

Modeling the electrical mismatch caused by potential-induced degradation in crystalline silicon photovoltaic modules and strings

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Received: 16 September 2025 / Accepted: 8 December 2025

Abstract. Potential-induced degradation (PID) can not only reduce the output power of a solar cell but also create additional power losses due to non-uniform degradation within a module, string or array, leading to mismatch in the electrical performance of the solar cells in the system. This work models the impact of PID-polarization (increases surface recombination velocity in a solar cell) and PID-shunting (increases recombination in depletion region and shunts the p-n junction of a solar cell) on the current-voltage (I-V) characteristics of a 22×8 photovoltaic array and estimates the array level power mismatch losses (the difference between array level power loss and the average power loss of the modules in the array). Each solar cell in the array is represented by a two-diode equivalent circuit model, and PID is introduced in a solar cell by degrading the model parameters including the light generated photocurrent, dark saturation currents, shunt resistance and ideality factor. The module level model is validated with modules that are PID degraded in the laboratory and is used as baseline for creating the array level model: the root-mean square error between simulated and measured I-V curves are within 0.2 A. To generate realistic PID affected I-V characteristics curves, the degradation in solar cells is applied non-uniformly within a module, string and array. For a PV array affected by PID-polarization and PID-shunting, the mismatch losses can increase up to 0.72% and 2.35% which is in addition to the power losses of ~5.25% and ~10% caused by PID itself, respectively. The annual energy losses are estimated by increasing the severity of PID in the arrays during a one-year-simulation and it resulted in 4.84% and 10% less in the annual energy production of the arrays, respectively.

Keywords: Modeling / electrical mismatch / potential-induced degradation / crystalline silicon / photovoltaic system

1 Introduction

Photovoltaic (PV) modules deployed in utility scale PV systems can be affected by different faults and/or degradation modes due to exposure to several operational and environmental stress factors. These external stress factors may, depending on the susceptibility of the deployed PV technology or a PV module composite to a certain fault and/or degradation mode, non-uniformly impact the interconnected modules and cause mismatch in their electrical current-voltage (I-V) characteristics [1–3]. This may not only affect the output power of the modules but may limit the power production of the entire PV system as modules in serial and parallel connections are limited by the current and voltage of the lowest rated module, respectively [1–4].

Work in [5] investigates the impact of applying different levels and types of soiling on field exposed PV modules under operating conditions and connected serially together into a 12-module PV string. The partial soiling on the PV modules causes drop in the output current of the PV string due to formation of step on the string level I-V characteristic curve, and which gets more pronounced under severe soiling [5]. A similar study [6] is carried out for a PV system consisting of 19 PV strings with each 20 PV modules connected serially where the impact of partial shading of different heaviness is investigated, resulting in drop in the output current [6–8]. The authors in [9] review the impact of solar cell cracks on cell-substring, module and string level I-V characteristics. The result shows that having two modules connected serially causes greater drop in output power than having them connected parallelly as the output current of the cracked module is the limiting factor [9].

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Mismatch in the output current and voltage between solar cells/modules represents a power loss that occurs on top of the actual module degradation, and which may increase over time as mismatch between the electrical characteristics of a module in a string or between strings in an array increase [1]. This may in the long term also have an impact on the annual energy production of the PV system.

Potential-induced degradation (PID) is one such degradation mode that, depending on the mechanism, can affect both the current and voltage output of a PV system that is operating at a high system voltage [10]. A high voltage difference between the active part of a PV module and the grounded module frame (and surfaces) generates an electric field that causes charges and/or ions in the p-n junction to migrate from their initial sites to a less desired site [10,11]. In the case of shunting type of PID (PID-s), sodium ions (Na^+) penetrate into stacking faults and cause recombination in the depletion region and shunting of the p-n junction [10,11]. This limits both the current and the voltage at maximum power point (MPP) due to 1) increase in second diode dark saturation current (J_{02}) and ideality-factor (n_2) and 2) decrease in shunt resistance (R_{SH}), fill factor (FF) and open circuit voltage (V_{OC}) [10–14]. PID-s is mainly observed on the front side of p-type aluminum back surface field (Al-BSF) and passivated emitter rear contact (PERC) PV modules that operate under negative voltage potential [10,15].

A PV module affected by polarization type of PID (PID-p) is, on the other hand, mainly limited by the current at MPP due to 1) increase in first diode dark saturation current (J_{01}) and ideality factor (n_1) and 2) decrease in short circuit current (I_{SC}) unless it is severely degraded, in that case, a decrease in V_{OC} also occurs [13,15]. PID-p is observed on 1) the front side of Al-BSF and PERC [15–18] and rear side of n-type passivated emitter rear totally diffused (PERT) [15] PV modules that are under positive voltage potential, 2) on the rear side of PERC [15,19,20] and 3) on the front side of PERT [21–25] and n-type tunnel oxide passivated contact (TOPCon) [26,27] PV modules that are under negative voltage potential [15]. The front side PID-p is caused by recombination between minority carrier holes or electrons and majority carrier electrons or holes due to change in the net charge of the anti-reflective coating (ARC), respectively [15,21]. The rear side degradation in PERC is described by neutralization of the rear passivation dielectric layer by positive charges and surface recombination between the majority carrier holes and minority carrier electrons at the rear dielectric layer [15,19,20].

Most of the PID studies are carried out in laboratory-based high voltage stress testing and the impact of PID is characterized on either cell or module level [10,15]. To what extent do the different PID types impact the electrical performance of a PV plant and how does this translate into the long-term performance of a PV plant is not clarified, especially for PV systems affected by PID-p as 1) it is not easily identified and/or isolated from other faults and/or degradation modes that cause similar deviation on the I-V characteristics, 2) multiple faults and/or degradation modes may co-exist in a PV cell, module and/or string and may contribute to the loss in the electrical output

parameters and 3) it can partially or fully recover from the ultra-violet (UV) range of the sun-light spectrum when operating in the field (may affect the rate of degradation) [27–30]. Also, the non-uniform voltage stress on the PV modules in a PV string contributes to different PID rates in solar cells/modules and affects their electrical performance unevenly, causing mismatch losses in the system in addition to losses that may occur due to PID [1,15,31,32].

There are a number of papers that document the effect of PID-s on the string and sub-string levels [31–34]. A mismatch loss of 1.9% is documented for a string with 17 serially connected PV modules that are degraded non-uniformly due to PID-s after 1.5 year operation in the field [31,32]. Another paper [34] documents an average loss in string output power of 9% due to degraded PV modules after 3 years of outdoor operation in a PV system consisting of PV strings with 15–24 serially connected PV modules.

The work in [35] shows the impact of PID-s on the electroluminescence (EL) signal emitted by PV modules that operate under negative voltage potential in a PV string with floating grounding configuration. The reduction in the EL signal is more pronounced for PV cells near the module frame (creates a chessboard pattern in modules) and for PV modules close to the negative pole of the string, characteristic for PID-s on string level [35]. A similar degradation pattern is observed in an infrared (IR) thermogram for a PV string affected by PID-s [29]. However, the severity of degradation and its string-level impact are not quantified in both cases [29,35].

Similar degradation patterns are observed in EL and IR images for PV modules operating under real operating conditions (i.e. in the field) [36]. However, only a difference of 3 to 4 Kelvin degrees between healthy and PID affected PV cells is determined from an IR thermogram [34,36]. The PV system consisted of six PV strings with 19 serially connected p-type PV modules, operating under floating grounding configuration with a system voltage of 850 V and under hot semi-arid climate [36]. PID was identified in PV modules near the negative pole after 26 months of operation, causing loss in the module output power of up to 10% [36]. For field-aged PV modules affected by PID (operated in the field for 20 years), the difference in cell temperature of a healthy and a PID-s affected cell is 7–15 °C [37].

The authors in [38] report the change in I-V characteristic curves of a PID-s affected PV string consisting of five serially connected polycrystalline silicon PV modules in outdoor condition and under -1000 V. The level of degradation in the five PV modules is almost similar and only a decrease in the I_{SC} (7.43%), V_{OC} (0.89%) and P_{MAX} (24.41%) are reported [38]. Similarly, the paper [39] reports the electrical parameters of a PV string affected by PID-s and a healthy PV string at different outdoor conditions (clear sky, partial shading and overcasting) with a decrease of 26.9, 1.23, 37.2 and 37.15% in V_{OC} , I_{SC} , V_{MPP} and P_{MPP} and 0.13% increase in I_{MPP} at clear sky condition, respectively [39]. However, an insignificant change in I_{MPP} and a decrease in I_{SC} differs from what is typically observed for PID-s on module level in laboratory-based characterization [10,15,39].

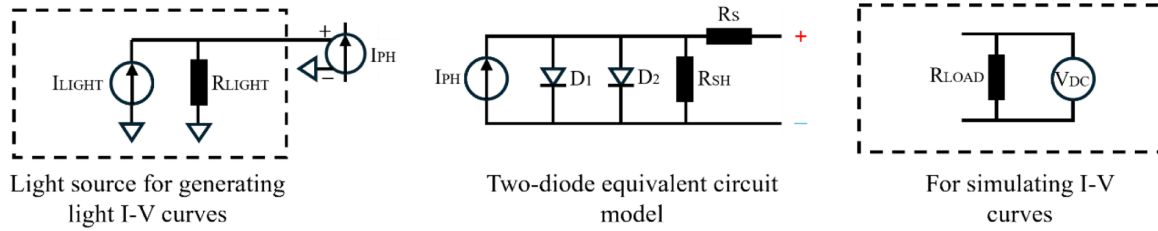


Fig. 1. The two-diode equivalent circuit model implemented with PySpice library.

Table 1. Input parameters of the two-diode equivalent circuit model for a healthy solar cell.

I_{PH} [A]	R_S [Ω]	R_{SH} [Ω]	I_{01} [A]	n_1	I_{02} [A]	n_2
9.85	0.005	1000	1×10^{-10}	1	1×10^{-19}	2

For PID-p, the outdoor characterization is done on module level only. The authors in [40] examine the susceptibility of PERC PV modules to PID-p in the field by stressing them with ± 1500 V during daytime. The results are shown for a period of six months [40]. A P_{Loss} of 4.5 – 6% (measured on the front side) is observed after 2.5 weeks of high voltage application for modules mounted on near ground as well as on elevated ground racks [40]. The power does not reduce any further but remains constant throughout the testing time reported [40]. A slight variation in the degradation rates in PV modules with the two different mounting configurations is observed due to the amount of albedo incident on the rear side of the PV modules [40]. From I-V flash testing in the laboratory, the rear side PID-p degradation is confirmed with reduction in the I_{SC} from 7.594 to 6.288 A (measured on the rear side after eight weeks of high voltage application) [40]. An EL image of a PID-p degraded PV module shows that solar cells near the perimeter of the module appear darker than solar cells in the center, characteristic of PID when induced on module level [40]. A similar study is carried out outdoors with a PERT PV mini module connected to the negative end of a PV string with ten other conventional PV mini modules [41]. A voltage potential of -1000 V is applied to the string [41]. The power saturates after a reduction of $\sim 15\%$ [41]. After 100 h, recovery (in sunny days) and further degradation (rainy days) are observed [41]. The I_{SC} and V_{OC} reduce with 10% and 5%, respectively [41].

The aim of this work is to model and investigate the impact of different levels of PID-s and PID-p on PV array I-V characteristics using PySpice library, and to quantify the additional mismatch loss caused by PID at array level, considering 1) the underlying PID mechanisms (i.e. which of the electrical and/or physical parameters of the PV modules/cells of a specific technology are affected when operating under positive or negative voltage potential); 2) different degradation rates and/or severity of solar cells (i.e. variability in solar cell performance) in a PV module due to non-uniform potential on the PV module's surface, leading to the PID characteristic chessboard pattern, as well as more degraded cells closer to the frame; and 3) variability in PV module performance in/of a PV string

due to different level of voltage stress depending on the location of the PV modules in the PV string. The model will be verified on module level and will serve as a basis for studying and quantifying the mismatch losses and the long-term performance of a PV array affected by PID.

2 Material and methods

2.1 Modeling of solar cells affected by PID

The modeling of a PV system is done in Python (version 3.8.5) using the PySpice library with default solver “ngspice-shared” (version 1.5) [42]. Each solar cell is represented by a two-diode equivalent circuit model with the following input parameters: light generated photocurrent (I_{PH}), series resistance (R_S), shunt resistance (R_{SH}), dark saturation currents (I_{01} and I_{02}) and ideality factors (n_1 and n_2) of the two diodes (referred to as cell level model) [43]. The electrical circuit model of the solar cell simulates a light I-V characteristic curve at a given irradiance and temperature level by doing a voltage sweep from 0 V to V_{DC} and measure the current running through a resistor (R_{LOAD}) that is generated from light source I_{LIGHT} (Fig. 1).

Table 1 shows the input parameters of the two-diode equivalent circuit model that is used for simulating a healthy solar cell. For introducing PID of a specific type/mechanism in the solar cells, the most affected two diode model parameters are modified/adjusted to what is experimentally observed and reported in the literature. The modeling of PID-p is based on mechanism that is observed on the front side of a *p*-type crystalline silicon (c-Si) PV module stressed with high positive voltage potential. A 5% decrease in the I_{PH} and increase of I_{01} from 1×10^{-10} A to 5×10^{-10} A is applied for the most degraded solar cell in the simulation, corresponding to a P_{Loss} of 10% on the cell level [16]. However, to consider different levels of severity and PID susceptibility of solar cells within a PV module, higher voltage stress near the module frame and at the positive end of a floating PV string, a range of I_{SC} and I_{01} between the given values are applied to the solar cells (Tab. 2).

Table 2. Input parameters of the two-diode equivalent circuit model for a PID-p degraded solar cell.

I_{PH} [A]	R_S [Ω]	R_{SH} [Ω]	I_{01} [A]	n_1	I_{02} [A]	n_2
>9.653	0.005	1000	2×10^{-10}	1	1×10^{-19}	2
$9.653 - 9.555$	0.005	1000	3×10^{-10}	1	1×10^{-19}	2
$9.555 - 9.456$	0.005	1000	4×10^{-10}	1	1×10^{-19}	2
<9.456	0.005	1000	5×10^{-10}	1	1×10^{-19}	2

Table 3. Input parameters of the two-diode equivalent circuit model for a PID-s degraded solar cell.

I_{PH} [A]	R_S [Ω]	R_{SH} [Ω]	I_{01} [A]	n_1	I_{02} [A]	n_2
9.85	0.005	>400	1×10^{-10}	1	1×10^{-17}	3
9.85	0.005	$400 - 200$	1×10^{-10}	1	1×10^{-15}	5
9.85	0.005	$200 - 100$	1×10^{-10}	1	1×10^{-13}	7
9.85	0.005	$100 - 20$	1×10^{-10}	1	1×10^{-6}	8
9.85	0.005	<20	1×10^{-10}	1	1×10^{-1}	9

Table 4. Parameter values of bypass diodes connected to the cell-substrings and PV module strings. Set to default values [42].

Saturation current I_S [A]	Ohmic resistance R_S [Ω]	Emission coefficient N	Recombination saturation current I_{SR} [A]	Activation energy E_G [eV]	Parameter measurement temperature T_{NOM} [$^{\circ}C$]
1×10^{-14}	0	1	1×10^{-14}	1.11	27

Similarly, for PID-s, observed on the front side of a *p*-type c-Si PV module operating under high negative voltage potential, the degradation in solar cells are introduced by reducing the R_{SH} of the solar cells from 1000Ω to $\sim 0.1 \Omega$ and increasing the I_{02} and n_2 from 1×10^{-19} A and 2 to 1×10^{-1} A and 9, respectively [13,14] (Tab. 3). This corresponds to a $P_{LOSS} > 30\%$ on the cell level [13].

2.2 Modeling of PV modules affected by PID

Solar cells are serially connected into a PV module as three 20-cell substrings, each connected parallelly to a bypass diode (Tab. 4) (Fig. 2, top left). A cell-substring is modelled by grouping identical solar cells into a single two-diode equivalent circuit model with input parameters: I_{PH} , $R_S \cdot N_X$, $R_{SH} \cdot N_X$, I_{01} , I_{02} , $n_1 \cdot N_X$ and $n_2 \cdot N_X$ (number of solar cells within a group, N_X) and connecting them together (Fig. 2, bottom left, i.e. three cell-substring, each with one group of 20 healthy solar cells). In a case with a PV module affected by PID-p, the non-uniformity is only minor within the module as the front side degradation is less severe however, each cell-substring is modeled to have 20 groups as each solar cell in the module has a slightly different level of degradation (Fig. 2 top center, the corresponding I_{PH} values are shown in Fig. 2 bottom center) [13,15]. For a PV module with PID-s, the cell-substrings have different numbers of groups depending on the PID severity. As an example, Figure 2 (top right) shows a PV module with a

cell-substring with total eight groups (the last cell-substring of the module): one group with 13 healthy solar cells and seven other groups, each with one PID-s affected solar cell (Fig. 2 bottom right shows the corresponding R_{SH} values). The module level non-uniformity, in this case, is more prominent thus, a greater variability in the parameters is applied [13,35].

2.3 Modeling of PV strings and array affected by PID

To scale the voltage of the PV system and consider string level PID characteristics, 22 PV modules are serially connected into a PV string. As PID-p occurs under positive voltage potential (described in previous sections), total eight PV modules closest to the positive end of a PV string are modeled with PID-p affected solar cells (Fig. 3, top). It is assumed that the voltage stress is greatest at the positive end and therefore, the PID is more severe (i.e. PV module 22 has more severely degraded solar cells compared to PV module 15). Similarly, PID-s is modeled in total five PV modules closest to the negative end of a PV string (Fig. 3, center). The remaining healthy PV modules are grouped together and connected serially to the degraded PV modules (Fig. 3, bottom). The final model of the PV system is an array with eight PV strings consisting of 22 PV modules and which are connected parallelly to each together. One string diode is connected serially to each PV string to block reverse current flow (Tab. 4). A certain level of voltage potential stress is required for PID to occur in PV modules. With 22 PV modules in a string under

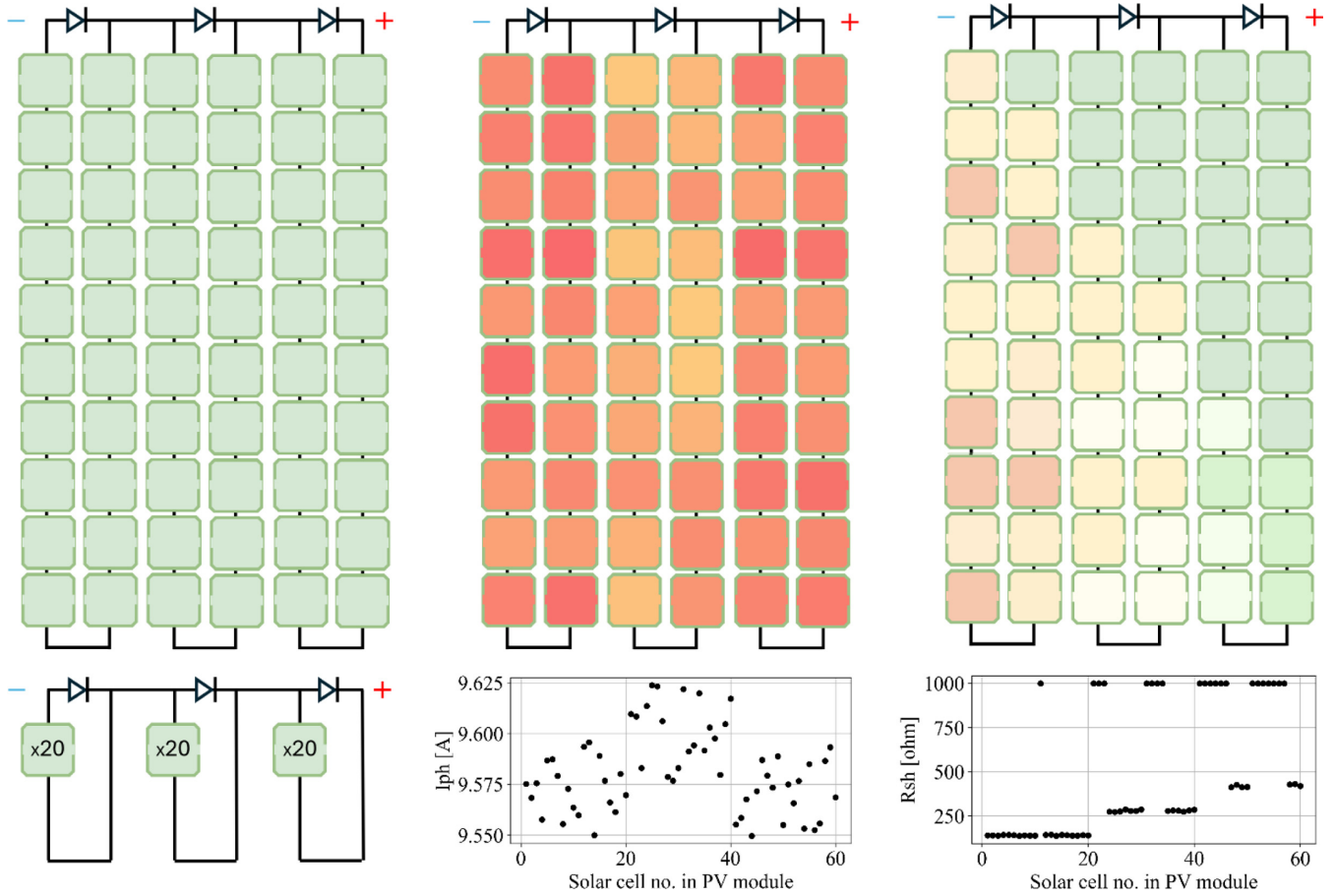


Fig. 2. Modeling 60-cell PV modules: healthy PV module (top left) with identical solar cells grouped in each cell-substring (bottom left), PV module with PID-p (top center) and the corresponding I_{PH} values (bottom center) and PV module with PID-s (top right) and the corresponding R_{SH} values (bottom right). Note: the colors of the solar cells qualitatively illustrate degradation levels and do not represent the actual values of the model input parameters.

floating grounding configuration, the voltage gets to maximum of ± 440 V, enough to cause PID-p and PID-s in eight and five PV modules, respectively.

2.4 PV array degradation scenarios

To increase the severity of PID in the array, the I_{PH} and R_{SH} values of solar cells affected with PID-p and PID-s are reduced by 0.5% and 50% (i.e. degrade the solar cells linearly) from their previous values, respectively. In the same way, twelve different degradation scenarios are created for a PV array affected by PID-p and PID-s, and each scenario is set to represent a point in time (i.e. degradation stages represent degradation after each month in a year) (Appendix Fig. A1).

2.5 Mismatch losses

The module to array power mismatch losses ($ML_{P_{MAX}}$) are calculated as the difference between the sum of the P_{MAX} values of all PV modules in the PV system and the P_{MAX} of the PV array at standard test conditions (Eq. (1)).

$$ML_{P_{MAX}}[W] = \sum_{Module M_i}^{176} P_{MAX, M_i} - P_{MAX, Array} \quad (1)$$

The mismatch loss (ML) in percentage is calculated by taking the difference between the array level P_{LOSS} and the average P_{LOSS} calculated from each PV module in the PV system, at STC (Eq. (2)). The P_{LOSS} is calculated as the relative change between module/array P_{MAX} and P_{MAX} of a healthy (reference) module/array (Eq. (3)).

$$ML[\%] = P_{Loss, Array} - \frac{\sum_{i=1}^{176} P_{Loss, Module, i}}{176} \quad (2)$$

$$P_{Loss}[\%] = \text{abs} \left(\frac{P_{MAX} - P_{MAX, reference}}{P_{MAX, reference}} \cdot 100 \% \right) \quad (3)$$

Two PV modules operating separately: one healthy PV module with 0% P_{LOSS} and one PID-p degraded PV module with a P_{LOSS} of 7.92% will have an average module P_{LOSS} of 3.96%. Connecting the two PV modules in series into PV string will give a P_{LOSS} of 4.16% (string-level P_{LOSS}) relative to a PV string with two healthy PV modules. The resulting ML will be 0.2% ($ML_{P_{MAX}}$ is 1.39 W). Figure 4 (right) shows the I-V and P-V curves of the two PV modules operating separately (green and red dashed lines)

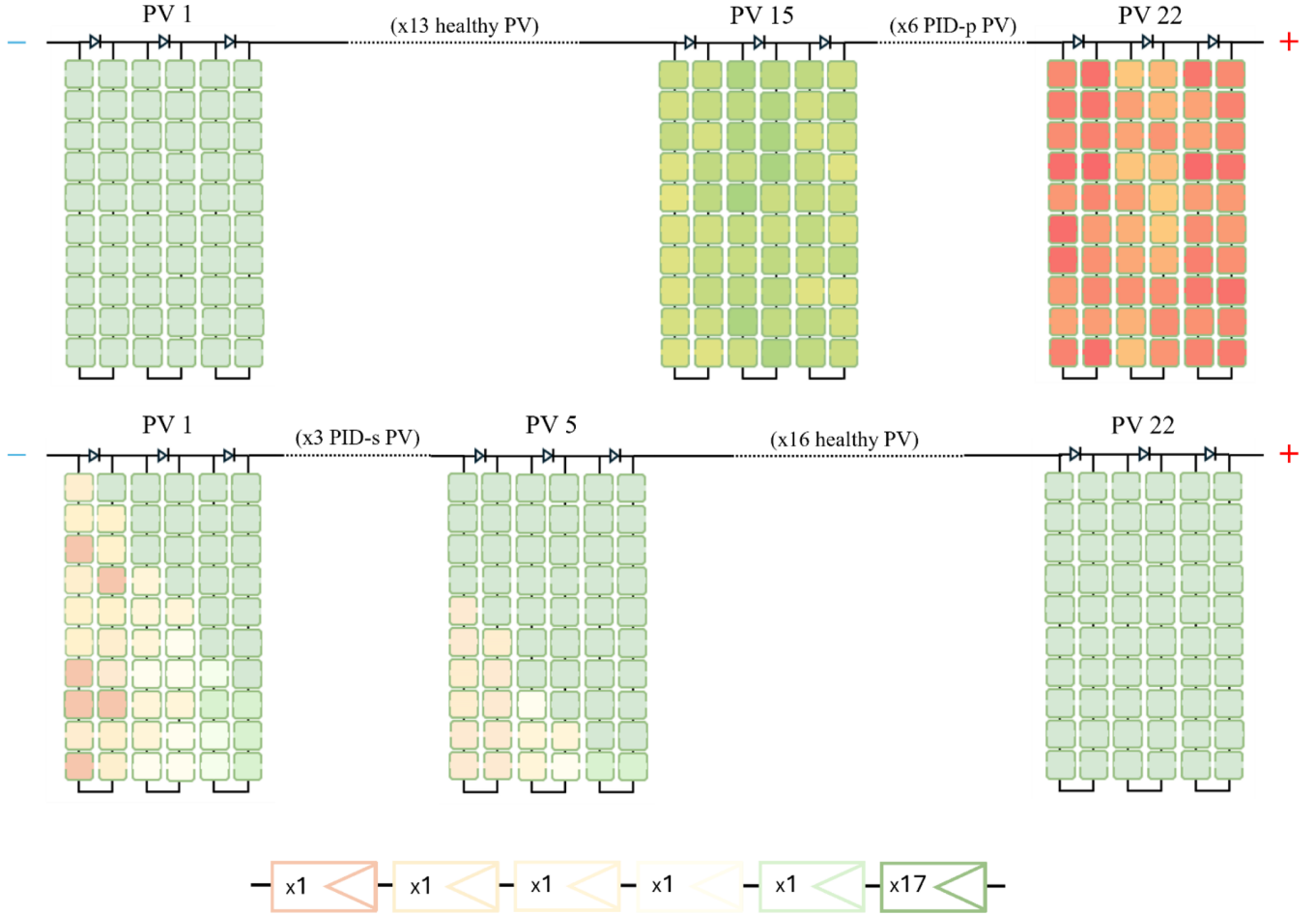


Fig. 3. Modeling a PV string with 22 PV modules affected by PID-p (top) and PID-s (center). Identical PV modules are grouped together and connected serially, e.g. for PV string with PID-s (bottom). Note: the colors of the solar cells qualitatively illustrate degradation levels and do not represent the actual values of the model input parameters.

and together within a string (black solid line). The output voltage of the PV systems is divided by the number of PV modules to make the I-V curves comparable.

3 Model verification

3.1 Verification of the module level model for PID-p

The model verification for PID-p is done on module level using the model described in Section 2.2, having 20 groups per cell-substring (i.e. a group for each solar cell in the PV module). The model is verified against an experimentally measured 60-cell mono facial *p*-type c-Si PERC PV module that is stress tested under high positive voltage potential (+1500 V) and in lab conditions (room temperature and low relative humidity) for up to 840 h using Al-foil method described in IEC TS 62804-1 2015 [44]. The model parameters for each solar cell are assessed by computing the relative change in the EL signal between the degraded solar cells and in-module best performing solar cell using an experimentally captured EL image at 10% I_{SC} after the stress test (Fig. 5). The I_{01} is increased from 7×10^{-11} A up to 1×10^{-10} A with maximum of 9% degradation in the I_{PH} (Tab. 5).

Figure 6 shows the measured and simulated I-V curves for healthy and PID-p affected PV modules. The deviation between the I-V curves in the healthy state may be due to manufacturing variation or aging of the experimentally measured module as a small slope is observed in range 0 – 0.8 V (black line, Fig. 6). The calculated root mean square error (RMSE) between the I-V curves is however still small (0.6885 mA/cm²).

In order to obtain this low RMSE, a smaller value of I_{01} had to be applied (ex. 7×10^{-11} A instead of 2×10^{-10} A for $I_{PH} > 9.653$). The value of I_{01} is highly dependent on the material properties of a solar cell/PV module and may vary for different PV technologies or when measuring on different scales (cell or module level), affecting the output voltage.

A maximum of 9% reduction in the I_{PH} is applied for solar cells in the model as the experimentally measured module is stressed in laboratory conditions without exposure to light, having a greater level of degradation compared to what may be observable in the field due to sunlight exposure on the front side of a module affected with this specific PID mechanism (PID-p can partially or fully recover from the UV range of the sun-light spectrum).

The RMSE between the measured and simulated I-V curves in degraded state is 0.6439 mA/cm². The step

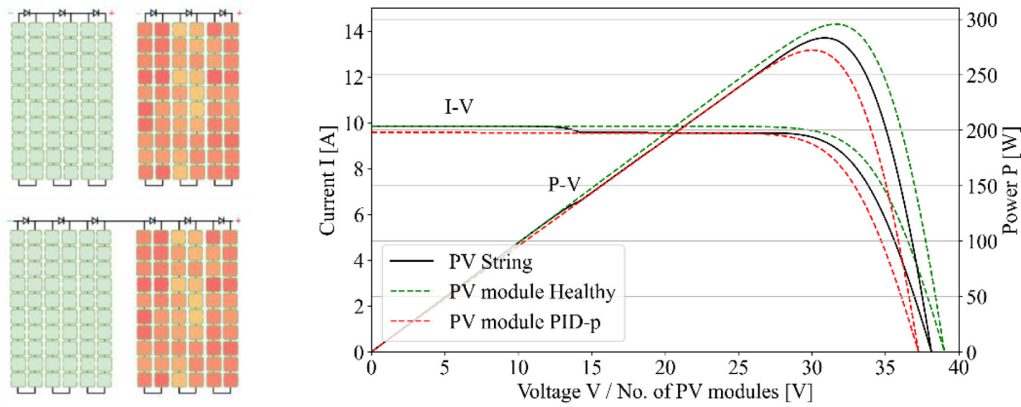


Fig. 4. Simulated I-V and P-V curves (right) of two PV modules operating separately (top left) and together in a PV string (bottom left) at STC.

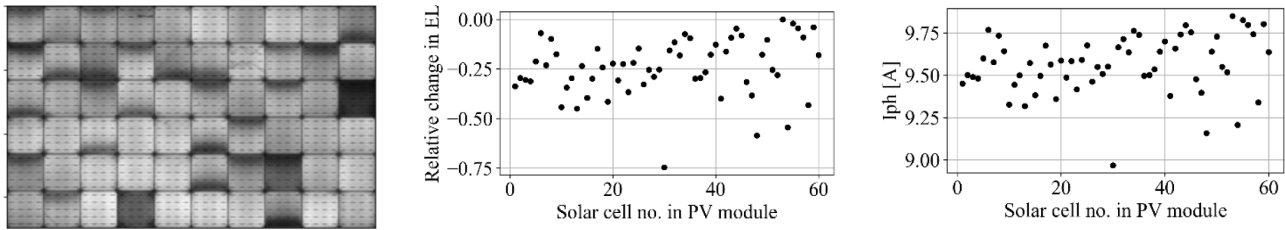


Fig. 5. Left: the experimentally captured EL image at 10% I_{SC} (left). Center: relative change in the EL signal between degraded and in-module best performing solar cell. Right: the I_{PH} values used as input to the model.

Table 5. Input parameters of the two-diode equivalent circuit model for a PID-p degraded solar cell. For model verification.

I_{PH} [A]	R_S [Ω]	R_{SH} [Ω]	I_{01} [A]	n_1	I_{02} [A]	n_2
>9.653	0.005	1000	7×10^{-11}	1	1×10^{-19}	2
$9.653 - 9.555$	0.005	1000	8×10^{-11}	1	1×10^{-19}	2
$9.555 - 9.456$	0.005	1000	9×10^{-11}	1	1×10^{-19}	2
<9.456	0.005	1000	1×10^{-10}	1	1×10^{-19}	2

formation due to solar cells limiting the output current of the cell-substrings is less pronounced on the measured I-V curve, suggesting same level of PID severity in solar cells limiting the current. Relating the EL signal with the level of degradation do have a certain level of inaccuracy as image processing including cropping of the EL image influences the mean EL intensity of the solar cells (i.e. presence of different amount of dark pixels/inactive area between solar cells in the cell-segmented EL images), and therefore, the PID severity in solar cells implemented in the model.

The difference in the relative change (i.e. level of degradation) in the I-V parameter extracted from the measured and simulated I-V curves at STC is within 2% (Tab. 6).

3.2 Verification of the module level model for PID-s

The model for PID-s is verified against an experimentally measured 60-cell mono facial *p*-type c-Si Al-BSF PV module that is stress tested under high negative voltage

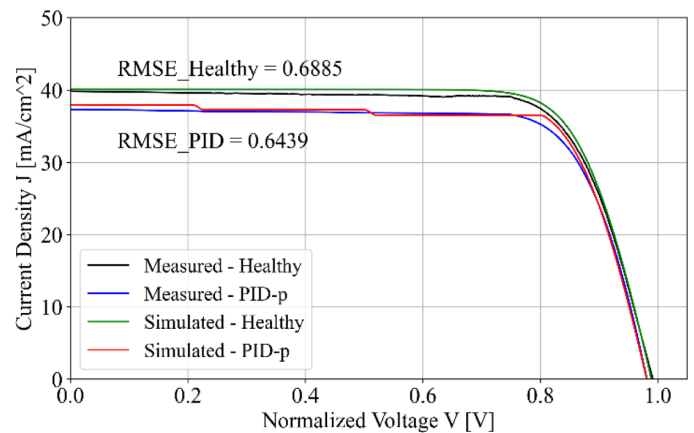
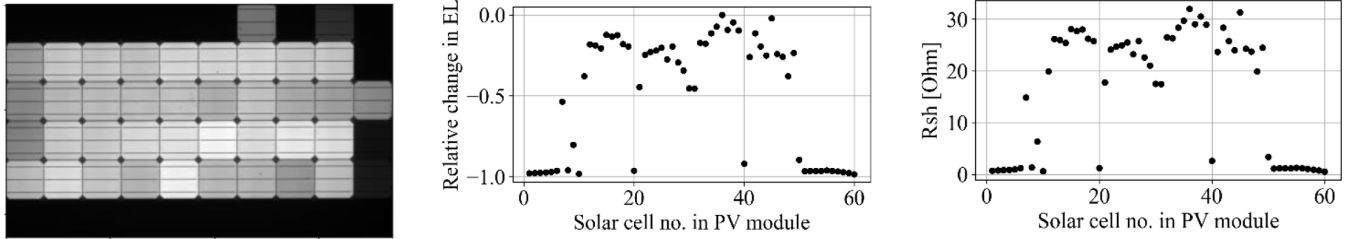


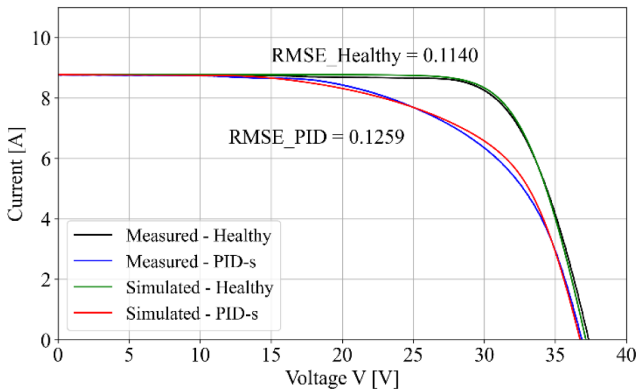
Fig. 6. Measured and simulated I-V curves of a healthy and PID-p affected 60-cell *p*-type c-Si PV module at STC.

Table 6. Relative change in the I-V parameters extracted from the measured and simulated I-V curves for PID-p.

	$J_{SC,rel}$ [%]	$V_{OC,rel}$ [%]	$J_{MPP,rel}$ [%]	$V_{MPP,rel}$ [%]	FF_{rel} [%]	$P_{MAX,rel}$ [%]
Measured results	-6.28	-0.98	-6.28	0.47	1.46	-4.94
Simulated results	-5.33	-0.76	-4.75	0.62	2.01	-4.75

**Fig. 7.** Left: the experimentally captured EL image at 10% I_{SC} (left). Center: relative change in the EL signal between degraded and in-module best performing solar cell. Right: the R_{SH} values used as input to the model.**Table 7.** Input parameters of the two-diode equivalent circuit model for a PID-p degraded solar cell. For model verification.

I_{PH} [A]	R_S [Ω]	R_{SH} [Ω]	I_{01} [A]	n_1	I_{02} [A]	n_2
8.77	0.005	> 400	3×10^{-10}	1	1×10^{-17}	3
8.77	0.005	$400 - 200$	3×10^{-10}	1	1×10^{-15}	5
8.77	0.005	$200 - 100$	3×10^{-10}	1	1×10^{-13}	7
8.77	0.005	$100 - 20$	3×10^{-10}	1	1×10^{-6}	8
8.77	0.005	< 20	3×10^{-10}	1	2.6×10^{-1}	9

**Fig. 8.** Measured and simulated I-V curves of a healthy and PID-s affected 60-cell *p*-type c-Si PV module at STC.

potential (-1000 V) and in humid conditions (60°C and 85% relative humidity) for up to 96 h in an environmental chamber. The procedure of verification is similar to what is described in Section 3.1 (Fig. 7). The R_{SH} , I_{02} and n_2 are adjusted from $1000\ \Omega$, 1×10^{-17} A and 2 down/up to $0.4\ \Omega$, 0.26 A and 9 for the degraded solar cells, respectively (Tab. 7).

Figure 8 shows the measured and simulated I-V curves for healthy and PID-s affected PV modules. The calculated RMSE values are within 1 A (0.1140 A and 0.1259 A). A slight deviation near the maximum power

point (MPP) of the I-V curves at degraded state may be due to slight change in the R_S value for the experimentally measured module after degradation (R_S value is not adjusted in the simulations). Both the I_{01} and I_{02} values are adjusted for the simulation to match with the measured results as the experimentally measured module is of different power rating and PV technology (*p*-type c-Si Al-BSF PV module). The difference in the relative change in the I-V parameter extracted from the measured and simulated I-V curves at STC is within 4% (Tab. 8).

4 Results

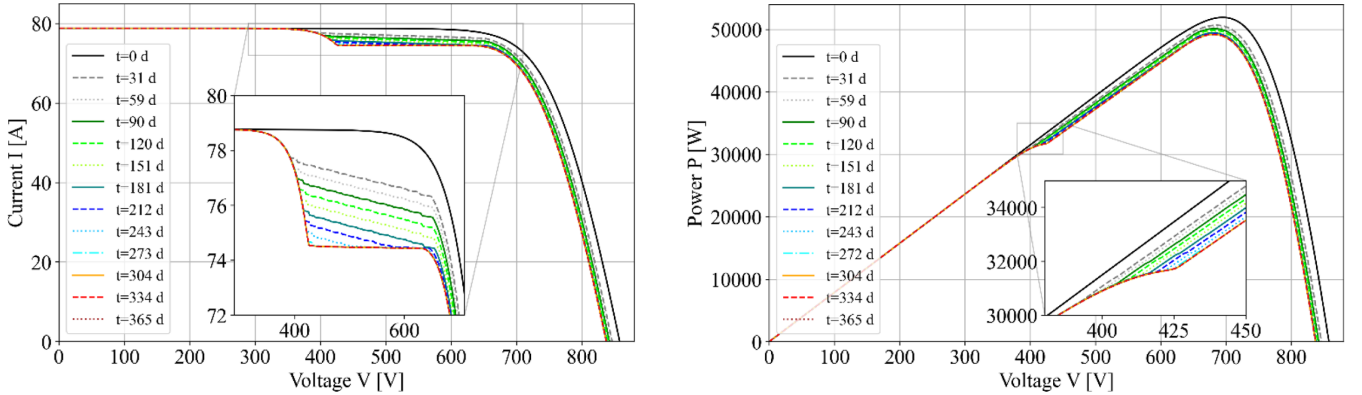
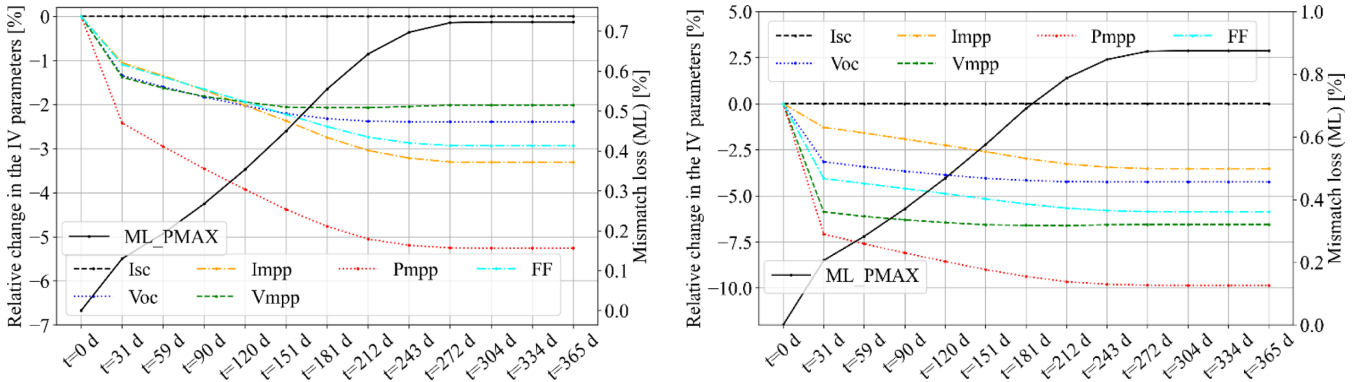
4.1 Mismatch losses caused by PID-p in the PV array

The electrical performance of a PV array is simulated for one whole year with irradiance and temperature levels applied for location at latitude and longitude of 55.696 and 12.105, respectively, and with increase in PID severity. Figures 9 and 11 show I-V curves of selected days: i.e. twelve different degradation stages corresponding to the last day of each month.

The non-uniformity in the electrical performance of the PV modules in the PV strings, that is caused by PID-p, is translated into a drop in the current output of the system due to activation of the bypass diodes of the degraded module cell-substrings and re-direction of the current (i.e. current mismatch within a PV module and in the PV

Table 8. Relative change in the I-V parameters extracted from the measured and simulated I-V curves for PID-s.

	$I_{SC,rel}$ [%]	$V_{OC,rel}$ [%]	$I_{MPP,rel}$ [%]	$V_{MPP,rel}$ [%]	FF_{rel} [%]	$P_{MAX,rel}$ [%]
Measured results	-0.04	-1.08	-15.87	-5.32	-19.45	-20.34
Simulated results	-0.09	-1.25	-13.32	-8.69	-19.78	-20.85

**Fig. 9.** Simulated I-V (left) and P-V (right) curves of a PV array affected by PID-p at different degradation stages, and at STC.**Fig. 10.** The relative change in the I-V parameters extracted from simulated I-V curves of the PV array (dashed lines) and the mismatch losses (solid line) at different PID-p degradation stages, and at STC (left) and NOCT (right).

strings) (Fig. 9, left). The I_{SC} of the system is not affected and is most likely to remain at its initial value irrespective of the PID severity as PID-p would only appear in PV modules operating under a specific polarity of the voltage stress in a PV string consisting of the same PV technology and at floating grounding configuration, and keep the other side of the PV string un-affected, unless other failure and/or degradation modes are present. The I_{MPP} of the system, on the contrary, is highly impacted. The I_{MPP}/I_{SC} ratio reduces from 0.9483 (healthy state, $t = 0$ d) to 0.9383 (degraded state, $t = 31$ d) when PID-p is introduced in the PV modules with $\sim 0.5\%$ degradation in the I_{PH} on the cell level at STC and it reduces further to 0.917 (degraded state, $t = 365$ d) with cell level I_{PH} degradation of $\sim 5\%$. This effect is prominent on the I-V curves (and P-V curves, Fig. 9) due to formation of a step near the MPP that is tilted due to the non-uniformity in the current output of

the degraded cell-substrings (Fig. 9, left). As degradation in the cell-substrings reaches the saturation point for PID-p (-5% degradation in I_{PH}), the step levels out.

The fraction of the absolute change in the system I_{MPP} at $t = 31$ d and $t = 365$ d is $\sim 1\%$ and $\sim 3.2\%$, respectively (Fig. 10, left). The V_{OC} and V_{MPP} degrade almost to the same extent: from 1.4% ($t = 31$ d) to 2.4% and 2% ($t = 365$ d), respectively. The resulting P_{LOSS} of the system is $\sim 5.25\%$ (reduce from 51920 W at $t = 0$ d to 49191 W at $t = 365$ d) and the corresponding FF reduces with $\sim 3\%$ ($t = 365$ d) at STC. Comparing the array level P_{MAX} to the module level values, shows that the PV system in the healthy state ($t = 0$ d) generates 96.7 W less by having the PV modules interconnected into an array than having them operating independently. This value increases to 468 W at the most degraded stage ($t = 365$ d) (i.e. loss in addition to losses caused by PID-p). This is equal to power

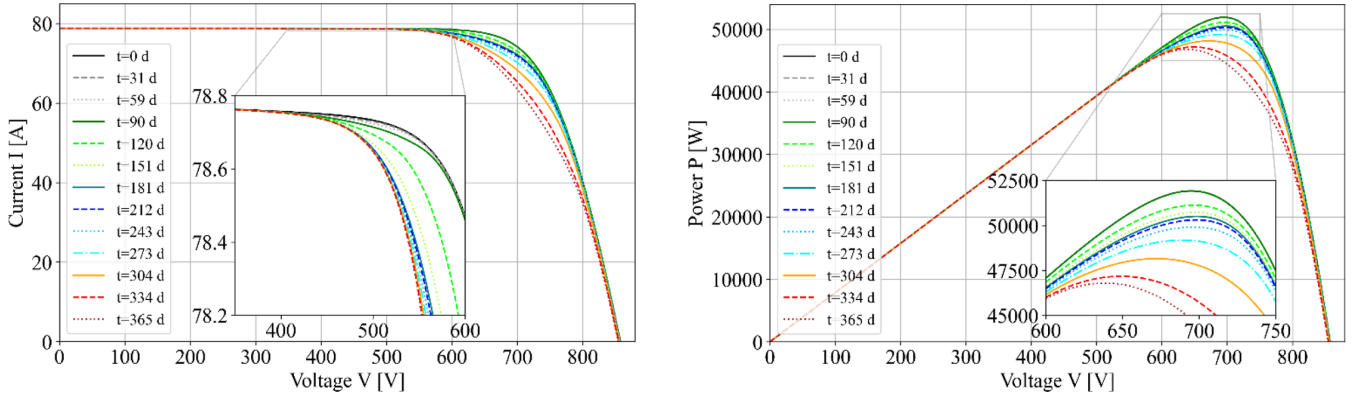


Fig. 11. Simulated I-V (left) and P-V (right) curves of a PV array affected by PID-s at different degradation stages, and at STC.

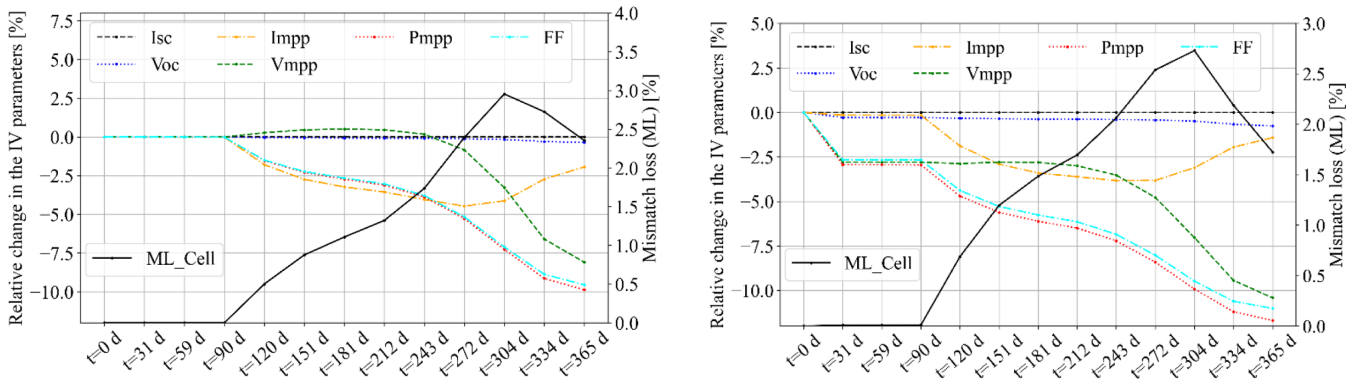


Fig. 12. The relative change in the I-V parameters extracted from simulated I-V curves of the PV array (dashed lines) and the mismatch losses in P_{MAX} (solid line) at different PID-s degradation stages, and at STC and NOCT (right).

contribution from almost 2 PV modules. Figure 10 (left) shows the ML calculated in percentage at each degradation stage. The ML increases from 0.13% to 0.72% for the PID-p affected array (Fig. 10, left).

For a more realistic estimation of the electrical performance of the PV array operating in the field, the I-V curves are simulated in conditions with irradiance level of 800 W/m^2 , ambient temperature of 20°C and nominal operating cell temperature (NOCT) of 44°C (Fig. 10, right). The output voltage of the array is highly impacted by the high cell operating temperature and is causing a greater voltage mismatch in the system, contributing to the loss in the output power of the array (P_{LOSS} of $\sim 10\%$) and ML which increases to 0.88% (Fig. 10, right).

4.2 Mismatch losses caused by PID-s in the PV array

The PV array affected with PID-s is relatively more impacted, considering that the degradation is introduced in fewer PV modules ($t = 365 \text{ d}$, Fig. 11). The R_{SH} is reduced by more than 90% to observe degradation on the I-V and P-V curves ($t = 181 \text{ d}$, $R_{SH} < 14 \Omega$, Fig. 11). A slope appears near the MPP due to the reduction in the R_{SH} and causes a drop in the current and voltage output of the system. The I_{MPP} reduces by 4.47% and is the main contributor to the P_{LOSS} and reduction in the FF at the first

few degradation stages at STC ($t = 120 \text{ d}$ to $t = 272 \text{ d}$). As the MPP changes its position due to change in the shape of the I-V curves, the I_{MPP} recovers with 2.53% while the V_{MPP} drops (reduces by 8% at $t = 365 \text{ d}$) and causes mismatch in the string output voltage as previously observed for a PV array affected with PID-p (Figs. 9 and 10). The P_{LOSS} increases to 9.87% (reduces from 51920 W at $t = 0 \text{ d}$ to 46796 W at $t = 365 \text{ d}$) and the FF drops by 9.54% ($t = 365 \text{ d}$, $R_{SH} < 2 \Omega$, Fig. 11).

Similar to, in the case of PID-p, the I_{SC} remains unaffected. The drop in the V_{OC} is insignificant (reduces by 0.36%), different from what is typically observed on the module level. This may suggest that the degradation in I_{O2} introduced in the solar cells is less severe ($1.0 \times 10^{-1} \text{ A}$) and there is a greater contribution from the healthy solar cells in each PV string as a larger voltage drop in the string would otherwise limit the voltage of the array (to the voltage of most degraded string) and cause a reduction in the V_{OC} of the system.

The drop in the current output of the system is translated into a $ML_{P_{MAX}}$ of 1312 W at the most degraded stage ($t = 365 \text{ d}$). This is almost thrice, the value calculated for the PV array with PID-p however, the degradation in the I_{MPP} and V_{MPP} in the case of PID-s is also greater. Figure 12 shows the ML which increases to 2.96% ($t = 304 \text{ d}$) but reduces to 2.35% ($t = 365 \text{ d}$) due to increased PID severity in all three cell-substrings of the degraded PV modules.

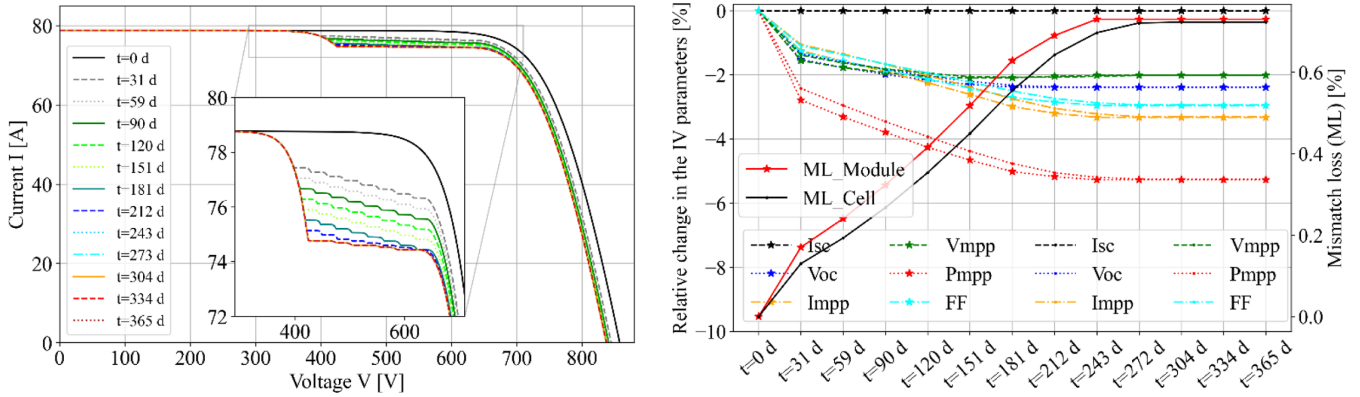


Fig. 13. Simulated I-V curves of a PV array affected by PID-p at different degradation stages, and at STC using module level model (left), the relative change in the corresponding I-V parameters and the ML (right) using cell (·) and module (*) level model.

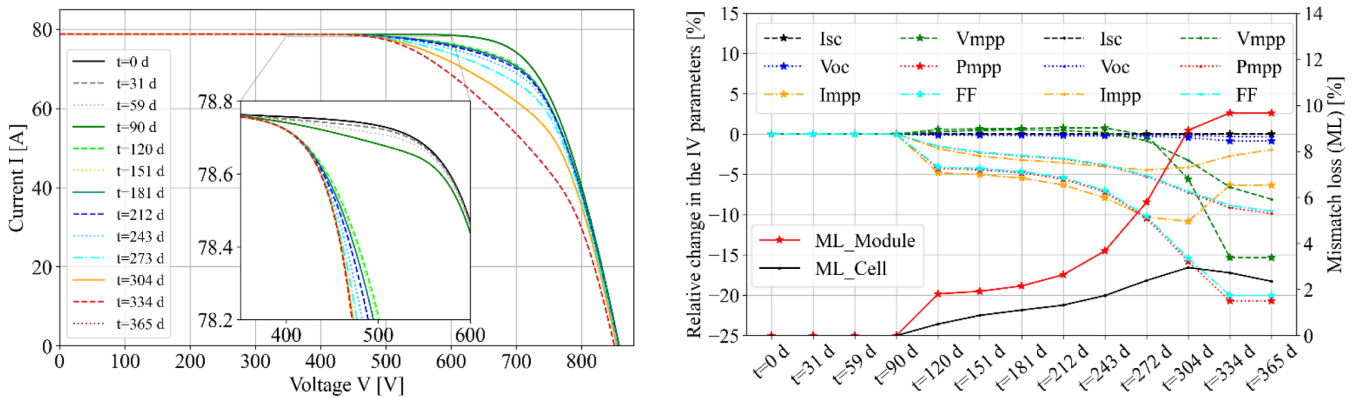


Fig. 14. Simulated I-V curves of a PV array affected by PID-s at different degradation stages, and at STC using module level model (left), the relative change in the corresponding I-V parameters and the ML (right) using cell (·) and module (*) level model.

The main contradiction when comparing the array level PID-s results presented in this section with the values reported for a PID-s degraded string in the literature (presented in the introduction section), is decrease in the system I_{SC} . The reported values are for PV strings with PID in all PV modules and which are operating in real outdoor/field conditions. As there is no contribution from the healthy solar cells/PV modules, the string I_{SC} is limited by the least degraded cell-substring. This scenario is unlikely to occur in the field, even under a different grounding configuration, as solar cell/PV modules require a certain level of voltage stress to degrade. The presence of other environmental (stress) factors may also have an influence on the I_{SC} .

The PV array performance under nominal operating condition is slightly worse ($P_{LOSS} > 10\%$) however, the ML reduces to 2.73% (ML maximum) and 1.72% (ML at $t = 365$ d). This may be due to the fact that the output voltage of the degraded PV modules is already affected and having a drop in output voltage of the healthy PV modules reduces the voltage mismatch in the system.

4.3 Impact of the model granularity on its accuracy

The cell level model considers the cell to module level mismatch that is caused by PID, which is typically observed on an experimentally captured EL image of a PID

affected PV module, and where each solar cell in the PV array is defined by the two-diode equivalent circuit model parameters with values that are reported in the literature. However, the cell level PID characterization and computation of the physical parameters are only reported for PID mechanisms observed at a certain range of stress factors and/or time durations, and the relative change in the parameters with increase in PID severity is not always documented. In addition, the performance of degraded solar cells within a PV module and their contribution to the PV module output parameters are not quantified but measured on module level. Moreover, defining the input parameters for each solar cell in an array ($> 10,000$ solar cells) adds a certain level of complexity to the modeling part and prolongs the I-V simulations, thus, the impact of reducing the granularity of the model on the generated I-V curves (i.e. if one is able to observe changes in the I-V parameters with the same level of detail) and the mismatch losses are analyzed. The input parameters for a PV module are defined using the model parameters of the in-module worst performing solar cell for each solar cell in the module and grouping them into one group per cell-substring, referred to as module level model.

Reducing the granularity of the model to module level has a slight impact on the output current of the system that

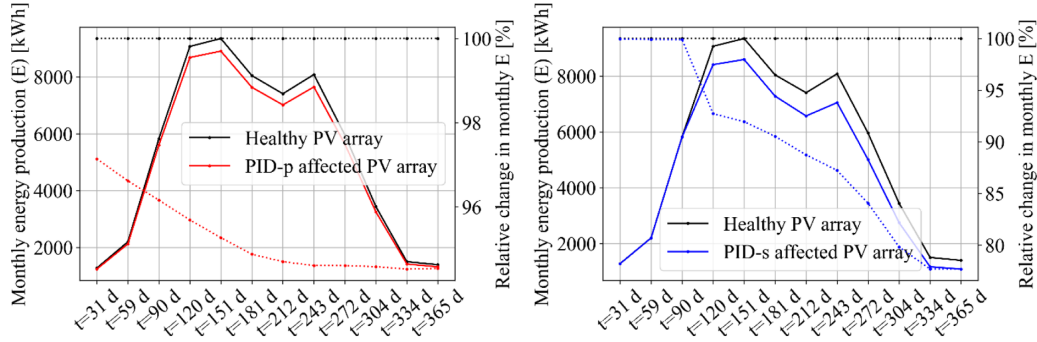


Fig. 15. Monthly energy production of the healthy, PID-p (left) and PID-s (right) degraded PV array (solid lines) and the relative change in the monthly energy production (dotted lines).

is affected by PID-p ($<1\%$) as all solar cells within a PV module are degraded to one I_{PH} level (Fig. 13). The I_{MPP}/I_{SC} ratio reduces from 0.9483 (healthy state, $t = 0$ d) to 0.9365 (degraded state, $t = 31$ d) and 0.9168 (degraded state, $t = 365$ d), a deviation below 0.002 when compared to the results using the cell level model. The change in the resulting P_{MAX} and FF is below 1% as well. The $ML_{P_{MAX}}$ increases with a maximum of 38 W at STC (or 0.074% in ML, Fig. 13 right).

On the contrary, the system affected by PID-s is highly impacted by reducing the model granularity (Fig. 14). This may be due to the fact that the cell to module level mismatch in degraded PV modules was greater in the cell level model (i.e. PV modules had cell-substrings that were less severe in PID) and defining the input parameters of the group in each cell-substring with in-module worst performing solar cell in the model level model have increased the severity in all cell-substring of the PID-s affected PV modules (the P_{LOSS} and ML increases to 20.7% and 9.67%, respectively, Fig. 14 right). Using an average R_{SH} value for the cell-substrings would have caused a smaller deviation of the output parameters from their primary values.

4.4 Estimation of energy losses due to PID-p and PID-s over a year of operation

The monthly and annual energy production of the PV arrays, operating in field condition with varying irradiance and temperature level, are calculated to quantify the accumulated monthly and annual energy losses caused by PID-p and PID-s, as the severity of the degradation increases.

To calculate the annual energy production of healthy and degraded PV arrays, an I-V curve is generated for each hour in the year by using the module level model and having as the input the hourly plane of array irradiance (G_{POA}) applied to I_{LIGHT} and the hourly cell temperature (T_{CELL}) applied to circuit temperature for the simulations. The G_{POA} and T_{CELL} are extracted from System Advisor Model (SAM, version 2021.12.2) simulation using 1) the TMY file for a PV array located at latitude and longitude of 55.696 and 12.105, respectively, 2) having the PV modules facing the south with a fixed tilt of 25° and 3) the datasheet parameters of a mono facial p-type mono c-Si PERC PV module (TSM-305DD05A.05 (II)). The P_{MAX} values are computed from each I-V curve

and are used to calculate the monthly and annual energy production (Eq. (4)).

$$E_{Annual}[kWh] = \sum_{i=0}^{3959} P_{MAX,hourly}[kW] \quad (4)$$

The total amount of energy that is generated by the healthy PV array over a year at the specified location (described in section 2.8) is 63560 kWh. This value reduces for a PV array affected by PID-p and PID-s to 60486 kWh and 57224 kWh, respectively. Figure 15 shows the monthly energy production of the PV arrays calculated from the hourly P_{MAX} values that are extracted from the I-V curves generated using the module level model. As the severity of PID increases in the PV arrays, the monthly energy production values drop relative to the values of the healthy PV array ($t = 31$ d to $t = 365$ d) as the degraded PV arrays are limited by their worst performing cell-substring. The irradiance and temperature levels may also have an influence on the electrical output parameters of the PID affected array, however, it is not confirmed by the results.

5 Discussion

In general, scripting netlists (i.e. a list of components in a circuit) and generating circuits for a PV array is much more efficient in Python using PySpice as one is able to programmatically construct a large PV system by defining classes for a solar cell, PV module and string, and simulate I-V curves for multiple circuits (i.e. circuits for solar cells, PV modules, strings and arrays) or at different irradiance and temperature levels in less time using simple control flow statements, compared to other graphical simulation programs with integrated circuit emphasis (SPICE) such as LTSpice. The code script is developed such that one can easily define model input parameters for each solar cell or solar cell group within a cell-substring in a database (Excel file uploaded in Python) and create different PV system configuration and/or degradation scenarios.

One limitation of the model is that it is developed for PV modules of relatively older PV technologies i.e. made of a number of full-sized and mono facial solar cells that are

divided into three equally sized cell-substrings, each connected parallelly to a bypass diode. Also, the impact of PID (or other failure and degradation modes) can only be assessed for one face/side of a PV module at a time. It is still relevant for studying degradation mechanisms such as PID-s and PID-p that are observed on the front side of conventional, PERC, PERT and TOPCon mono facial PV modules or PID-p that is observed on the rear side of a PERC PV module (i.e. without including the contribution from the front side). PV modules of current PV technologies are typically made of bifacial half-cut cells that are serially connected into six equally sized cell-substrings, and which form two strings (each with three cell-substring) that are connected parallelly to each other and the three bypass diodes. To include contribution of the rear side of bifacial PV modules of different designs to the overall module electrical output, additional components must be incorporated into the circuit model described in Sections 2.1, 2.2 and 2.3 (e.g. may be required to study the impact of rear side PID-p degradation in PERC PV modules in the field with contribution of both, the front and rear side to the system level performance).

In addition, the electrical performance of solar cells/PV modules operating in the field is influenced by irradiance and ambient temperature levels present. The temperature dependency of the two-diode equivalent circuit model parameters (I_{PH} , I_{01} , I_{02} , R_{SH} and R_S) may be implemented to the circuit/code script to simulate more realistic I-V curves however, deriving accurate formulas for the parameters (with their temperature dependencies) is not always straightforward. Also, a high ambient temperature can heat up solar cells and change their temperature coefficients (i.e. how much the electrical output parameters of a solar cell change with change in the ambient temperature). It is more common to use one-diode equivalent circuit model due to its easy implementation; however, it is not useful when modeling PID-s as I_{02} is an important parameter to consider when modeling this specific degradation mechanism.

Also, the current code script only takes as input the two-diode equivalent circuit model parameters for each solar cell while the temperature value is applied to the whole system/circuit of the PV array during the simulations. An additional temperature parameter may be added to the solar cell model input list to simulate the array I-V curves while having temperature variations in the solar cells. This will allow considering the temperature variations that arise due to shunting of the solar cells or other temperature influences for more realistic I-V curves.

To reduce the complexity of modeling PID in a PV system, a linear degradation rate is applied to the model input parameters. However, this is different from real world observations as PID rate is observed to be non-linear and highly dependent on 1) the PV technology used, 2) the irradiance, temperature and relative humidity level present, and 3) the magnitude of the system voltage applied/experienced to/by the solar cells/PV modules [40,41]. Similarly, the recovery of PID is not considered when applying linear degradation rate though it is known from the literature that the effect of PID-s and PID-p can be neutralized and partially recovered by charge equalization during nighttime when the PV modules are not

operating, and/or by charge neutralization during daylight [15]. Applying non-linear degradation rate may have an impact on how PID progresses with time e.g. PV modules may degrade slower due to less extreme weather conditions or if the PV module is recovering at certain environmental or operating conditions. The monthly and annual energy production of the PV system may also, in that case, be greater.

Besides these limiting factors, one is able to simulate different PID types/mechanisms by degrading one or more parameters of the two-diode equivalent circuit model. Reducing the I_{PH} of solar cells with PID-p does directly impact the output current of the system. Even a maximum 3% reduction in the I_{PH} in solar cells is causing above 2% loss in the output power of the system which is noticeable on the I-V curve as well. Increasing the severity to maximum 5.5% reduction in the I_{PH} causes $\sim 5.25\%$ loss in the output power. The system voltage is affected by change in the I_{01} value. The I_{01} is increased by 1×10^{-10} A for every 1–2% reduction in the I_{PH} once the I_{01} value is set/estimated for a healthy solar cell/PV module (give a reasonable fit between the measured and simulated I-V curves near the V_{OC} when doing model verification in Sect. 3). However, there is a certain level of uncertainty when increasing the I_{01} as the actual relationship between I_{PH} and I_{01} is not known.

In case of PID-s, the electrical output parameters of the system are less sensitive to change in the R_{SH} . Early stage PID-s may not be detectable on array level I-V curve as no prominent PID signature is observed until the R_{SH} of degraded solar cells reduces more than 90%, in that case, the output power of the array is already reduced by $\sim 5\%$. Also, PID-s can progress to more severe degradation. In our case, with nearly 100% reduction in the R_{SH} , the output power of the array reduces by 9.87%. Similarly, the impact of I_{02} on the system voltage is only minor although it is increased by several magnitudes. It may be increased further to observe degradation in the V_{OC} , characteristic for PID-s. In addition, the uncertainty may be greater as both I_{02} and n_2 are adjusted with change in the R_{SH} .

Nevertheless, it is possible to estimate the mismatch losses (in addition to power losses caused by PID) as the difference between the array level loss in output power and the average loss in output power calculated from each PV module in the PV system for different PID mechanisms, degradation stages or scenarios: estimated up to 0.72% and 2.96% for PID-p and PID-s affected PV systems, respectively. However, the mismatch losses are highly dependent on how solar cells are interconnected in a PV array (i.e. the number of cell-substrings and their connection to the bypass diodes, and the number of PV modules and PV strings connected serially and parallelly to each other, respectively) but also on how many solar cells are degraded in the PV array, the severity of the degradation and their location in the array.

The impact of PID-s seems more severe as both the output current and voltage of a degraded solar cell are affected and therefore, both the output current of serially connected PV modules and the output voltage of parallelly connected PV string are limited by the worst performing module and string, respectively. This is true for front side PID-p as well; however, it causes minor mismatch losses

only. In a case of rear side PID-p which mainly impact the output current of a solar cell: having several PV modules affected by PID-p in a string would cause less loss in the output power of the system (i.e. may have less voltage mismatch loss) than having one or more PV modules affected by PID-p in each string as the worst performing cell-substring is limiting the output current of the string (i.e. may have high current mismatch loss).

The mismatch losses quantified (exclusively due to PID) are comparable and can be added, in worst case scenario, to other mismatch losses that occur in a PV system such as losses due to variation in module electrical parameters (ML of 0.5 – 2%) [45,46] or due to non-uniformity in irradiance on the rear side of bifacial PV modules (ML of 2%) [47]. Thus, relevant to consider when modeling the energy output of a PV system affected by PID (which may also be affected by module mismatch and losses caused by non-uniformity in irradiance or soiling).

The string or array level model may be validated against PID data obtained from string or array I-V characteristics of a PV system operating in the field. However, such PID data is not available and for certain PID types the string or array level data does not exist (e.g. for PID-p). The module level model verification lacks the string level PID characteristics and mismatch losses. In addition, knowing the contribution of every solar cell in a PV module to the overall module output parameter would improve the verification process and modeling of PID. Also, relating the mean EL signal from solar cells to their electric performance may require more work.

6 Conclusion

The impact of polarization and shunting type of PID on the I-V characteristics of a PV array is modeled and quantified using cell level PID characteristics reported in the literature. A healthy PV array is composed of eight parallelly connected PV strings, each with 22 serially connected 60-cell PV modules.

PID-p is introduced in total eight PV modules in each PV string of a PV array by reducing the I_{PH} and I_{01} of the solar cells. The P_{LOSS} of the system at the most degraded state is $\sim 5.25\%$ i.e. 2728.87 W from which 0.72% (or 467.57 W) is due to the mismatch loss that is caused by non-uniform degradation and progression of PID in the PV strings. Due to degradation in the power output, the PV system generates 3074.63 kWh less in a year compared to a healthy PV array.

PID-s is modeled with reduction in the R_{SH} , I_{02} and n_2 of the solar cells in five PV modules in each PV string. The P_{LOSS} is $\sim 10\%$ and the mismatch loss is 2.35% at the most degraded state. The power and mismatch losses are relatively high considering that fewer PV modules are degraded with PID-s compared to PID-p. The greater level of degradation in a PV array with PID-s is translated into an annual energy production of 6336 kWh less compared to a healthy PV array.

Even by reducing the granularity of the model by defining model input parameters for each PV module instead of each solar cell in the PV array, the I-V characteristic curves generated were able to provide distinctive diagnostic indicators for PV system affected by PID-p and PID-s. However, the model may be improved by considering newer PV technologies, non-linear degradation rate, recovery as well as other environmental or operational stress factors.

Nevertheless, it is possible to model the impact of cell level failures at array level within reasonable time and effort. Further degradation studies can be carried out for different PID mechanisms as PID progresses in severity and/or by the number of modules affected in a PV array. This may be relevant for: 1) PV plant designers when modeling mismatch over time in a PV plant; 2) PV plant operators that need to assess whether to install anti-PID measures if PID is detected or need to quantify the long-term impact on the plant output; and 3) generating training data for PV fault detection methods, as well as in identifying PID diagnostic parameters from the string I-V characteristic curves for optimizing the fault detection algorithms.

Furthermore, it would also be possible to model the impact of other failures and/or degradation modes (i.e. introducing single or multiple failures and/or degradation modes in a PV system) on the electrical output performance of a PV plant over longer periods to get closer to what happens in a real PV plant.

Funding

This research is carried out in the DTEC project: High voltage stress testing for potential-induced degradation and recovery modeling of utility scale PV, a collaboration between Total-Energies and Technical University of Denmark.

Conflicts of interest

The authors declare no conflict of interest.

Data availability statement

The data that supports the findings of this study is available from the corresponding author upon reasonable request.

Author contribution statement

This work is carried out under supervision of S.V. Spataru and co-supervision of G. Alves dos Reis Benatto and S. Thorsteinsson. The conceptualization of the project and code script is developed by S.V. Spataru. The data generation, processing and analysis is done by A. Mahmood. The manuscript (original draft) is written by A. Mahmood, and reviewed and edited by S.V. Spataru, G. Alves dos Reis Benatto and S. Thorsteinsson. The funding acquisition is done by P.B. Poulsen.

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Cite this article as: Aysha Mahmood, Gisele Alves dos Reis Benatto, Sune Thorsteinsson, Peter Behrendorff Poulsen, Sergiu Viorel Spataru, Modeling the electrical mismatch caused by potential-induced degradation in crystalline silicon photovoltaic modules and strings, *EPJ Photovoltaics* **17**, 5 (2026), <https://doi.org/10.1051/epjpv/2025028>

Appendix A

Figure A1 (top left (A and C) and top right (B and D)) shows two different degradation stages for string 1 in the PV array, affected by PID-p and PID-s. The I_{PH} and R_{SH} values of PID-p and PID-s affected solar cells are reduced by 0.5% and 50% their previous values (Fig. A1, bottom showing values for degradation stage 1), respectively.

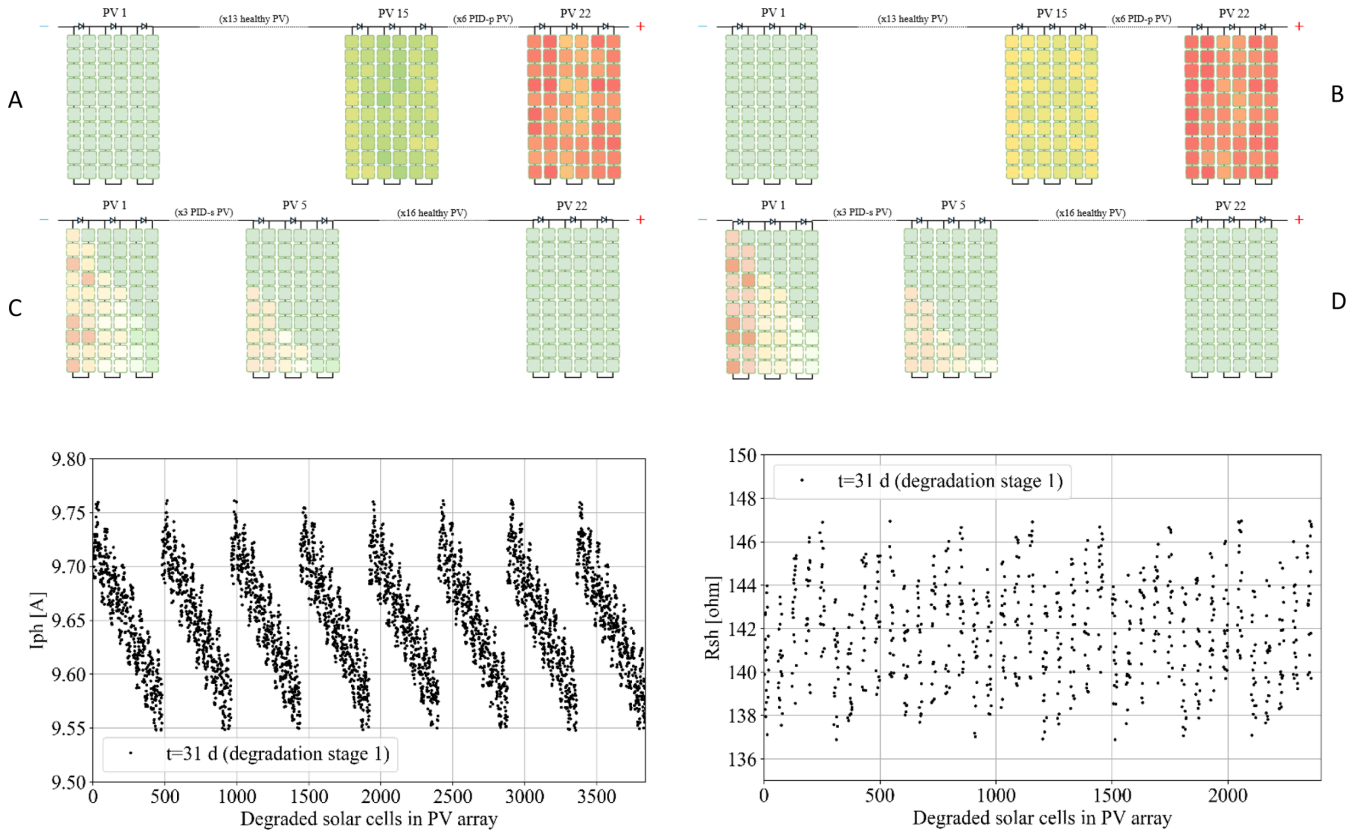


Fig. A1. PV string 1 at PID degradation stage 1 (top A and C) and 2 (top B and D). I_{PH} (bottom left) and R_{SH} (bottom right) input values for PID degradation stage 1. Each data point represents a degraded solar cell in the PV array. Note: the colors of the solar cells qualitatively illustrate degradation levels and do not represent the actual values of the model input parameters.