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THE DOCTORS OF SOLAR PLANTS

# Automation of PV Fault Classification Using AI and ML.

*"Leveraging AI/ML for proactive and early identification/classification of photovoltaic (PV) system faults and underperformance"*

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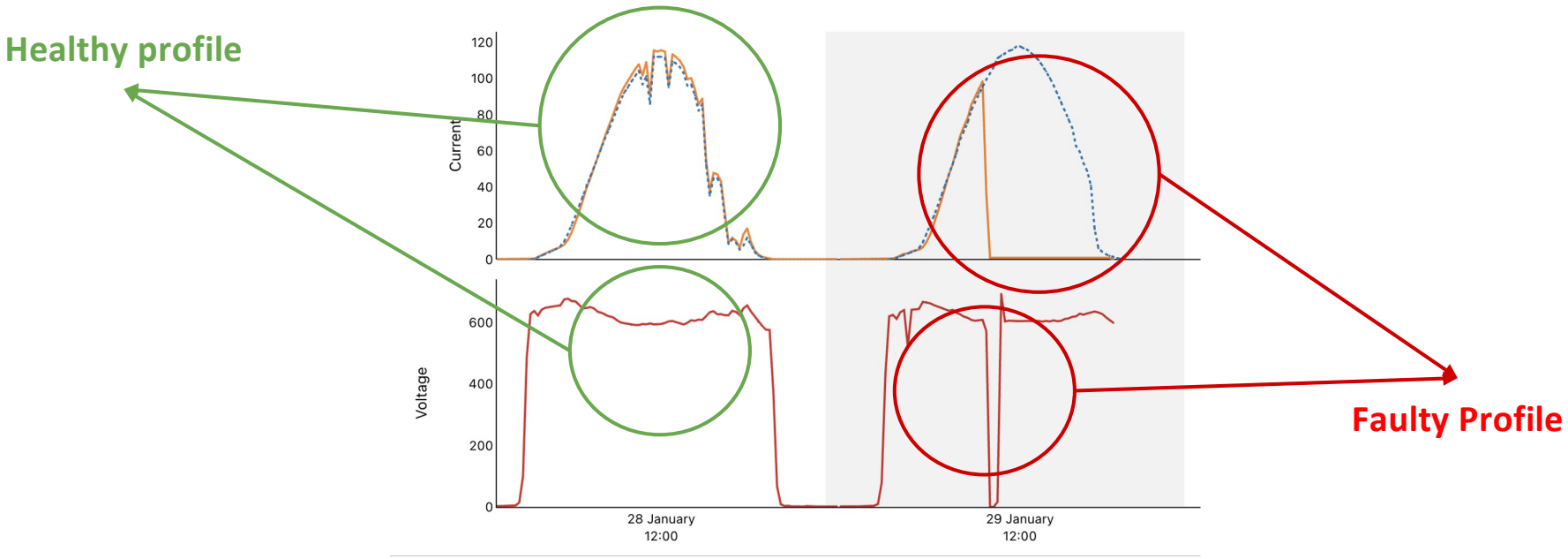

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# PV Fault/Underperformance?

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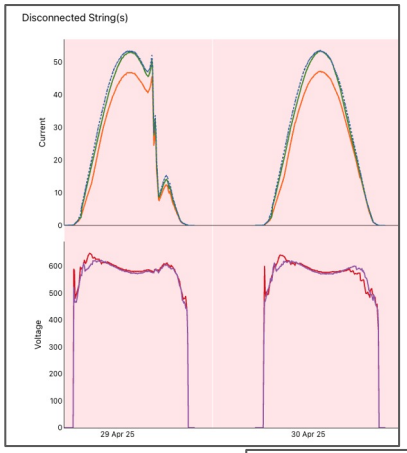
**“Abnormal condition disrupting the regular behaviour.”**

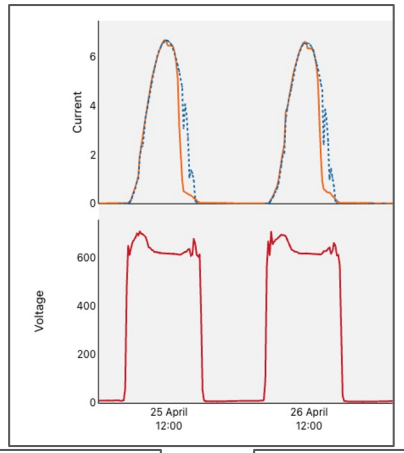


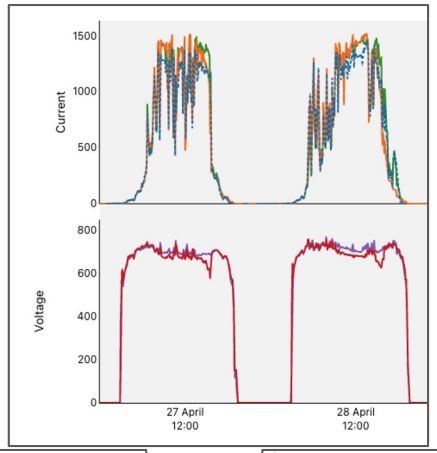

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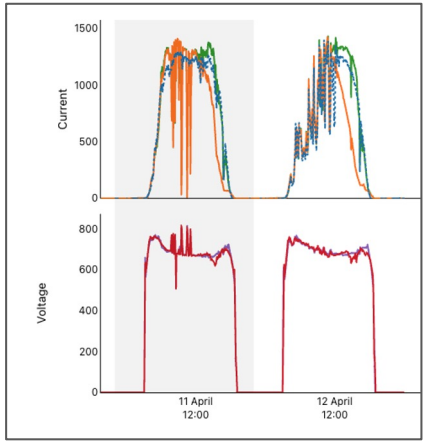
# Some Fault Signatures

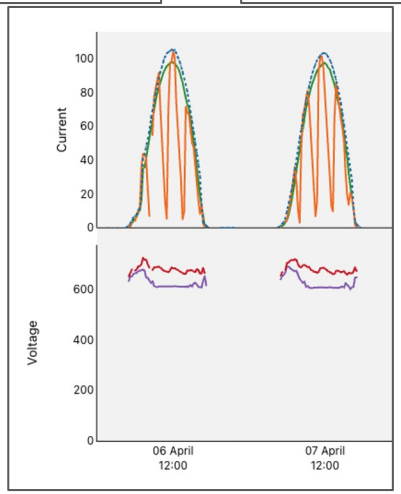
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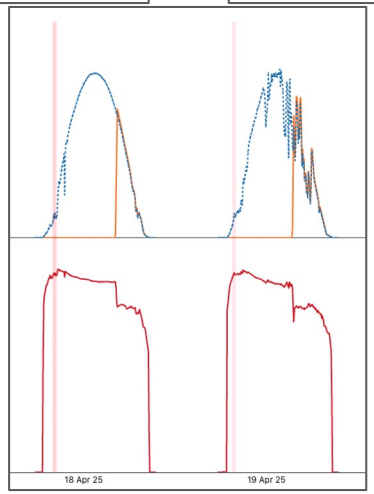


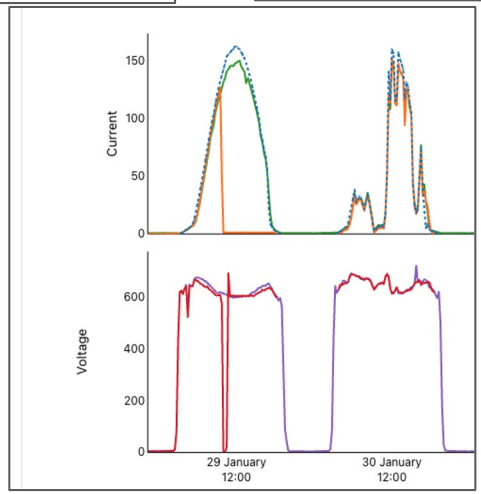




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# How to Detect & Classify Faults?

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# Fundamental Approach

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- **Hypothesis**: PV Faults have unique signatures.

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# Fundamental Approach

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- **Hypothesis**: PV Faults have unique signatures.
  - ***Challenge 1****: What are their Signatures and encodings?*
  - ***Challenge 2****: How these signatures behave in real-world conditions?*
  - **Challenge 3***: How these signatures appear at different data granularities?*
  - ***Challenge 4****: How to decouple 2 or more than 2 simultaneously present faults?*

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- ***Possibility****: PV faults and their signatures are detectable using the time-series data.*

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# Fundamental Approach

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- **Hypothesis**: PV Faults have unique signatures.
  - ***Challenge 1****: What are their Signatures and encodings?*
  - ***Challenge 2****: How these signatures behave in real-world conditions?*
  - **Challenge 3***: How these signatures appear at different data granularities?*
  - ***Challenge 4****: How to decouple 2 or more than 2 simultaneously present faults?*
- ***Possibility****: PV faults and their signatures are detectable using the time-series data.*
  - ***Solution 1****: Semantic algorithms (Scientific, rule-based) for fault signatures that are encoded in 1 or max 3 parameters/features.*
  - ***Solution 2****: Semantic algorithms with strong statistical analysis for fault signatures which require extended temporal ( > 1 Day) and spatial analysis.*
  - ***Solution 3****: ML/Deep-learning-based classifiers for complex signatures are encoded into multidimensional signatures over a time-series.*

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# Faults' Signature Exploration

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# Exploring Signatures/Patterns

**Timeline:** 2019 - 2022 (~3 years)

**Activity:** Controlled experiments on roof-top and C&I installations in various locations.

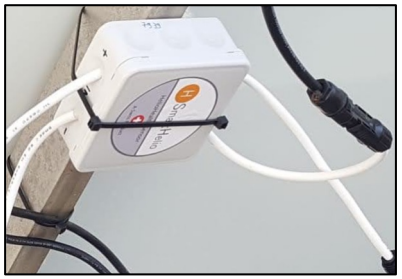
1. Ticino, Switzerland
2. Lausanne, Switzerland
3. Lucerne, Switzerland
4. New Delhi - Multiple site

**Key Learnings or Achievement:**

1. Developed ***Smart Edge-device*** for module and string monitoring and control.
2. Consolidation of hundreds of millions of labelled data-sets from different steups.







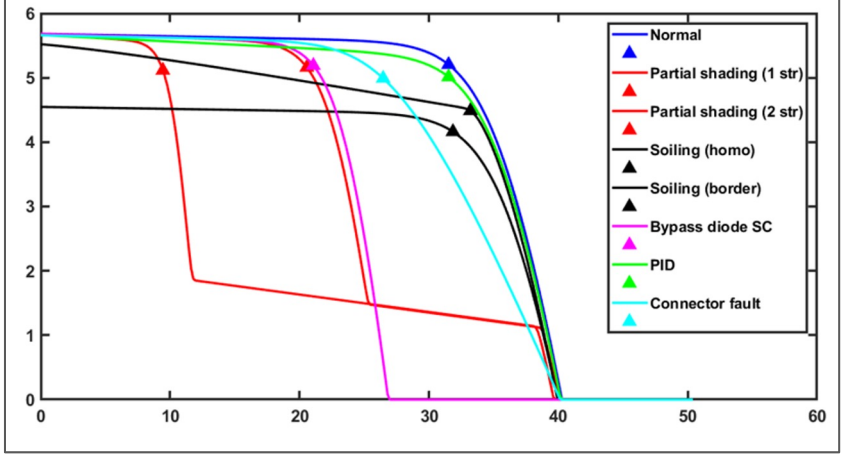


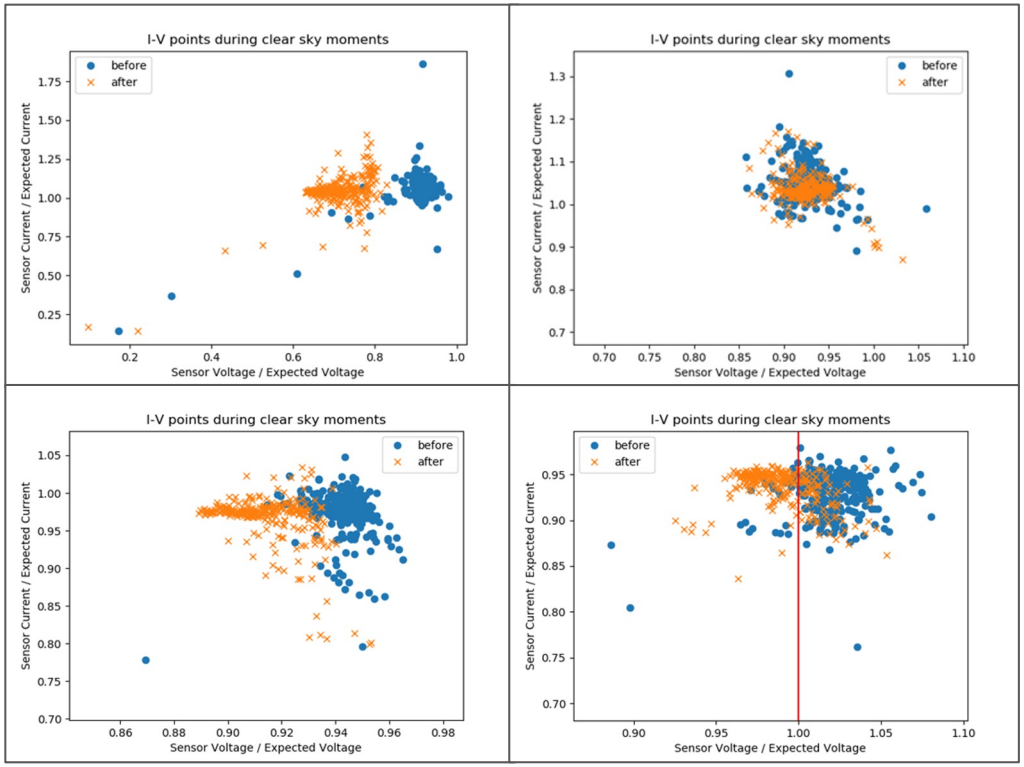
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# Signatures/Patterns Explored

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How different photovoltaic faults characterize in the I-V plane *(Indicative)*




Published: https://www.mdpi.com/1540454

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# Fault Classification Using Inverter-level Data

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# Learning & Correlating Signatures/Patterns

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**Timeline:** 2020 - 2023 (~3 years)

**Activity:** Deploy edge-devices across large scale systems to collect Inverter/MPPT-level along with module level performance details.

1. European sites - Spain, Italy, France, Switzerland
2. Indian Sites - South, Central, and North-West

**Key Learnings or Achievement:**

1. Collect MPPT/Inv/Module data.
2. Label MPPT/Inv data - Module-level fault signatures.
3. Fault classification models - MPPT/Inverter data

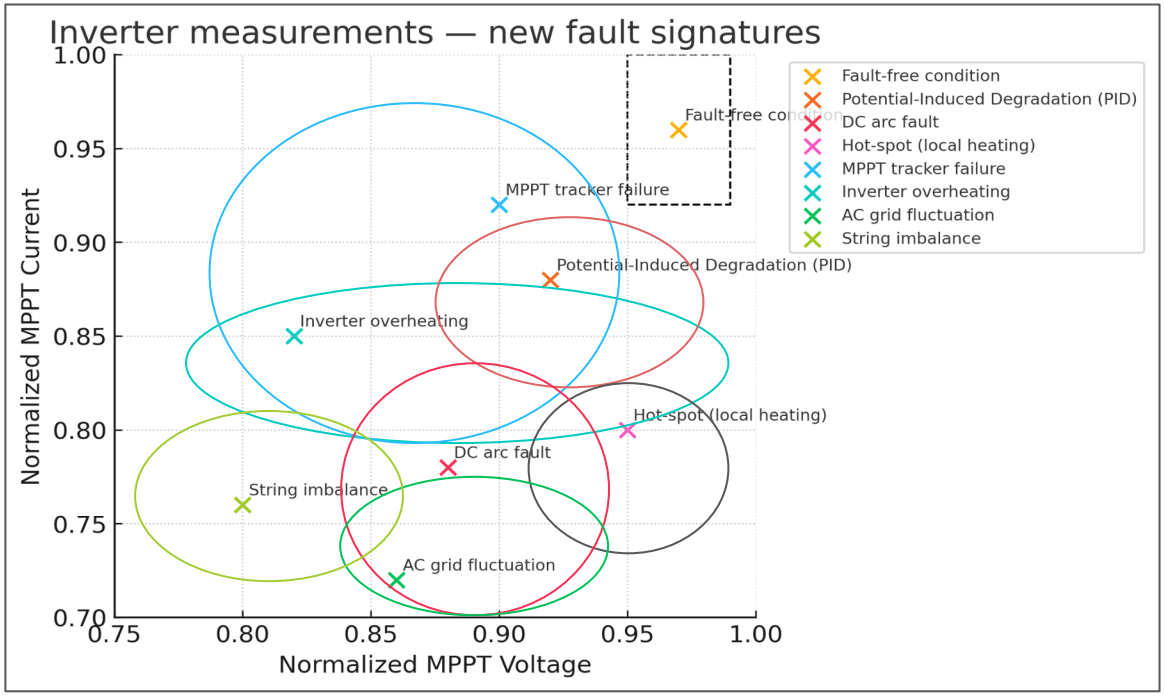


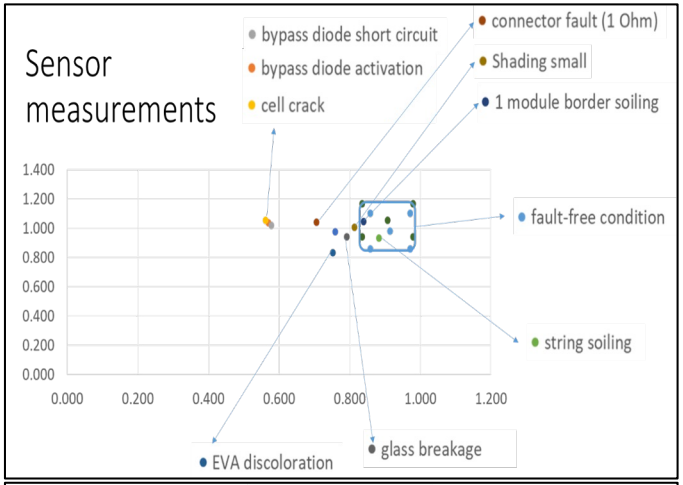
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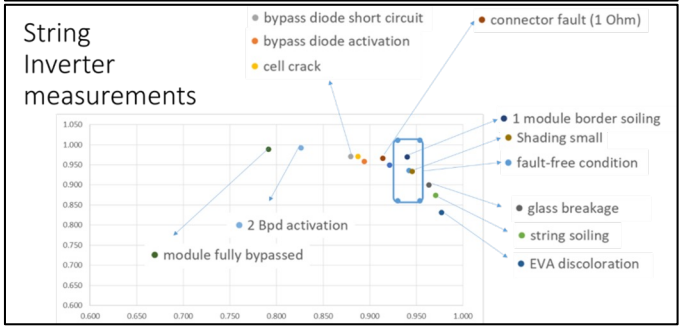
# Signatures/Patterns Mapped (1/2)

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## Mapped Characteristics *(indicative)*



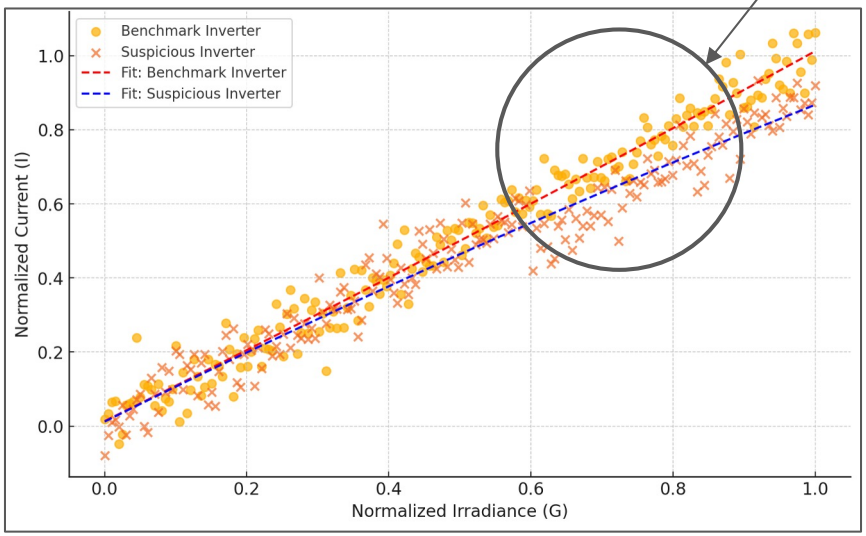



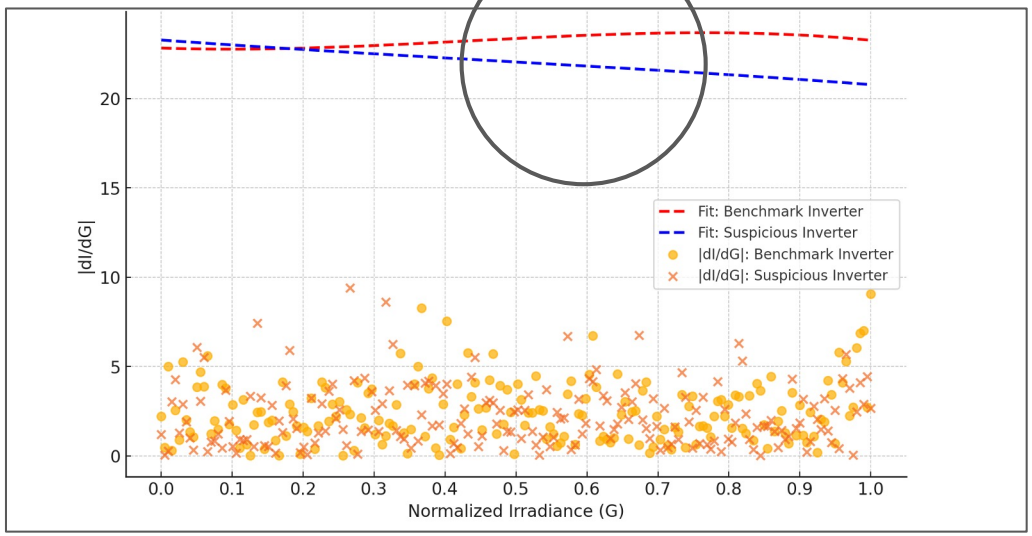

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# Signatures/Patterns Mapped (2/2)

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Efficient Feature Engineering is required for decoupling complex faults in the PV System.
(Timestamps with continuous Irradiance change for an hourly window with continuous clear-sky-non-faulty moments)




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# Signatures/Patterns Categorised

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| Fault Signature Class | Representative Faults | Pref. Classification Approach |
|---|---|---|
| **Class 1: Repeating pattern in V & I**<br>- sustained motif | - Shading<br>- Inverter derated<br>- RISO - Moisture Ingression, etc. | - Statistical + Analytical (Physics-based Algo). |
| **Class 2: Sustained underperformed V or I**<br>- days-long deviation | - String Disconnection<br>- CB Failure<br>- PV Module damage, etc. | - Statistical + Analytical (Physics-based Algo).<br>- ML based (for larger Inputs) |
| **Class 3: Spatiotemporal anomaly**<br>- abnormal pattern vs. peers | - Ground Fault, and AC side Faults<br>- MPPT Malfunction<br>- Soiling, and degradation, etc. | - Statistical + Analytical (Physics-based Algo).<br>- ML based (for larger Inputs) |
| **Class 4. n-Dimensional derivative pattern**<br>- in V, I, G, dV/dI, dI/dG, etc. space | - Most of the Inv. Faults<br>  - Component Failures - Capacitor, IGBT Failure, Hot spots, etc. | - Deep Learning<br>- For a few faults statistical-analytics models also work reliably. |

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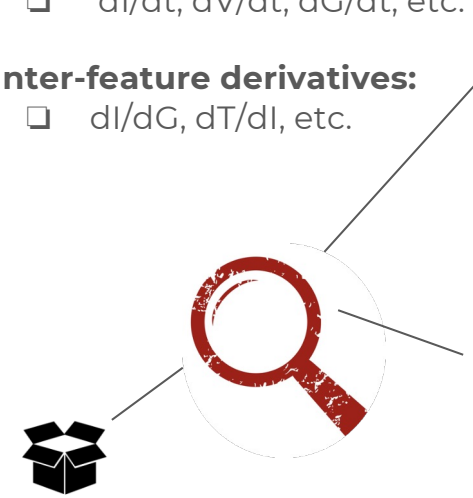
# Classification Model Breakdown

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**Input Data** (I, V, G, AT, logs)

**Time derivatives:**
- ❑ dI/dt, dV/dt, dG/dt, etc.

**Inter-feature derivatives:**
- ❑ dI/dG, dT/dI, etc.



**Exploding the Model (Black box)**

- Filter Data Outliers
- Selective Data Preparation
- multi-order time-derivatives
- inter-feature derivatives/prod.
- temporal/spatial trend
- Pattern Recog. (ML or DL)
- Model Validation (Optional)

- Data Selection & Preparation
- Advanced Featuring Engineering
- Physics Based Statistical Analysis
- ML/DL-based Pattern Recognition

**Output** (Prediction)

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# Performance of ML/DL Models?

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| Fault Signature Class | Best ML Model | Best DL Model | Observed Performance |
|---|---|---|---|
| **Repeating pattern in V & I**<br>- sustained motif | **XGBoost**<br>- Boosted trees on freq./shape features) | **1D CNN**<br>- convolutional network for time-series | **~98%**<br>- near-perfect detection of recurring faults |
| **Sustained abnormal V or I**<br>- days-long deviation | **Random Forest**<br>- tree ensemble on rolling stats | **LSTM**<br>- sequence model capturing trends | **~97%**<br>- persistent anomalies easily caught |
| **Spatiotemporal anomaly**<br>- abnormal pattern vs. peers | – conventional ML struggles to use spatial context<br>- logical algorithms after statistical treatment are effective | **Graph Neural Network + LSTM**<br>- e.g. STADN with graph attention | **~96%**<br>- high accuracy with multi-device correlation |
| **4. n-Dimensional derivative pattern**<br>- in V, I, G, dV/dI, dI/dG, etc. space | **SVM / Tree Ensemble**<br>- on derivative features | **Multi-channel CNN**<br>- or autoencoder on V, I, G and derivatives | **~93%**<br>- complex multi-feature faults detected |

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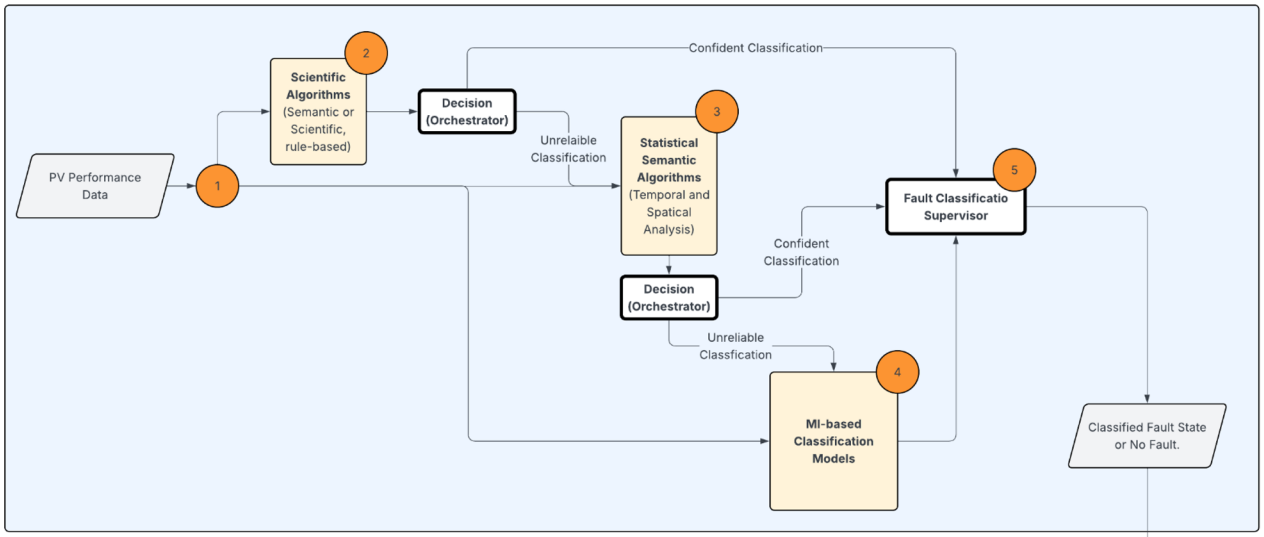
# Continuous Learning

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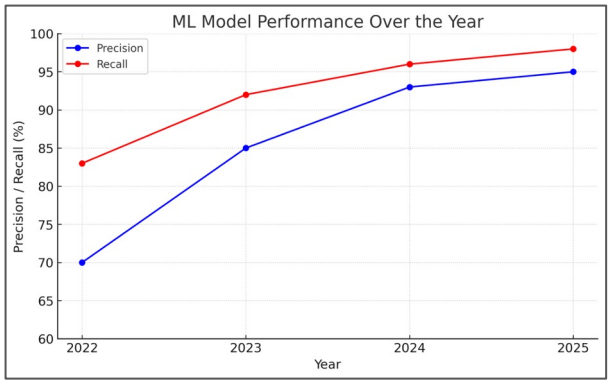
# Deploy & Learn (Application & Continuous Learning Era)

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**Integrated Fault Classification Model**

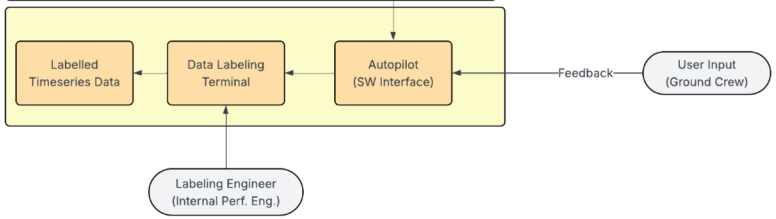



- Train Locally
- Learn Globally




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**Incremental Data Labeling & Model Validation**




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# Thank You!

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