Detection of Faults in Photovoltaic Module in the Frequency Domain

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Article Info

Article history:

Received 27 July, 2021
Revised 28 Octobre, 2021
Accepted 14 December , 2021

Keywords:

Photovoltaic module
Faults
Diagnosis
Spectral analysis
Principal component analysis

ABSTRACT

A photovoltaic system can be subject to various faults and anomalies during its operation, leading to a drop in performance. Allowing fine diagnosis, detection and localisation of faults in a Photovoltaic (PV) installation reduces maintenance costs and above all increases productivity. In what follows, we focus specifically on the detection and localisation of faults on the AC side of the PV system. For this purpose, the choice was made to analyse the power generated by the PV in the frequency domain for the various operating modes under consideration. Based on the spectral analysis of the three phases of the generated currents, faults characteristic frequencies are highlighted in the power spectral density of the first principal component. The diagnosis method gives a good basis for a non intrusive condition monitoring tool for PV system.

I. Introduction

Renewable energies have enormous potential and can meet the current global energy demand. They can improve diversity in energy supply markets, secure the long-term supply of sustainable energy, and reduce air emissions.

Photovoltaic solar energy is the direct conversion of part of the solar radiation into electrical energy. This energy conversion is carried out through a so-called photovoltaic (PV) cell [1] based on a physical phenomenon known as the photovoltaic effect of producing an electromotive force when the surface of the cell is exposed to light.

The combination of several PV cells in series/parallel give a photovoltaic generator which has a current-voltage characteristic (I-V) non-linear with a maximum power point. The photovoltaic module performance and its degradation depend on the weather conditions [2, 3] such as irradiation and temperature, wind, humidity...

Like all other industrial processes, a photovoltaic system can be subject, during its operation, to various faults and anomalies leading to a decrease in the system's performance and even to the total unavailability of the system. All these adverse consequences will obviously reduce the productivity of the installation, and therefore reduce the profit of the installation, not to mention the cost of maintenance to return the system to normal [4-6].

Allowing fine diagnosis, detection and localisation of faults in a PV installation reduces maintenance costs and, above all, increases productivity by increasing the availability rate of the installations by ensuring that their output is optimal.

We are specifically interested in detecting and locating faults on the AC side of the PV system. Currently, monitoring systems are available that allow the power supplied by the panels and the associated energy to be calculated by means of voltage and current sensors.

The behaviour of PV systems under fault conditions is evaluated through the I-V curve methods from the ideal model and empirical data. The obtained results show that the open circuit voltage of damaged bypass diode is a little higher than the when partial shading occurs. Meanwhile, the temperature of the junction box due to shading problems is higher than when bypass diode damage occurs. However, when the PV module is not operational because of bypass diode damages, extremely high temperatures might be observed in the PV module junction box [11].

Nowadays, smart monitoring and modern data acquisition can be readily implemented due to the availability of advanced devices, such as such as sensor networks, smart combiner boxes and smart inverters. The aim of our work is to separate the case of a PV system with and without faults and then progress on to the fault identification and classification. The PCA method in frequency domain uses an approach to avoid several problems in conventional fault detection systems. This method reduces the need for additional hardware and sensors that impacts the cost.

II. Description of the PV system

II.1. Structure of the photovoltaic generator

The photovoltaic generator is the unit for producing electrical energy in the form of direct current. The elementary component of this unit that converts solar energy into electrical energy is the photovoltaic cell. The voltage generated by a photovoltaic cell is limited to the gap value of the material from which it is made. It is of the order of 0.6 V for crystalline and amorphous cells [1-2]. The current depends on the surface area of the cell and, for the same surface area, it depends on the efficiency of the cell. The voltage and current, and therefore the power, of a cell are not adapted to common applications, so it is necessary to combine them. Moreover, photovoltaic cells are fragile and sensitive to the external environment, so they are equipped with mechanical protection (encapsulation). For all these reasons, the cells are assembled into photovoltaic modules [3-5].

The cells are generally connected in series in the standard modules. By connecting the cells in series, the power output can be increased. The current remains the same while the voltage is multiplied by the number of cells in series. The cells in a module are combined into several groups. Each group is then connected in anti-parallel with a diode, called a bypass diode [4-5]. This diode is used to protect the cells from operating in the reverse regime. In order to obtain powers of a few kW, at a suitable voltage, it is necessary to group the modules in series and in parallel. This grouping forms a photovoltaic field. The role of the converter group is to extract the maximum power from the PV generator and convert it into AC power before injecting it into the grid. To fulfil this role, this converter group consists of a chopper stage followed by an inverter stage. A PV field can be characterised by its static current/voltage characteristic, often referred to as the I-V characteristic [4, 6]. Such a characteristic of a PV field in normal operation is shown in Figure 1.

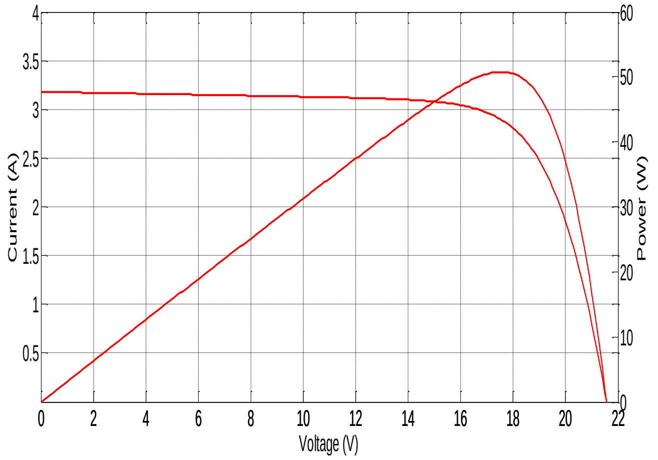


Figure 1. I-V Characteristic of a PV field in normal operation.

II.2. Experimental setup

The tests were carried out in Electrical laboratory at Bejaia University, using the parameters and experimental data presented in the table1.

Table 1. Experimental data

Model of PV panel	STP085B-12/BEA
Power	80W
Current I_{PM}	4.9A
Voltage V_{PM}	17.7
Current I_{CC}	5.1A
Open circuit voltage V_{CO}	22.1V
Length	1190mm
Width	540mm
Weight	8 kg
Cell number	36

The figure below presents the Hardware and software used in the experiments.

Figure 2. Photovoltaic panel model STP08B-12/BEA

Figure 3. Solar meter

Figure 4. The acquisition bench

III. Diagnosis and different types of defects in the photovoltaic module

III.1. Different types of defects

The photovoltaic module performance and efficiency can be degraded due to several factors: climatic condition (irradiation temperature, humidity), and external cause such as mechanical shock [9].

During operation, a PV system may be subject to various faults and abnormal operating conditions. These vary from one installation to another depending on its design, installation and maintenance. The main faults encountered are [10]:

a. in the PV generator: Deterioration of the cells, cracks, heating of the cells Penetration of humidity, deterioration of the interconnections, corrosion of the links between the cells pollution, ...

b. at the junction box: Breaking of the electrical circuit, short circuit of the electrical circuit, destruction of the connection, corrosion of the connections, ...

c. Wiring and connector: Open circuit, Short circuit, Contact corrosion, ...

d. Protection diode (baypass and anti-backflow): Destruction of the diodes, Reverse polarity of the diodes, diode incorrectly connected, ...

Figure 5. Examples of degradation with the impact of the climatic conditions on the photovoltaic module [6].

III.2. Diagnostic methods

We cite the Non-electrical methods such as the thermal camera (infrared imaging) and electrical methods which are based on the measurement of quantities such as [3, 6, 9-10]:

- The current and/or voltage delivered by the PV field.
- The insulation resistance between the positive and negative terminals of the PV field
- Analysis of the power and energy produced by the PV field
- Operating point analysis (maximum power)
- Analysis of the static current/voltage characteristic

In our case we have measured electrical quantities (I, V) at the output of the converter AC, under the same conditions of sunshine and temperature, we artificially created a fault in the PV (short-circuited bypass diode), and then we plotted the power spectrum in the frequency domain in the healthy and faulty case (Figure 6).

IV. Mathematical description of PCA method

The techniques presented here focus on extracting relevant information from spectral matrices. In fact, the new diagnosis method obtains data from the three phases of the current by exploring special fault characteristic frequencies in the power spectral density of the first principal component.

Classical principal component analysis is concerned with explaining the variance –covariance structure among “ p ” variables, $x(t)=\left[x_1(t),\, x_2(t),\ldots,x_p(t)\right]^T$, through a few linear combinations of the components of the vector “x.” The problem can be stated as to find a linear combination

$$y = C^T.\, x = c_1 x_1 + \ldots. + c_p x_p \tag{1}$$

of the components of x such that var(y) is as large as possible with “ C ” to be of unit length; that is $C^T \cdot C = 1$. Noting that $\mathrm{var}(y) = C^T \cdot \Gamma_x \cdot C$, where Γ_x is the “ $p \times p$ ” variance-covariance matrix of x, another way of stating the problem is to find “ C ” such that the amount below is maximal [7]:

$$\max_{C \neq 0} \frac{C^T \cdot \Gamma_x \cdot C}{C^T \cdot C}. \tag{2}$$

For the case of signals, suppose we have a zero mean, “ $p \times 1$”, stationary vector process “ $x(t) = [x_1(t),\ldots,x_p(t)]^T$ ” that has a “ $p \times p$ ” spectral density matrix $S_x(f)$. This matrix is a complex–valued, nonnegative-definite Hermitian matrix [7]. Using the analogy of classical principal components, and in particular (1) and (2), suppose, for a fixed value of “ f ”, we want to find a complex-valued univariate process $y(f) = C^*(f) \cdot x(f)$, where $C(f)$ is complex, such that the spectral density of $y(f)$ is maximized at frequency “ f ”, and $C(f)$ is of unit length, $C^*(f) \cdot C(f) = 1$. Note that the operator “*” is the conjugate transpose operator. Because, at frequency “ f ”, the spectral density of $y(f)$ is $S_y(f) = C^*(f) \cdot S_x(f) \cdot C(f)$, the problem can be stated as : find complex vector $C(f)$ such that the following amount is maximal [7, 8].

$$\max_{C(f) \neq 0} \frac{C^*(f) \cdot S_x(f) \cdot C(f)}{C^*(f) \cdot C(f)}. \tag{3}$$

Let $\{(\lambda_i(f), e_i(f))\}$, $i = 1, 2, \ldots, p$, denote the eigenvalue - eigenvector pairs of $S_x(f)$, where $\lambda_1(f) \geq \lambda_2(f) \geq \ldots. \geq \lambda_p(f) \geq 0$, and the eigenvectors are of unit length. The solution to (3) is to choose $C(f) = e_1(f)$; in which case the desired linear combination is $y(f) = e^*{}_1(f) \cdot x(f)$ [8]. For this choice,

$$\max_{C(f) \neq 0} \frac{C^*(f) \cdot S_x(f) \cdot C(f)}{C^*(f) \cdot C(f)} = \frac{e_1^*(f) \cdot S_x(f) \cdot e_1(f)}{e^*(f) \cdot e_1(f)} = \lambda_1(f) \tag{4}$$

This process may be repeated for any frequency f, and the complex-valued process, $y_1(f)=e^{*}{}_1(f)\cdot x(f)$ is called the first principal component at frequency f. The k-th principal component at frequency f, for $k=1,2,....,p$ is the complex–valued signals $y_k(f)=e^{*}{}_k(f)\cdot x(f)$. In this case, the spectral density of $y_k(f)$ at frequency “ f ” is $S_{yk}(f)=e_k^{\ *}(f)\cdot S_x(f)\cdot e_k(f)=\lambda_k(f)$ [7-8].

The vector of the signals $x_t(t)=[x_1(t),x_2(t),x_3(t)]^T$ is now defined as the consecutive measures of the three current signals intensity where $x_1(t)=i_a(t)$, $x_2(t)=i_b(t)$, $x_3(t)=i_c(t)$. The main advantage of the principal component analysis is its capability in indicating which signals are responding or do not contribute to the estimation of the spectral power. Previous research confirms that the three currents are affected identically when defects occur [1], [6]. In consequence we will expect to have an equal contribution to the estimation of the spectral power.

V. Results and discussions

We present some results obtained by analyzing in the frequency domain the alternating power delivered by the PV in the case with and without defects, in first case we use the classical spectral analysis with the FT : “Fourier transform” (fig.6). For a better illustration we move on to the plotting of the eigenvalue spectrum.

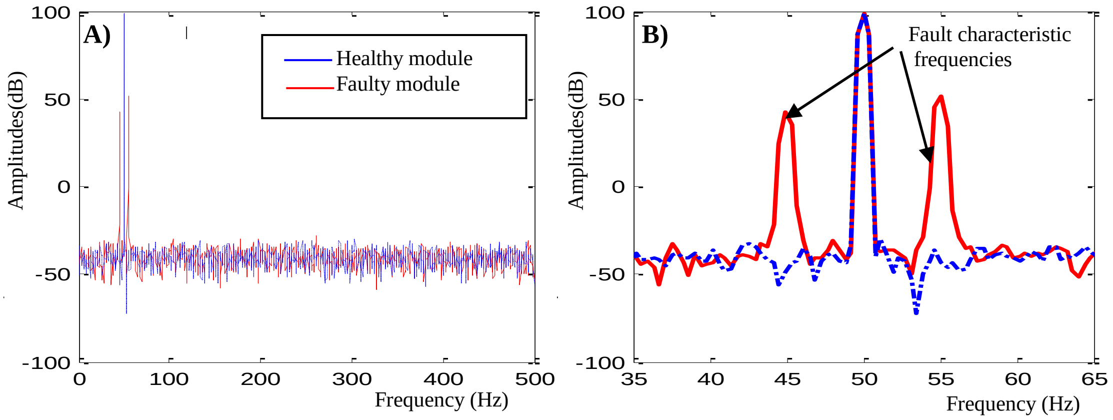
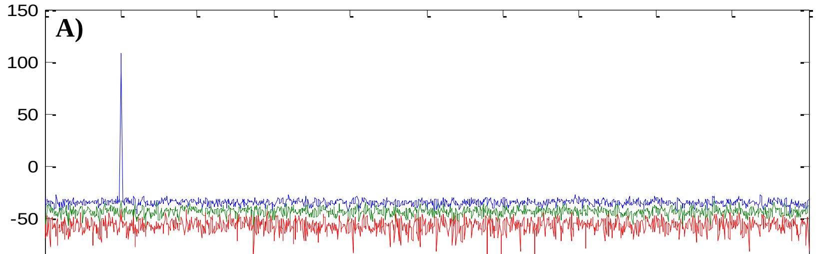


Figure. 6 Power spectral density for a healthy and faulty module. A) full frequency range [0, 500] Hz, B) zooming to range [35, 65] Hz

From (fig.6.A) we can see three frequencies: the fundamental supply frequency ($f_e=50Hz$) and two sideband components. In the second step we proceed to computing the spectral matrix of the vector constructed by the three supply currents signals. The eigenvalues as well as the eigenvectors are computed in order to extract relevant information about PV abnormalities. In fact, we can obtain the estimated spectrum of the first principal component series by calculating the largest eigenvalue for each frequency.



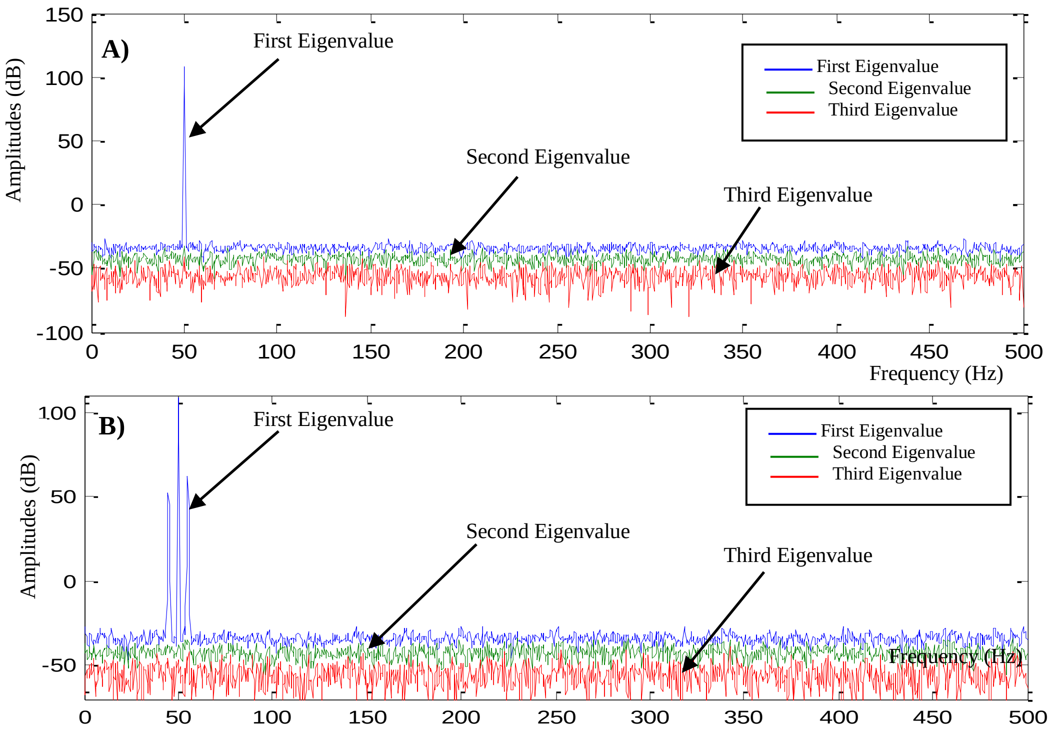


Figure. 7 Eigenvalues of the power spectral density matrix as a function of frequency. A) for a healthy module, B) for a faulty module

From figure 7, we can notice, as expected, the presence of a large peak at the supply frequency only in the first eigenvalue. The other eigenvalues are not affected.

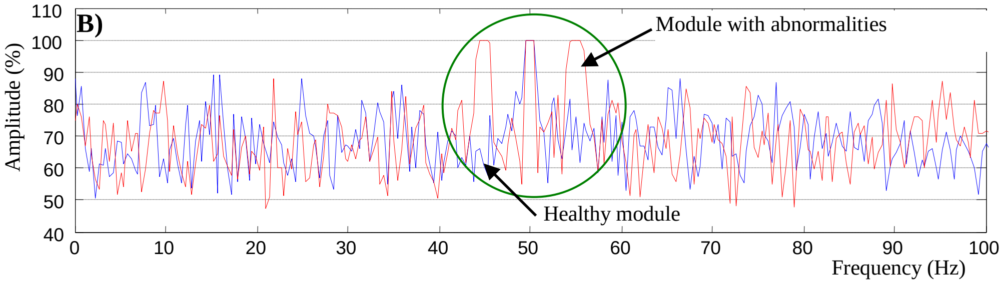


Figure. 8 Proportion of the power, in % of the total power, attributed to the first principal component as a function of frequency.

Figure 8 show a zooming in the last interesting area. We can see clearly that the power proportion attributed to the first principal component is maximal for only the supply frequency in the case of the healthy PV and this proportion is maximal and reaches nearly 100% of the total power for the supply frequency as well as for the two fault characteristic frequencies for a faulty PV. Here we can reveal that the power proportion, in % of the total power, attributed to the first principal component can be used as a first frequency extraction criterion in order to qualify the PV operating mode.

Figure 9 shows a comparison between the set of frequencies detected using the last frequency extraction criterion for a healthy module (figure 9A) and for a faulty module (figure 9B). We can see clearly the good ability of this criterion to detect fault characteristic frequencies.

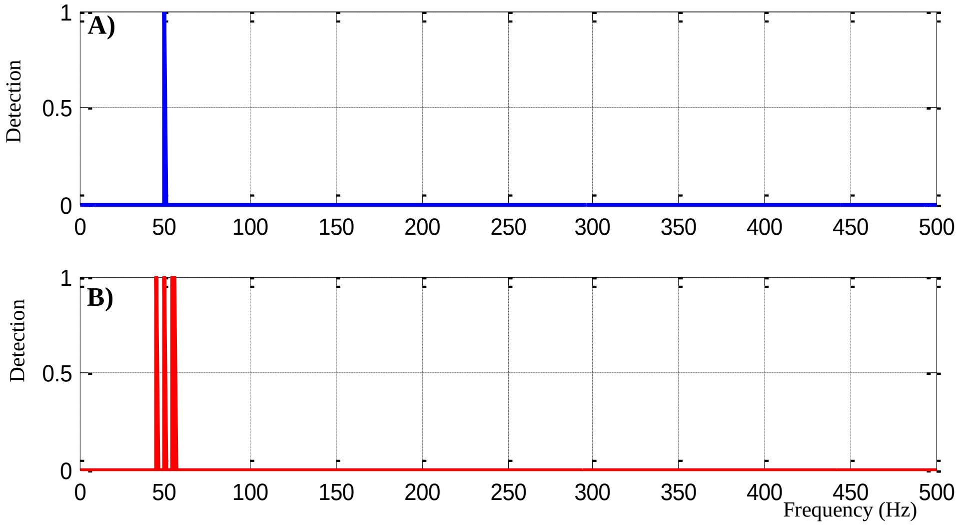


Figure. 9 Automatic detection of the motor characteristic frequencies for two functioning modes. A) Healthy module, B) Faulty module.

VI. Conclusion

In this work, we presented a non-intrusive diagnostic method for photovoltaic panels. This method uses voltage and current sensors at the output of the AC inverter. Our diagnostic procedure proved to be an attractive method, because it has two characteristics. The first is the detection of large amplitude peaks at the characteristic frequencies of the fault. The second corresponds to its ability to automatically extract the characteristic frequencies from the operating mode. This extraction is made completely automatic by calculating the contribution of the current and voltage sensors in the estimation of the power of the frequencies in the first main component. In perspective, we propose the automatic recognition of the fault using Neural Networks (NN) or Support Vector Machine (SVM).

Acknowledgements

The authors wish to express their gratefulness to the members of the General directorate of scientific Research and Technological Development (DGRSDT) of Algeria for supplying the experimental data.

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List of Nomenclature

AC: Alternating Current

FT: Fourier Transform

I_{PM}: Maximum Power Current

I_{CC} : Short circuit current

PV: Photovoltaic

PCA: *Principal Components Analysis*

V_{CO}: Open circuit voltage

V_{PM}: Maximum Power Voltage