



Diagnostic for Photovoltaic panels: models and methods for the “on-line” identification of the PV degradation

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Unisa Collaboration in the PV field



Power and productivity
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NOTE: ABB solar inverters were
previously branded "Power-One"



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The activities related to diagnostic on PV modules have been carried out in collaboration with

- Universidad del Valle, Escuela de Ing. Eléctrica y Electrónica, Cali-Colombia
- Universidad Nacional de Colombia – Sede Medellín



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Key Action 1 Inter-institutional Agreement 2014 / 2020 between Programme Countries

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A. Information about Higher Education Institutions

NAME OF THE INSTITUTION	ERASMUS CODE	ADMINISTRATIVE CONTACT	ACADEMIC CONTACT	WEBSITE
Università degli Studi di Salerno	I SALERNO01	<p>Contact person: Nunzia FRAIESE Address: Ufficio Relazioni Internazionali – Erasmus – Via Giovanni Paolo II, 132 – 84084 Fisciano (SA) – Italy Phone: +39 089 96 2368 – 2486 Email: erasmus@unisa.it Website: www.international.unisa.it</p>	<p>Prof. Giovanni Petrone Dep. of Informatics, Electrical Eng. and Applied Mathematics</p>	<p>University: www.unisa.it Didactics: www.didattica.unisa.it</p>
Universidad de Málaga	E MALAGA01	<p>Contact person: Lilian Barranco Address: International Relations and Cooperation Unit, Aulario Rosa de Gálvez, Bulevar Louis Pasteur, 35. Campus de Teatinos, 29071 Málaga. Phone: Lilian Barranco Tel.: +34 952 134144 Email: lbarranco@uma.es Website: http://www.uma.es/relaciones-internacionales/</p>	<p>Prof. Francisco José Sánchez Pacheco Escuela Politécnica Superior Dept. de Tecnología Electrónica</p>	<p>University: www.uma.es Didactics:</p>

Agenda

1. Monitoring vs. Diagnostic functionalities of commercial products
2. Overview of degradation phenomena occurring in PV modules
3. Diagnostic to monitor performance degradation in operative PV arrays
4. A new approach for the “on-line” detection of PV modules degradation
5. Experimental results
6. Conclusions

Why on-line PV diagnostic

- PV modules **operating in outdoor conditions** are subjected to degradation effects not reproducible and not predictable with the laboratory tests.
- The working conditions might be not properly correct (mismatch, partial shading, installation defects, faults)
- Need to maximize the energy productivity for all the lifetime of the PV plant (maximization the return of the investment)
- Programmed PV plant maintenance and Faults detection.

Several PV inverter are equipped with monitoring systems but they work at the **AC side** in some case at the **field level** or at the **string level** and are aimed to evaluate the energy production only.

Measures at the **PV panel level** are required for a detailed and reliable PV degradation analysis.

PV monitoring vs. PV diagnostic

New products in the market



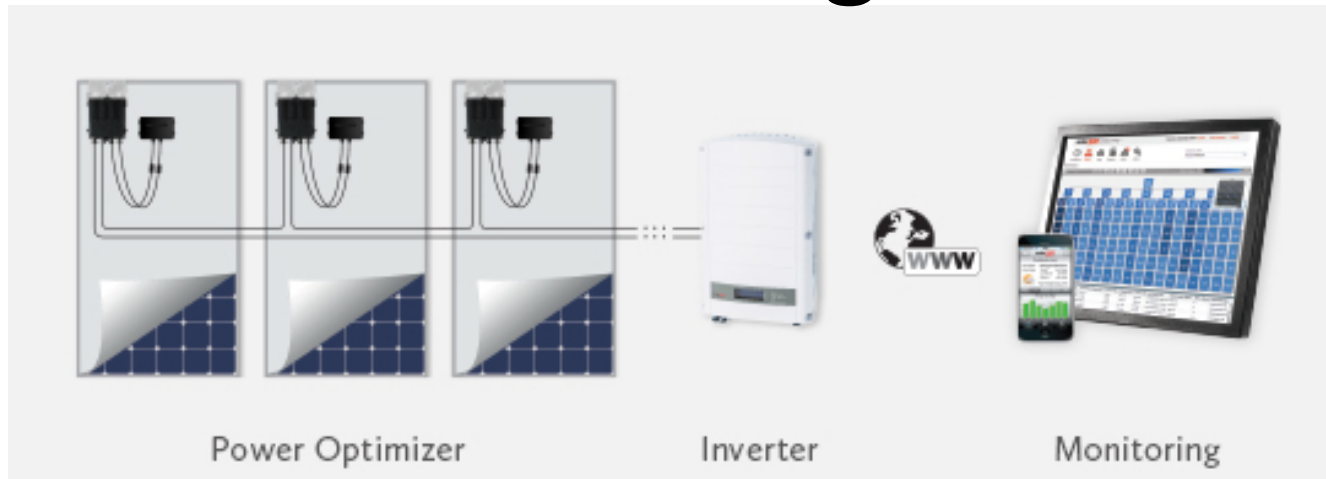
<http://enphase.com/commercial-solution/system/>

<http://www.bitronenergy.com/endana-photovoltaic-optimizer-monitor-safety-alarm/>

<http://www.sma.de/en/products/monitoring-control.html>

<http://www.pvresources.com/PVSystems/Monitoring.aspx>

PV monitoring vs. PV diagnostic



solaredge
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- Module-level, string-level and system-level PV monitoring
- The monitoring portal allows for enhanced maintenance and yield assurance through module-level **performance monitoring**, **fault detection** and automatic alerts localized on a virtual site map for accurate troubleshooting.
- The monitoring web-based portal can be accessed from smart-phone or tablet

Further benefits of using the power optimizer:

- Mismatch between PV module is removed → High Energy Yield
- High flexibility in the installation (modularity)
- Disconnection of each PV module in case of fire

As drawbacks:

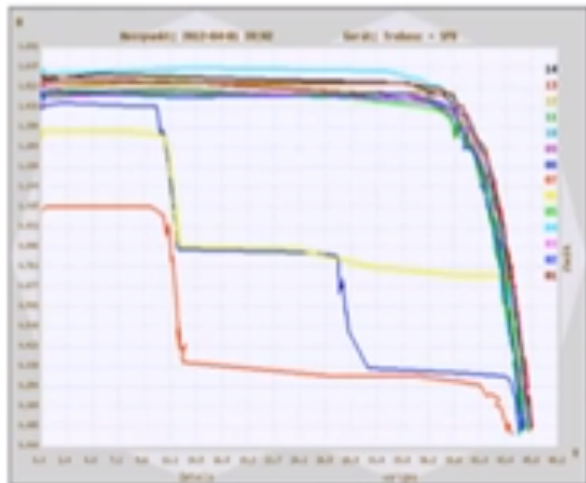
- High Cost
- Low Conversion Efficiency

PV monitoring vs. PV diagnostic

PV field re-configuration system



Optimization, monitoring and safety for photovoltaics

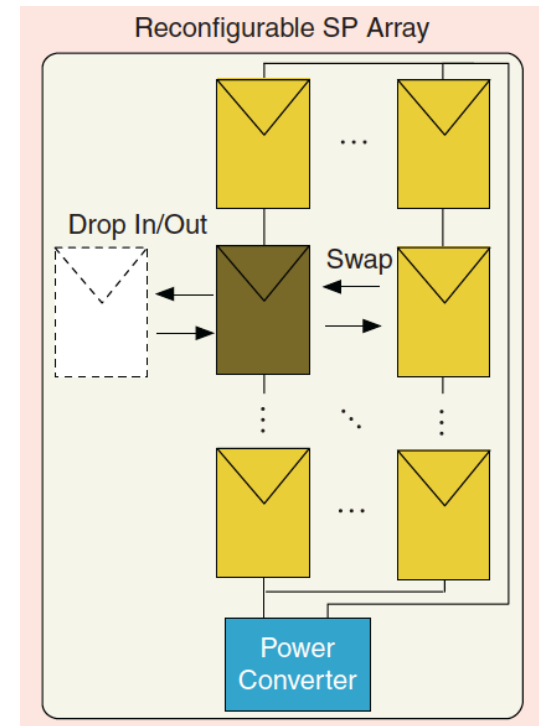


RU Remote units

- Installed under the PV solar panels, one remote unit per 4 panels
- Simple wiring direct to panels

CU Central Unit

- Acts as intelligent hub for the remote units (activate relays for)
- Connects the two string to any inverter
- Analyse the I-V curve of each PV panel



Benefits:

- No additional losses due to dc/dc converter.
- Simple circuitry (ON-OFF switch) -> Low cost, high reliability.
- Easy electrical disconnection of module in presence of fire

Drawbacks

- No energy production during the reconfiguration
- Limited flexibility and applicable only for small PV plant

PV monitoring vs. PV diagnostic

- In **medium/high power plants** the location of a malfunctioning module is very hard to identify (thousand of PV modules).
- Often is required to **disconnect or disassembling** the whole string with a significant energy loss.
- **Low cost** PV monitoring system at PV module level is required

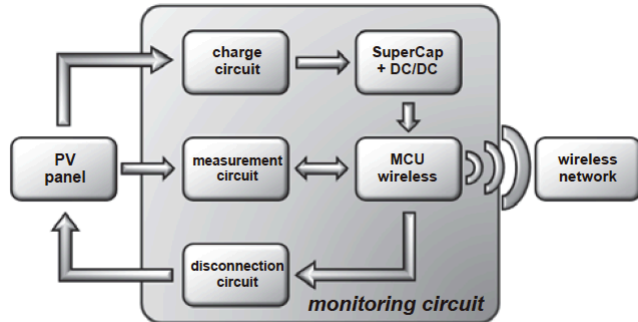
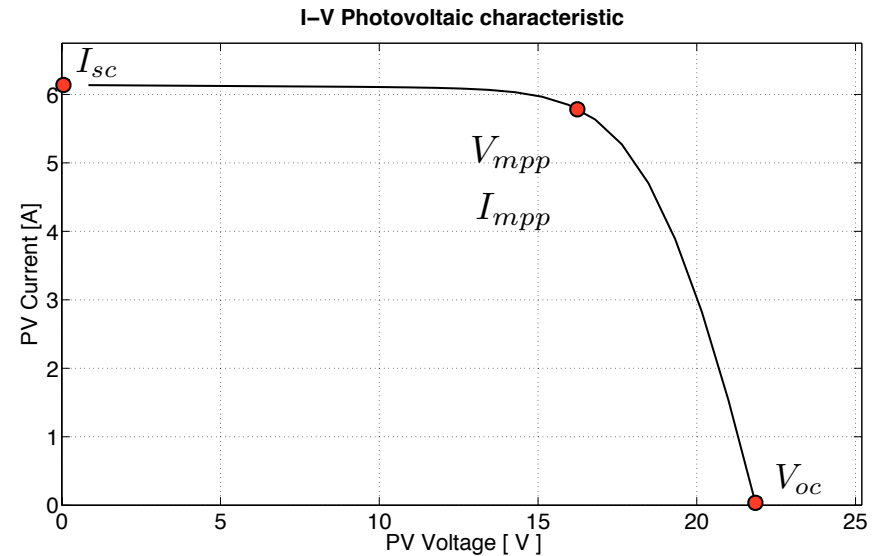
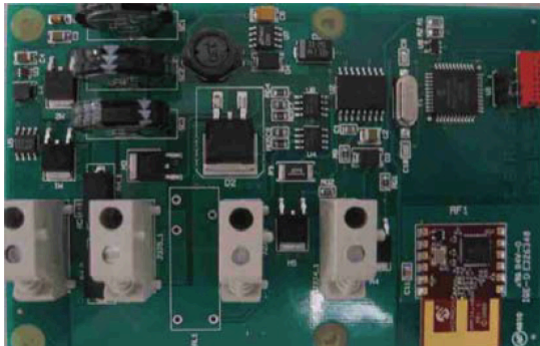


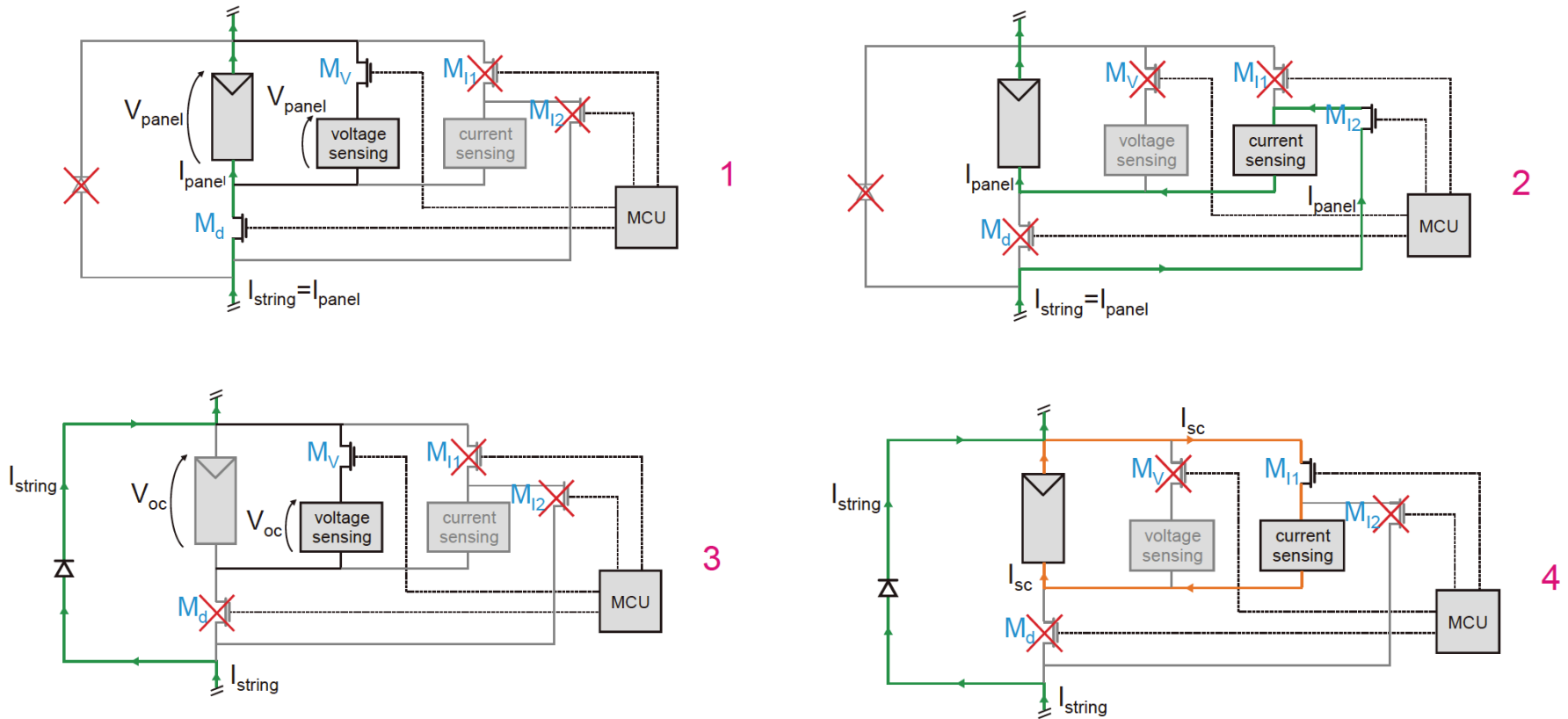
Fig. 1. Schematic diagram of the monitoring circuit.

- Integrated in junction box
- Fully self-powered
- Wireless communication for data transfer
- Measures in different operating condition



Guerriero, P.; d'Alessandro, V.; Petrazzuoli, L.; Vallone, G.; Daliento, S., "Effective real-time performance monitoring and diagnostics of individual panels in PV plants," *Clean Electrical Power (ICCEP), 2013 International Conference on*, vol., no., pp.14,19, 11-13 June 2013

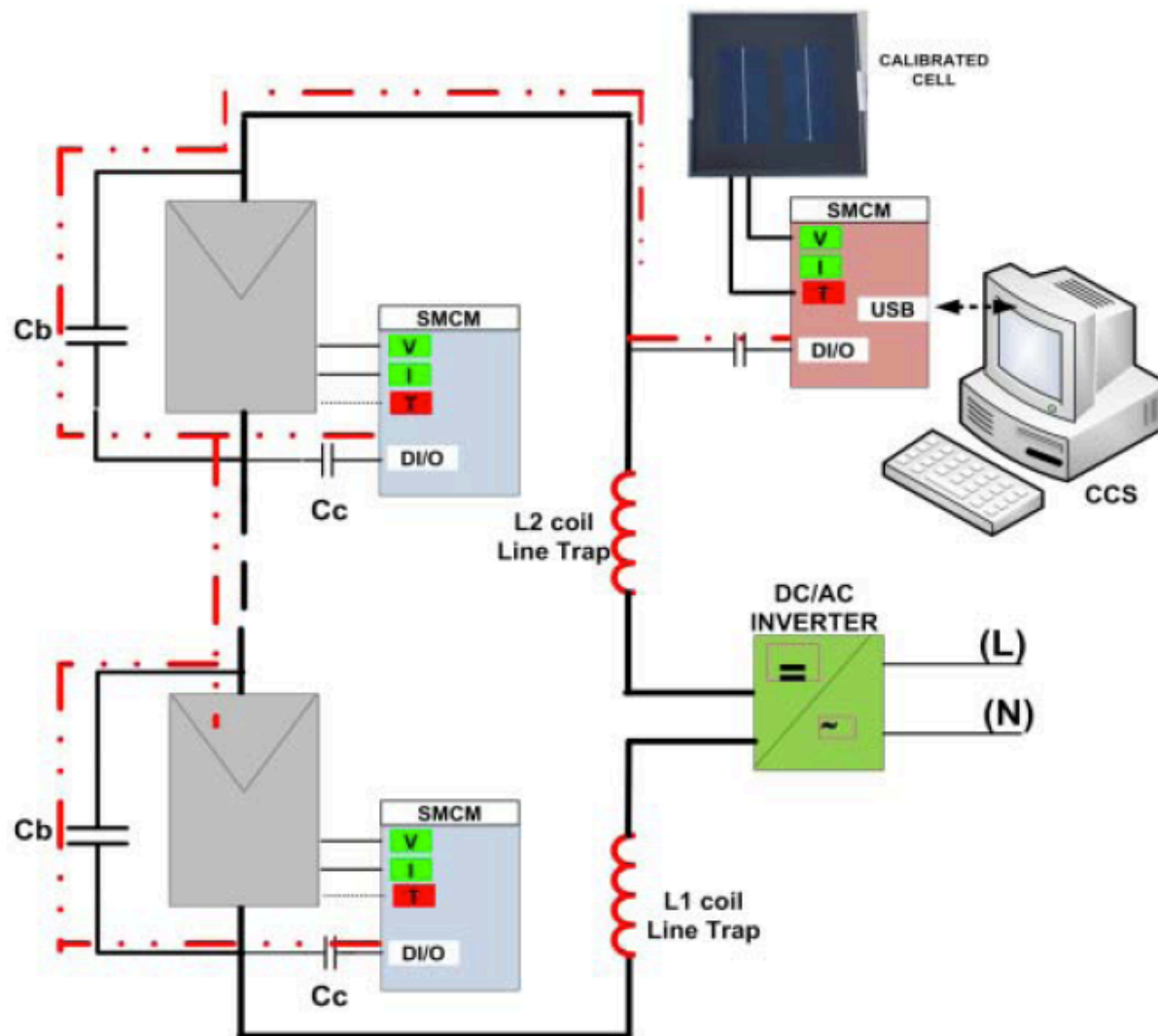
PV monitoring vs. PV diagnostic



- Measures il normal operating conditions: voltage (1) and current (2)
- Open circuit voltage (3) measure
- Short circuit current (4) measure

PV monitoring vs. PV diagnostic

Low cost
PV monitoring



- Power line communication with capacitive coupling
- PV voltage, current and temperature of each module are available

PV monitoring vs. PV diagnostic

New commercial devices:

- Microinverter
- Power Optimizer
- PV field reconfiguration systems
- Low cost PV panel monitoring system



- Monitoring of the energy production
- Diagnosis of the PV modules



- Rough diagnostic functionalities
- Poor information on the state of health of the PV modules

Open problems:

- How the PV modules might be diagnosed ?
- What are the degradation phenomena to be detected ?
- What are the parameters to be sensed ?
- What are the best indicators for diagnostic purposes?
- How to do diagnosis of the bypass diodes ?

Degradation in PV modules

What we would like to know

The **Degradation Mechanisms:**

- related to the physical process involved in the solar cell (photon degradation) **short term effects**
- related to weathering and degradation of the module package **long term effects.**

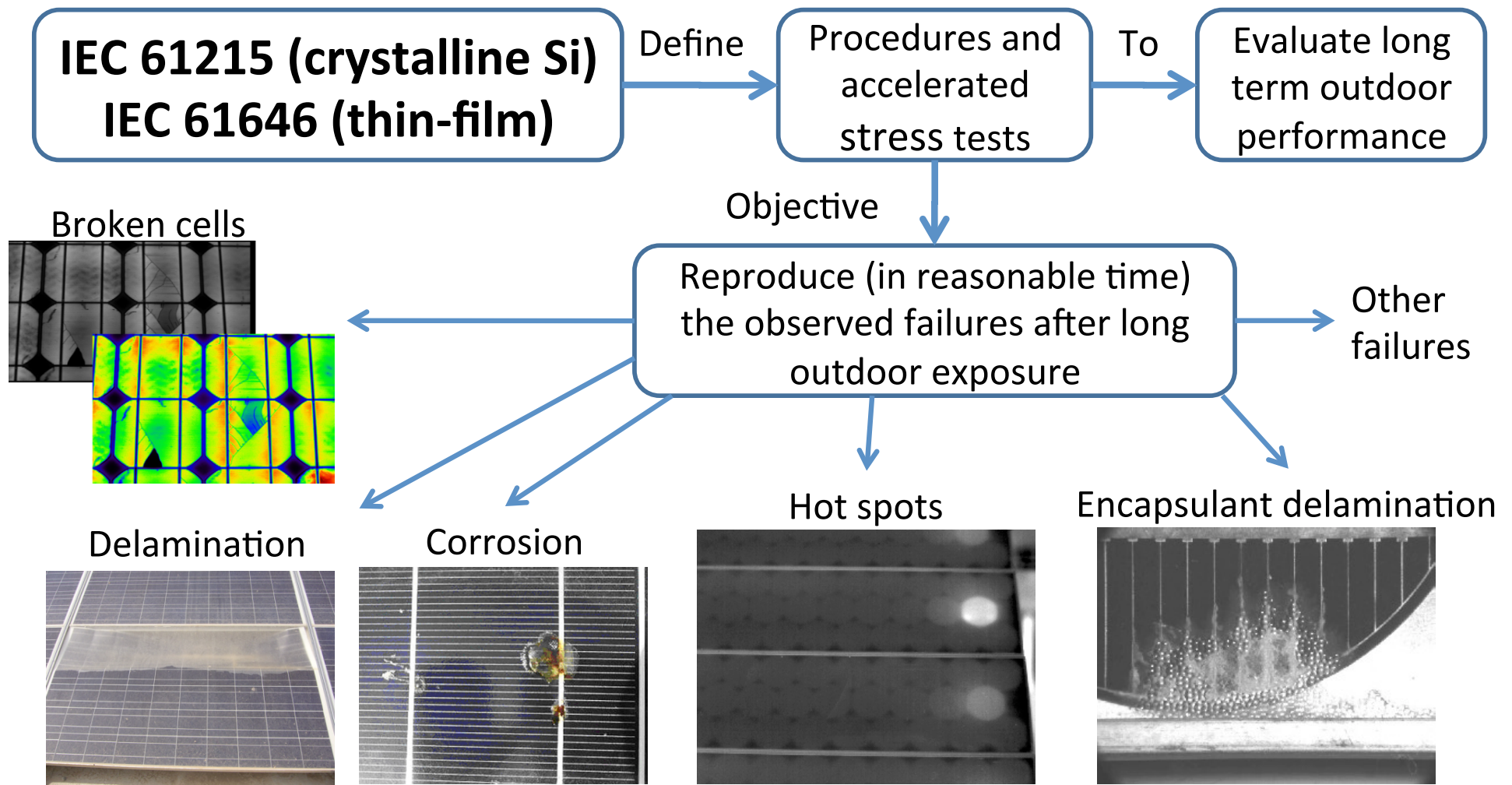
The **Degradation Rate:**

The total effect of the degradation mechanisms on the energy production of a PV module over its lifetime.

The **Life Expectancy:** (it is not the PV lifetime)

The time in which the energy delivered by the PV module can be predicted by assuming an assigned degradation rate (many PV manufacturers guarantee an energy production greater than the 90% of the nominal power for the first ten years and greater than the 80% of the nominal power within the first 20 years of the PV lifetime).

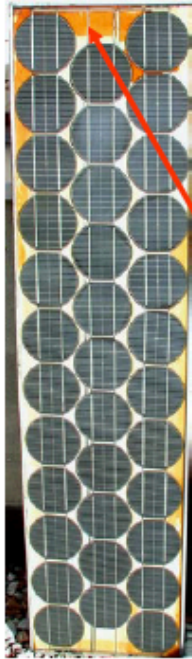
Diagnostic to improve manufacturing process



Taken from: M.A. Munoz et al., 2011 Early degradation of silicon PV modules and guaranty conditions

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Degradation in PV modules (indoor tests)



- 1220 Thermal Cycles:
no major defects
no measurable power losses
- 6000 hours Damp Heat:
dark yellowing
detachment of tedlar backsheet
(not observed outside)
no measurable power losses

Observed delamination outdoor, not reproduced through indoor tests



Thermal Cycling Test: module temperature between $-40\text{ }^{\circ}\text{C} \pm 2\text{ }^{\circ}\text{C}$ and $+85\text{ }^{\circ}\text{C} \pm 2\text{ }^{\circ}\text{C}$. The rate of change of temperature shall not exceed $100\text{ }^{\circ}\text{C}/\text{h}$ and the module temperature shall remain stable at each extreme for a period of at least 10 min.

Damp Heat Test: the module(s), being at room temperature, shall be introduced into the chamber without preconditioning. Temperature: $85\text{ }^{\circ}\text{C} \pm 2\text{ }^{\circ}\text{C}$, Relative humidity: $85\% \pm 5\%$, Duration: 1 000 h.

Degradation in PV modules (operating in outdoor condition)

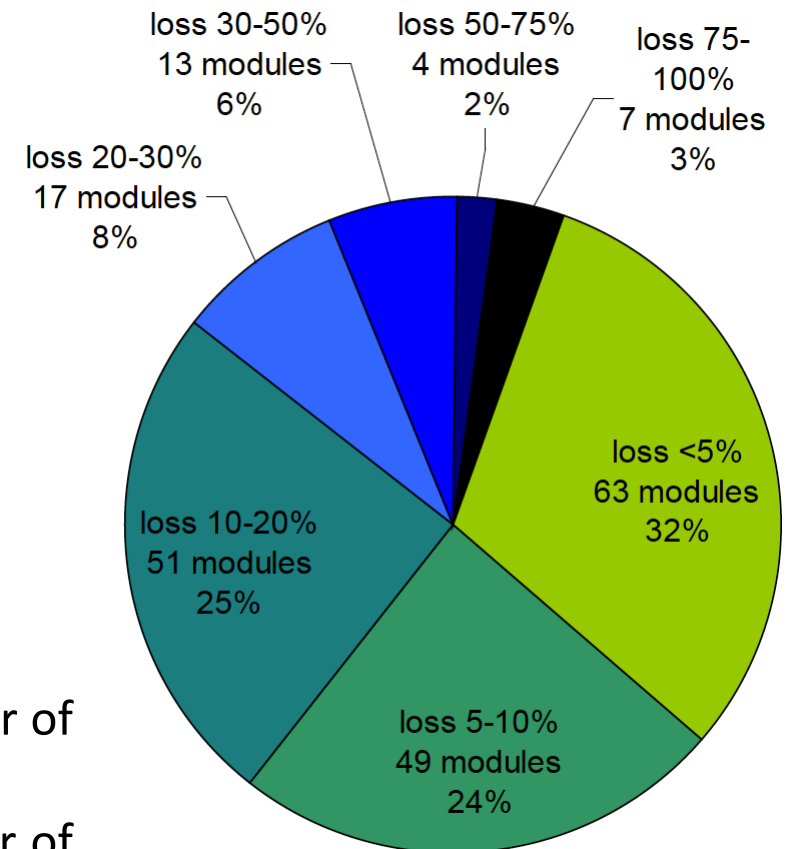
- The **ultraviolet (UV)** component of the sunlight is one of the main cause of the PV modules damage and degradation.
- **Geographical location and altitude** affect significantly the amount of sunlight
 - A module in a sunny environment will degrade faster due to increased UV content and elevated temperature.
 - Exposure at elevated altitudes can significantly increase exposure to ultraviolet light and therefore significantly reduce the expected lifetime.
- The **rain** and the **atmospheric humidity** have a significant impact on the weathering resistance of the PV modules.
- **Air pollution** (e.g sea salt, dust, sulfur, acid fumes and other industrial gases) speeds up the PV degradation.
- **Electrical operating conditions** of PV modules affect on its own degradation.
- **High voltage**, due to the series connection of modules, is a stress factor that leads to power degradation (Potential Induced Degradation PID).
- Module **mounting** system has an impact on modules aging especially because different temperature conditions occur
 - Roof mounted or building integrated modules usually are hotter than free rack-mounted ones.

Some studies taken from literature

- Data taken from a **report of the European Commission, DG JRC, Institute for Energy, Ispra, Italy**, will be used as examples.
- Main references are:
 - http://www1.eere.energy.gov/solar/pdfs/pvmrw2011_28_csi_sample.pdf)
 - Skoczek, Artur; Sample, Tony; Dunlop, Ewan D.: “The results of performance measurements of field-aged crystalline silicon photovoltaic modules”; Progress in Photovoltaics: Research and Applications, Vol. 17, n°4, pp. 227-240, 2009.

Long-term (18 -24 years) outdoor exposure

No of modules		204
No of producers		20
No of module types		53
Cell type	Mono	123
	Poly	81
Encapsulant	PVB	59
	Silicone	40
	EVA	101
	Other (unknown)	4
Substrate / Backsheet	Glass	68
	Tedlar, Tedlar/Aluminium/Tedlar	62
	Tedlar/Aluminium/Polyester	8
	Polyester/Aluminium	20
	Silicone	20
	Others, polyethylene, "plastic" Unknown	26

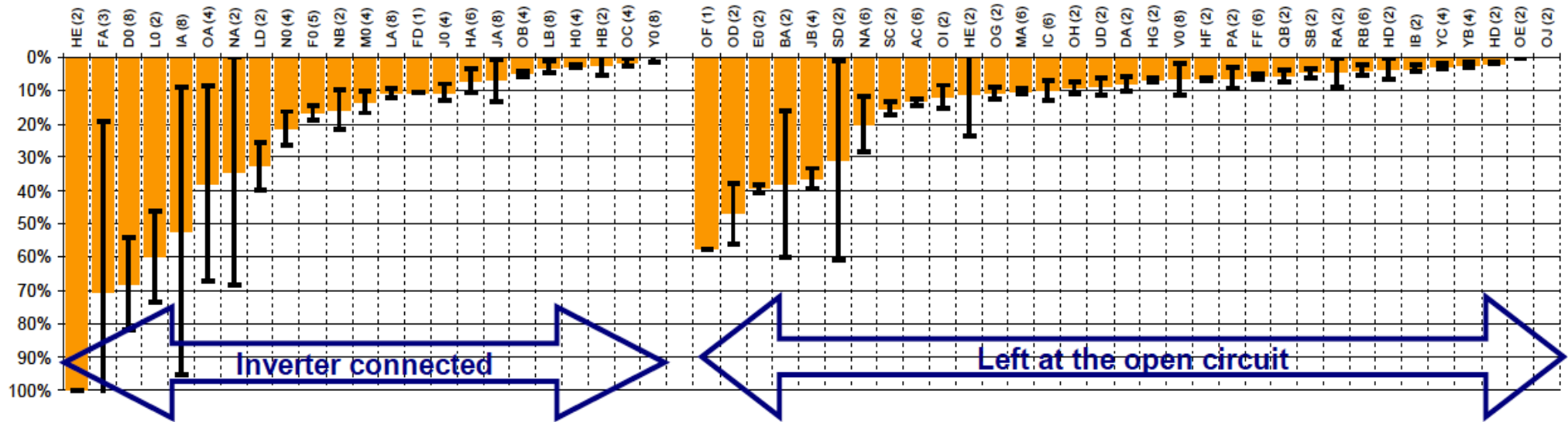


Short Term Losses: have been shown to be in the order of $2.4\% \pm 1.7\%$.

Long Term Losses: have been shown to be in the order of 0.2% per annum up to 1% per annum.

Effect of electrical operating condition

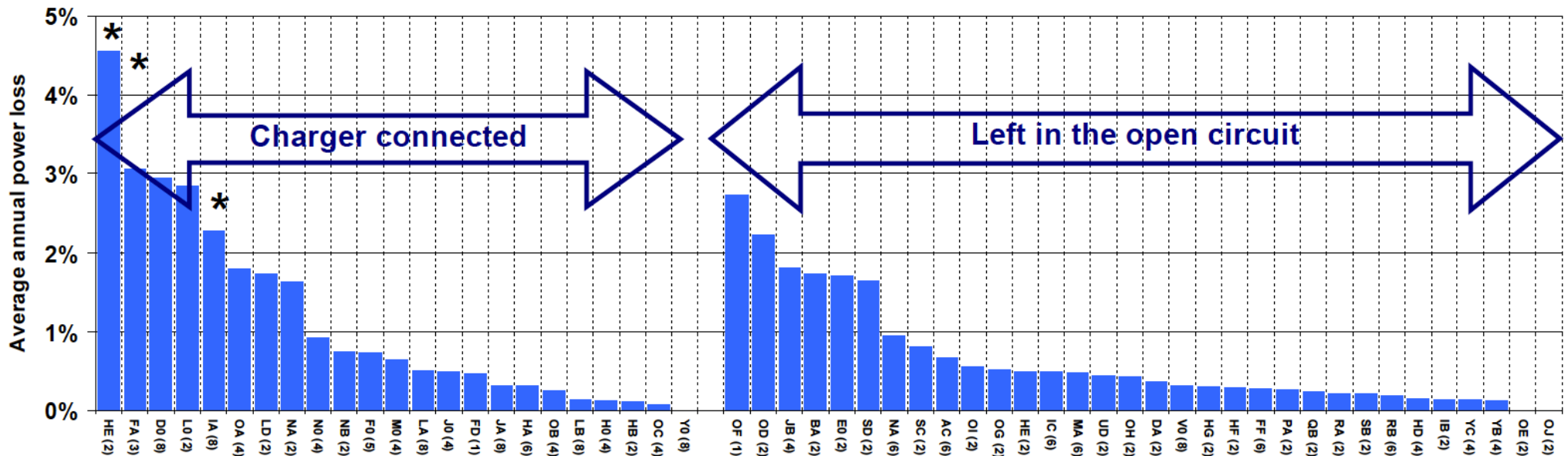
Relative P_{max} losses of modules series grouped by module's test conditions



PV modules connected to the inverter (operating in MPP) exhibited approximately **twice** the average degradation in comparison to modules left in open circuit.

All of the modules (7) which exhibited **total circuit breakage** were connected to the inverter.

Annual degradation rates

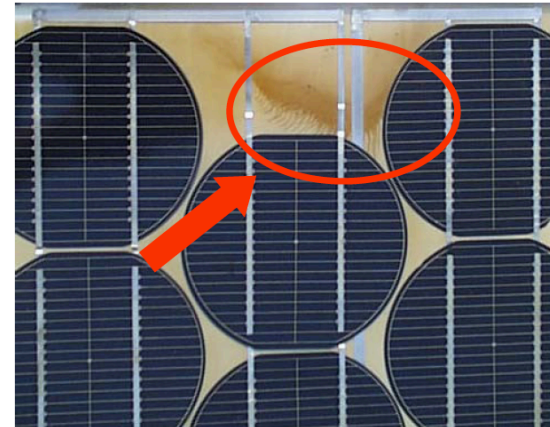


- An average annual degradation of **1%** (0.8% excluding total failures) is calculated for the PV modules operating with inverters
- An average annual degradation of **0.6%** is calculated for the PV modules left in open circuit

Defects due to UV and weathering

Yellowing:

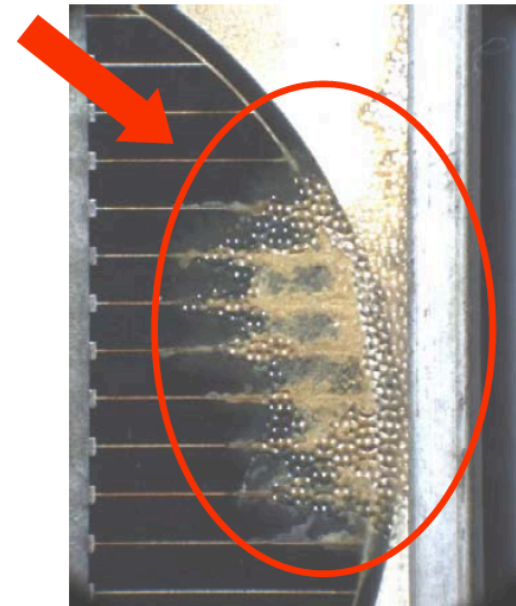
Practically no influence on encapsulant transparency (same spectral response for white and yellow modules)



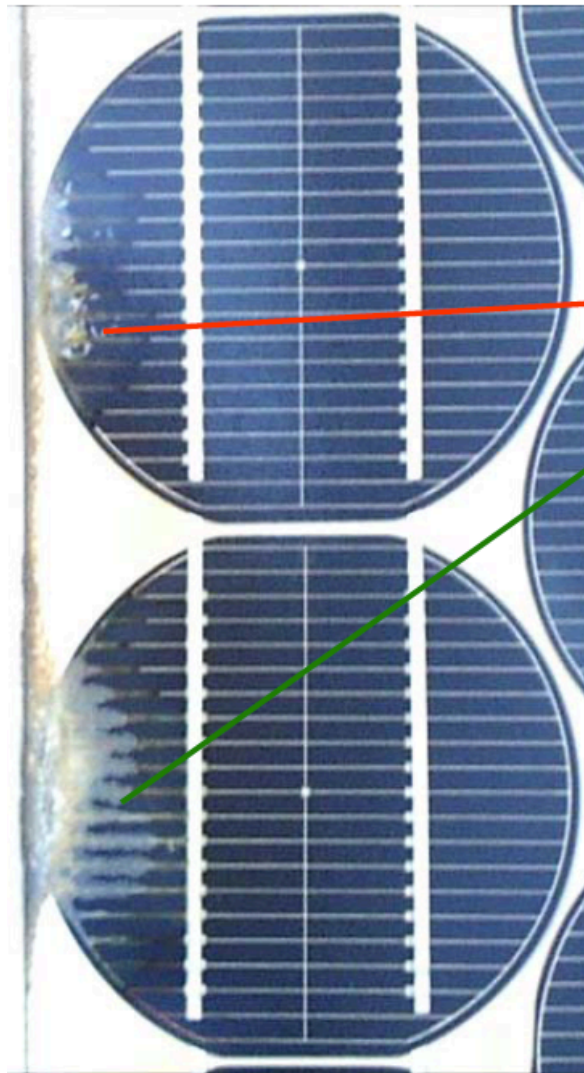
Delamination:

Can affect modules insulation
(dry & wet insulation tests)

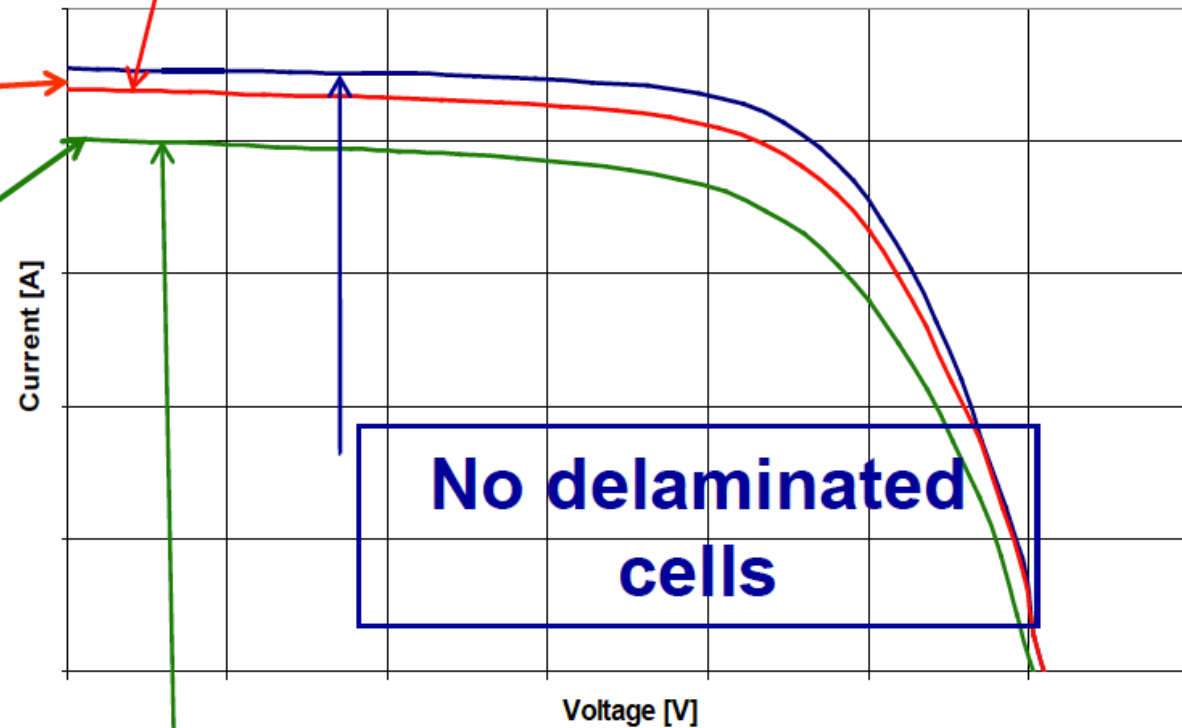
Cumulative effects on modules performance
(Delamination in front of cells)



PV degradation vs. mismatch

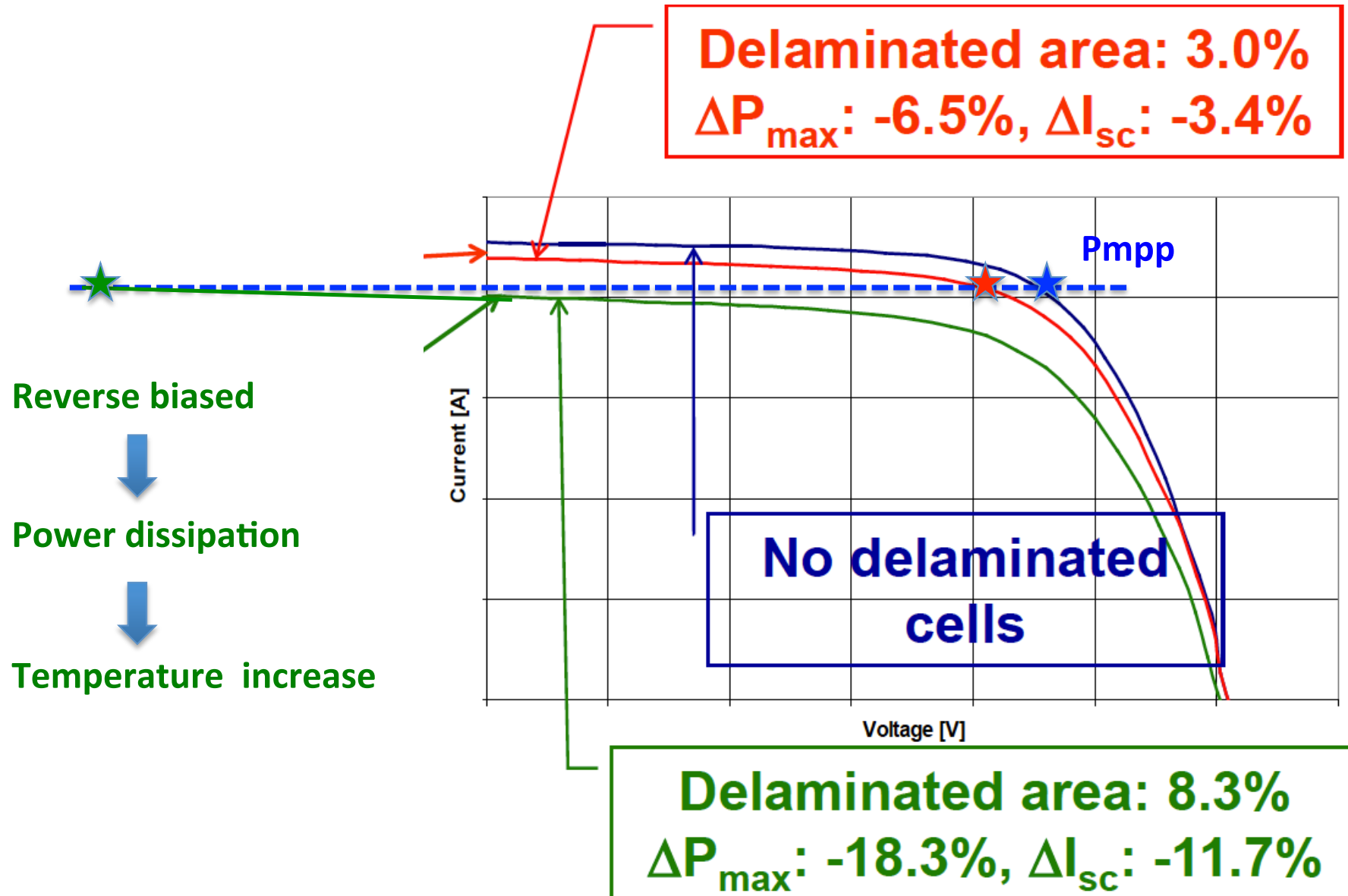


Delaminated area: 3.0%
 ΔP_{\max} : -6.5%, ΔI_{sc} : -3.4%



Delaminated area: 8.3%
 ΔP_{\max} : -18.3%, ΔI_{sc} : -11.7%

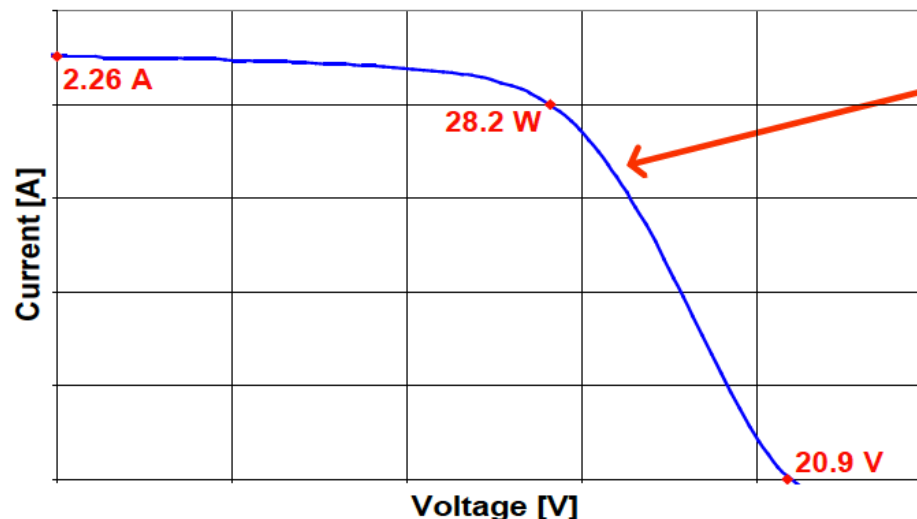
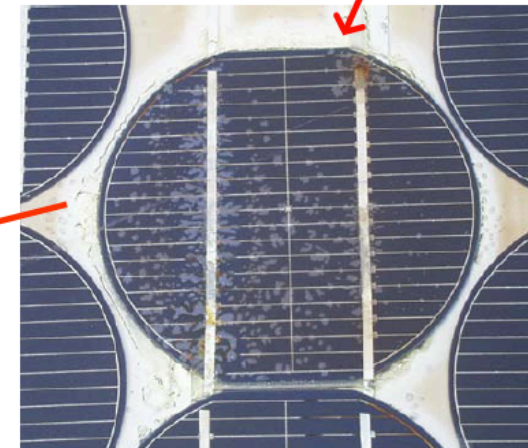
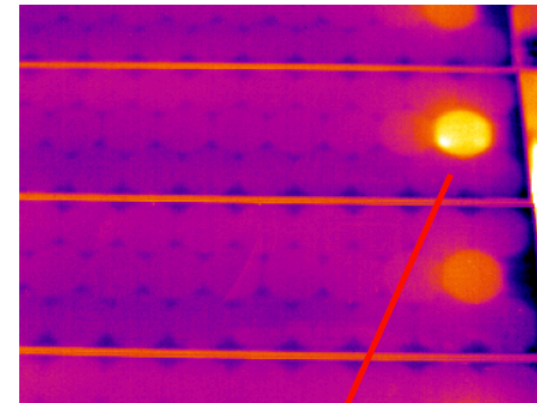
PV degradation vs. mismatch



PV degradation vs. mismatch

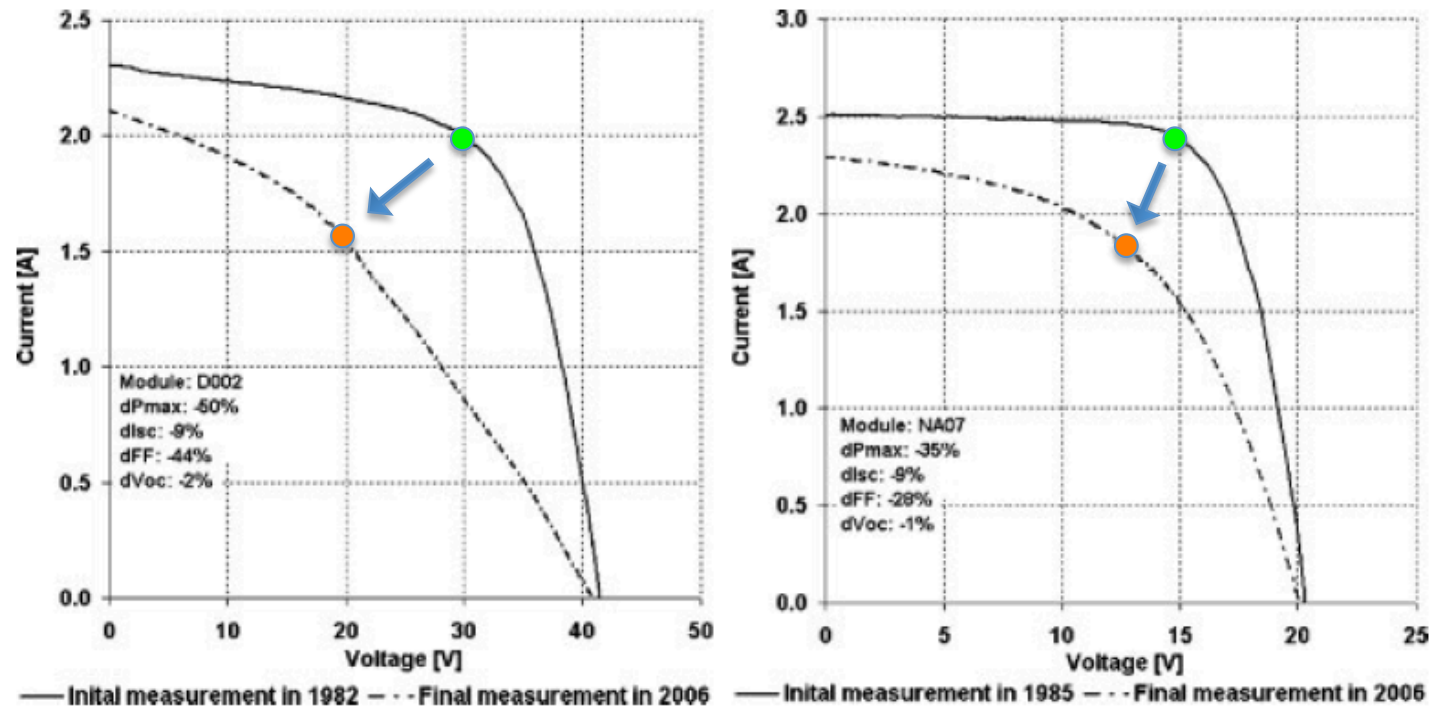
A strictly correlation exists:

- PV module degradation, which is non-uniform by its nature, causes mismatching among cells and modules.
- A PV module/string operating in mismatched conditions, **leads to localized degradation** mainly due to thermal effects (hot spot phenomena)
- Modification of the **electrical operating conditions** due to mismatch (e.g. by-pass diode activation) might contribute to the system degradation and failure.



P_{\max} : -24% vs P_n
(-15% vs average actual P_{\max})

PV degradation on the I-V curve



- Approximately 9% reduction on Isc and 1% reduction on Voc due to 20 years aging for both cases.
- Fill Factor degradation (43.7% and 28.9%, respectively)
- Maximum Power degradation (49% and 36%, respectively)

Generally high Pmax losses (>20%) are attributed to series resistance increase.

Moderate Pmax losses (<20%) can be attributed to Isc losses (optical properties degradation)

Summary of degradation mechanism

Degradation source	Produced by	Effects in the PV module
Front surface soiling.	Lack of maintenance and cleaning.	Reduction in I_{sc}
Optical degradation	Degradation and/or cracks in the transparent cover that protect the cells, (e.g. browning).	Reduction in I_{sc} .
Cell degradation.	Delamination, Daily thermal cycling, humidity that enter through the small cracks or holes that produces oxidation in the terminals, etc.	Increase in R_s .
	Small breaks in the isolation between the cells and the frame, crystal damages, semiconductor problems that increase leakage currents.	Reduction in R_h .
Mismatched cells.	Degradation of Anti-Reflective coating, cracked cells and shadowing.	Reduction in I_{sc} and V_{oc} and/or increase in R_s .
Light Induced Degradation (LID).	Changes in semiconductor materials due to the initial outdoor operation hours.	Reduction in I_{sc} and V_{oc} , increase in R_s and/or decrease in R_h .
Potential Induced Degradation (PID).	Grounding problems. High voltages between the module frame and the surfaces that carries the charges in the module like cells and cables.	Reduction of R_h .

Literature Overview of PV diagnostic methods

1. **Methods to improve manufacturing process**
 2. **Methods to monitor performance degradation in operative PV arrays**
- **Some performance indicators** are defined and evaluated periodically during the normal working condition of the PV panel. Comparison with the reference values calculated at the beginning of the monitoring process give the estimation of the PV degradation.
 - **Off-line methods** require the disconnection of the module from the PV array and/or specialized *in situ measurements* to evaluate the indicators.
 - Allow to detect many types of degradation phenomena and failures.
 - **On-line methods** perform the measurements on the PV panel by avoiding its physical disconnection from the PV field.
 - Diagnostic methods based on the **parameters estimation** of the electrical models of the PV panel are also available in literature.
 - The estimation of the electrical parameters during the PV panels lifetime allows to predict the **state of health of the PV field**.

PV module diagnostic: a literature overview

To improve manufacturing process:

[16] **IEC 61215** accelerated stress test for crystalline Si modules.

[17] **IEC 61646** accelerated stress tests for thin-film modules.

[18,19] module safety qualification.

To monitor performance degradation in operative PV arrays:

Off-line -> they use:

[11]: Light and dark I-V curve, estimation of **R_h** and thermal measurements.

[24]: Estimation of **R_h** and **P_{mpp}** (from dark I-V curve).

[26]: Estimation of **R_s, R_h, I_{sc}, V_{oc}, P_{mpp} and FF**.

[15]: Estimation of **FF, R_s, and R_h**.

[27]: Estimation of light I-V performance from dark I-V curves.

[12,21,13,22,23]: Thermal, infrared, electroluminescence and ultrasonic images.

[20]: Laser (or Light) beam induced current.

On-line -> they use:

[29]: **R_s** estimation integrated with MPPT technique.

[30]: **R_s** estimation from 3 I-V curves.

[32]: Detection of modules in open-circuit and short-circuit.

[33]: Deviation from **V_{mpp}** of the array without degradation.

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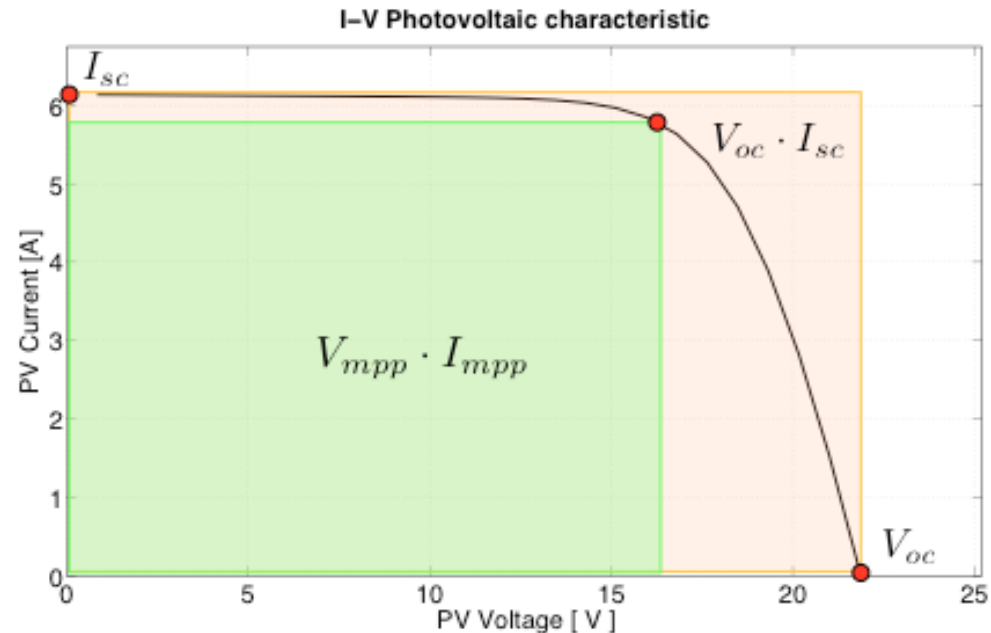
The **references** are the ones listed in:

Bastidas-Rodriguez, J.D.; Petrone, G.; Ramos-Paja, C.A.; Spagnuolo, G., "Photovoltaic modules diagnostic: An overview," *Industrial Electronics Society, IECON 2013 - 39th Annual Conference of the IEEE*, vol., no., pp.96,101, 10-13 Nov. 2013

Fill Factor (FF) and Normalized Fill Factor (NFF)

$$FF = \frac{V_{mpp} \cdot I_{mpp}}{V_{oc} \cdot I_{sc}}$$

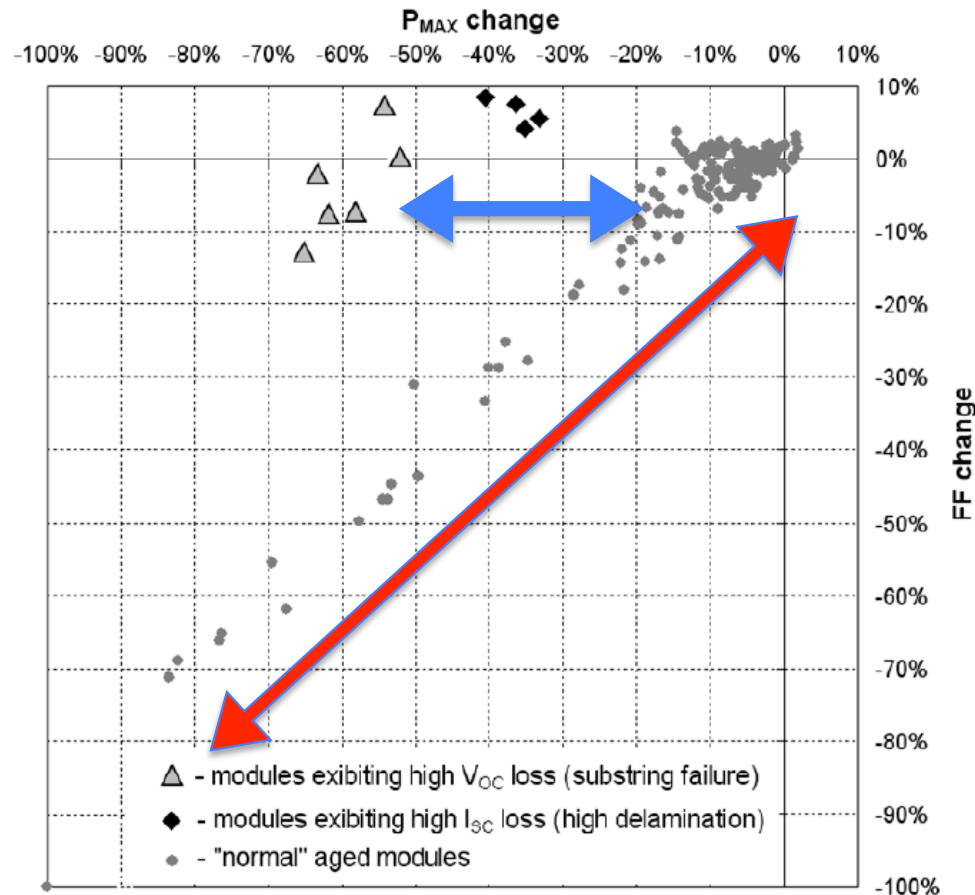
$$NFF = \frac{FF}{FF_{STC}}$$



- The NFF indicator is sensible to the position of MPP with respect to I_{sc} and V_{oc} ;
- Any parameter variation affects FF and NFF, thus such indicators are not adequate to distinguish the origin of the PV degradation.
- One current and one voltage sensor are required to measure I_{sc} , V_{oc} , I_{mpp} and V_{mpp} as well as the datasheet information (I_{scSTC} , V_{ocSTC} , I_{mppSTC} and V_{mppSTC}).

- S. Kaplanis and E. Kaplani, "Energy performance and degradation over 20 years performance of BP c-Si PV modules," *Simulation Modelling Practice and Theory*, vol. 19, no. 4, pp. 1201–1211, Apr. 2011.
- E. L. Meyer and E. E. Van Dyk, "Assessing the Reliability and Degradation of Photovoltaic Module Performance Parameters," *IEEE Transactions on Reliability*, vol. 53, no. 1, pp. 83–92, 2004.

Pmax variation vs. Fill Factor variation

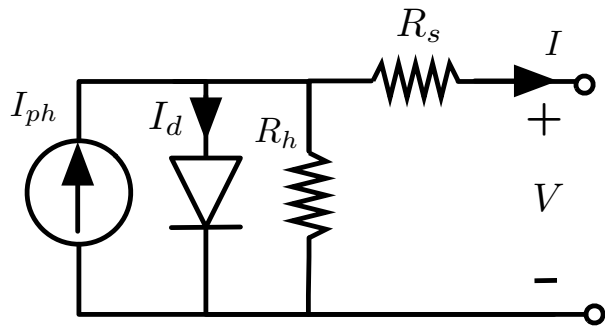


From literature is also confirmed that:

- “Normal aged “ modules have large variation on FF.
- “Normal aged” and “Degraded” modules might exhibit the same FF variation depending on the respective operating condition
- P_{mpp} losses (>20%) are generally attributed to the series resistance increase.

The FF gives a direct measure of the PV performance; it is suitable to compare different PV modules in the same environmental conditions

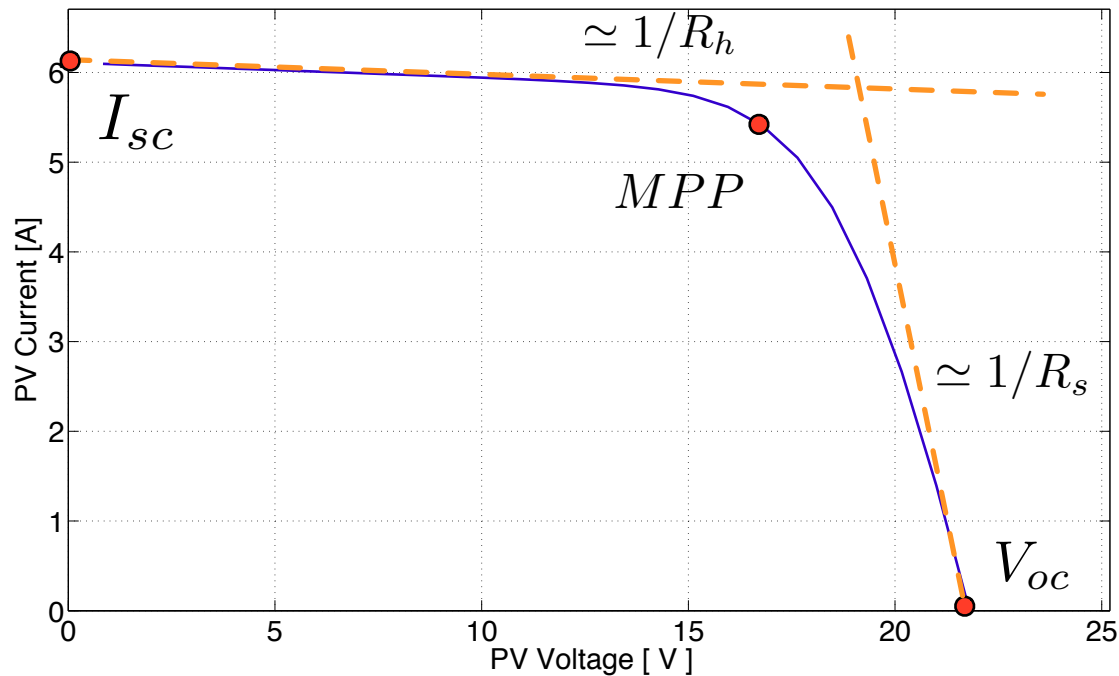
Rs & Rh estimation on the I-V curves



$$I = I_{ph} - I_{sat} \left(e^{\left(\frac{V + R_s \cdot I}{\eta V_t} \right)} - 1 \right) - \frac{V + R_s \cdot I}{R_h}$$

1/R_h approx. with the slope of the I-V curve @ I_{sc}
 1/R_s approx. with the slope of the I-V curve @ V_{oc}

I-V Photovoltaic characteristic

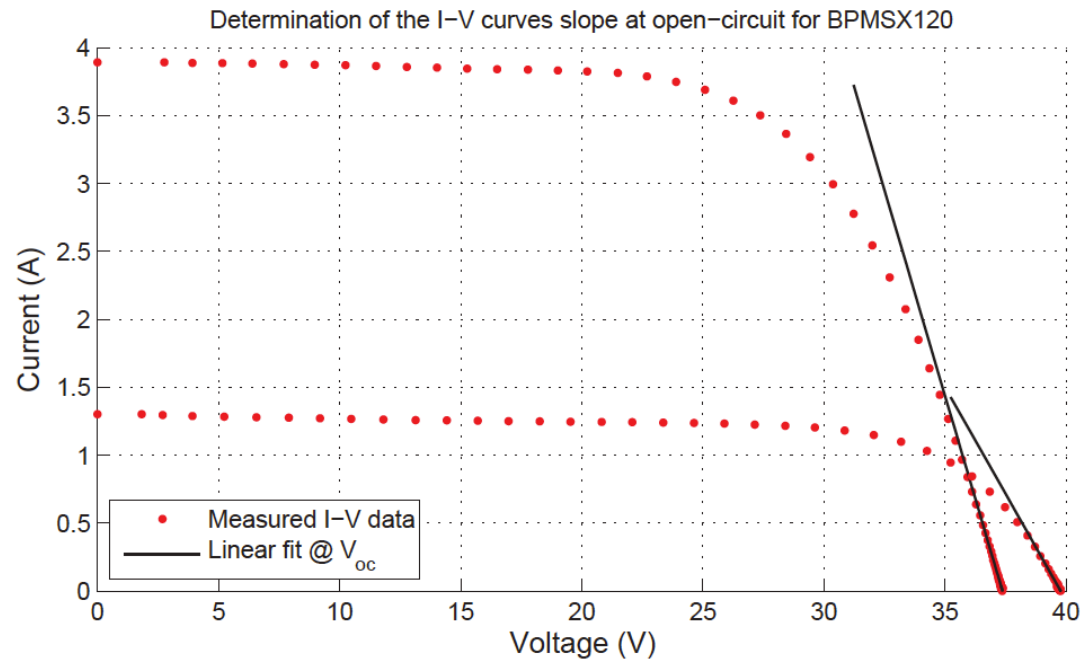


- Experimental values of the I-V curve close to V_{oc} and I_{sc} are required to calculate the slopes

Rs estimated @ Voc (Method-Sera1)

$$R_{s,e} = -\left. \frac{dV}{dI} \right|_{V \approx V_{oc}} = -\left. \frac{V_2 - V_1}{I_2 - I_1} \right|_{V \approx V_{oc}}$$
$$R_{s,1} = R_{s,e} + \frac{V_t}{I_{sc}} \cdot \left(\frac{G}{G_{STC}} \cdot \frac{T_{STC}}{T} - 1 \right)$$

It is suggested to choice $V_2 - V_1 = 1$



The evaluation of $R_{s,1}$ requires:

- voltage and current measurements of at least two points of the I-V curve close to V_{oc} to calculate $dV=dI$ as a discrete derivative.
- irradiance and temperature sensors (or estimated by means other methods) to perform the translation of the estimated series resistance.

Rs estimated close to MPP (Method-Sera2)

Assumption:

By considering an operating point that is at a predefined fixed distance (Q) from I_{sc} , the slope measurement will not be affected by the actual irradiation conditions.

$$R_{s,2} \simeq - \left. \frac{dV}{dI} \right|_{I=I_m} = \frac{V_2 - V_1}{I_2 - I_1}$$

$$I_m = I_{sc} - Q$$

It is suggested to choose:

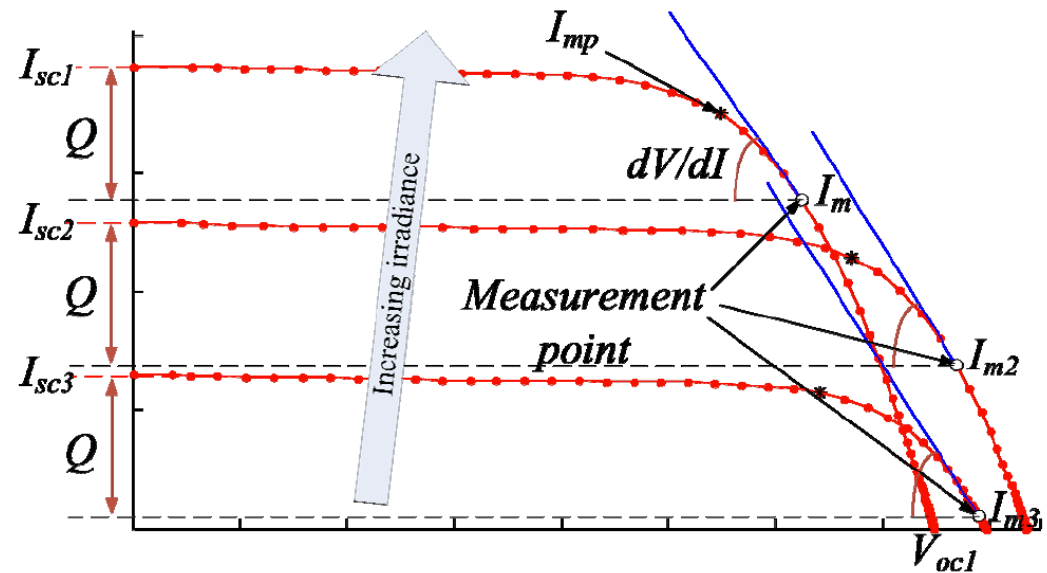
$$I_m = 0.75 \cdot I_{mpp}$$

$$I_m = 0.6 \cdot I_{mpp}$$

The choice of I_m is a trade-off between precision and energy loss

The evaluation of $R_{s,2}$ requires:

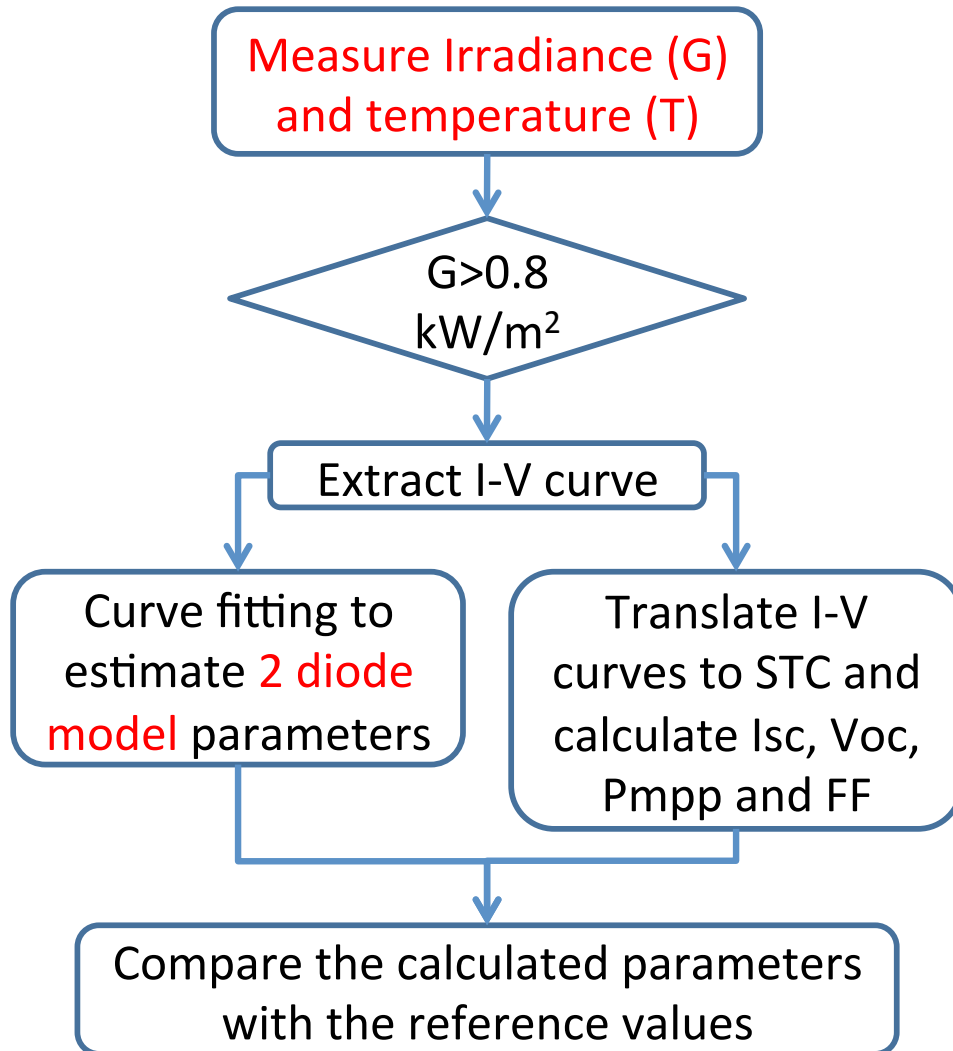
- voltage and current measurements of at least two points of the I-V curve close to I_m (25%-30% far from I_{mpp}) thus the MPPT algorithm must be disabled.
- **No** irradiance and temperature sensors are required



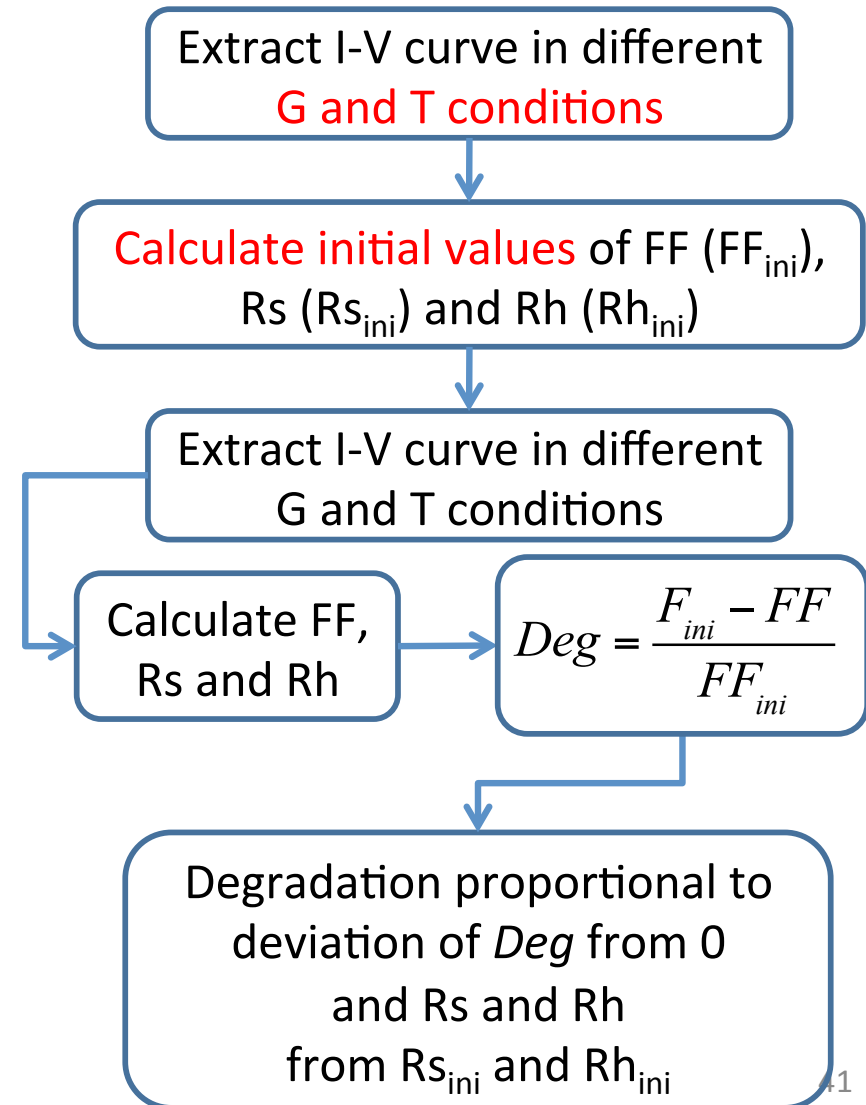
D. Sera, L. Mathe, T. Kerekes, R. Teodorescu, and P. Rodriguez, "A low-disturbance diagnostic function integrated in the PV arrays' MPPT algorithm," in IECON 2011 - 37th Annual Conference of the IEEE Industrial Electronics Society, no. 2. IEEE, Nov. 2011, pp. 2456–2460.

Others diagnostic methods

C. Radue and E. van Dyk, 2010.

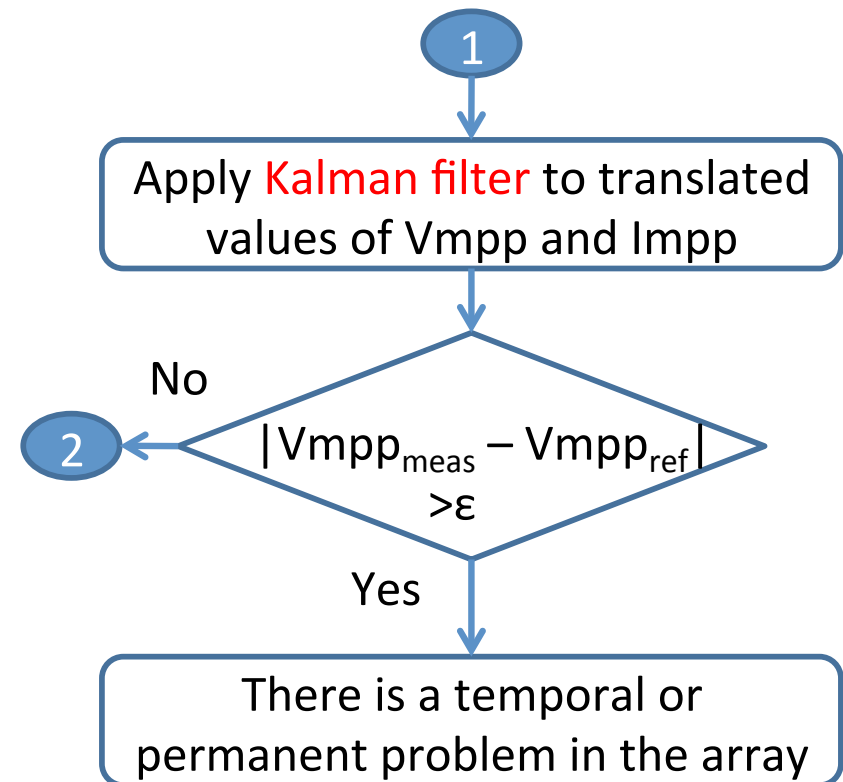
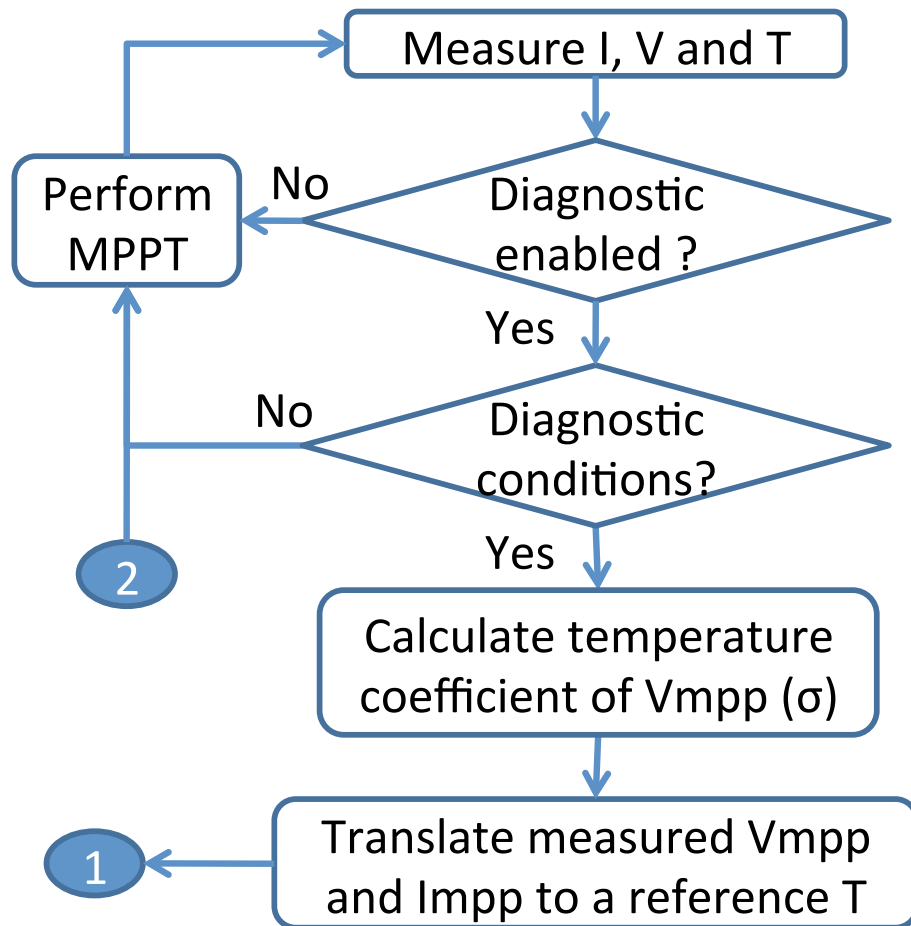


S. Kaplanis and E. Kaplani, 2011.



Others diagnostic methods

B.K. Kang, et al., 2012: detect temporal or permanent Pmpp reduction.



It assumes that the string is always operating under regular conditions.

Remarks

- The literature overview shown that very few diagnostic methods are potentially applicable as “on-line” methods.
- R_s , R_h and Fill Factor (FF) are the most common diagnosed parameters because the degradation phenomena mainly act on these parameters.
- It is required to acquire information from the PV field (I-V curves, irradiance, temperature). R_s and R_h are calculated close to V_{oc} and I_{sc} .
- In some cases complex algorithms and detailed models of the PV panels must be developed to achieve diagnostic functionalities.
- The choice of the diagnostic method is directly related to the type of measure available on the PV field. Devices dedicated to the electrical measure at PV panel level are appearing in the market.
- The methods that require the minimum impact on the PV plant hardware are the ones in which the PV degradation is evaluated with the support of detailed models.

The new approach for the “on-line” detection of PV modules degradation

References:

- J. D. Bastidas-Rodriguez, E. Franco, G. Petrone, C. Ramos-Paja, and G. Spagnuolo, “Quantification of photovoltaic module degradation using model based indicators,” Accepted for publication on Mathematics and Computers in Simulation MATCOM journal.
- J. D. Bastidas-Rodriguez, E. Franco, C. A. Ramos-Paja, G. Petrone, and G. Spagnuolo, “Model based indicators to quantify photovoltaic module degradation,” *Electrimacs*, pp. 49–54, May. 2014. ISBN: 978-84-616-9961-2.
- J. D. Bastidas-Rodriguez, E. Franco, C. A. Ramos-Paja, G. Petrone, and G. Spagnuolo, "Model based degradation analysis of photovoltaic modules through series resistance estimation" submitted to *Transaction on Industrial Informatics*

Identification of the PV degradation based on the single diode model

- The PV degradation phenomenon will be identified by **monitoring the MPP** translation on the I-V plane.
- The **single diode model (SDM)** will be used for estimating the PV degradation.
- Simulation results shown that:
 - the **Impp** reduction is mainly due to the **Isc** degradation and **Rh** reduction
 - the **Vmpp** reduction is mainly due to **Voc** degradation and **Rs** increase.
- Two indicators will be defined for characterising separately the PV degradation phenomenon affecting the **Vmpp** and **Impp** respectively.

Single diode model and parameters characterization

$$I = I_{ph} - I_{sat} \left(e^{\left(\frac{V + R_s \cdot I}{\eta V_t} \right)} - 1 \right) - \frac{V + R_s \cdot I}{R_h}$$

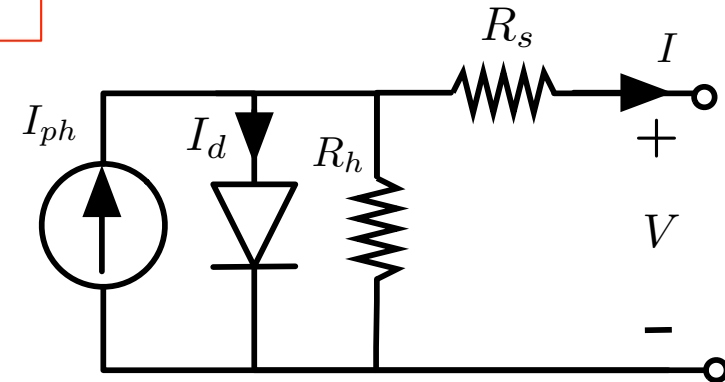
$$I_{ph} = \frac{G}{G_{STC}} (I_{ph,STC} + \alpha_{Isc} (T - T_{STC}))$$

$$\eta = \eta_{STC} \cdot \frac{T}{T_{STC}}$$

$$I_{sat} = \frac{I_{sc,STC} + \alpha_{Isc} \cdot I_{sc,STC} \cdot (T - T_{STC})}{\exp\left(\frac{V_{oc,STC} + \alpha_{Voc} \cdot V_{oc,STC} \cdot (T - T_{STC})}{Ns \cdot k \cdot \eta \cdot T / q}\right) - 1}$$

$$R_s = R_{s,STC} \cdot \frac{T}{T_{STC}} \cdot \left(1 - 0.217 \cdot \ln\left(\frac{G}{G_{STC}}\right) \right)$$

$$R_h = R_{h,STC} \cdot \frac{G}{G_{STC}}$$



The terms with the subscript STC refer to the parameters calculated in standard test condition by using the information reported in the PV panel datasheet

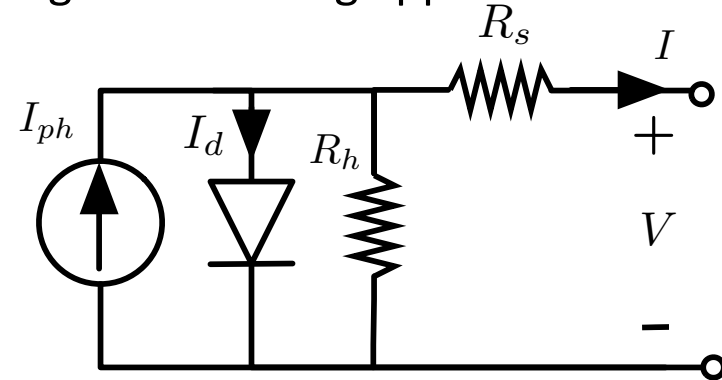
- N. Femia, G. Petrone, G. Spagnuolo, and M. Vitelli, "Power electronics and control techniques for maximum energy harvesting in photovoltaic systems," Taylor & Francis - CRC Press; 1 edition, p. 368, December 2012. ISBN:978-1466506909.
- W. De Soto, S. Klein, and W. Beckman, "Improvement and validation of a model for photovoltaic array performance," Sol. Energy, vol. 80, no. 1, pp. 78–88, Jan. 2006.
- M. Villalva, J. Gazoli, and E. Filho, "Comprehensive Approach to Modeling and Simulation of Photovoltaic Arrays," IEEE Transactions on Power Electronics, vol. 24, no. 5, pp. 1198–1208, May 2009.
- J. Bai, S. Liu, Y. Hao, Z. Zhang, M. Jiang, and Y. Zhang, "Development of a new compound method to extract the five parameters of PV modules," Energy Conversion and Management, vol. 79, pp. 294–303, Mar. 2014.

Single diode model and parameters characterization

To minimize the number of sensors, the irradiance value is calculate by measuring the PV panel short circuit current (I_{sc}) and applying the following approximation:

$$I_{ph} \approx I_{sc}$$

$$G = \frac{I_{sc}}{I_{sc,STC} + \alpha_{I_{sc}} \cdot (T - T_{STC})}$$



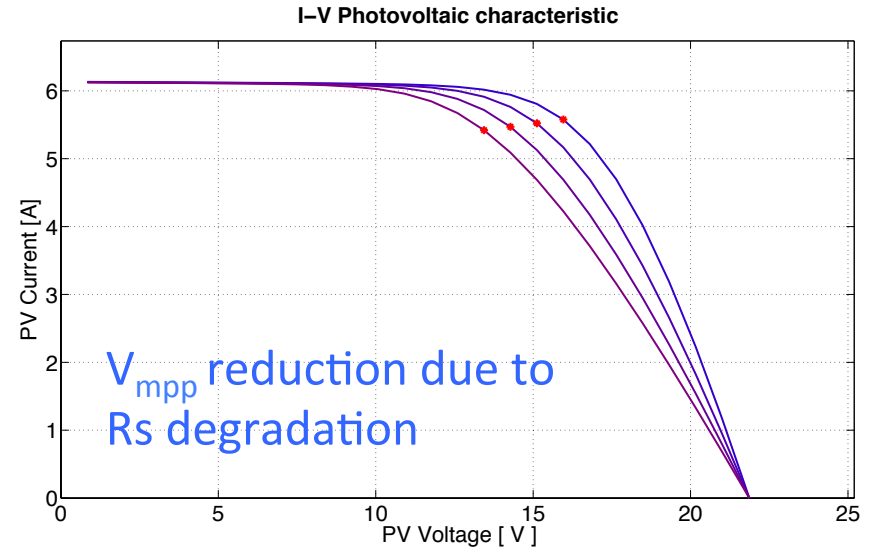
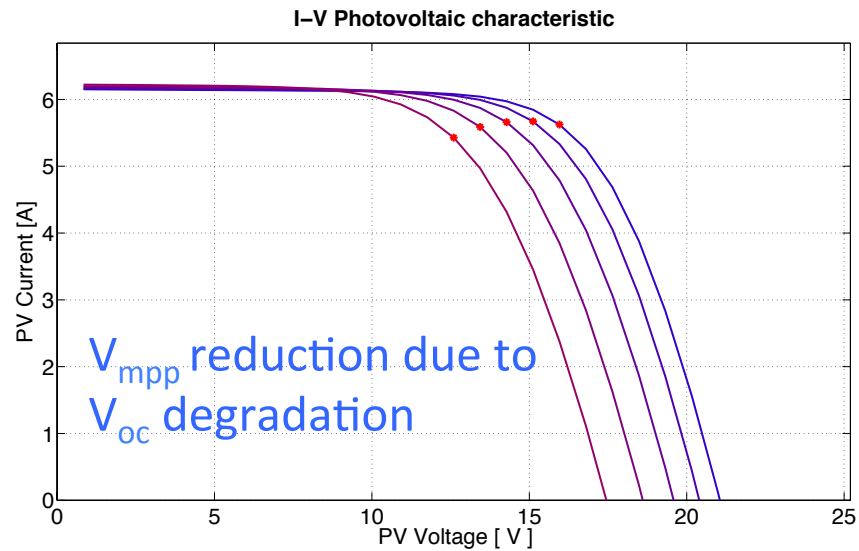
The ambient temperature (T_a) and the cell temperature (T) might be related as follow:

$$T = T_a + \left(\frac{NOCT - 20}{800} \cdot G \right)$$

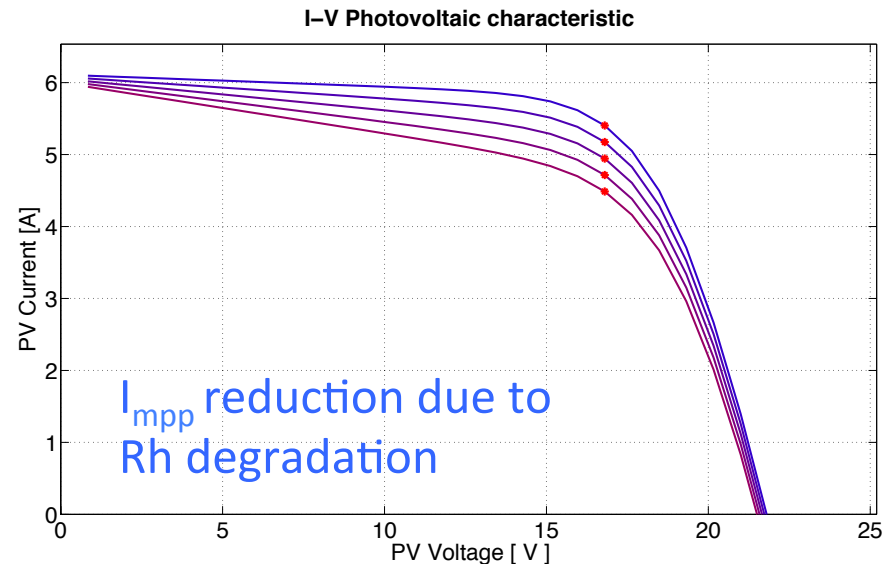
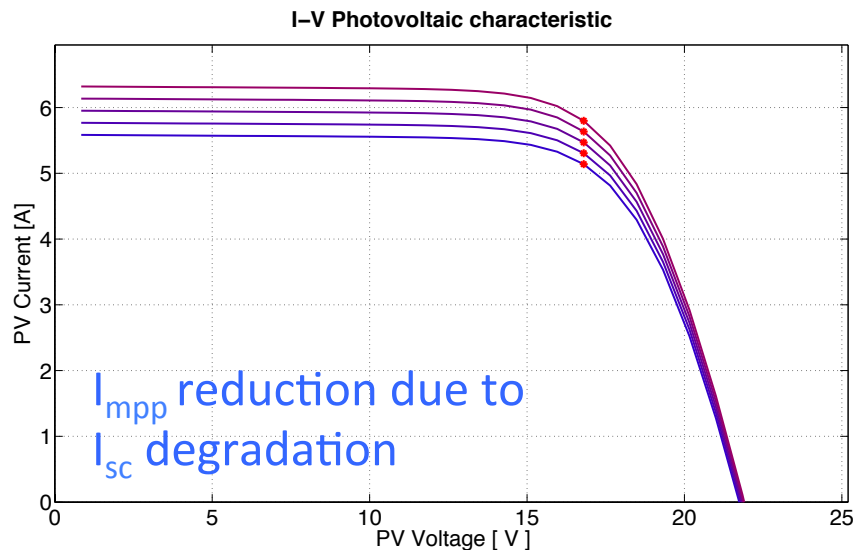
By combining the two equation T is given by solving the following quadratic equation:

$$\alpha_{I_{sc}} T^2 + (I_{ph,STC} - \alpha_{I_{sc}}(T_a + T_{STC})) T - T_a(I_{ph,STC} - \alpha_{I_{sc}} T_{STC}) - I_{ph} G_{STC} \frac{NOCT - 20}{800} = 0$$

Emulating the PV degradation on the single diode model



V_{oc} degradation and R_s increase is reflected in a V_{mpp} drop



I_{sc} degradation and R_h reduction are reflected in a I_{mpp} drop

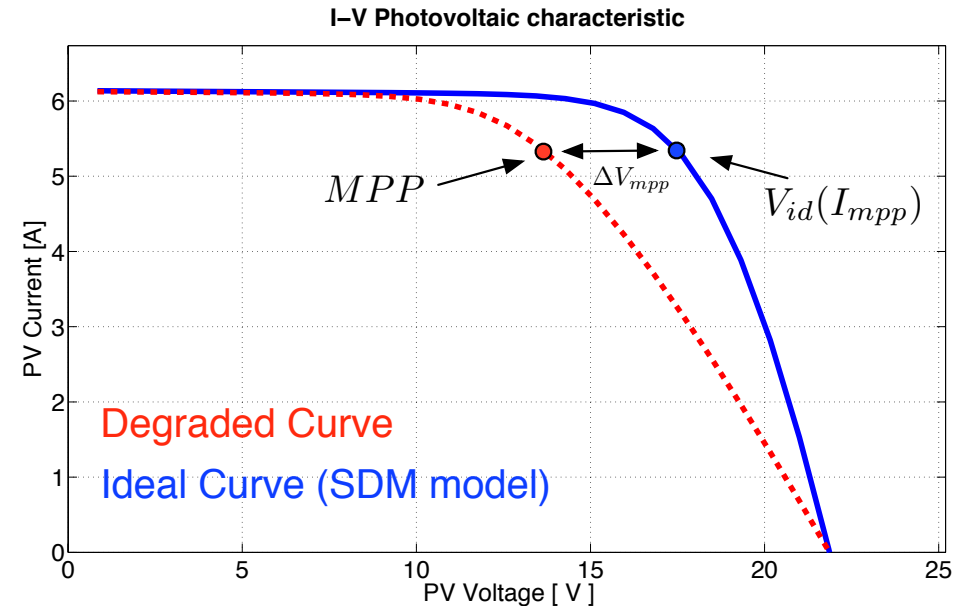
Definition of the ΔR_s indicator

(aimed to estimate the V_{mpp} reduction)

$$\Delta V_{mpp} = V_{id}(I_{mpp}) - V_{mpp}$$

$$\Delta R_s = \frac{\Delta V_{mpp}}{I_{mpp}}$$

$$N \Delta R_s = \frac{\Delta R_s}{R_s}$$

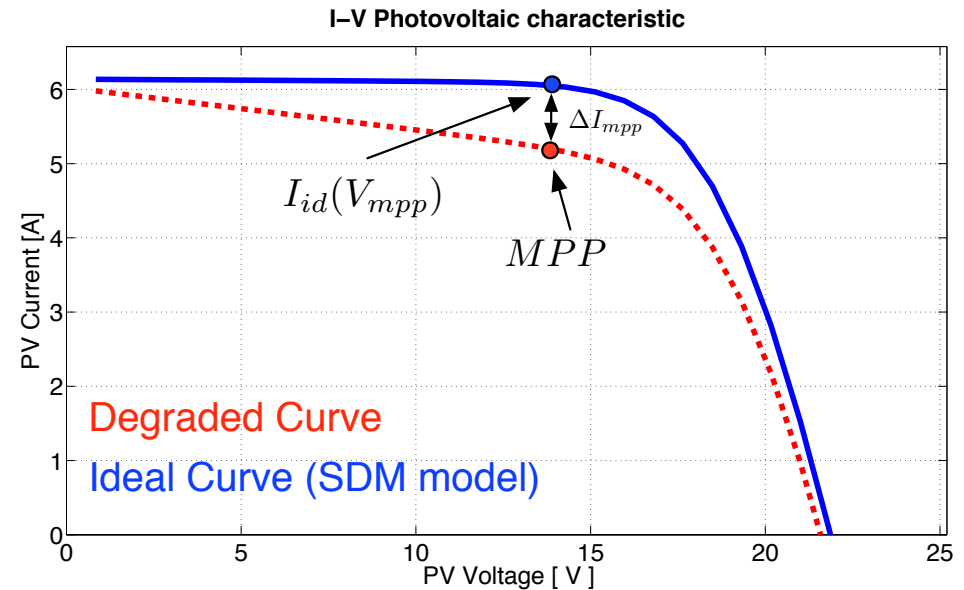


- The V_{mpp} translation in the I-V curve can be related to an additional resistance (ΔR_s) connected in series to R_s that produces the same reduction in V_{mpp} .
- R_s is the series resistance of the module without degradation, thus it is estimated by the SDM model.
- The ideal voltage (V_{id}) is calculated with the SDM model at the measured current I_{mpp} .
- $N\Delta R_s$ is the normalized indicator and give the relative increase of R_s .

Definition of the ΔR_h indicator

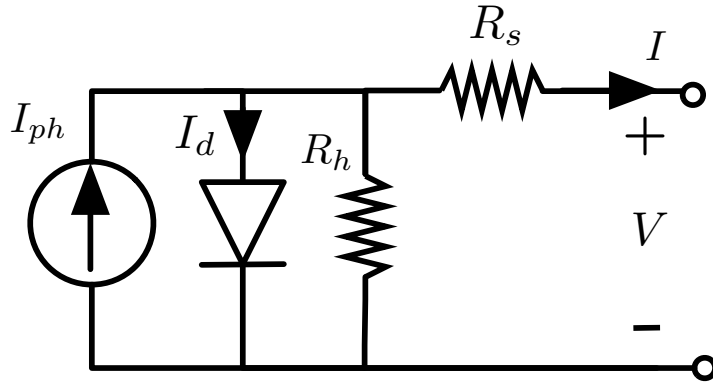
(aimed to estimate the I_{mpp} reduction)

$$\Delta R_h = \frac{V_{mpp}}{I_{id}(V_{mpp}) - I_{mpp}} = \frac{V_{mpp}}{\Delta I_{mpp}}$$
$$N \Delta R_h = \frac{\Delta R_h}{R_h}$$



- The I_{mpp} translation in the I-V curve can be related to an additional resistance (ΔR_h) connected in parallel to R_h that produces the same reduction in I_{mpp} .
- R_h is the parallel resistance of the module without degradation, thus it is estimated by the SDM model.
- The ideal current (I_{id}) is calculated with the SDM model at the measured voltage V_{mpp} .
- $N\Delta R_h$ is the normalized indicator and give the relative increase of R_h .

Explicit solution for the single diode model equation



Lambert W is solution of:
 $\theta = \sigma \cdot e^\sigma$
 $\sigma = W(\theta)$

$$I = I_{ph} - I_{sat} \left(e^{\left(\frac{V + R_s \cdot I}{\eta V_t} \right)} - 1 \right) - \frac{V + R_s \cdot I}{R_h}$$

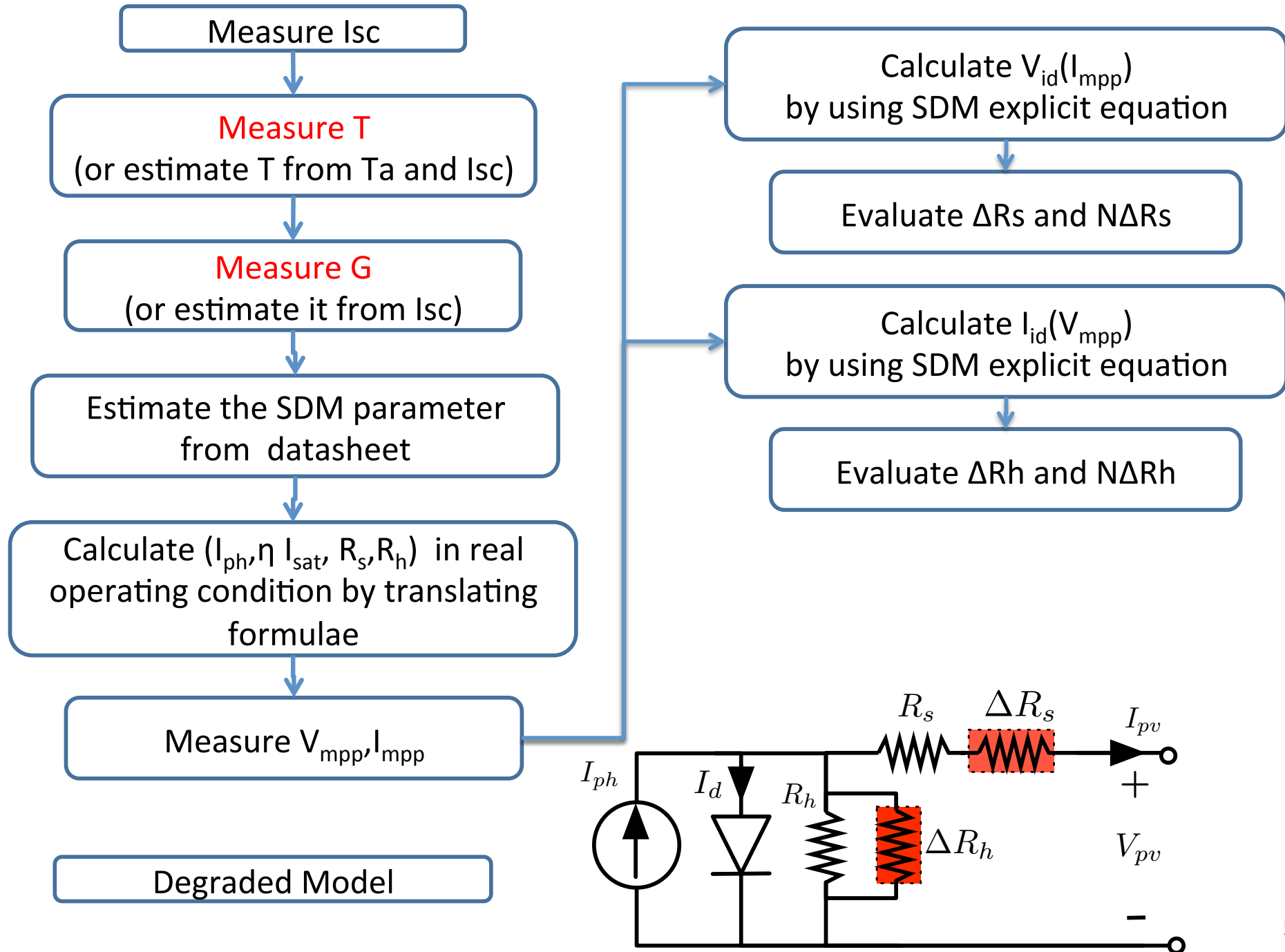
The SDM transcendental equation can be expressed in explicit form by using the **Lambert W function**.
 The W function can be solved numerically with a **simple C code or Look-Up Table**, thus its implementation on embedded system is assured

$$I = I(V) = \frac{R_h \cdot (I_{ph} + I_{sat}) - V}{R_s + R_h} - \frac{\eta \cdot V_t}{R_s} \cdot W(\theta_I)$$

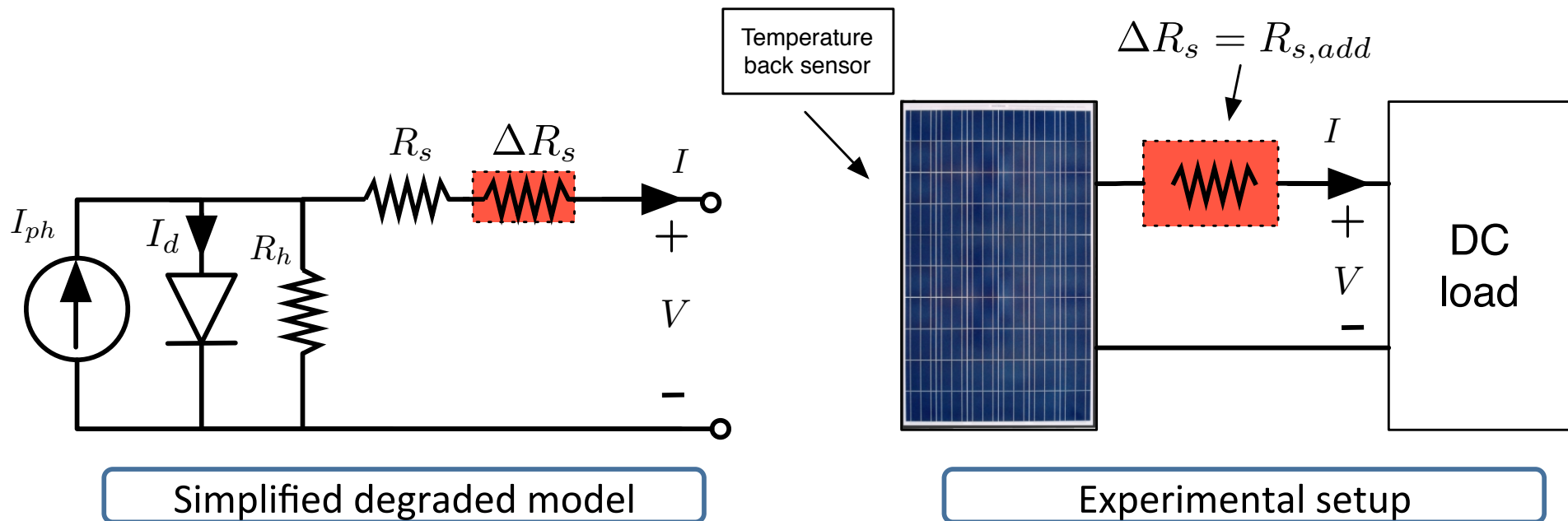
$$V = V(I) = R_h(I + I_{sat}) - (R_h + R_s)I - \eta \cdot V_t \cdot W(\theta_V)$$

$$\theta_I = \frac{(R_h // R_s) \cdot I_{sat} \cdot e^{\frac{R_h \cdot R_s \cdot (I_{ph} + I_{sat}) + R_h \cdot V_{pv}}{\eta \cdot V_t \cdot (R_h + R_s)}}}{\eta \cdot V_t} \quad \theta_V = \frac{R_h \cdot I_{sat} \cdot e^{\frac{R_h \cdot (I_{ph} + I_{sat}) - I_{pv}}{\eta \cdot V_t}}}{\eta \cdot V_t}$$

Calculation of ΔR_s & ΔR_h indicators



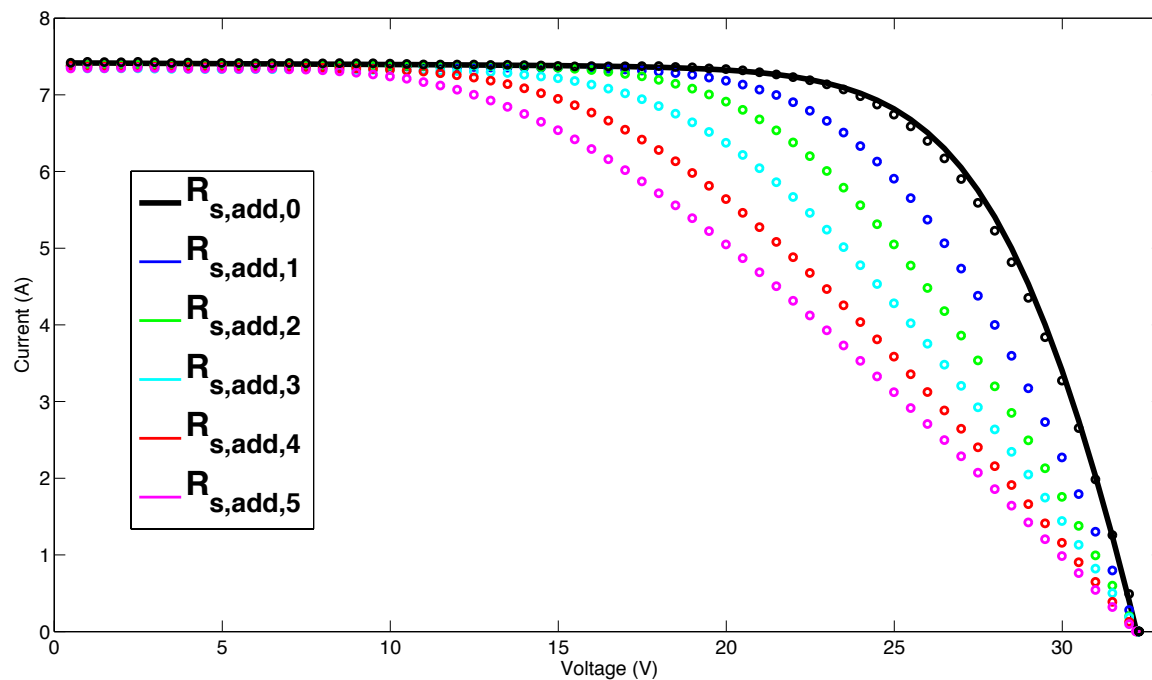
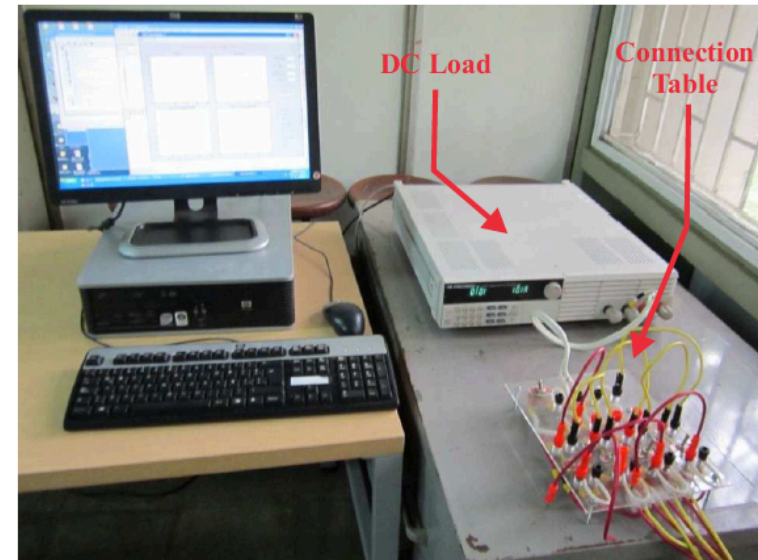
Experimental validation of the ΔR_s indicator



- A series resistance ($R_{s,add}$) in series with the PV panel emulates the R_s degradation effect.
- The validation is performed by comparing the ΔR_s indicator calculated with the experimental data with the one obtained by using the SDM model in different operative environmental condition.

Experiments @ Universidad del Valle

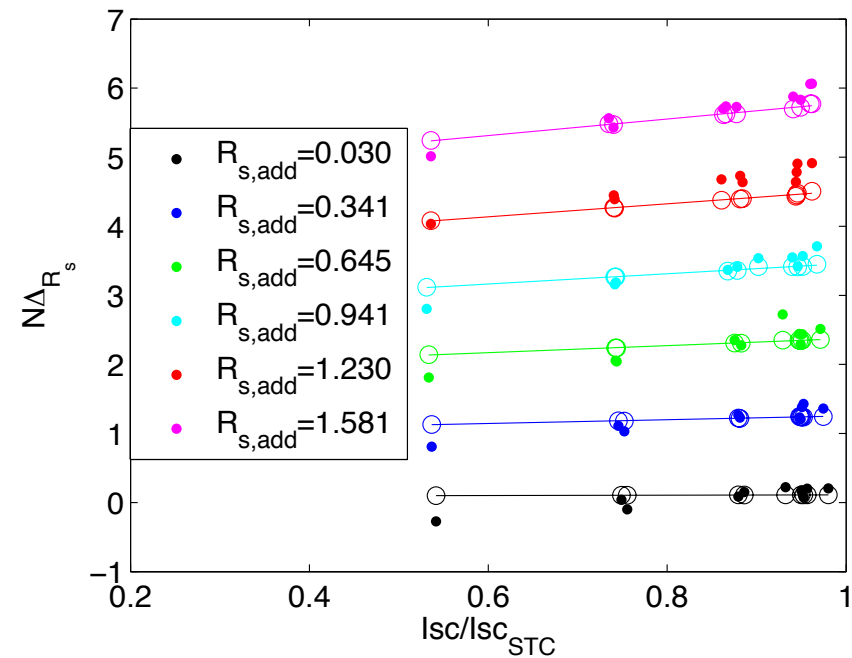
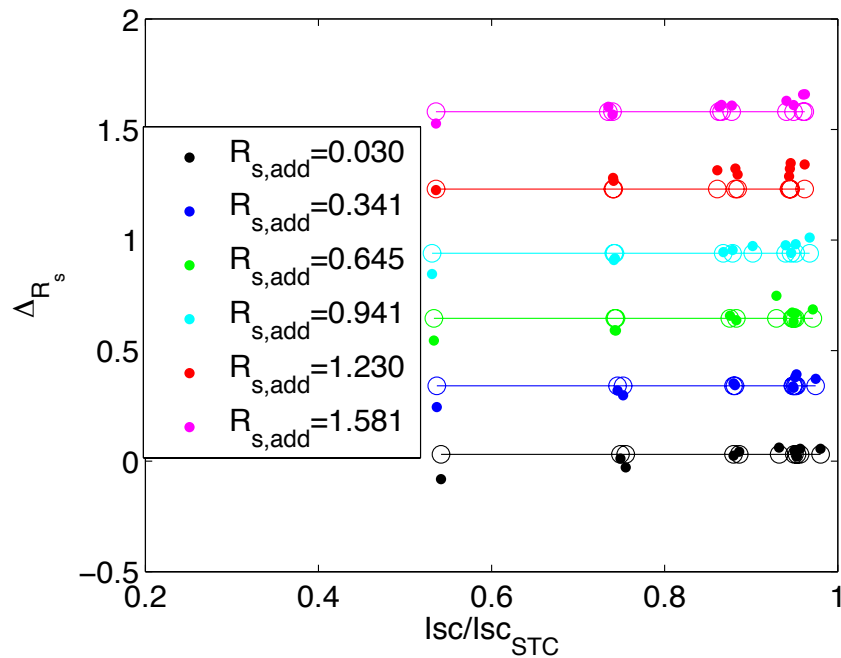
External R_s	Value (Ω)	$(R_{s,add}) / (R_{s,STC})$
$R_{s,add,0}$	0.061	0.252
$R_{s,add,1}$	0.371	1.531
$R_{s,add,2}$	0.676	2.789
$R_{s,add,3}$	0.971	4.006
$R_{s,add,4}$	1.261	5.202
$R_{s,add,5}$	1.611	6.646



Laboratory test on a new panel:
Trina TSM-PC05

The SDM (black line) matches with the experimental data of the PV panel with $R_{s,add,0}$.

ΔR_s and $N\Delta R_s$ indicators for Trina TSM-PC05

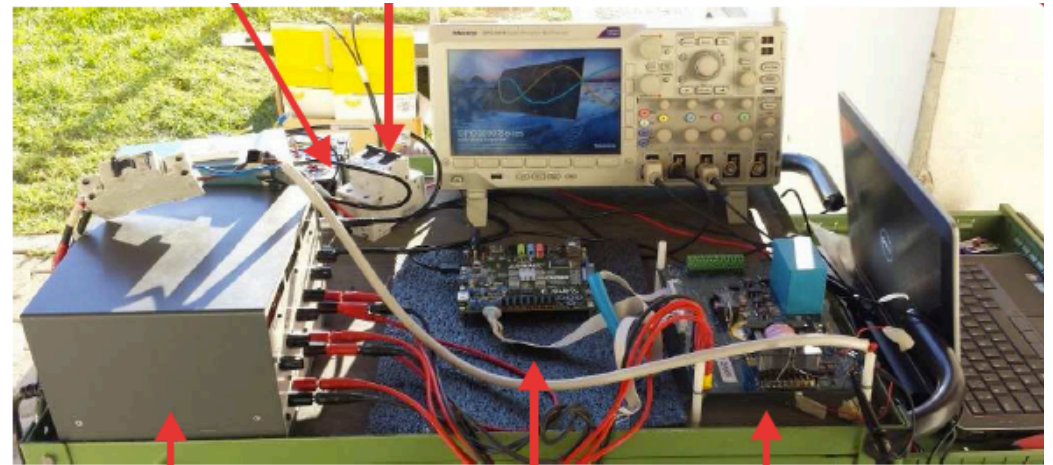


- The two indicators have been evaluated in ten different operating conditions by considering the six additional resistance shown in previous table
- Dots are the values of the indicators evaluated by using the experimental data.
- Circles are the same indicators calculated by using the I-V curves generated with the SDM and used as references.
- The SDM includes the known value of the additional series resistance ($R_{s,add}$) and the series resistance of the module without degradation (R_s)
- Continuous lines represent the trend of the reference values.

The proposed indicators are able to detect and quantify the degradation accurately. The two indicators are almost insensible to the irradiance and temperature variation.

Experiments @ Unisa on Kyocera KC 120

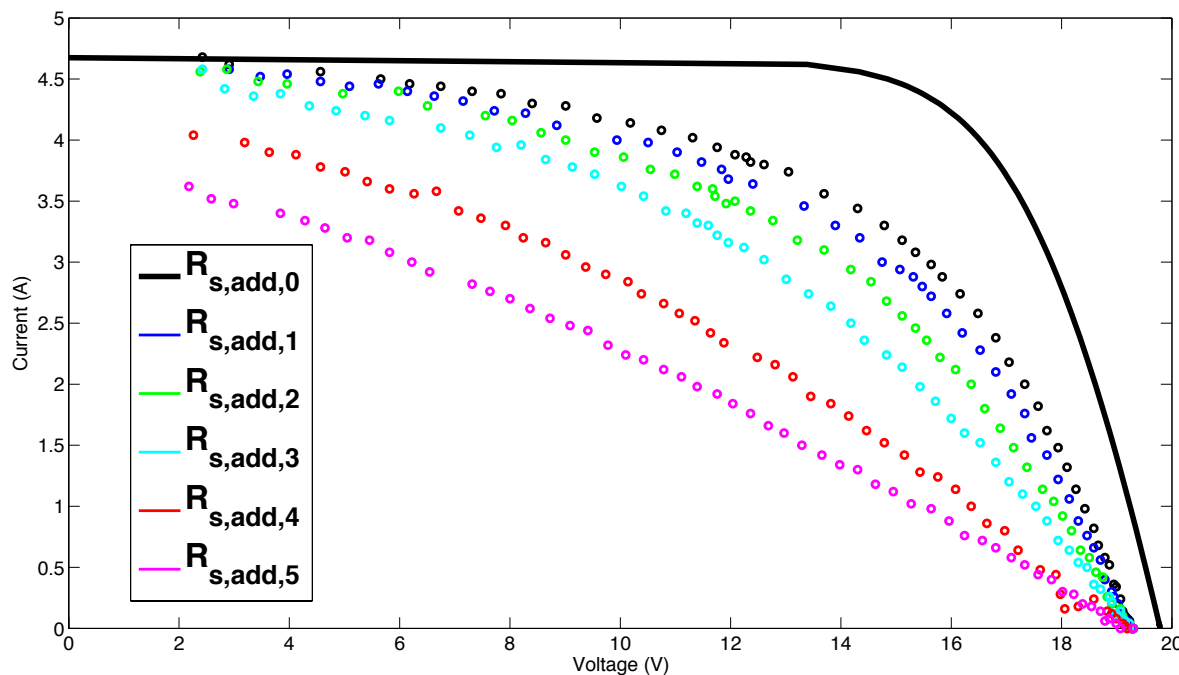
External R_s	Value (Ω)	$(R_{s,add}) / (R_{s,STC})$
$R_{s,add,0}$	0.022	0.091
$R_{s,add,1}$	0.168	0.693
$R_{s,add,2}$	0.517	2.133
$R_{s,add,3}$	1.013	4.179
$R_{s,add,4}$	2.028	8.366
$R_{s,add,5}$	3.000	12.376



DC power supply

FPGA

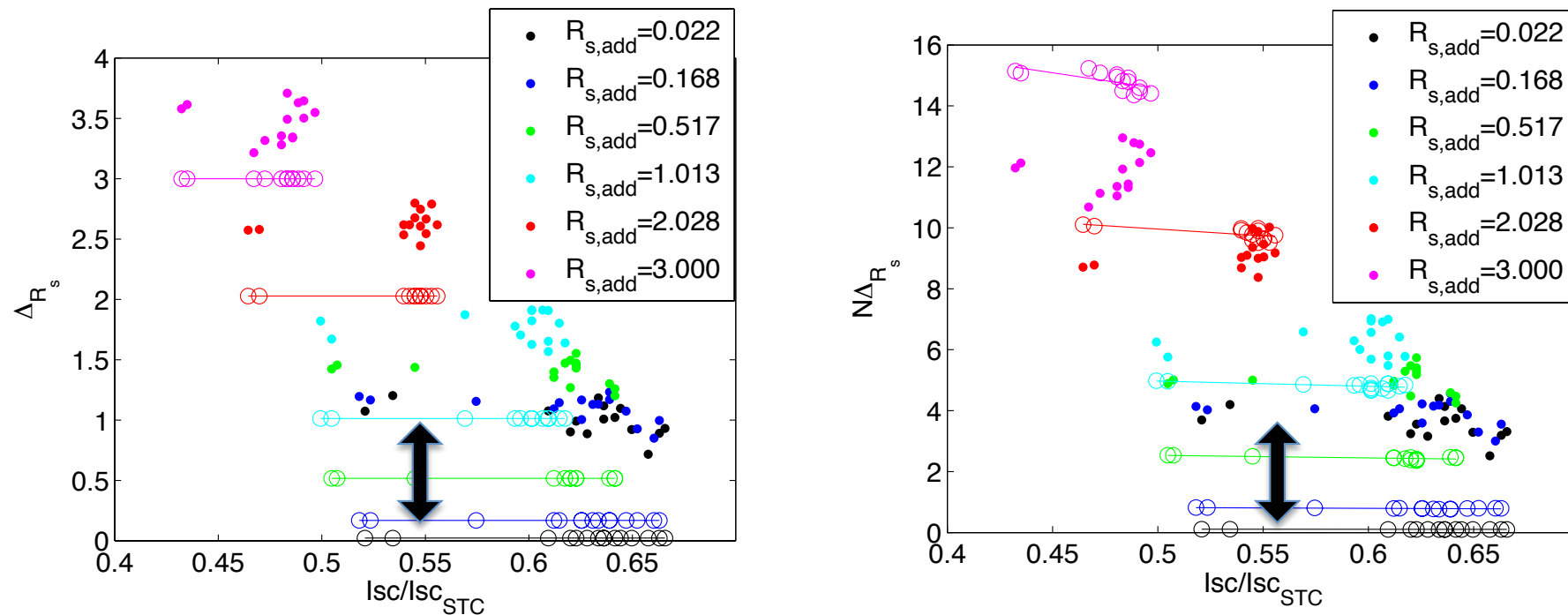
Power Converter



Test performed by using an embedded system on a ten year old PV panel: Kyocera KC-120

- A significant voltage difference between the SDM (black line) and the experimental data with $R_{s,add,0}$
- It is expected that the ΔR_s indicator predicts the degradation due to the ten year aging.

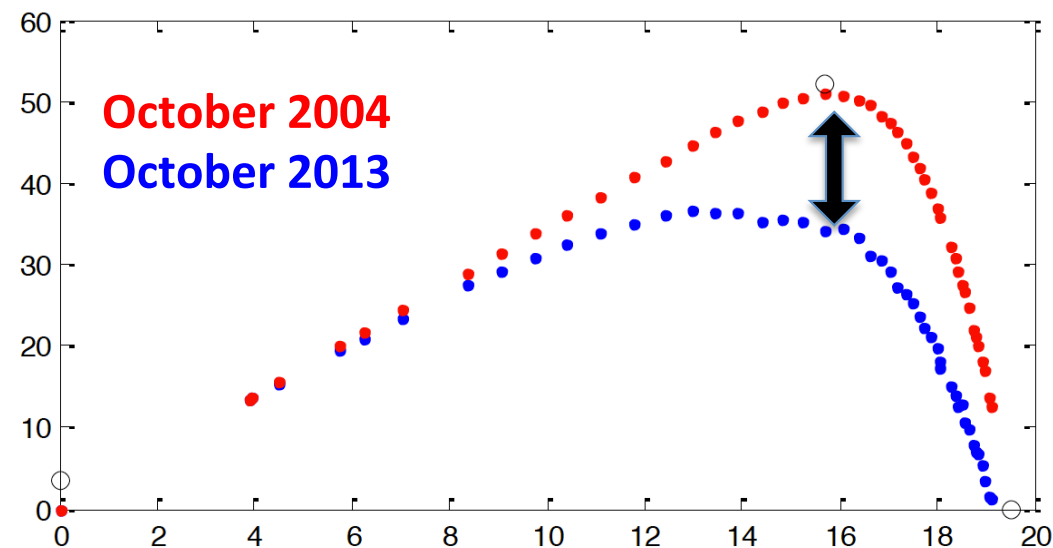
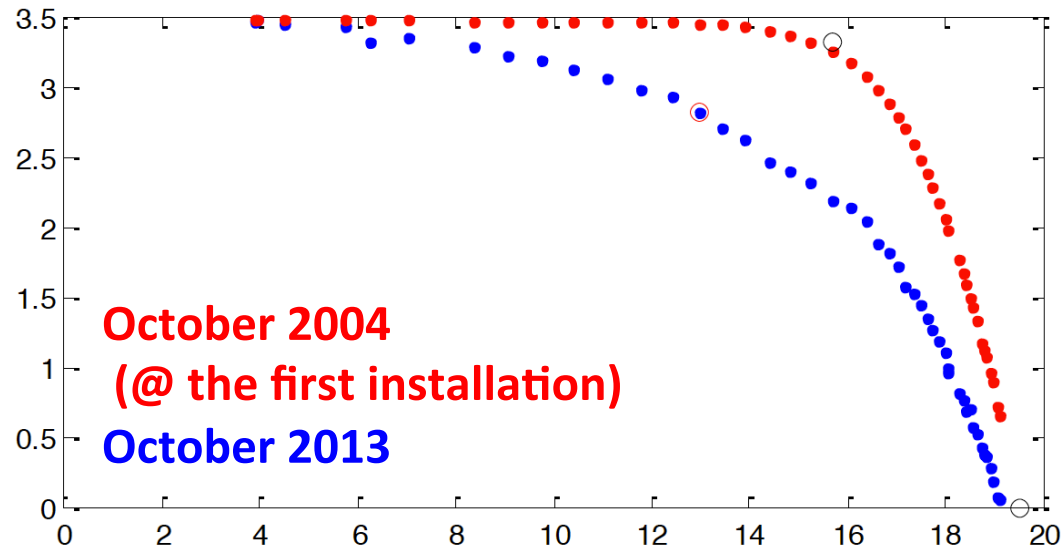
ΔR_s and $N\Delta R_s$ indicators for Kyocera KC-120 (10 years old)



- The experimental data are less stable due to the low cost sensors and switching noise appearing on the embedded system.
- The distance between circles and dots of the same color indicates **the PV degradation** of the series resistance due to the 10 years aging.
- The aging is the difference between the black dots and circles ($R_{s,add}=0$)

The proposed indicators are able to detect a PV degradation without any preceding experimental data, this because it uses as reference the SDM model.
The accuracy on the measures and noise do not affect significantly the diagnosis results

Experiments @ Unisa on Kyocera KC 120



- The ΔR_s indicator allows to quantify the PV power degradation without any experimental data on the new panel

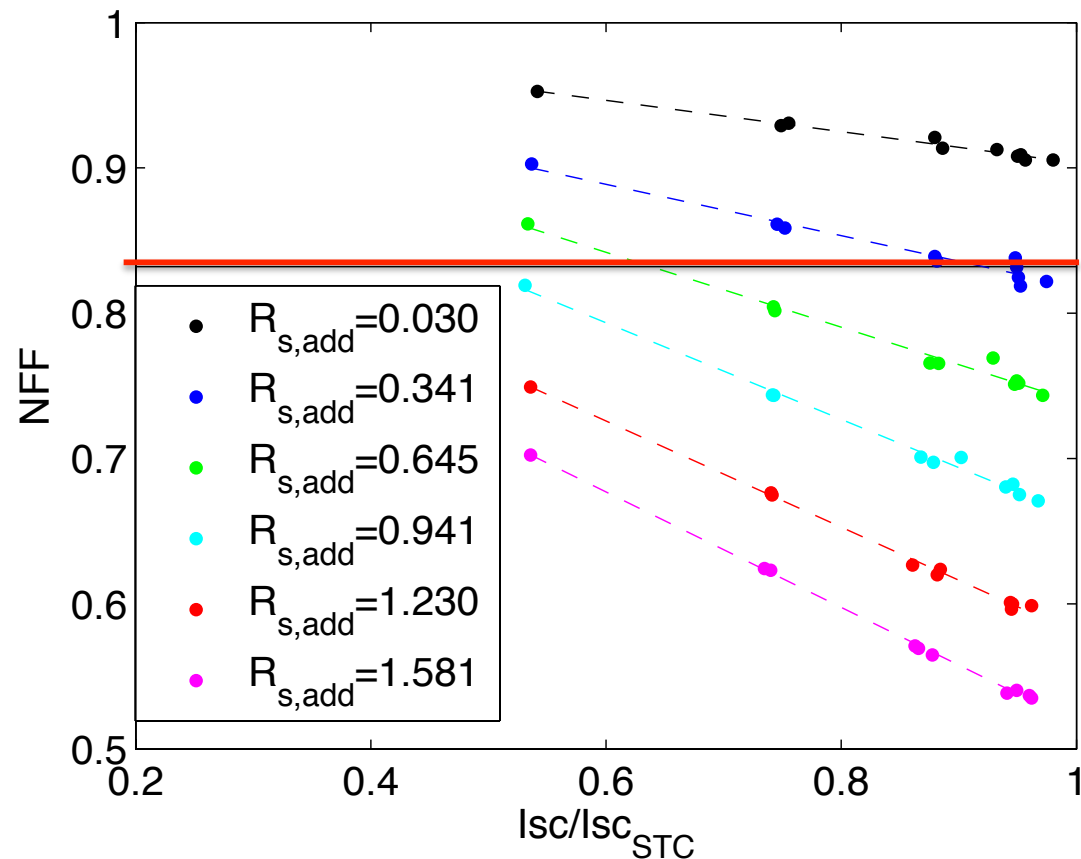
Performance analysis of proposed indicators vs. existing indicators

- Three indicators taken from the literature have been tested by using the same experimental data collected in the previous tests:
 1. Normalized Fill Factor
 2. R_s calculated @ V_{oc}
 3. R_s calculated close to MPP

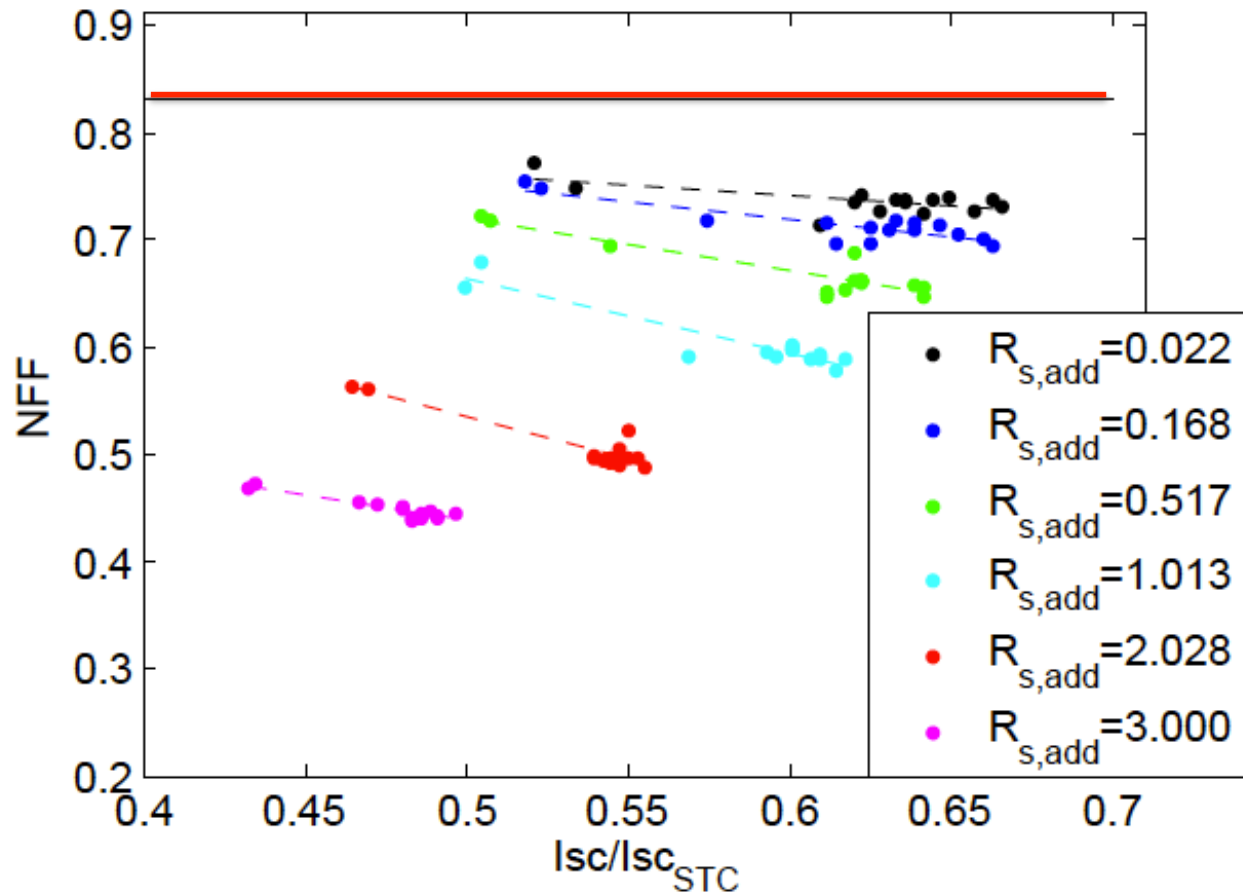
Normalized Fill Factor for Trina TSM-PC05

- The **red line** represents the NFF threshold ($NFF_{th} = 0.832$)
- In this example the NFF_{th} is the minimum value calculated by simulating the single-diode model without degradation in different environmental condition

- Same value of NFF for different degradation condition (temperature and I_{sc} dependency)
- Only a deep degradation can be detected easily.
- NFF is strongly sensible to the irradiance



Normalized Fill Factor for Kyocera KC-120

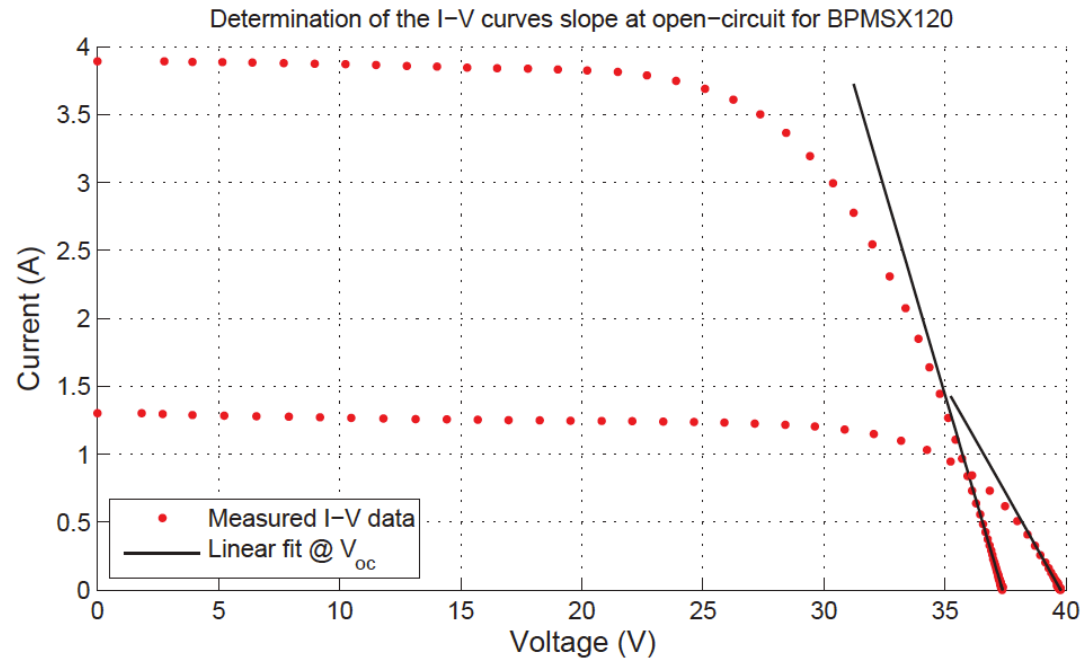


- The ten years exposure to weathering produced a very large PV degradation, thus the NFF allows to predict it.
- However the black dots are close to the reference threshold thus a reliable identification of the PV degradation is not always assured.

Rs estimated @ Voc (Method-Sera1)

$$R_{s,e} = -\left. \frac{dV}{dI} \right|_{V \approx V_{oc}} = -\left. \frac{V_2 - V_1}{I_2 - I_1} \right|_{V \approx V_{oc}}$$
$$R_{s,1} = R_{s,e} + \frac{V_t}{I_{sc}} \cdot \left(\frac{G}{G_{STC}} \cdot \frac{T_{STC}}{T} - 1 \right)$$

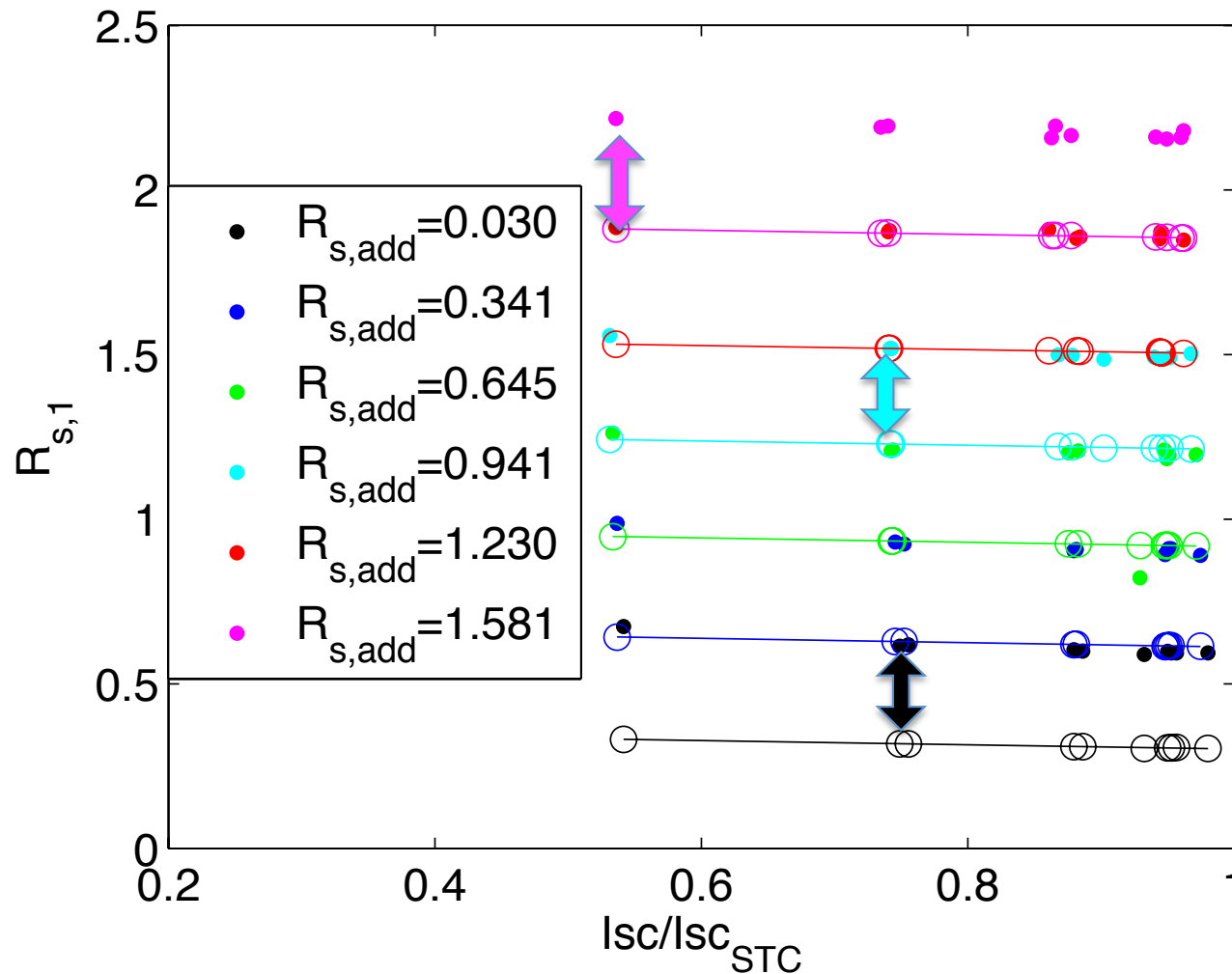
It is suggested to choice $V_2 - V_1 = 1$



The evaluation of $R_{s,1}$ requires:

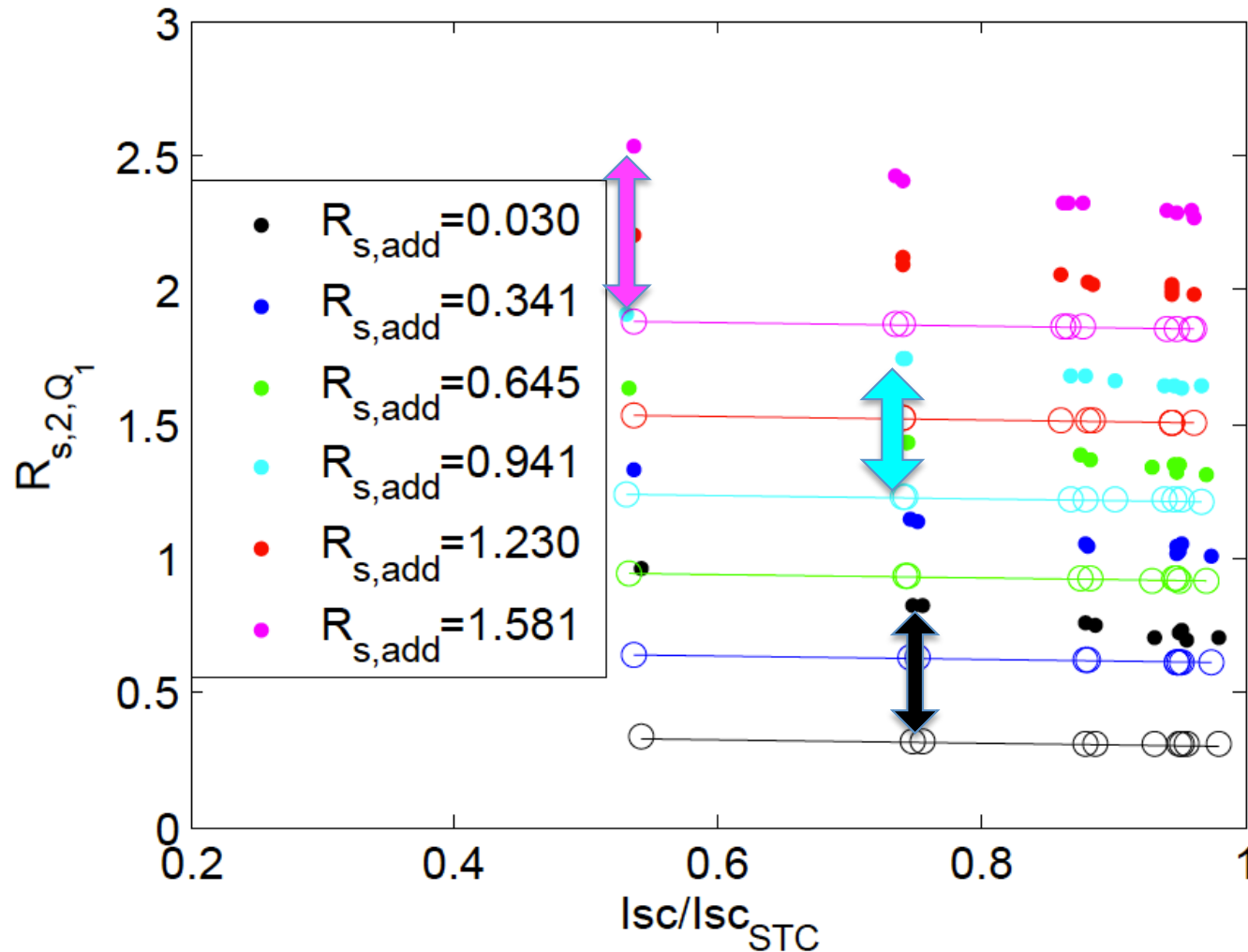
- voltage and current measurements of at least two points of the I-V curve close to V_{oc} to calculate $dV=dI$ as a discrete derivative.
- irradiance and temperature sensors (or estimated by means other methods) to perform the translation of the estimated series resistance.

Method-Sera1 applied to Trina TSM-PC05



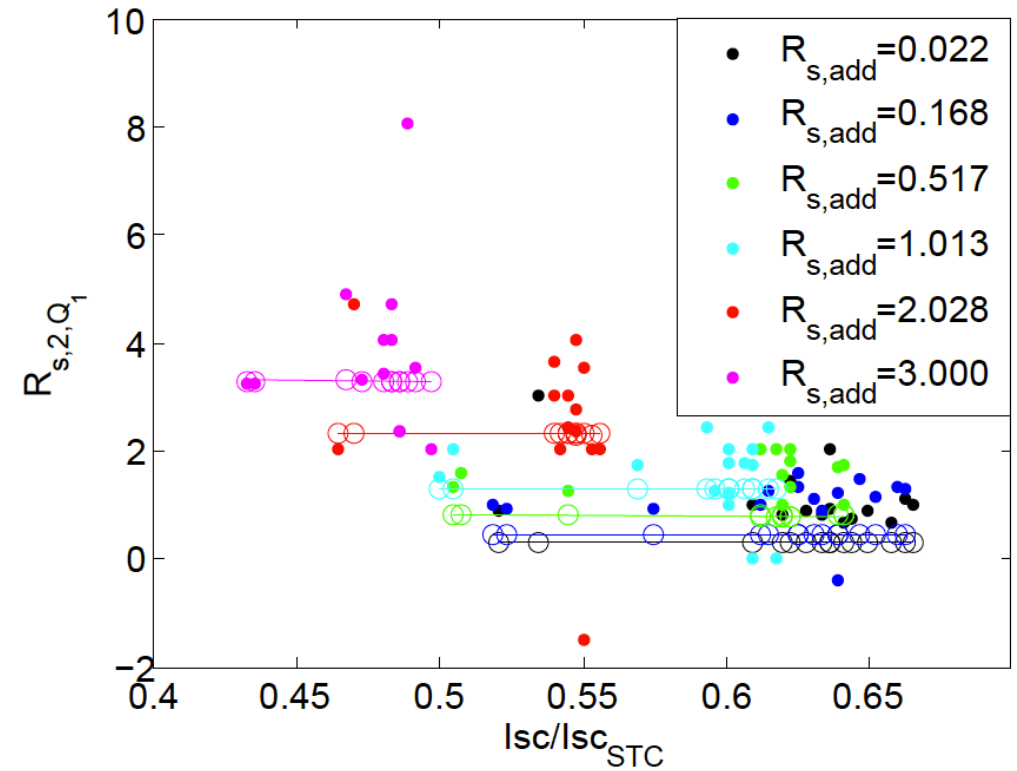
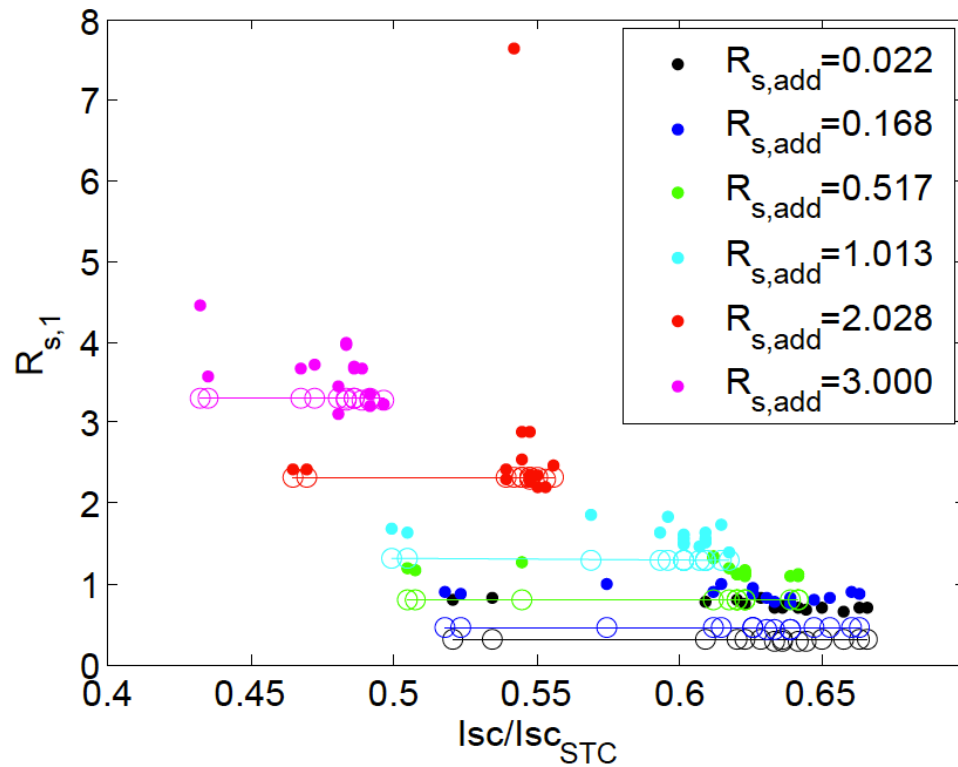
- The distance between circles and dots of the same color indicates **wrong estimation** of the series resistance.
- The R_s overestimation may produce wrong predictions of PV degradation
- The error is directly proportional to $R_{s,add}$ and almost independent with Irradiance and temperature.

Method-Sera2 applied to Trina TSM-PC05



- Significant R_s overestimation, 3-4 times the real value
- Less precise than Method-Sera1
- More sensible to the irradiance value

Sera's Methods applied to Kyocera KC-120



- There is no significant distance between circles and dots of the same color, this means that both methods are not able to distinguish the pre-existing PV degradation due to the aging

Summary

- The **new indicators** allow to estimate the PV degradation phenomenon affecting the V_{mpp} and I_{mpp} separately.
- Experimental results for ΔR s and $N\Delta R$ s shown that:
 - they are almost insensible to the weather condition thus the diagnosis can be performed in a wide range of the irradiance and temperature conditions.
 - they are able to detect the degradation on old PV panel without any preceding experimental data, this because they use as reference the SDM model.
 - the accuracy of the measures and noise do not affect significantly the diagnosis results
- Similar considerations are valid for ΔR_h and $N\Delta R_h$ but not yet verified experimentally.
- **Main drawbacks:**
 - Needs to measure the module temperature (or ambient temperature)
 - Needs to measure I_{sc} thus the operating point is periodically moved far from the MPP

Summary

- The proposed indicators have been compared with three existing methods taken from the literature. The latter show lower performances:
 - they are more sensitive to the irradiance condition
 - in some cases give a **wrong estimation** of the PV degradation because of R_s is overestimated.
 - no reliable information can be extracted on the old PV panel (an experimental reference value for the not degraded PV panel is required).
- The by-pass diagnosis has been not yet afforded



Thank you for your
attention !!!!