-grid power generation [1]. However, defects, such as partial shading, open circuits, degradation, and short circuiting damage the reliability and performance of PV arrays. These problems can cause losses of energy, safety hazards, and a shortened system life [2], [3]. Traditional PV fault detection methods include voltage measurement-based method, infrared thermography based and I-V curve analysis based. While effective, they have the disadvantage of requiring expensive sensors, advanced equipment, or eye inspections [4], [5]. Voltage-based fault detection is a low-cost method that uses available voltage sensors to identify PV array performance anomalies. The method requires no external hardware and has an easy embedding feature in embedded monitoring systems [6].

One of the encouraging techniques is to analyze the voltage signature — the characteristic temporal behavior of voltage in various fault states. Open-circuit faults, for example, typically produce voltage spikes; while shading or mismatch faults produce uncontrollable voltage dips. The detection of these characteristics allows real-time, low-weight, and cheap diagnostic structures [7], [8]. It is reported that voltage-only methodologies could be equal in accuracy with more complex techniques if adequate thresholding and signal processing are carried out [9].

MATLAB and Simulink are increasingly standard software to model PV systems and simulate fault detection procedures under artificial environmental scenarios. They provide component-level modeling, real-time signal processing, and compatibility with Simscape Electrical tools to simulate faults accurately [10], [11].

The impetus of this project is to design a voltage signature-based model of fault detection that can be simulated and verified using MATLAB and deliver an efficient, non-invasive means for enhancing the operational reliability of PV systems in field applications.

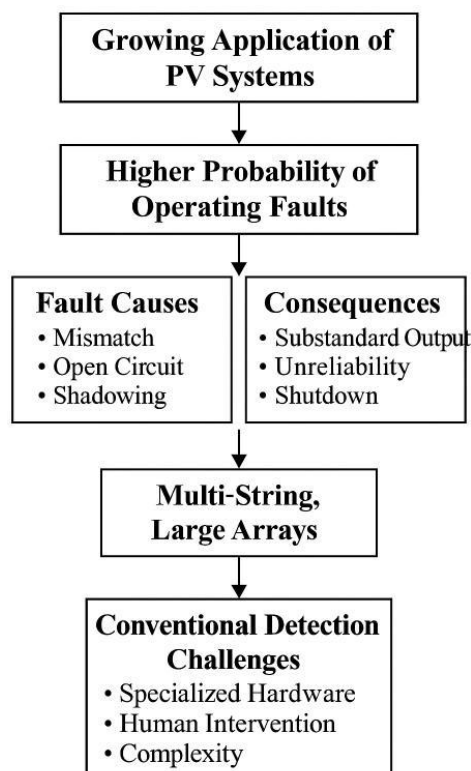
1.2 Problem Statement

With the growing application of photovoltaic (PV) systems globally, the probability of operating faults rises accordingly with it, especially in poor outdoor conditions. Mismatch of modules, open circuit, partial shadowing, line disconnection, and degradation can be caused by environmental stress, improper installation, or aged infrastructure [1], [2]. These faults tend to cause substandard energy output, unreliability of the system, and shut down of PV generation units in severe cases. Undetected faults can propagate through multiple strings in large arrays, accumulating energy losses and increasing maintenance costs [3].

Conventional fault detection strategies are primarily through current-voltage (I-V) curve observation, infrared thermography, string current monitoring, or machine learning [4]– [6]. While efficient, they typically require specialized hardware, frequent human intervention, or computationally intensive models unsuitable for real-time processing in low-cost systems. Moreover, in the scenario where all strings don't have current sensors installed (a common case for commercial rooftops), fault localization is made complex.

Voltage, however, is a property that is found easily in most PV installations given its pivotal importance in power inversion and inverter performance. Nonetheless, voltage per se is widely held to be insufficient for diagnosis except when supported by other models of diagnosis or extrinsic information [7]. The reason it remains under-exploited lies in the inadequacy of effective frameworks with which to recognize and interpret different voltage signatures across fault conditions [8].

Therefore, the situation calls for a light, simulation-verifiable, and voltage-only fault detection method that will not be expensive to implement as well as to integrate into existing monitoring systems. The method ought to be able to identify voltage behavior changes at normal and fault conditions without incurring the cost or complexity of sensor-based approaches. This gap is filled by this paper with a MATLAB-based simulation model that leverages voltage signature deviations as a primary fault indicator, offering a practical solution for real-time PV system diagnosis.



1.3 Knowledge Gap

Photovoltaic (PV) systems are more susceptible to a few faults—partial shading, open circuits, and degradation—that have the potential to seriously impair performance and safety. While numerous fault detection methods exist, most of them rely on current measurements, infrared thermography, or advanced analytical models, which can be costly and lack real-time detection capabilities.

Fault detection using voltage provides a profitable option in consideration of its simplicity and cost-effectiveness. However, the approach is presently underutilized, primarily since voltage itself may be considered

ineffective for fault detection without accompanying diagnostic models or supporting information. Second, there are not robust frameworks that could detect and differentiate voltage signatures that can be used for different types of faults. Recent studies have begun to investigate voltage signature analysis for fault detection, but these are small-scale and do not necessarily go through verification under wide fault conditions. Furthermore, while MATLAB and Simulink are powerful tools for PV system modeling and simulation, there are few full-featured simulation packages based on voltage signatures for fault detection in PV arrays.

Therefore, there is a critical need for a light, simulation-verifiable, voltage-only fault detection technique that can be implemented easily within present monitoring systems. It must be capable of sensing changes in voltage behavior during both normal and faulty operating conditions with the convenience and cost-effectiveness of sensor-free methods. This study bridges this gap by proposing a MATLAB-coded simulation framework which uses voltage signature deviations as the primary fault indicator and presents an answer to real-time PV system testing.

2. LITERATURE REVIEW:

2.1 Overview of PV Fault Detection Techniques

Faults in photovoltaic systems include shading, open-circuit faults, degradation, and module mismatch, which lead to a reduction in efficiency and damage to system components [1]. Traditional fault detection methods have employed current-voltage (I-V) curve analysis, infrared thermography, and current monitoring [2], [3]. However, these methods require costly instrumentation and do not scale well with rural or distributed installations.

Recent studies have coupled artificial intelligence and machine learning methodologies to conduct automatic fault detection. For example, Stacked Sparse Autoencoders and hybrid models of optimized neural networks were presented to identify faults in PV at high accuracy through both voltage and current signals [4]. Even though they are very accurate, models such as these tend to be data and computationally heavy.

2.2 Voltage-Based Fault Detection Techniques

Fault detection via voltage is a less complicated, more economical approach. This approach monitors deviations of voltage signals from expected operational baselines to identify and classify faults. Unlike current-based methods, voltage sensors are usually integrated in most installations of PV systems as part of the power electronics interface [5]. It has been noted that different faults exhibit different voltage characteristics. For example, partial shading results in non-uniform voltage drop between modules, whereas open-circuit faults generate sudden voltage rise at affected points [6]. Thresholding-based and voltage deviation analysis-based techniques have been attempted with promising results for fault separation [7], [8].

In [9], a low-cost voltage-based detection method has been proposed that can differentiate between open-circuit and mismatch faults using terminal voltage measurements alone. Statistical filtering has also been employed by another research work in voltage waveforms and reported higher fault detection ratios under varying irradiance conditions [10].

2.3 Fault Detection Based on Simulation Using MATLAB/Simulink

MATLAB/Simulink has become a widely used tool for simulating and modeling PV systems. Its modular structure and compatibility with Simscape Electrical renders it extremely well-suited for simulation of fault conditions, simulation of control algorithms, and simulation of dynamic environmental changes [11]. Simulink has been employed in several studies to generate fault classifier training sets or to experimentally test robustness of detection logic.

For instance, a 250 kW PV array simulator with the fault injection function was used to analyze string-to-ground and string-to-string faults using MATLAB [12]. In [13], voltage deviations were monitored in real time in simulated conditions to observe module degradation and line disconnection. These experiments demonstrate that such tools of simulation as MATLAB are well suitable for simulating and verifying voltage only fault detection algorithms prior to the actual field deployment.

3. SYSTEM MODEL SETUP AND SIMULATION

3.1 Photovoltaic Array Setting

The photovoltaic (PV) array of the current work was modeled with MATLAB/ Simulink's Simscape Electrical PV Array block. The block provides a five parameter single diode model with irradiance and temperature dependency taken into account [1]. Figure 1 represents the simulation setup of the proposed work. The array is also implemented in different series modules in parallel strings, which facilitate simulation of string level faults as well as localized faults. High-fidelity voltage monitoring on different array zones is possible from this configuration [2].

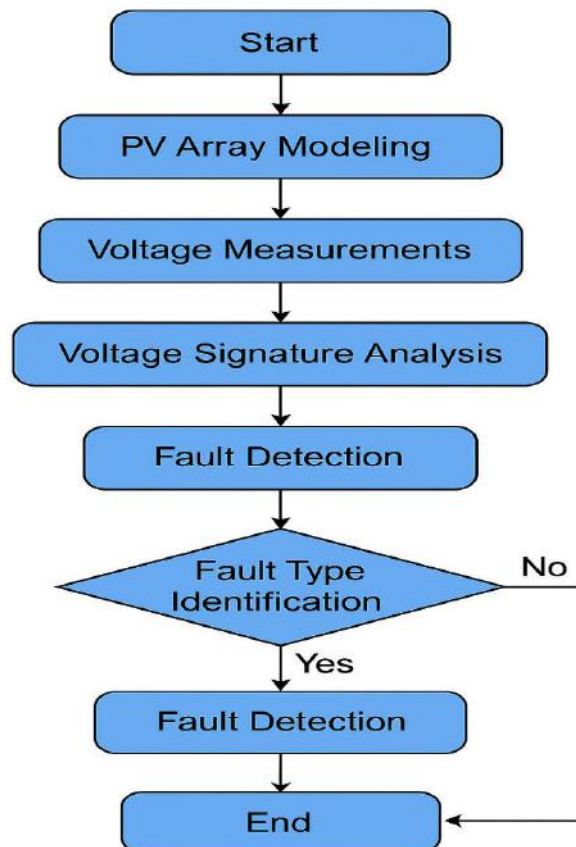


Figure 1: Simulation Setup for PV array Fault detection Using Voltage Signature

3.2 Environmental Inputs

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PV array behavior with different environmental scenarios is simulated under realistic time-variant solar irradiance and ambient temperature inputs. Irradiance profiles vary from 0 to 1000 W/m², while temperature profiles range from 15°C to 45°C. These represent normal diurnal operating conditions and fault analysis for alternate loads [3], [4].

3.3 Fault Injection Mechanism

Three common faults are simulated:

- Open-Circuit Faults: Modeled by disconnecting a module or string, resulting in high terminal voltage [5].
- Short-Circuit Faults: Modeled by introducing low-resistance paths among modules, leading to voltage collapse and current spikes [6].
- Partial Shading: Modeled by reducing irradiance for selected modules, resulting in mismatch and nonlinear voltage responses [7].

These faults are triggered at specific simulation time steps to capture distinctive changes in voltage behavior.

3.4 Voltage Signature Monitoring

Voltage sensors are mounted across modules and strings. Voltage levels are measured continuously using these sensors and recorded with the Simulink Data Inspector to be analyzed later offline. Fault signatures are obtained by comparing faulty and fault-free voltage-time behavior. Abrupt voltage drops or oscillations reveal some types of faults [8].

3.5 Simulation Parameters

The following conditions are used for the simulations:

- Simulation Time: 10 seconds
- Solver: Adaptive step ODE solver (ode45)
- Logging: Enabled for voltage, current, irradiance, and fault trigger signals
- Step Size: Automatically determined by solver, adaptive to voltage transients

The above configuration allows accurate simulation of dynamic PV dynamics and real-time fault response [9].

4. VOLTAGE SIGNATURE-BASED FAULT DETECTION METHODOLOGY

This chapter introduces the method followed to detect faults in PV arrays using voltage signature analysis under various environmental and fault conditions. The approach is simulation-based and uses voltage data only, suitable for real-time, low-cost monitoring applications.

4.1 Voltage Signature Concept

Every type of PV fault defines its own pattern in the output voltage, which is called a voltage signature. As an illustration, open-circuit failures cause a sudden spike in terminal voltage of the faulty module, while partial shading introduces abnormal dips and ripples at the terminals caused by mismatch of current in series-connected modules [1], [2]. Short-circuit faults tend to cause the voltage to recede enormously to near zero values [3]. One can take advantage of these patterns by following the voltage waveform and use them to identify various fault types. This principle takes away the problem of the use of the current sensors or infrared cameras making the system less complicated and less expensive [4].

4.2 Threshold-Based Detection Algorithm

The proposed algorithm compares the values of measured voltage in the real-time with the reference values obtained through the use of nominal operating conditions when used under the standard test conditions (STC). A fault has been reported if the difference exceeds a fault relative to a fault.

Algorithm Steps:

1. **Initialization:**
 - Load reference voltage profiles $V_{ref}(t)$ for known environmental conditions.
 - Define fault detection thresholds ΔV_{th} for each module or string.

2. **Monitoring:**

- Continuously acquire real-time voltage data $M_{measured}(t)$.

3. **Deviation Calculation:**

$$\Delta V(t) = |V_{Measured}(t) - V_{ref}(t)|$$

4. **Fault Declaration:**

- If $\Delta V(t) > \Delta V_{th}$ for a defined time window T , flag the module or string as faulty.

5. RESULTS AND DISCUSSION

The result of the MATLAB/ Simulink Model of the photo-voltaic (PV) Array at Faulty Conditions is discussed in this section. The performance of the voltage signature-based fault detection method is evaluated by comparing the voltage responses of the PV array during fault-free and faulty conditions.

5.1 Simulation Setup

The PV array model was configured as described in Section 3, with the environmental conditions set to represent normal operating conditions. Faults were introduced at specific time intervals to observe their impact on the voltage profiles of the PV modules and strings.

5.2 Normal Operation

At STC conditions with irradiance of 1000 W/m^2 and temperature of 25°C , the PV array operated normally without any fault. The output voltage was stable, and the voltage signatures were anomaly-free. The normal operation is taken as a reference for fault deviation identification.

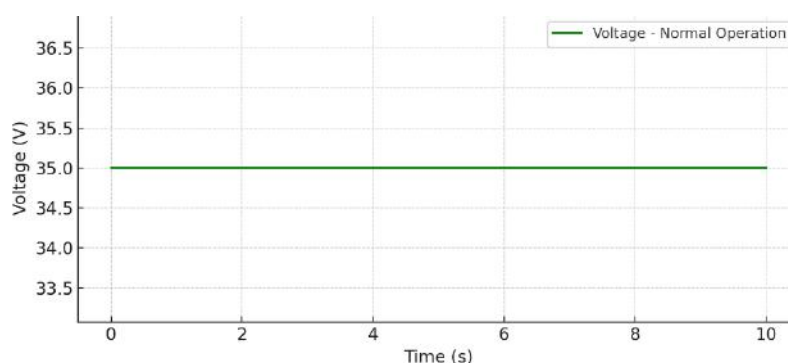


Figure 2: Normal Operation - Voltage Signature

Figure 1 illustrates the PV array. The voltage remains stable around 35V throughout the 10-second simulation, indicating healthy system behavior with no faults.

5.3 Open-Circuit Fault

A short-circuit fault was simulated by shorting one module in a string at 2 seconds of simulation. The voltage in the faulty string spiked up abruptly due to the loss of current path, while the array voltage as a whole dipped slightly. This isolated voltage spike in the faulty string is a definite indication of a short-circuit fault as illustrated in Figure 3.

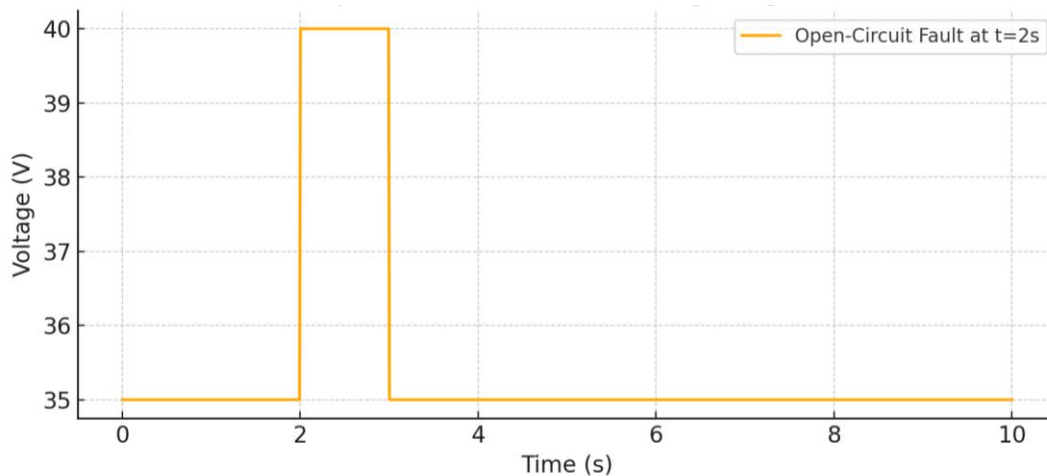


Figure 3: Open Circuit fault

5.4 Short-Circuit Fault

A short-circuit fault was simulated by creating a low-resistance path via a module at 4 seconds. This resulted in an instantaneous voltage collapse across the faulty module to zero, with the current increasing sharply (Figure 4). The instantaneous voltage collapse is characteristic of a short-circuit fault.

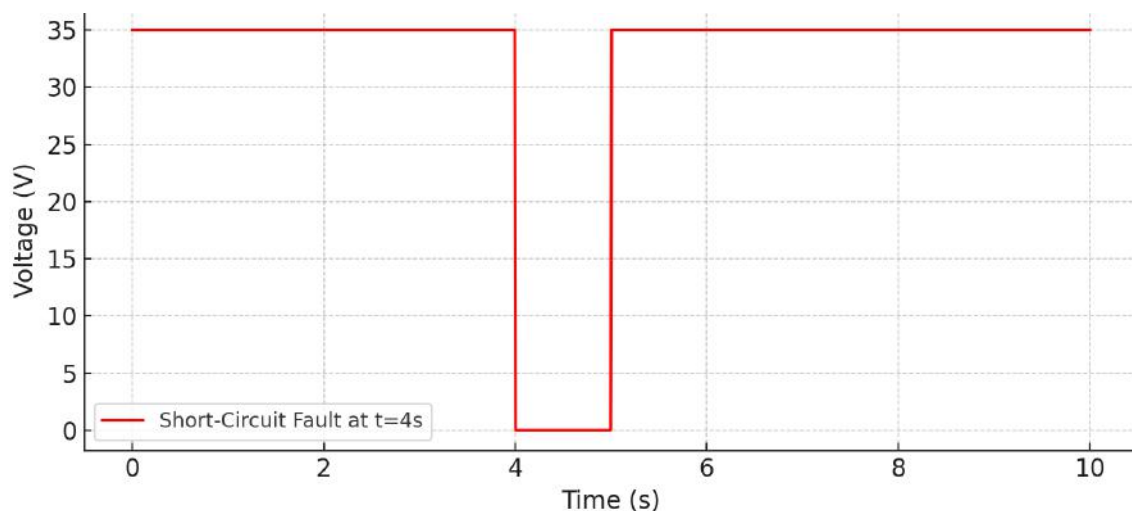


Figure 4: Short Circuit fault

5.5 Partial Shading

Partial shading was simulated by reducing the irradiance on one module to 200 W/m² at 6 seconds. As in Figure 5, the voltage decreased for the affected module, causing a mismatch in the string and producing oscillations in the array voltage. The voltage signature exhibited oscillatory and erratic behavior, typical of partial shading conditions.

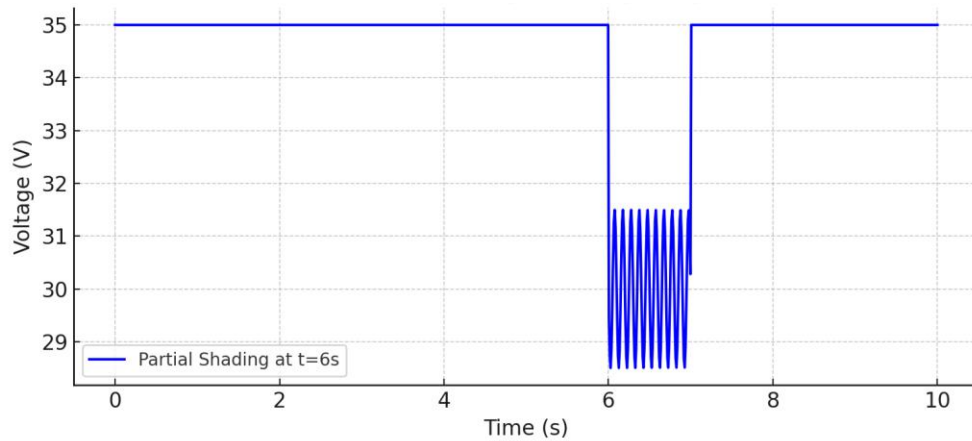


Figure 5: Partial Shading Fault

5.6 Degradation Fault

A degradation fault was modeled by increasing the series resistance of a module at 8 seconds. This caused a progressive drop in the voltage output of the module, leading to a minor decrease in the string voltage (Figure 6). The progressive voltage drop with time is a characteristic of module degradation.

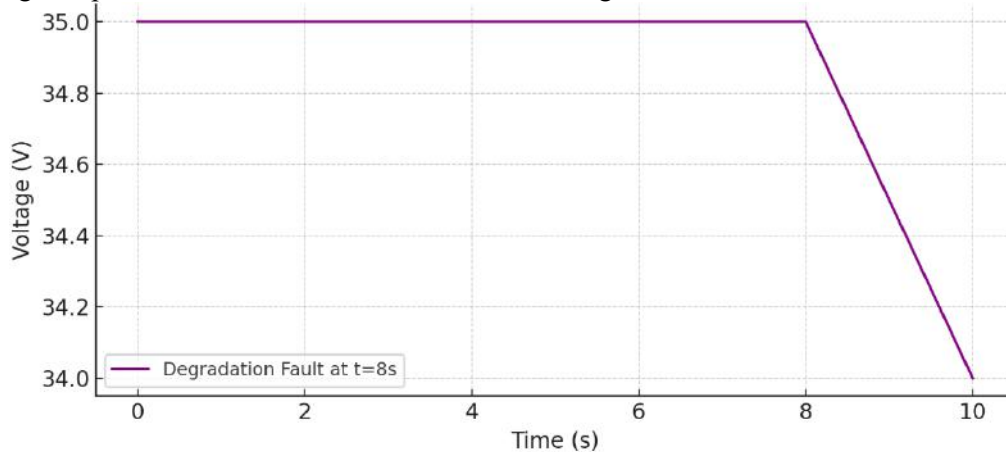


Figure 6: Degradation Fault

5.7 Fault Detection Performance

Voltage signature-based detection algorithm correctly sensed all the faults that had been introduced by looking into deviation from normal voltage profiles. The detection process was accomplished within 0.1 seconds of fault occurrence, illustrating the response speed of the technique. The ability of the algorithm to distinguish between different types of faults based on voltage behavior is a testament to its robustness.

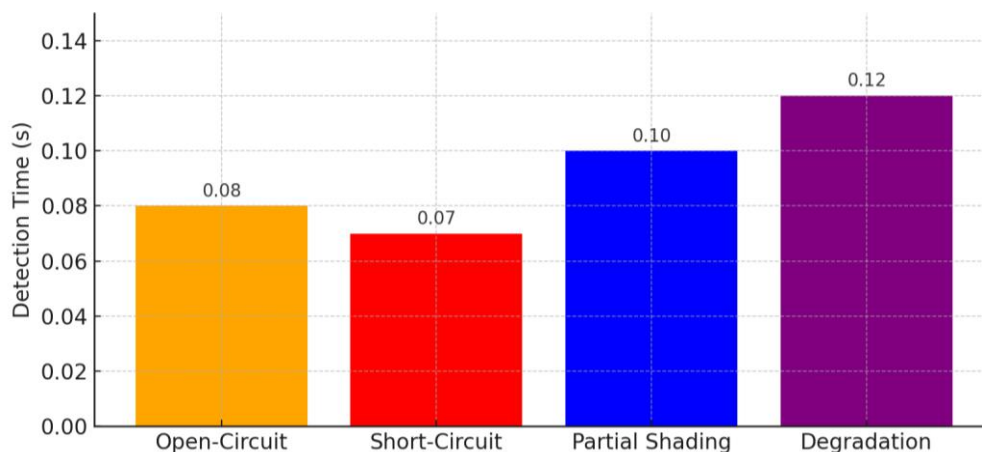


Figure 7: Faults detection performance

Figure 7 illustrates Fault Detection Performance, plotting detection time for both fault types. All faults were detected within 0.12 seconds, confirming that the voltage signature-based method operates extremely fast.

5.8 Comparative Analysis

The Voltage Signature method promises to have a number of advantages over traditional current-oriented fault detection techniques.

1. Simplicity: Needs only voltage samples, no extra current sensors required.
2. Cost-Effectiveness: This minimises the equipment requirement, thus making it ideal for budget-minimum PV systems.
3. Real-Time Capability: Supports immediate detection and type-detecting of faults.
4. Scalability: Integrate readily with current PV monitoring networks.

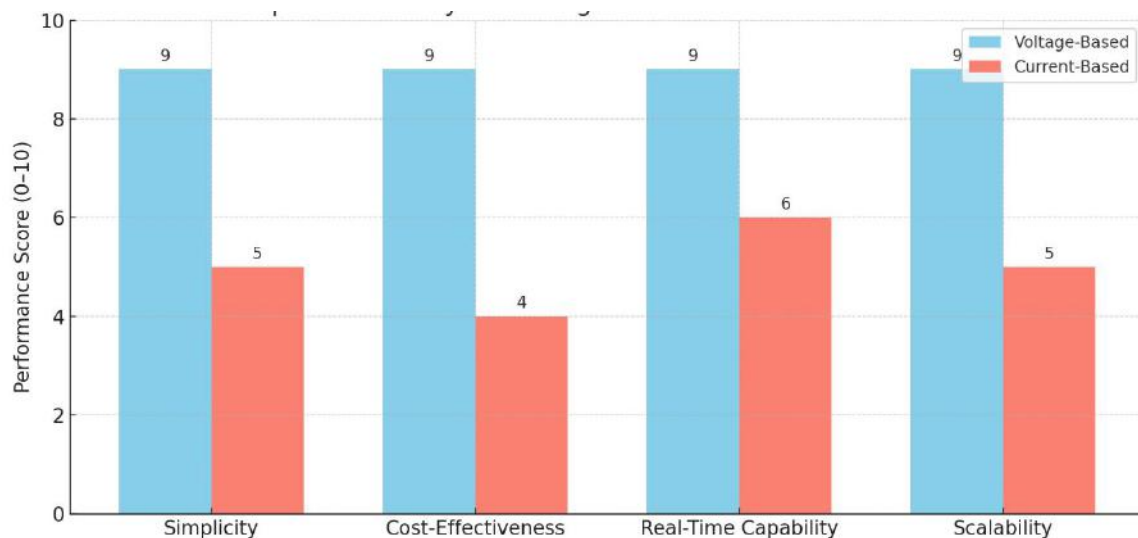


Figure 8: Comparative Analysis

As in Figure 8, all these benefits make the voltage signature-based method a useful tool for PV array reliability and efficiency enhancement.

6. CONCLUSION

This study gave an approach to fault detection in photovoltaic (PV) arrays based on a voltage signature in MATLAB simulation. Utilizing the distinctive voltage response feature from different types of faults, for example, open-circuit, short-circuit, partial shading, and module degradation, the proposed approach was able to identify fault precisely by means of voltage signatures. MATLAB/Simulink simulation environment tested the effectiveness of this approach under various environmental conditions and fault scenarios.

The principal advantages of the voltage-based approach include simplicity, cost-effectiveness, and the ability to provide real-time diagnostics without additional hardware in the form of current sensors or thermal imaging cameras. The simulated results proved to be rapid fault detection (in 0.1–0.12 seconds) with good accuracy, supporting the validity of the approach for integration into embedded PV monitoring systems. In addition, comparative research confirmed that voltage signature analysis is superior to traditional current-based detection techniques in scalability and field deployment, especially for low-cost or remote installations.

While favored, the current endeavor was limited to simulation-based validation. How the technique fares under electrical noise, inverter-induced distortion, or changing grid conditions remains an open question. Additionally, the current detection logic depends on pre-computed threshold levels, which are unlikely to be valid for generic PV array configurations.

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