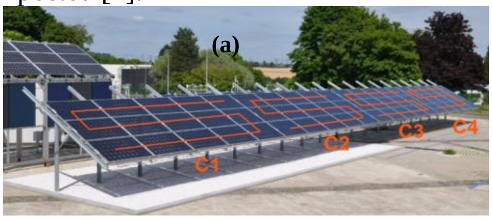
Quantitative Electroluminescence Investigation of PID on Field-Installed n-PERT *Si* Modules

Julien DUPUIS[1], Christine ABDEL NOUR[1], João Victor OLIVEIRA SANTOS[1,3], Arthur SORARUFF[1], Daniel ORY[2], Olivier PALAIS[3], Damien BARAKEL[3]
[1]EDF R&D, EDF Lab Les Renardières, Avenue des Renardières, Moret Loing et Orvanne 77250, France
[2]EDF R&D – IPVF, 18 boulevard Thomas Gobert, 91190 Palaiseau, France
[3]Aix-Marseille Univ, Université de Toulon, CNRS, IM2NP, Marseille, France

Potential-induced degradation (PID) is a degradation mode on photovoltaic modules linked to the potential difference between the module terminals and its grounded frame [1]. Module and solar cells' dielectric stacks do not completely insulate cells, and thus leakage current and even ions (especially Na+) can move and in some conditions migrate to the solar cells reducing their performance. This study comprises the analysis of field-installed PID sensitive bifacial n-PERT modules which remained operating in field for 8 years in ungrounded string configuration (fig. 1-a), ranging from -300V to 300V. Sixty modules were distributed into four strings (C1, C2, C3, and C4), the top of each string being negatively polarized while the bottom was positively polarized. This study presents valuable insights on n-PERT middle-term performance degradation. Moreover, these modules present a similar front side architecture to n-TOPCon Si modules - which might represent more than 80% of market share by the end of this decade [2]. Thus, some analogous PID behavior can be expected [1].



(b)

-8,2	-7,5	-5,1	-1,4	-2,3
C1.05	C1.04	C1.03	C1.02	C1.01
-7,9	-7,6	-6,3	-3,7	-1,2
C1.06	C1.07	C1.08	C1.09	C1.10
0,6	0,7	0,7	0,4	-0,8
C1.15	C1.14	C1.13	C1.12	C1.11

Figure 1*.*
(a) Modules divided into four strings of fifteen modules, noted as C1, C2, C3, and C4.
(b) Ratio between initial and final power generation for modules in string C1.

Figure 1-b shows the power generation percentual change between current-voltage (I-V) measurements before installation and after an outdoor period where the modules were removed from string C1 to be measured. The inhomogeneous values are a sign of PID ("potential" PID type); one might note, however, that the module closest to the negative terminal was not the one that degraded the most and the intriguing observation that positively biased modules had their performance increased after operating in the field for 8 years.

C1 modules were submitted to quantitative EL imaging and the dark saturation current densities (J_0), which is an indicator of recombination, was computed for each cell within these modules according to Ref. [4]. For module C1.05, the one that presented the highest performance decrease, a map of J_0 is provided in Figure 2-a, displaying higher values close to the frame, and hence confirming a PID as the frame conduction enhanced the degradation effect. The distribution of J_0 within C1 was also analyzed (fig. 2-b), pointing out increasing recombination in the beginning of the string up to C1.03 (Region A) in comparison to a control module which was not under operation during the period (noted as "Ref."), reaching a maximal value at C1.04 and remaining mostly high up to C1.09 (Region B), then decreasing until the end of the string (Region C).

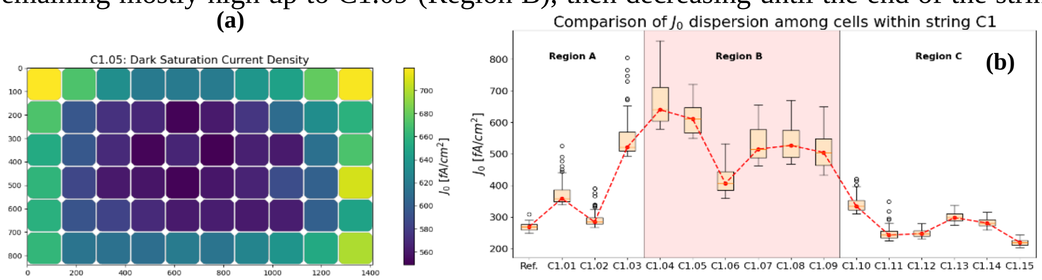


Figure 2*.*
(a) J_0 map for module C1.05
(b) J_0 dispersion among cells for modules within string C1.

These results present a similar behavior to what P. Hacke et al. [3] recently obtained in a numerical simulation of the ratio between maximal power and initial maximal power for varying surface rear charges in bifacial p-PERC modules. This simulation provided three regimes: accumulation, depletion, and inversion. Accumulation is when holes are the majority at the surface and electrons are gradually accumulating, slightly increasing recombination. Depletion is characterized with holes and electrons reaching an equilibrium, and thus a maximal recombination rate is obtained. And inversion is when the electrons outnumber the holes, and recombination falls back again. Even though no inversion was verified by the authors in fielded modules, regions A, B, and C shown in figure 2-b indicate an outdoor observation of accumulation, depletion, and inversion, respectively.

To sum up, the J_0 analysis presented on this work matches the three regimes investigated by P. Hacke et al. [3] with inversion being the reason behind no power losses for positively biased modules after 8 years. It is, to the best of our knowledge, the first time such a behavior was observed on n-PERT in outdoor environment. Further enhancements will be performed to refine results, including overcoming the limitations of the "Fuyuki linear approximation" used by Ref. [4] for computing J_0, which were discussed on Ref. [5]. Moreover, a complementary study of J_0 considering all the cells within the string to be in series was performed and will be presented in the final manuscript as well as the results obtained for all four strings to provide a broader analysis.

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