Fault diagnosis in PV plants with monitoring data

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Some Premises

The IEC 61724-1 standard defines monitoring system classes, measurement accuracy, and performance assessment of PV systems; it does not provide detailed fault protocols but…

- *'For detecting and localizing faults there should be greater resolution at sub-levels of the system and an emphasis on measurement repeatability and correlation metrics'* ->

….it highlights the importance of **high-resolution, repeatable measurements** to support fault localization

NO DATA NO FAULT DIAGNOSIS

In this study, diagnosis in PV monitoring refers to the identification and characterization of the fault type through the interpretation of patterns and correlations among monitored parameters.

PV DIAGNOSIS GOES BEYOND DETECTING ANOMALIES — IT EXPLAINS THE FAULT BEHIND THEM.

The goal is **not to replace field inspections or safety systems**, but to complement them — **supporting O&M with faster and more informed fault diagnosis.**

Why Fault Diagnosis from Monitoring Data Matters

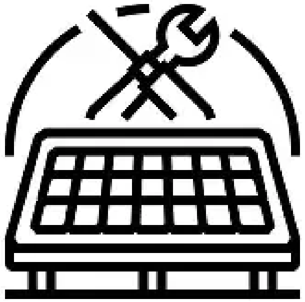
Managing large PV portfolios requires moving from data collection to intelligent diagnosis.

Main drivers/challenges

- Rapid expansion of large PV portfolios -> **thousands of assets to supervise**
- Massive volume of data calls for **automated and time-efficient analysis methods**

Goals to be achieved

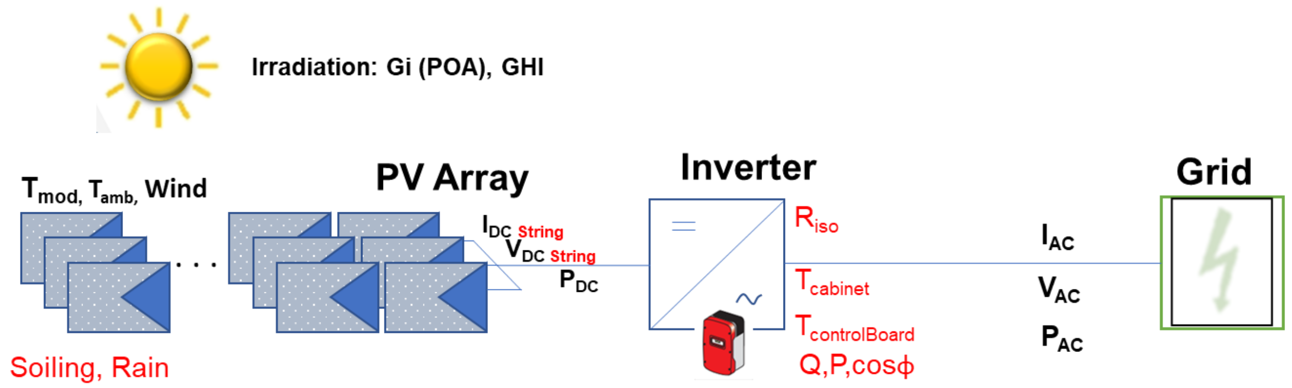
- **Reduce O&M costs and downtime** through early fault detection and accurate diagnosis
- **Ensure long-term reliability** of PV assets and support **predictive maintenance strategies**
- Leverage **digitalisation and automation** as key enablers of scalable and intelligent PV fleet management



Challenges in PV Fault Diagnosis Using Monitoring Data

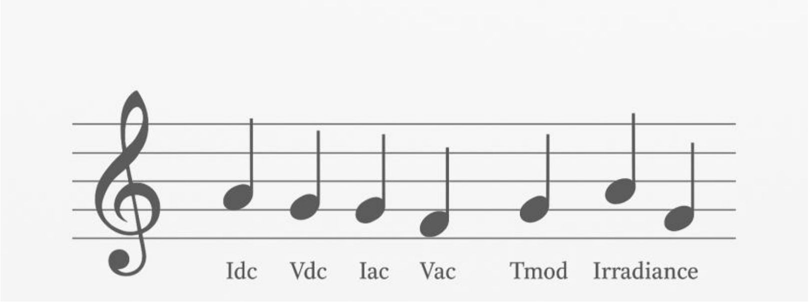
PV monitoring systems typically provide:

Irradiance (G), module temperature (Tmod), **DC current (Idc), DC voltage (Vdc),** AC current (Iac), and AC voltage (Vac).



Identifying the fault type only through data can be challenging, particularly when different effects occur simultaneously.

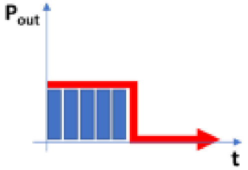
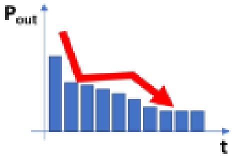
But… it is like playing a concert with just seven musical notes — limited, yet full of hidden potential when interpreted correctly.



Understanding Fault Behavior in PV Systems

Each fault type exhibits a characteristic temporal pattern depending on its causes and operating conditions.

Temporal Charachteristics

Performance characteristics	Permanent Faults	Intermittent Faults	Incipient Faults
Acute Faults $P_{out\ Inv.} \sim 0$ 	Line – to - Line Ground Fault Open circuit Electric Arc	Low insulation Resistance	
Critical Faults $P_{out\ Inv.} \sim -[\%]$ 	Bypass diode fault Damaged Jbox Hotspot Low insulation Resistance Broken Module Inverter OverHeating	Shading and partial shading Bird dropping Snow Soiling	Degradation (PID, LeTid,LID) Contact Corrosion Partially damaged connectors

FAULT CLINICAL PROFILE

The characteristics of a fault can therefore determine and suggest the most **appropriate diagnostic approach** and **the parameters** to be observed.

FAULT

Analysis Windows
Time window used for diagnostic computation

Observed Parameters
Aggregated KPIs within the window: e.g., ΔP, ΔV, I_ratio, modTemp, G_PoA

Baseline
Reference to the baseline or normal condition for comparison

temporalPattern
Temporal behavior of the fault with support metrics (number of events, average duration, period in which it happens)

component
Type of asset where the fault occurs

OperatingRegime
Irradiance level, tracker pose, modTemp

faultClass
Fault class detected: openCircuit, mismatch, thermalDerating, unstableMPPT, soiling, Shading, other

performanceSeverity
Severity calculated from relative performance and economic loss: high, medium, low

RSE's PV Fault Facility in Milan, Italy[3]

An experimental setup to generate PV datasets with appropriately labeled failure events for training and validation of ML algorithms.

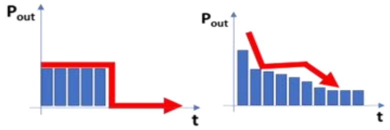
BENEFITS

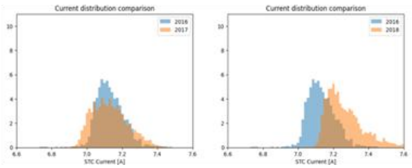
- Controlled **fault replication**.
- **Offer large data sets of labeled PV** failures
- **Training and validation for AI-based diagnosis**

Facility Guasti FV

PV DataLake

PV fault characterizzation

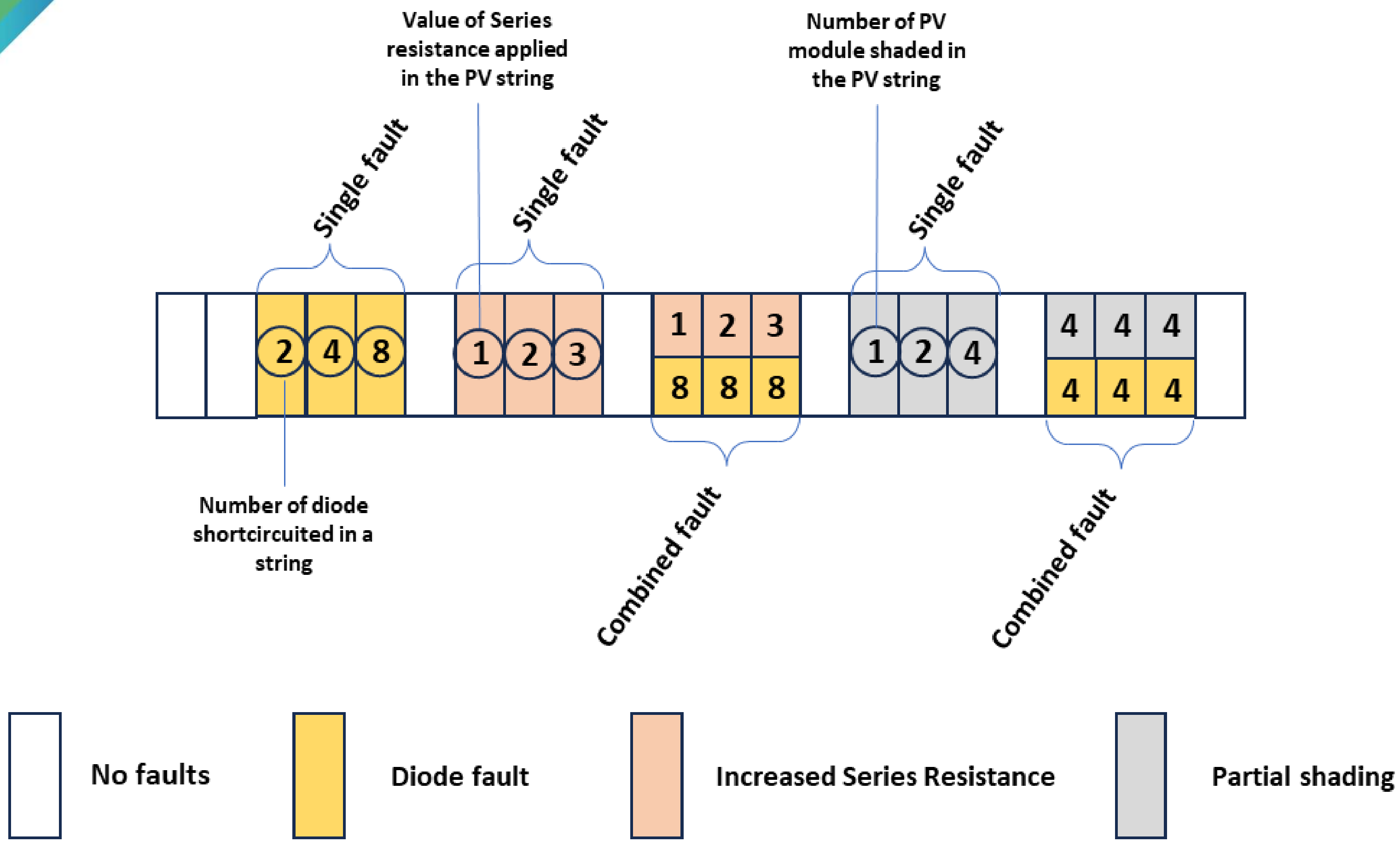




PV fault detection and diagnosis models

[3] G. Maugeri, et. al, "A Facility Test to Generate Data from Real PV Systems Affected by Faults," in WCPEC-8, the 8th World Conference on Photovoltaic, Milan, Italy, 2022.

Failure mode implementation: scheduling



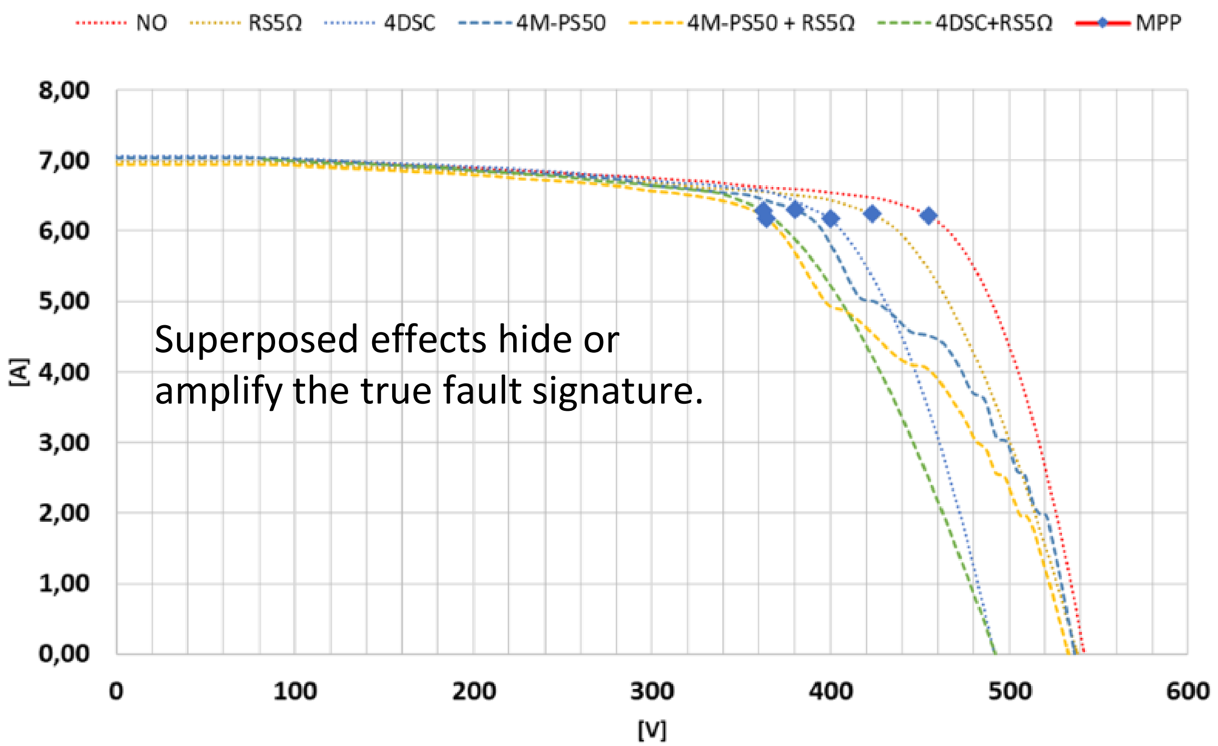
Fault datasets were generated according to a specific testing program.

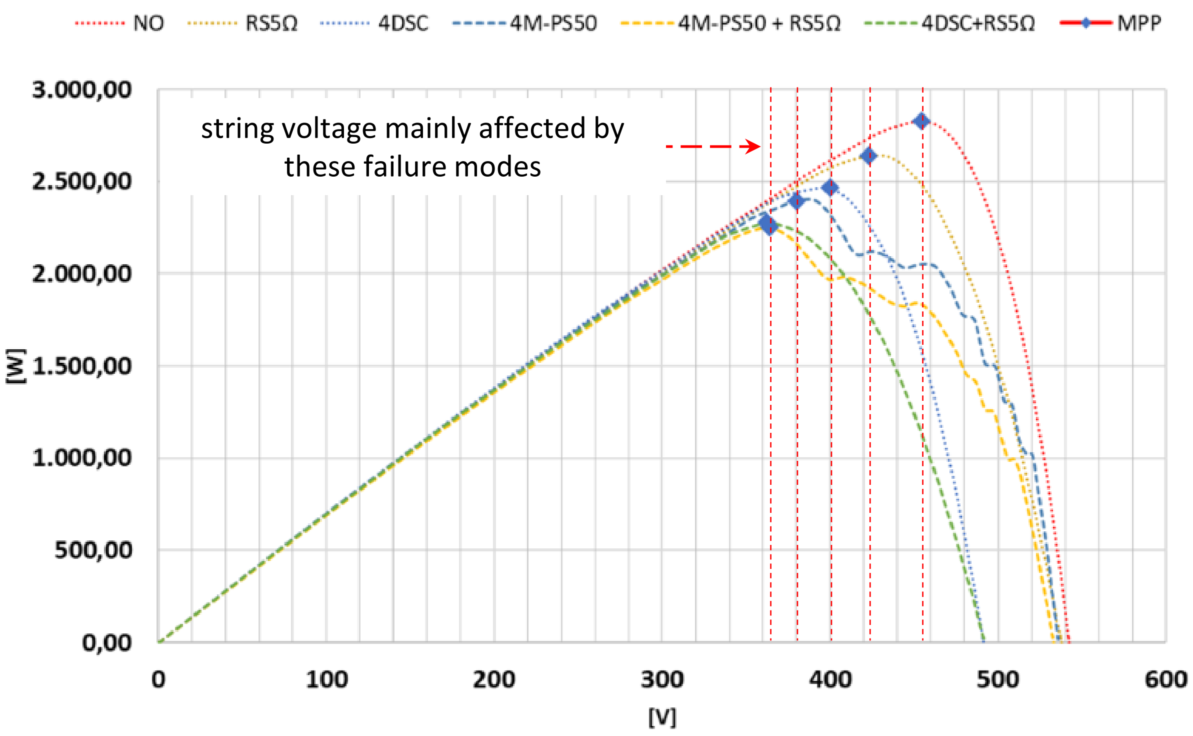
- periods **free of faults**, with **single faults** and **combined faults**
- for each implemented failure mode, field measurements were **conducted**

WARNING!! In real PV plants, multiple faults often overlap, creating diagnostic ambiguity where symptoms interact non-linearly!

Experimental Setup and Failure characterizzation

Series Resistance (RS), shorted BP Diodes (DSC), Partial Shading (PS)





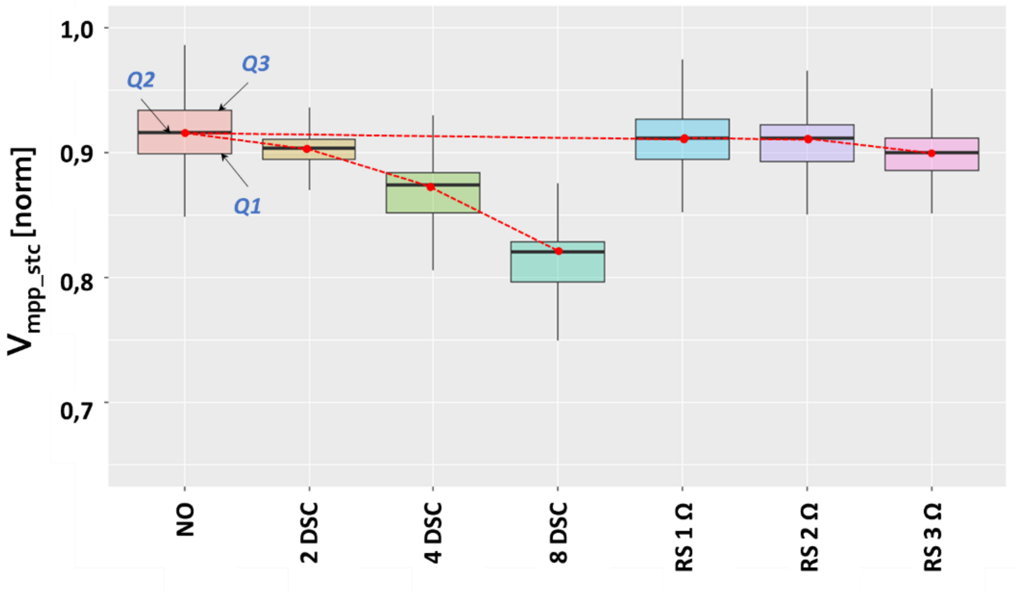
NO	Normal Operation	**4M-PS50 + RS5Ω**	Four PV modules partially shaded, with 50% of the cell area shaded at the bottom of each module, combined with a string series resistance of 5 Ω
RS5Ω	String Series Resistance 5 Ω		
4DSC	Four bypass diode shorted in the PV string	**4DSC + RS5Ω**	Four bypass diodes short-circuited in the PV string combined with a string series resistance of 5 Ω
4M-PS50	Four PV modules partially shaded, with 50% of the cell area shaded at the bottom of each module	**MPP**	Maximum Power Point of the curve

Use of Early-Morning Voltage

Defining $V_{*oc,meas}$, daily measured by SCADA

- temperature-corrected voltage (V_{MPP_STC})
- low string DC current values (I_{dc}<<0,5 A)
- solar irradiance values are between 10 and 100 W/m²

Analysing String Voltage @ MPP in the presence of bypass diode failure and string series resistance increase



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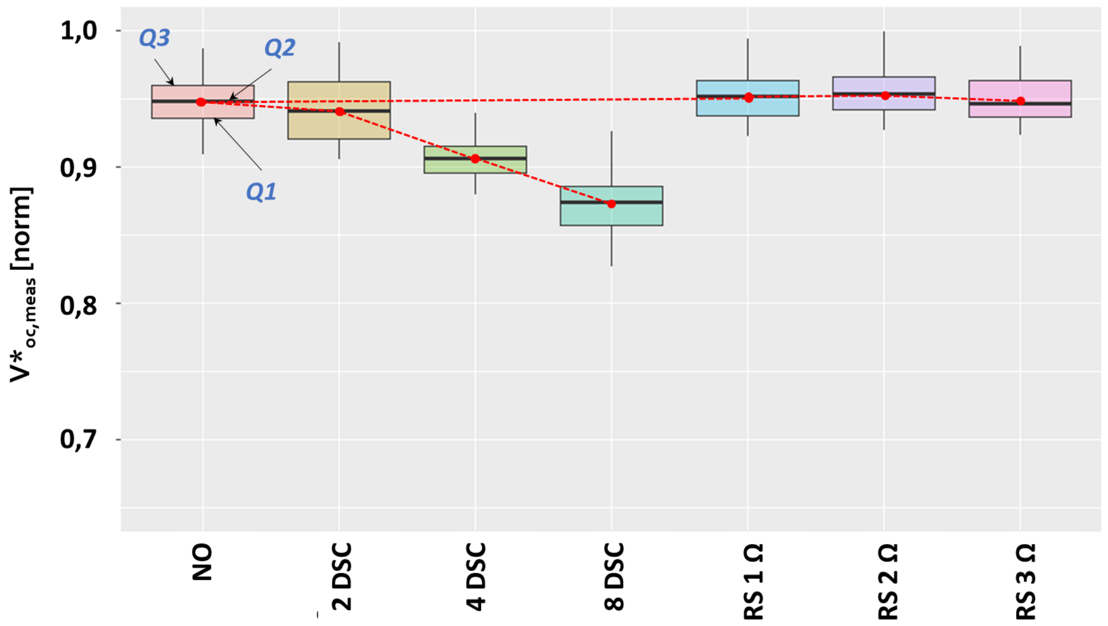

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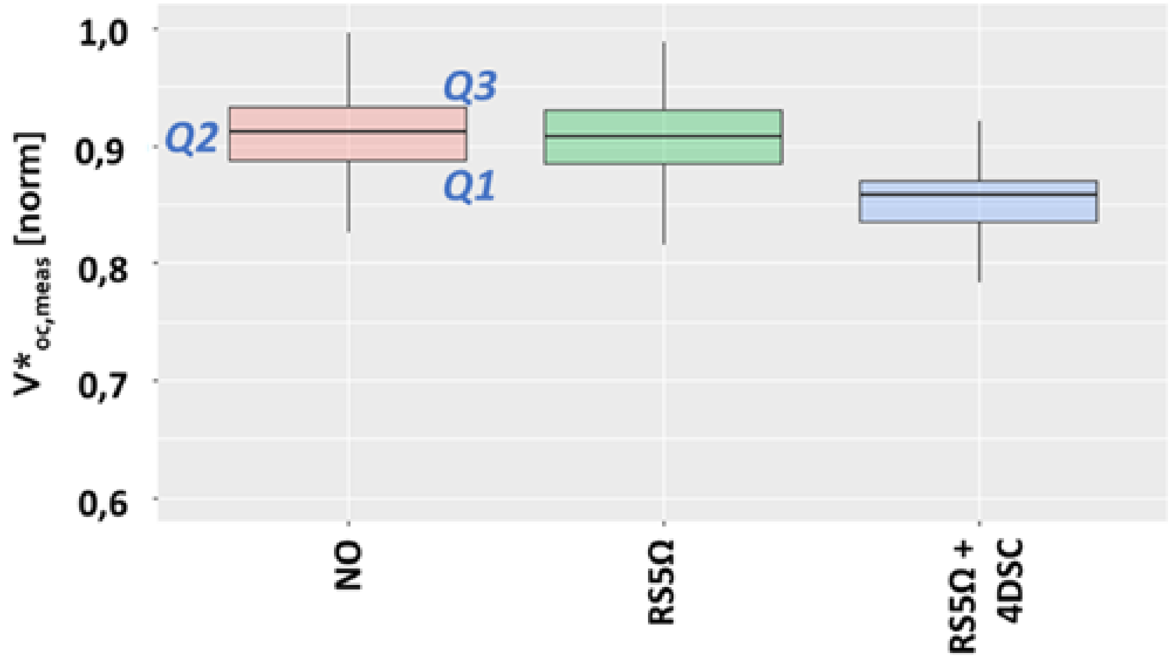
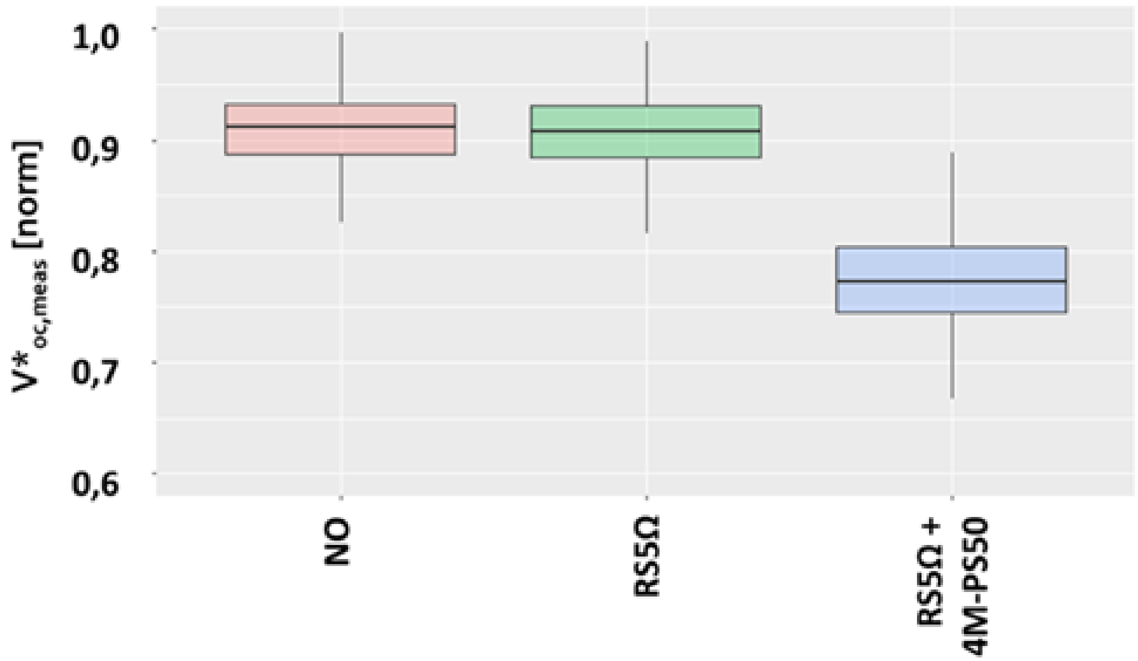
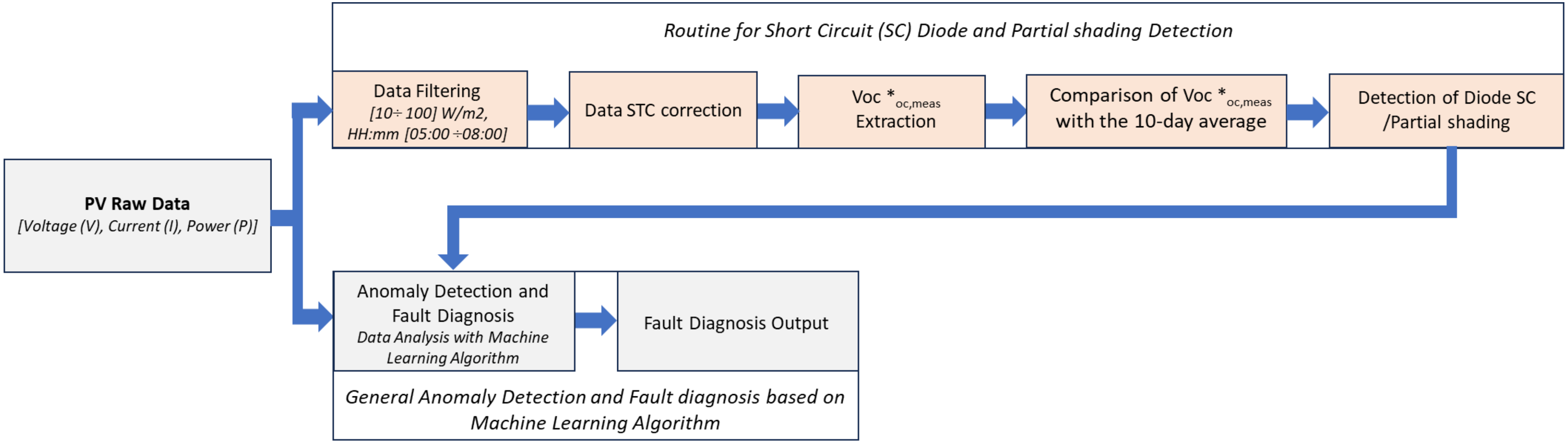




Analysing the V*oc,meas values in the presence of both faults - increasing series resistance and shorted bypass diode - the V*oc,meas reveals a clear distinction between the effects of the two fault types

ML Fault detection and diagnosis - Flowchart



Diagnostic workflow for fault detection and analysis in photovoltaic (PV) systems: integration of early-morning voltage analysis ($V^*_{oc,meas}$) in Machine Learning (ML) algorithms enables differentiation and identification of simultaneous faults such as diode short-circuiting, partial shading, and increased series resistance.

Highlight & Conclusions

- **From detection to diagnosis:**
  Monitoring data are not just for performance tracking — they can explain the *nature* and *context* of faults.
- **Context matters:**
  Fault signatures evolve under varying operating conditions and may overlap; understanding interactions is essential for accurate diagnosis.
- **A data–physics–intelligence approach:**
  Combining monitoring data, physical insight, and AI enables faster and more reliable fault identification — supporting O&M decisions rather than replacing field diagnostics.
- **Outlook:**
  Experimental results from the RSE PV Fault Facility highlight the importance of realistic, controlled datasets to validate and improve fault diagnosis algorithms for PV monitoring.

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