1 Abstract

Photovoltaic (PV) systems have become one of the most promising renewable energy sources in the last years. Inevitable, these systems face different degradation effects associated with environmental and operative conditions, manufacturing defects, and mismatch conditions that accelerate the degradation. The diagnosis of degradation processes has become an important topic for increasing the reliability and efficiency of PV devices. It seeks to maximize the performance of solar devices and contribute to early detection processes for enhancing the maintenance planning tasks saving energy and money losses.

The contribution of this thesis is aimed to propose methodological tools for carrying out early detection tasks of degradation effects on PV devices. Online implementations are in the spotlight since they bring the benefit of avoiding modifying the nominal operative condition of the PV devices. For achieving that goal, this thesis has addressed three main proposals for carrying out diagnosis of degradation processes on PV devices.

The first approach analyzed a selection of *analytical* or *explicit* methods validated in previous studies with good performance modeling photovoltaic devices in healthy conditions. In this case, the aim was to test their capability to detect degradation in photovoltaic modules. The study focused on the series resistance estimation since many degradation phenomena occurring in photovoltaic devices are reflected in a variation of the series resistance of the single diode equivalent circuit. A comparison of different explicit methods, used to estimate the model parameters from experimental I-V curves of a photovoltaic module operating in normal as well as degraded states under outdoor conditions, is proposed. It showed that only few methods exhibit enough reliability to estimate correctly the model parameters in presence of degradation and low sensitivity to the environmental operating conditions.

The second approach moved on to more complex parameter estimation methods such as *optimization* techniques. Here, neural networks (ANNs) are used for isolating faults and degradation phenomena occurring in photovoltaic (PV) panels. In literature, it is well known that the values of the single diode model (SDM) associated with the PV source are strongly related to degradation phenomena, and their variation is an indicator of panel degradation. On the other hand, the values of parameters that allow identifying the degraded conditions are unknown a priori. They are different from panel to panel and strongly dependent on environmental conditions, PV technology, and manufacturing process. For these reasons, to correctly detect the presence of degradation, the effect of environmental conditions and manufacturing processes must be properly filtered out.

This approach exploits the intrinsic capability of multilayer perceptron (MLP) ANN to map in its architecture two effects: 1) the non-linear relations existing among the SDM parameters and the environmental conditions, 2) the effect of the degradation phenomena on the I-V curves and consequently on the SDM parameters. The variation of each parameter, calculated as the difference between the output of the two ANN stages, gives a direct identification of the type of degradation occurring on the PV panel. The method has been initially tested by using the experimental I-V curves provided by the National Renewable Energy Laboratory (NREL) database where the degradation effects were introduced artificially, and later tested by using some degraded experimental I-V curves.

The third approach is addressed to complement the aforementioned methodologies by extending the analysis to frequency-domain techniques. Thus, it presents a challenging and innovative approach for detecting degradation phenomena on photovoltaic (PV) panels using the

Electrochemical Impedance Spectroscopy (EIS) technique. This technique has been applied to the chemistry field for a long time ago, but, it has a short history with PV devices. Previous studies have shown promising results with EIS as a tool for the diagnosis of PV devices but, most of them were limited to cell level and controlled conditions in the laboratory.

The innovation of this proposal is supported by two basic aspects that differentiate it from previous ones in the literature: the operating environmental conditions and the operating point. First, this work is aimed to detect degradation phenomena on photovoltaic (PV) devices at the panel level working under outdoor conditions by using the EIS technique. Secondly, the impedance is measured by leaving the PV panel in the real-operative status corresponding to the maximum power point without altering its power production. The implementation of the analysis in these conditions are innovative, but, at the same time mean a challenge due to it requires a detailed and careful implementation of the methods in the right way for characterizing the process.

As a preliminary step, the EIS technique is applied in simulation to analyze the PV panel dynamic response through a detailed LTSpice model including by-pass diodes. The degradation effect to analyze was partial shading conditions. Simulation results showed particular changes in the impedance shape under partial shading conditions only by performing the EIS with the panel operating in MPP thus without scanning the whole I-V curve. This confirmed the usefulness of EIS but also the necessity of going in deep with experimental data for obtaining a more reliable representation of the device with its own representative element values.

As the experimental campaign had different challenges and required most careful steps, the first experimental implementation used a single PV panel. Since variations on the series resistance are associated with multiple degradation phenomena, this first experimental campaign sought to estimate changes in this parameter using a dynamic model fitted to the experimental impedance measurements. Hence, the PV panel impedance measurements are compared in nominal and degraded conditions. The results show that the dynamic model provides higher accuracy in comparison with the series resistance variation identified through the single–diode model, which is the most usual approach. Thus, it is demonstrated the feasibility of detecting degradation effects by using the dynamic model of PV panels working under outdoor conditions.

The next step consisted in extending the analysis to other effects as partial shading with two PV panels in series connection. Here, the number of PV panels for analyzing is restricted due to hardware limitations.

The objective of this stage was to compare the experimental impedance measurements in two conditions, uniform operating conditions and partial shading conditions. The preliminary results show that the partial shading conditions are also detectable by using EIS. But, the complete characterization of the whole effect requires extending the dynamic model to more complex models able to represent both dynamics in a representative model. Due to the reduced database with partial shading conditions currently available, a final assessment cannot be discussed. Nevertheless, the achieved results are very encouraging with interesting perspective for the future work.