Detection of Potential Induced Degradation in c-Si PV Panels Using Electrical Impedance Spectroscopy

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***Abstract* — Impedance spectroscopy (IS) is an established characterization and diagnostic method for different electrical and chemical research areas such as batteries and fuel cells, but not yet widely adopted for photovoltaics (PV). This work, for the first time, investigates an IS based method for detecting potential-induced degradation (PID) in c-Si PV panels. The method has been experimentally tested on a set of panels that were confirmed to be affected by PID by using traditional current-voltage (I-V) characterization methods, as well as electroluminescence (EL) imaging. The results confirm the effectiveness of the new approach to identify PID in PV panels.**

***Index Terms* — c-Si PV panel, Impedance spectroscopy, Potential induced degradation, AC modelling, Parameter fitting, Current-voltage characterization, Electroluminescence imaging**

I. INTRODUCTION

Potential-induced degradation (PID) is a failure mode in solar cells caused by voltage stress on the photovoltaic (PV) module. PID can affect both crystalline and thin film modules, to an extent depending on material and environmental factors. In this work only the shunting type PID (PID-s) will be considered. PID-s is a common degradation than can develop rapidly and can cause significant reductions in module performance [1], due to the decreased parallel (shunt) resistance (R_p) and a reduction of fill factor (FF). PID can be reversed to some extent if detected in time [2].

In previous related studies [3-11], impedance spectroscopy (IS) has been used to characterize new solar cells or small PV modules primarily for extracting the dynamic parameters. For the first time in this work, this method is applied to degrading modules, for fault diagnosis. Since IS enables the measurement of the panels equivalent parallel capacitance, it may provide an extra indicator over DC current-voltage (I-V) characterisation methods that can be used for fault diagnosis.

IS has some potential advantages over current commercially available I-V characterization methods when it comes to outdoor measurements. First, it is more economically efficient, as it does not require a high power circuit. Second, IS measurements can be performed during the night, without interrupting the power production of the PV system.

In this work, a residential PV system experiencing a considerable decrease in performance due to PID was analysed. The best and worst performing modules have been selected for detailed laboratory testing. By employing I-V and electroluminescence (EL) measurements, the degradation of the modules has been confirmed as PID.

The IS tests confirmed the degradation of the PV panels observed from the I-V and EL laboratory measurements, and showed similarly decreased shunt resistance. Furthermore, the IS measurements have shown that the capacitance of the panels has also increased due to PID of the PV panels.

The results support the hypothesis that IS can be a suitable diagnostic method for PV panels. These findings open new possibilities in faults and degradations studies through AC characterization means.

In the next section the AC modelling is briefly presented. Section III describes the characterization means utilized to observe the severity of the degradation. The findings of this research are shown in section IV. The last section contains the discussion and final remarks.

II. AC MODELLING

Commonly, the AC behaviour of solar cell and PV modules is modelled using lumped electrical circuits, for both light [11, 12] and dark solar cell operation conditions [9, 11, 13]. In this work we focus on dark IS characterization of PV modules, and consequently we use the AC solar cell model shown Fig. 1, to analyse the PV module degradation.

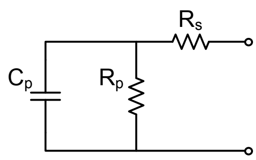

Fig. 1 The equivalent circuit model used for the parameter fitting. In this case the emphasis is on the parallel components C_p and R_p.

Derivations of this model have been done in [3, 6, 9] together with parameter extraction [14]. However, to determine the parameters of equivalent circuit the equation (1) is derived in real (2) and imaginary (3) parts. The two corresponding models are fitted to the IS measurements. Typically in c-Si PV panels the series resistance (R_s) is three orders of magnitude smaller than the shunt resistance (R_p). Although R_s is included in the fitting equation, the results of the fitting for this parameter are neglected and will not be presented.

The IS measurements consist of norm (absolute value) and phase (angle) of the PV panel impedance. To determine the lumped circuit model parameters we need to convert the norm and phase measurements to their real and imaginary counterparts, using Euler's formula.

$$Z = R_s + \frac{R_p}{1 + j\omega\, C_p R} \tag{1}$$

$$\mathrm{Re}(Z) = R_s + \frac{R_p}{1 + \omega^2 C_p^2 R_p^2} \tag{2}$$

$$\mathrm{Im}(Z) = -\frac{\omega\, C_p R_p^2}{1 + \omega^2 C_p^2 R_p^2} \tag{3}$$

Where Z represents the impedance of the circuit, j is the imaginary unit and ω is the angular frequency defined as:

$$\omega = 2\pi f \tag{4}$$

III. Experiment Setup

The I-V characterization is performed in light as well as in dark conditions using a Spi-Sun 5600SLP sun simulator [15]. The flasher is an A+A+A+ rated device.

The EL images are taken with a Photonic Science short wave infrared (SWIR) camera [16]. The test is executed in a dark chamber with the PV module forward biased. The current is set at 10% of the rated short circuit current (I_{sc}) as this value is recommended for observing PID [17].

IS characterization is performed using a HP 4284A Precision LCR meter [18]. The frequency range employed is 20 Hz – 100 kHz. Above this frequency range, the impedance of the connection circuit (lead wires, connectors) becomes dominant and the assumptions made for fitting are no longer valid. The excitation signal is a sinusoidal voltage with $2V_{peak}$. A DC forward bias of equivalent value is used to keep the bypass diodes of the module blocked. The IS measurements are executed in dark conditions.

IV. Study Case

A residential PV plant located in southern Denmark, with a total installed capacity of 9.36 kW, was inspected for faults, since the plant experienced a dramatic loss in power generation compared to the installed power, as shown in Fig. 2.

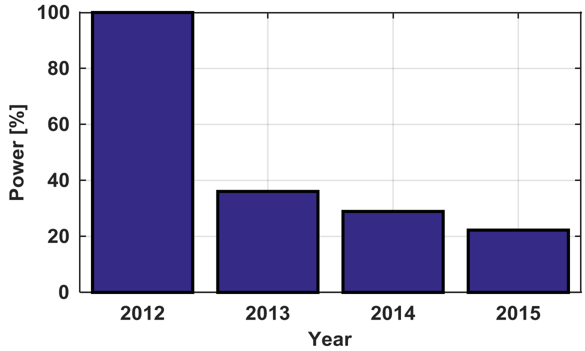

Fig. 2 Plant recorded yearly production from installation, normalized to the first year. The pattern shows a fault rather than a natural degradation, since the power drops in one year to less than 40% of the initial output.

The plant consists of a total of 36 c-Si panels connected in 3 strings with each having 12 modules in series. The strings are connected to a SMA inverter [19], limited to 6 kW due to grid connectivity rules. The converter has two maximum power point tracker (MPPT) inputs, thus one string is connected to MPPT2 while the other two are paralleled at MPPT1 as it can be seen in Fig. 3.

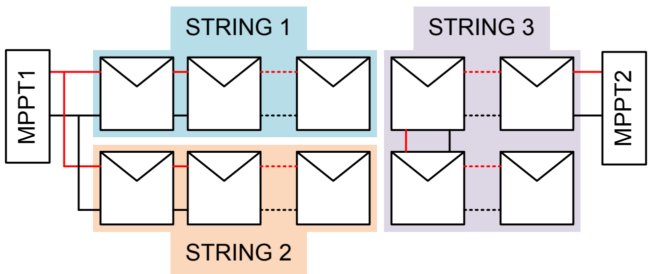

Fig. 3 Plant setup is composed by 36 PV panels connected in 3 equal strings to a SMA converter. The inverter has 2 MPPT channels hence two of the string are parallel on one input while the third string is connected to the second channel.

Field tests with the Z100 PV analyzer, an IS based diagnostic tool for PV arrays [20], have reflected the state of the panels. The best one and worst five performing modules have been selected for laboratory testing with the purpose to evaluate the overall performance and confirm the degradation type, which at the time was suspected to be PID.

The laboratory EL imaging and I-V characterization tests confirm that this is a case of PID of shunting type. The maximum power has dropped from the datasheet rating, as well as the fill factor. Fig. 7 shows EL measurements, confirming the suspected degradation in this case. The pattern is consistent with PID [21].

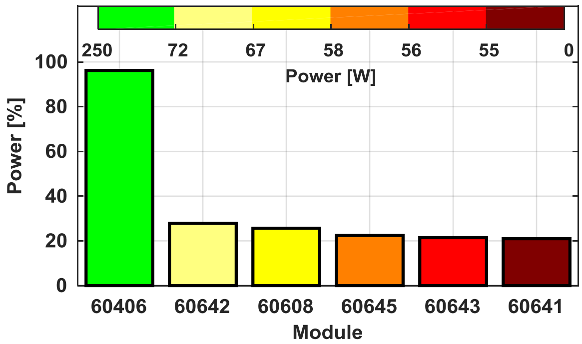

Fig. 4 Decrease of STC P_{max} of the modules relative to their datasheet value. It can be observed that the best performing module has an expected loss in power of around 1% per year from the rated value, while the other worst performing modules have an indisputable degradation problem.

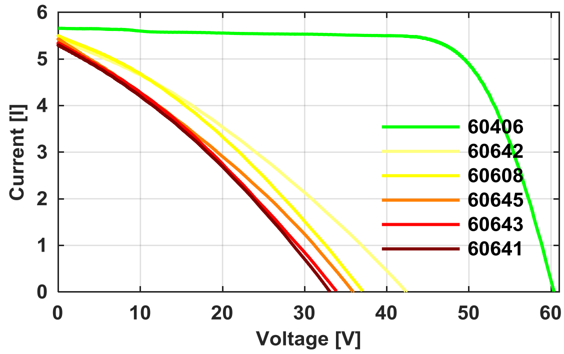

Fig. 5 Modules light I-V characteristic accentuate the advanced state of degradation of the PV panels.

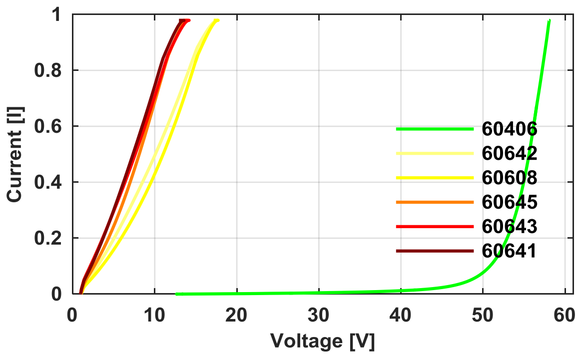

Fig. 6 Dark I-V characteristics of the PV modules correlated with the EL results point out the degradation to be PID. The shunt resistance had dropped considerably.

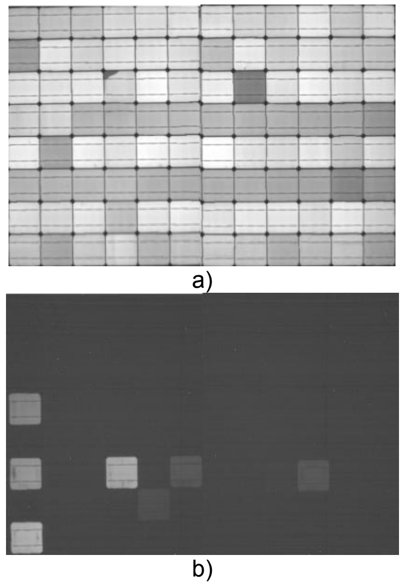

Fig. 7 EL image of a good panel, a) module 60406 , versus a degraded panel, b) module 60608, taken in low current bias conditions.

The results obtained using I-V characterization and EL imaging demonstrate the severity of PID [21]. The drop in FF can be observed from the light I-V characteristic presented in Fig. 5. The accentuated slope in the region denotes a drop in shunt resistance, visible also in dark I-V (Fig. 6). The EL images support these results by revealing an overall cell degradation in the affected modules as shown in Fig. 7 b).

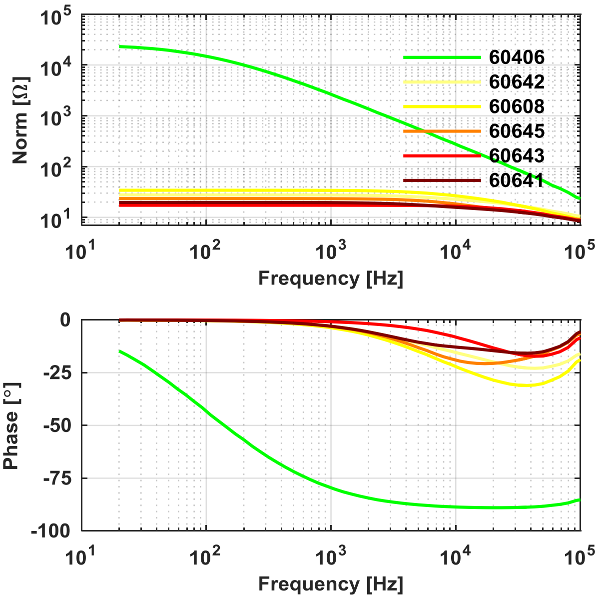

Fig. 8 Impedance spectra of the six PV modules, measured in dark condition in a frequency range from 20Hz to 100 kHz. The difference is evident between the best performing module (60406) and the others.

PID in the early stages of degradation. It should be noted that other types of faults may have a similar effect on the parallel capacitance, therefore further research is needed for assessing the value of this parameter in presence of various faults.

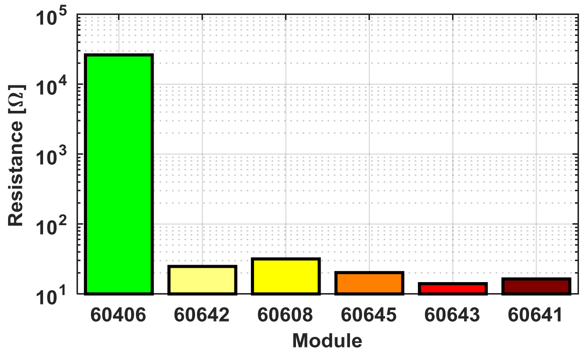

Fig. 9 Shunt resistance values determined from the IS measurements illustrate the same picture as the other characterizations. The PID modules have an R_p much lower than the typical value for c-Si PV panels, which is around few kΩ.

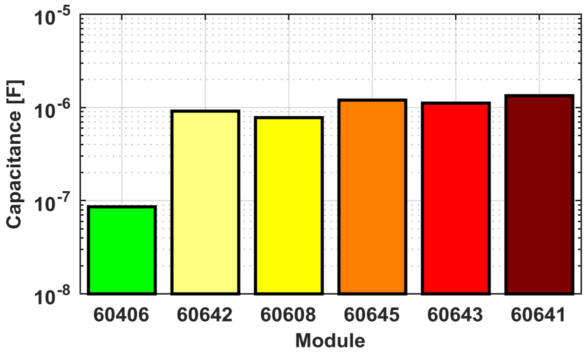

Fig. 10 The parallel capacitance shows one order of magnitude increase in value for the degraded modules in comparison to the well performing module. The change is significant and supports the hypothesis that the AC parameters can be used to observe changes in the PV panel state.

The shunt resistance determined by IS in Fig. 9 shows good correlation with the light and dark I-V measurement results. Furthermore, the panels' parallel capacitance in Fig. 10 show a strong increase in the degraded panels, consistent with the trends in shunt resistance and fill factor decrease.

V. Conclusions

In this work a case study of c-Si PV panels that experienced PID in the field has been investigated. It has been shown that PID can affect the capacitance of PV panels, and simple IS methods can be used to detect the change in the parallel capacitance of commercial PV panels. In the study case a significant increase in capacitance has been detected in the presence of extensive PID. The results confirm the potential of IS as a diagnostic method for PV modules also in the field, however further controlled degradation tests are needed to better assess the dependency of the parallel capacitance on

References

[1] P. Hacke, S. Spataru, K. Terwilliger, G. Perrin, S. Glick, S. Kurtz, *et al.*, "Accelerated Testing and Modeling of Potential-Induced Degradation as a Function of Temperature and Relative Humidity," *IEEE JOURNAL OF PHOTOVOLTAICS,* vol. 5, pp. 1549-1553, 2015.

[2] S. Pingel, S. Janke, and O. Frank, "Recovery methods for modules affected by potential induced degradation (PID)," in *27th European Photovoltaic Solar Energy Conference and Exhibition (Frankfurt)*, 2012, pp. 3379-3383.

[3] R. L. Mueller, M. T. Wallace, and P. Iles, "Scaling nominal solar cell impedances for array design," in *Photovoltaic Energy Conversion, 1994., Conference Record of the Twenty Fourth. IEEE Photovoltaic Specialists Conference - 1994, 1994 IEEE First World Conference on* vol. 2, ed, 1994, pp. 2034-2037 vol.2.

[4] J. H. Scofield and O. College, "Admittance measurements on Cu(In,Ga)Se2 polycrystalline thin-film solar cells," *Renewable Energy,* pp. 291-294, 1995.

[5] M. S. Suresh, "Measurement of solar cell parameters using impedance spectroscopy," *Elsevier,* vol. 43, pp. 21-28, 1996.

[6] R. Anil Kumar, M. S. Suresh, and J. Nagaraju, "Measurement and comparison of AC parameters of silicon (BSR and BSFR) and gallium arsenide (GaAs/Ge) solar cells used in space applications," *Solar Energy Materials and Solar Cells,* vol. 60, pp. 155-166, 2000.

[7] R. A. Kumar, M. S. Suresh, and J. Nagaraju, "Facility to measure solar cell ac parameters using an impedance spectroscopy technique," *Review of Scientific Instruments,* vol. 72, pp. 3422-3426, 2001.

[8] R. Anil Kumar, M. S. Suresh, and J. Nagaraju, "GaAs/Ge solar cell AC parameters under illumination," *Solar Energy,* vol. 76, pp. 417-421, 2004.

[9] D. Chenvidhya, K. Kirtikara, and C. Jivacate, "PV module dynamic impedance and its voltage and frequency dependencies," *Solar Energy Materials and Solar Cells,* vol. 86, pp. 243-251, 2005.

[10] L. Raniero, E. Fortunato, I. Ferreira, and R. Martins, "Study of nanostructured/amorphous silicon solar cell by impedance spectroscopy technique," *Journal of Non-Crystalline Solids,* vol. 352, pp. 1880-1883, 2006.

[11] I. Mora-Seró, G. Garcia-Belmonte, P. P. Boix, M. a. Vázquez, and J. Bisquert, "Impedance spectroscopy characterisation of highly efficient silicon solar cells under different light illumination intensities," *Energy & Environmental Science,* vol. 2, p. 678, 2009.

[12] L. a. Mallette and R. L. Phillips, "Modeling solar cells for use as optical detectors: background illumination effects.," *Applied optics,* vol. 17, pp. 1786-1788, 1978.

[13] D. Chenvidhya, K. Kirtikara, and C. Jivacate, "A new characterization method for solar cell dynamic impedance," *Solar Energy Materials and Solar Cells,* vol. 80, pp. 459-464, 2003.

[14] E. Barsoukov and J. R. Macdonald, "Impedance Spectroscopy," *Impedance Spectroscopy: Theory, Experiment, and Applications,* pp. 1-595, 2005.

[15] (2016). *Spi-Sun Simulatoror 5600SLP*. Available: http://www.spirecorp.com/products/class-a-sun-simulation.cfm

[16] (2016). *SWIR camera - NIR camera - InGaAs camera*. Available: http://www.photonic-science.com/products/swir-ingaas-cameras.html

[17] P. Hacke, K. Terwilliger, R. Smith, S. Glick, J. Pankow, M. Kempe*, et al.*, "System voltage potential-induced degradation mechanisms in PV modules and methods for test," in *Photovoltaic Specialists Conference (PVSC), 2011 37th IEEE*, 2011, pp. 000814-000820.

[18] "Model 4284A Precision LCR Meter," in *Operation Manual (Dec. 1991) pp*, ed: Hewlett-Packard, 1991, pp. 2-1.

[19] "SUNNY TRIPOWER 5000TL - 12000TL Three-Phase Inverter datasheet," ed: SMA Solar Technology AG, 2014.

[20] (2016). *EmaZys Z100□□ PV Test Instrument*. Available: http://emazys.com/z100-pv-test-instrument/

[21] S. Pingel, O. Frank, M. Winkler, S. Daryan, T. Geipel, H. Hoehne*, et al.*, "Potential Induced Degradation of solar cells and panels," in *Photovoltaic Specialists Conference (PVSC), 2010 35th IEEE*, 2010, pp. 002817-002822.