



# Online fault detection and the economic analysis of grid-connected photovoltaic systems



Siva Ramakrishna Madeti<sup>\*</sup>, S.N. Singh

Alternate Hydro Energy Centre, Indian Institute of Technology Roorkee, Uttarakhand, 247667, India

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## ABSTRACT

Monitoring system is essential to maintain optimal performance of photovoltaic systems. An automatic fault diagnosis technique in a monitoring system plays critical role in detecting causes affecting the energy production. This paper proposes a new fault detection technique that analyzes the anomalies observed in terminal characteristics of faulty PV strings and corresponding array. The terminal voltage difference between the module in healthy string and the healthy module in unhealthy string can be employed to locate faulty modules. The main advantage of proposed approach is that it voids the need of string current sensors, and reduces the number of voltage sensors using optimal location of voltage sensors. In this technique, power line communication technology based data transmission is used to monitor each PV module. Additionally, a user friendly web application is developed for easy access of monitored data via Internet. Moreover, an economic analysis has also been carried out to study the cost effectiveness of the proposed fault detection technique; considering different values of interest rate and energy tariffs. The profitability of installed grid connected photovoltaic system is determined through its parameters net present value and pay-back period. Experimental results are provided to demonstrate the effectiveness of proposed fault detection technique.

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## 1. Introduction

Owing to the increase in industrial expansion and continuous growth in energy consumption, global energy demand per capita is on rise. This paved the way for intensive research of new, safe and sustainable green power technologies such as, solar, wind, hydro, tidal, biomass, geothermal, etc. The prime focus of renewable energy technologies research focuses on ways to convert renewable energy into electrical energy in order to feed the utility grid or consumer loads. Among all the renewable energy sources (RES), solar energy generation is recognized as the best way to extract energy from the environment [1–4]. Global installed photovoltaic (PV) capacity at the end of 2016 was reported as 310GWp [5]. However, as they are installed in outdoor environment, continuous exposure to harsh environmental conditions (sun beam, rainfall, etc.) may reduce the optimal performance of system. The monitoring study of PV system is conducted in Ref. [6] and it was reported that the annual power loss due to various faults is about

18.9%. Hence, continuous monitoring along with fault diagnosis techniques is essential to detect the causes affecting the performance of the PV system. A fault detection algorithm for PV system can provide an accurate estimation of electricity generation under normal operating condition and detection of faults present in the PV system. This would enable operator to take corrective measures, which improve the performance of PV system by minimizing the power losses caused by the faults. In this paper, any factor which reduces the output power is considered as “fault”. It may be temporary (shadows, bird droppings, and dust or snow accumulation on the surface of the PV panel) or permanent (electrical disconnection, wiring losses and ageing). A permanent fault would remain for prolonged time whereas a temporary fault can be cleared within the specific time period.

Many diagnostic techniques have been developed to detect faults in grid connected photovoltaic (GCPV) systems [7]. Some of these techniques are based on simulations of PV module electrical-circuit [8,9], while some use statistical analysis of different PV module output terminal electrical signatures, such as current and voltage [10]. The earth capacitance measurement (ECM) is proposed by Takashima et al. [11] to detect disconnection of PV module in a string. The time-domain reflectometry (TDR) technique is

<sup>\*</sup> Corresponding author.

E-mail address: [ramakrishna.iitroorkee@gmail.com](mailto:ramakrishna.iitroorkee@gmail.com) (S.R. Madeti).

developed by Schirone et al. which measure the electrical characteristics of transmission line to detect breakdown point, faults and impedance change due to degradation, without requiring climatic data [12]. However, these methods can operate in offline mode only. Some other monitoring techniques for PV plants are investigated in Refs. [13–15].

In order to take measurements in online mode of operation, new fault diagnosis methods are needed. For online fault detection in PV system based on the difference between the measured and the simulated PV system outputs was proposed in Refs. [16–18]. However, it needs climatic data such as solar radiation and temperature, and requires personal computer (PC) to be connected all the time, the use of commercially available software (MATLAB, LabVIEW, etc.). This increases the price of the monitoring system and fails to identify the faulty module. In Ref. [19] power loss analysis based fault diagnosis technique is proposed. The identification of open and short circuit faults in GCPV system can be detected by evaluation of voltage and current indicators as reported in Ref. [20]. But even this technique fails to detect the faulty module in PV array.

So far, many online and offline fault diagnosis techniques have been developed. However, major short coming in online fault diagnosis techniques is its inability to locate faulty modules whereas offline diagnosis techniques cannot give real-time fault information. In Ref. [21], procedure for the fault detection of PV plants using voltage and current sensors is proposed, but the cost of the system is very high.

The evaluation of economic and environmental viability of GCPV plant is crucial for satisfactory operation. In order to get successful dissemination at a given location, the evaluation should start with the assessment of technology, economic feasibility and financial incentives. The importance of the pre-evaluation of techno-economical parameters of the GCPV system was discussed in Ref. [22]. Reddy et al. [23], highlights the significance in the choice of technology development in rural areas for quality energy service. In addition, economical assessment of centralized, decentralized and energy conversion technologies was reported. Lastly, the costs for useful energy were also compared. In Ref. [24], the profitability of the GCPV system in Spanish was investigated by using the payback period and net present value parameters. To determine the economic viability and technical feasibility of hybrid (solar/wind) system, techno-economic assessment have been conducted. The energy output and payback period was calculated using commercial simulation packages and Life cycle cost method respectively [25]. The Ministry of New and Renewable Energy (MNRE) annual report-2004 [26], evaluates life cycle cost to determine the environmental benefits of PV plants, reduction of emissions and effects

module level on-line monitoring system with optimized voltage sensor locations. The proposed fault detection technique is capable of localizing faults occurring in GCPV plant to particular PV string and/or PV module. Moreover, this technique does not involve/require math intensive artificial intelligence techniques and commercial energy simulation software packages. Therefore, the proposed fault detection technique is implemented in the same microcontroller used for data transmission to reduce the overall cost. Further, a web based application is also implemented for easy access of the data over the internet. Finally, an economic analysis has also been carried out to study the cost effectiveness of the proposed fault detection technique. This study is performed by considering different values of interest rate and energy tariffs.

This paper is organized as follows: Section 2 provides methodology used. Experimental test results are given in Section 3. In Section 4, the economic analysis of installed GCPV with monitoring system is evaluated. Finally, Section 5 summarizes the conclusion of this work.

## 2. Methodology

In this section, fault mechanism, sensor placement strategy and fault detection and diagnosis procedure is presented.

### 2.1. PV system description and fault mechanism

The PV system under study is a 2.2 kWp GCPV plant installed at National Institute of Solar Energy (NISE), India. The system consists of 9 multicrystalline silicon PV modules with a normal power of 230Wp. This system is composed of 3 strings and each PV string consists of 3 series connected modules to form an array. Under partial shading conditions, the healthy cells/module in a PV array has a higher solar irradiance than the faulty cells/module. It causes overheating of faulty cells/modules and also leads to reduction in terminal voltage, current, output power and generation efficiency [27]. Mono-string fault condition in  $3 \times 3$  PV array and its  $V-I$  characteristics are illustrated in Fig. 1 (a) and (b) respectively.

In this  $3 \times 3$  PV array, it is assumed that module number  $M_{21}$  in String – 2 is a faulty module. Then the voltage across the module in healthy string i.e.,  $V_{11}$  and the voltage across the healthy module in unhealthy string,  $V_{22}$  can be given as

$$V_{11} = \frac{V_{array}}{\text{No. of modules connected in series to form string}} = \frac{V_{array}}{3} \quad (1)$$

$$V_{22} = \frac{V_{array}}{\text{Modules connected in series to form string} - \text{Faulty modules present in string}} = \frac{V_{array}}{2} \quad (2)$$

of Kyoto protocol.

Common disadvantage of the proposed methods is that they do not consider one or more important GCPV design aspects, which can highly influence the total economic benefits achieved. These aspects include manufacturing cost of installed PV modules which minimizes the extrinsic influences of location, scaling and time, energy loss due to faults and the impact of reliability on the PV inverter lifetime cost/energy production.

The main contribution of this work is to propose a low-cost

where,  $V_{array}$  is the voltage across the array.

Since all modules contribute to electrical power generation, these two output characteristics have three working points. The working points of healthy module in healthy string ( $WP_{11}$ ), healthy and unhealthy module in unhealthy string ( $WP_{22}$  and  $WP_{21}$ ) are different from each other. The working points  $WP_{11}$  and  $WP_{22}$  share the same output curve characteristics because these modules are healthy. Since,  $WP_{22}$  and  $WP_{21}$  are the working points of a healthy and unhealthy module in the same string, they have the same

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