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Novel PV Array Monitoring Strategies (Failure Analysis)

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PVPS

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

PV Performance Monitoring Background

Motivation

- **PV systems have a high number of components (modules, inverters, connectors) and many potential points of failure.**
  - **Even low probability of individual component failure can result in lost energy due to the large number of components and serial design**
  - **Not all failures result in zero energy**
  - **Performance guarantees demand high availability**
  - **Failures can lead to safety issues**
    - **Arc faults can cause fires**

This presentation will review some common monitoring practices as well as provide insights into new and novel methods being developed to gain insight into PV system health, safety, and performance.

Monitoring Methods

Conventional Methods

1. **Compare measured output to initial predictions - Irradiance not needed.**
2. **Monitoring production and Normalized production, alarming on deviation of normalized values from typical values – Irradiance not needed.**
3. **Measure output at numerous points in the system and compare –**
   - Multi inverter monitoring
   - Combiner level monitoring
   - String level monitoring
   - Module-level monitoring (AC modules or voltage optimizers such as Tigo, Solar Edge, etc.)
4. **Monitoring temperature corrected PR (ER or PR*)**
   a) Local irradiance sensor used in larger homogeneous systems
   b) Regional irradiance sensor used for fleets of smaller systems

Some New and Novel Methods (including fault identification and location)

5. **Measure irradiance, temperature, wind speed and use model to predict performance.**
6. **Measure DC circuit (e.g., Vmp, Imp, Voc, etc.) and estimate system health**
   - Measure Vmp, Imp, and Voc to estimate Rs.
   - Periodic string IV curves (expensive and labor intensive)
   - In situ string and module IV curves (can this be done at modest cost?)
7. **Arc and Ground Fault Detection and Location**
8. **Predicting faults before they occur using machine learning**

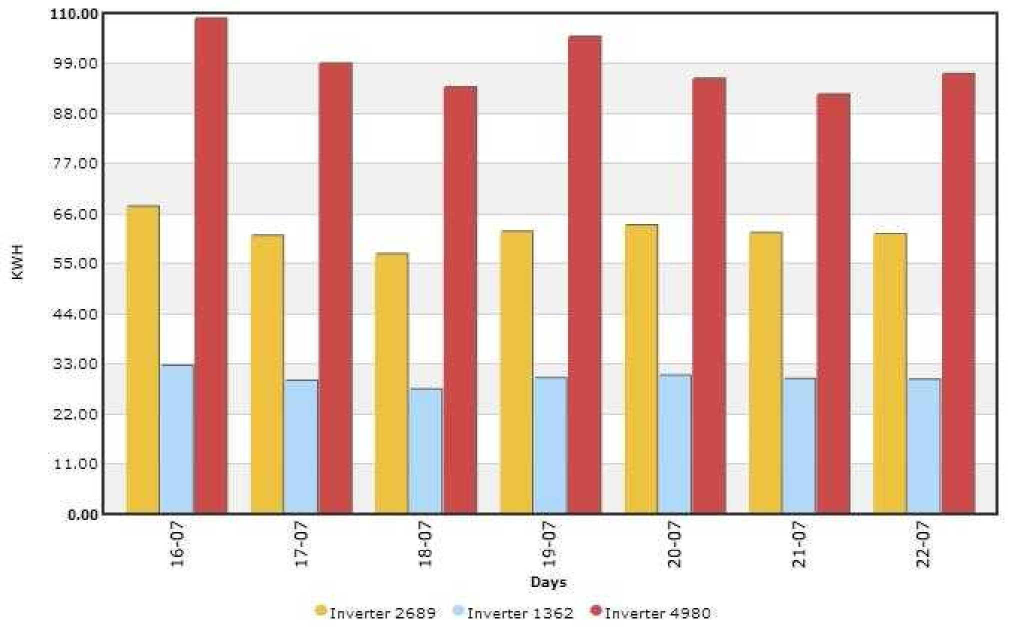
1: Compare measured output to initial predictions

Quantity	August	September	October
AC Energy Produced	687.3 kWhr	560.0 kWhr	523.2 kWhr
AC Energy Lost from outages	11.5 kWhr	0 kWhr	0.7 kWhr
Minutes of outage	212	0	15
Total Estimated Potential Energy Production	698.8 kWhr	560.0 kWhr	523.9 kWhr
PVWatts Estimate (V.1)	706 kWhr	580 kWhr	503 kWhr
PVWatts Estimate (V.2)	702 kWhr	580 kWhr	483 kWhr

- **Very common for small residential systems**
- **Can be difficult to separate out inverter outages (e.g., from grid fluctuations)**
- **Difficult to detect system problems unless they are severe.**

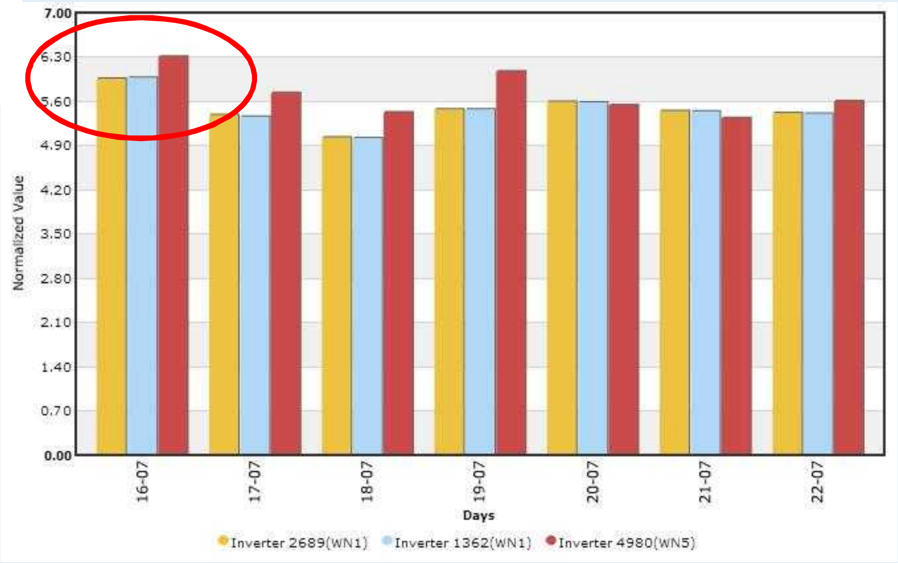
Historical irradiance measurements are needed!

2: Monitoring production and Normalized production, alarming on deviation of normalized values from typical values



Production (hourly or daily)

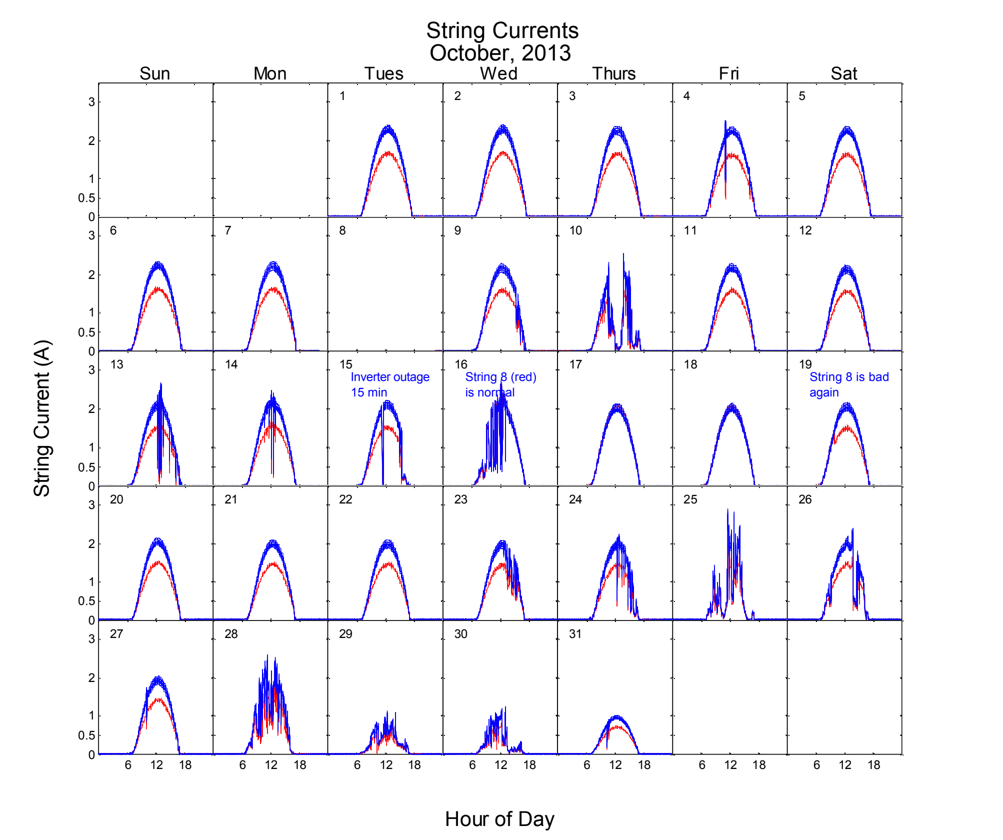
Normalized Production kWh/kWp (hourly or daily)



- **Irradiance is not needed**
- **Requires multiple meters or systems to compare**
- **Best for identifying changes over time**

3a. Measure output at numerous points in the system and compare – (a) String Level Monitoring Example

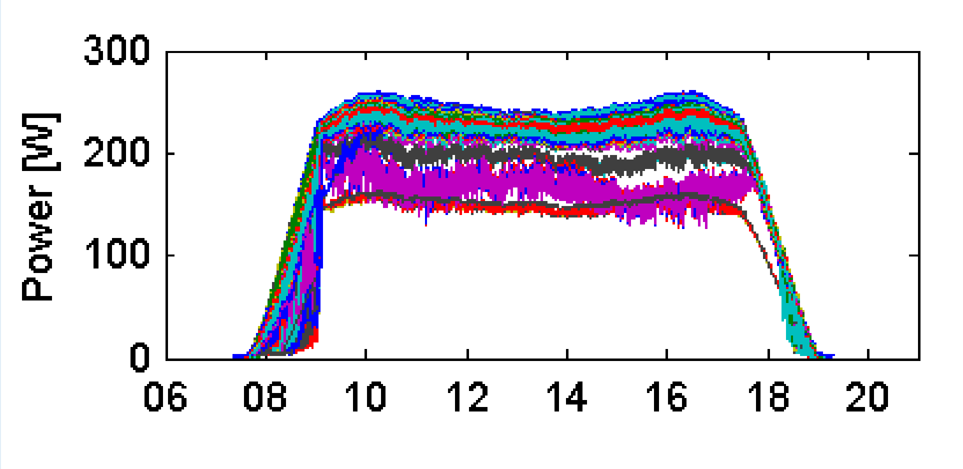
- String-level monitoring on a small PV system (10 strings)
- String 8 (red) is reading low
- Oct 16, String 8 is consistent with other strings
- Oct 19: String 8 returns to its original pattern of low performance
- Source of problem is not known.

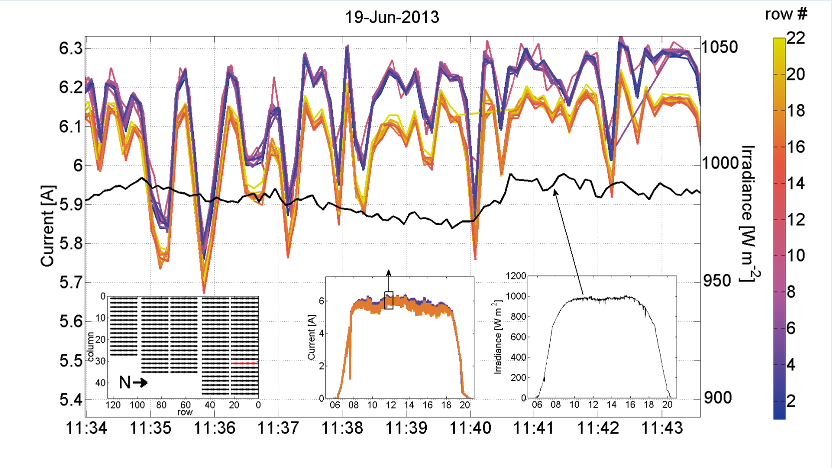


3b. Module Level Monitoring

- **Sandia is investigating module/string-level monitoring on a 1-MW, single-axis tracked bipolar PV plant in New Mexico, USA.**
- **412 modules in strings monitored every 8 sec using Draker Energy's Clarity DC monitors.**
- **Module power and string current are collected.**
- **Results demonstrate that detailed monitoring can uncover poor performing modules.**
- **Question: How much value is this information?**

- **System was very helpful for tuning and commissioning the 1-axis tracking system.**





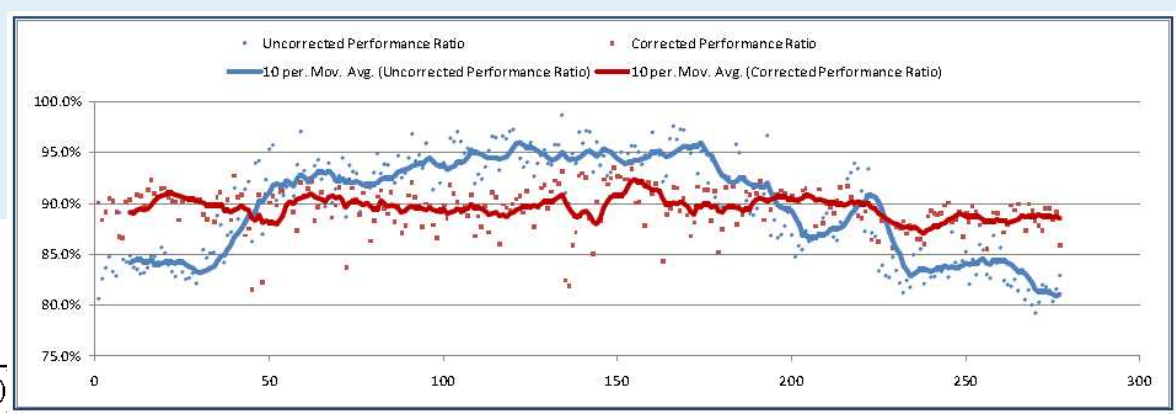
4. Performance Ratios

- Performance ratio (PR) combines measured output, POA irradiance, and system STC rating.
- Temperature Corrected Performance ratio (PR*) corrects PR for module temperature and results in a more uniform response across this year.
- PR* is a good indicator of overall system performance.
- Uncertainty arises from calculating cell temperatures during variable periods.
  - Thermal lags
  - Wind effects
  - Irradiance effects

$$PR = \frac{\sum_i EN_{AC\_i}}{\sum_i \left[P_{STC}\left(\frac{G_{POA\_i}}{G_{STC}}\right)\right]}$$

$$PR_{corr} = \frac{\sum_i EN_{AC\_i}}{\sum_i \left[P_{STC}\left(\frac{G_{POA\_i}}{G_{STC}}\right)\left(1-\frac{\delta}{100}\left(T_{cell\_typ\_avg} - T_{cell\_i}\right)\right)\right]}$$

Example daily PR and PR* for a 24 MW PV Plant

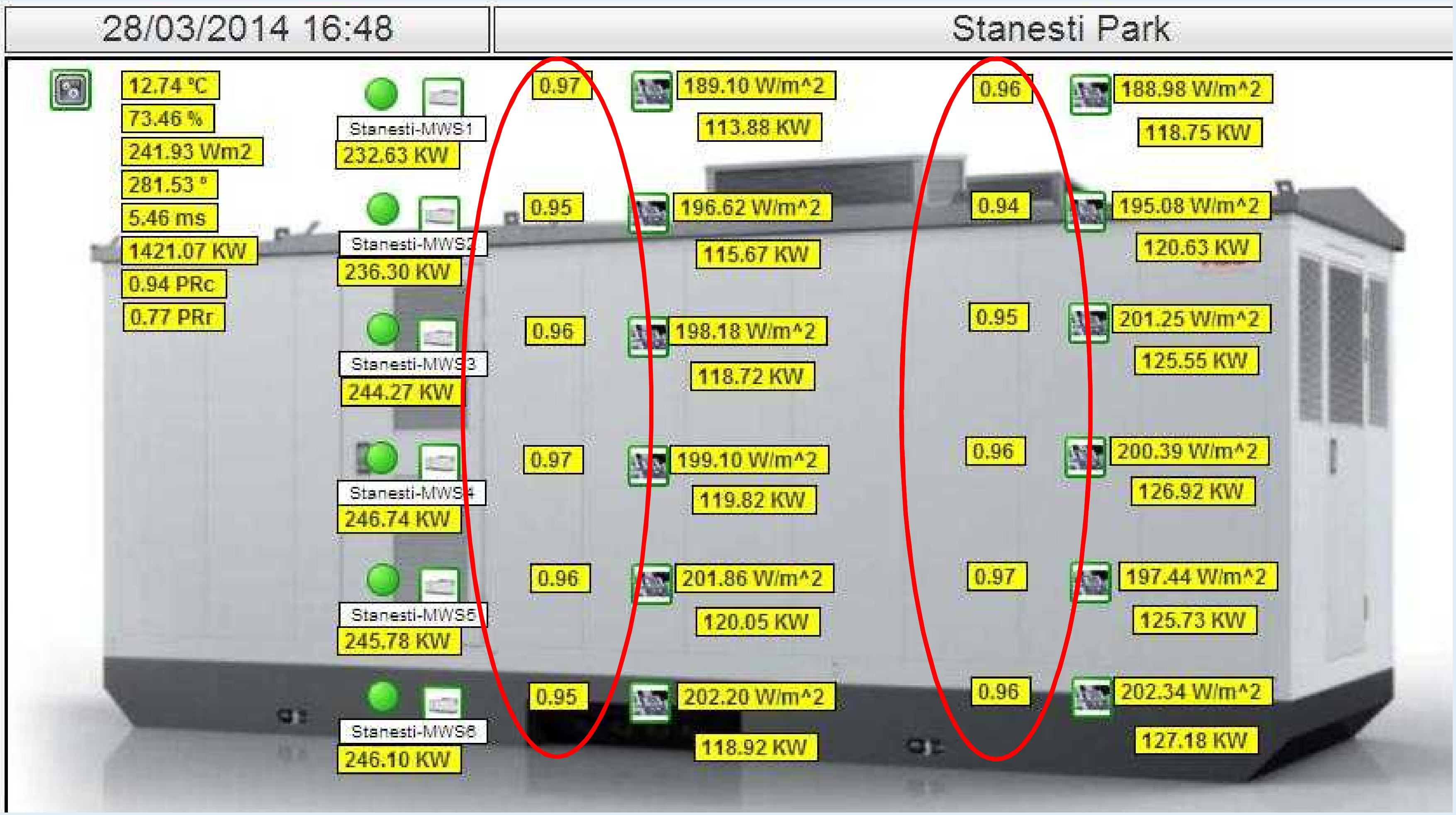


Day of year

Figures from NREL/TP-5200-57991

4a. Monitoring temperature corrected PR (ER or PR*) Local Irradiance Sensor

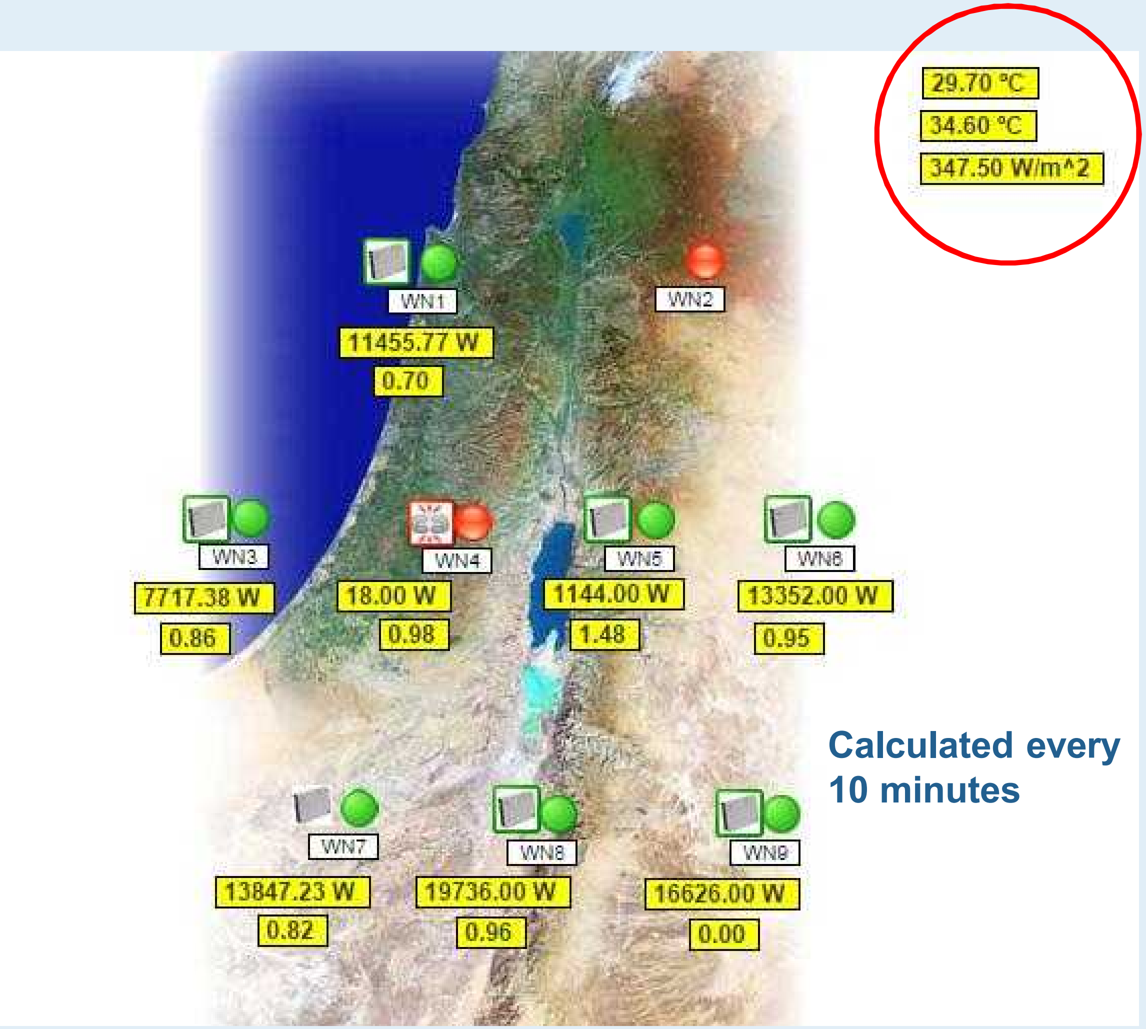
PR* is calculated for each monitoring point (inverter) in the plant.



Example monitoring system output from M.G. Lightning

4a. Monitoring temperature corrected PR (ER or PR*) Regional Irradiance Sensor

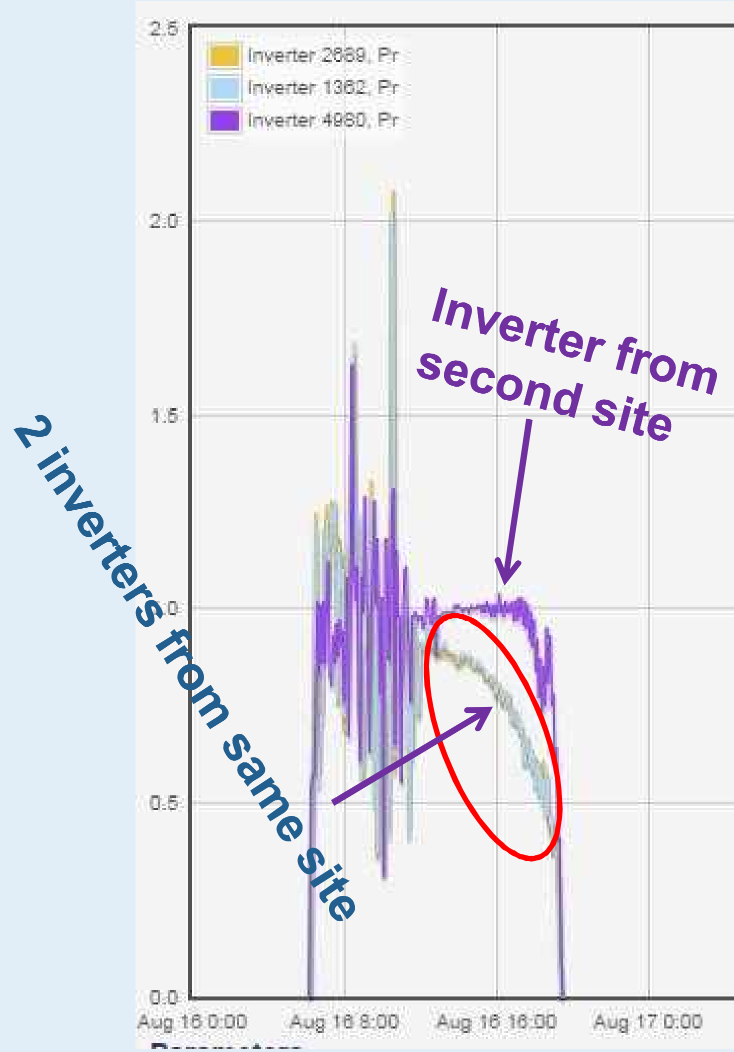
- Uses a single "neighborhood reference cell" for nearby smaller independent systems
- Because module orientation can vary between systems alarming is based on deviation from PR values at specific times of day



Calculated every 10 minutes

Example monitoring system output from M.G. Lightning

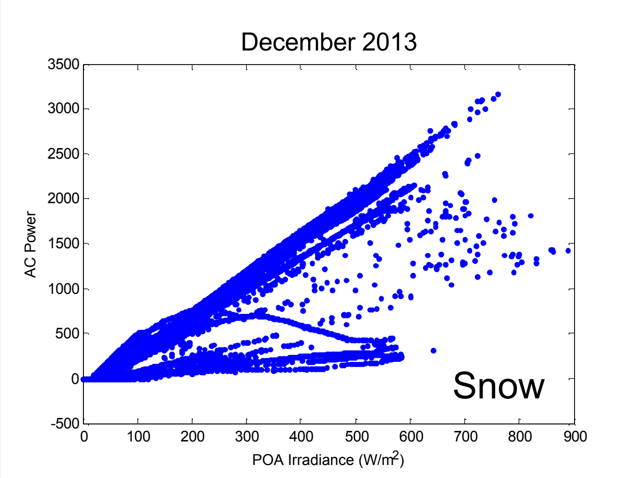
4a. Monitoring temperature corrected PR (ER or PR*) Regional Irradiance Sensor

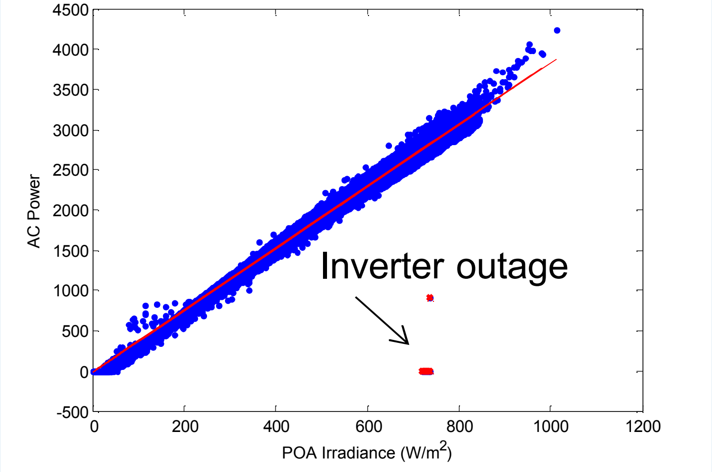


Example data from M.G. Lightning

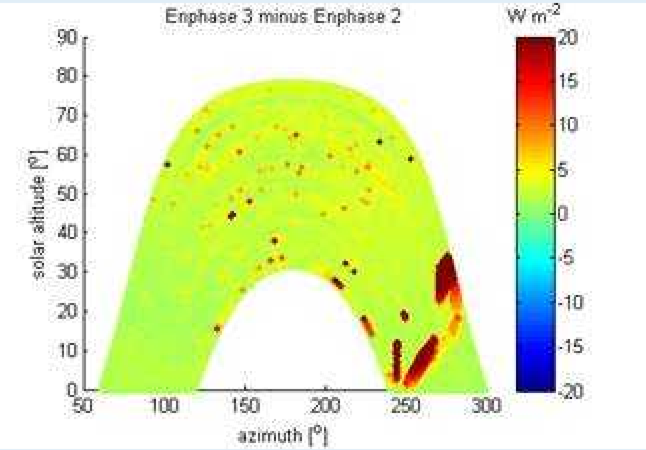
4c. Compare PV Output to POA Irradiance

- If you have POA irradiance, it is very useful for identifying problems.
- Task 13 developed "stamp collections" as a means for better understanding performance of PV arrays.





- Compare subsystem output and plot in context of another variable
- Example: Comparison of two microinverter power outputs plotted as a function of sun position helps to identify shading patterns in array (see figure)

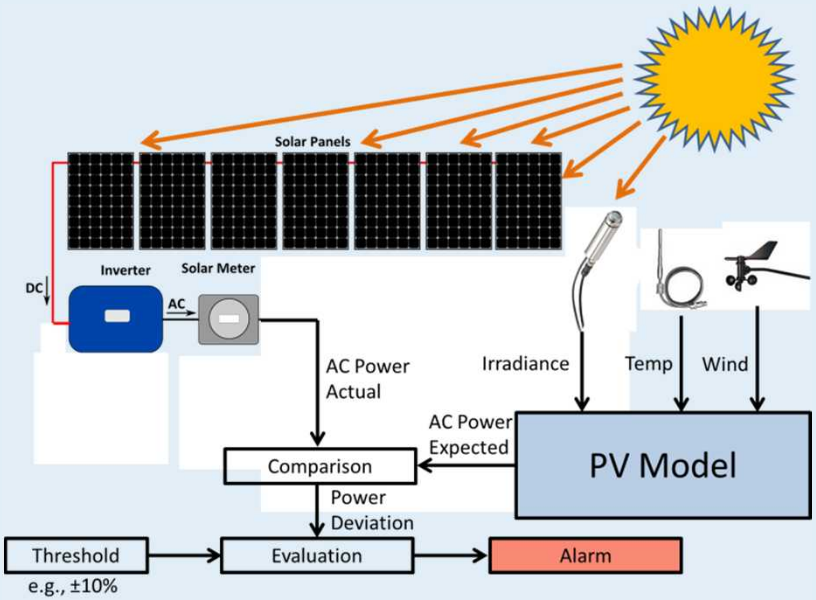


Woyte et al., "Analytical Monitoring of Grid-Connected Photovoltaic Systems – Good Practices for Monitoring and Performance Analysis," Report IEA-PVPS-T13-03:2014

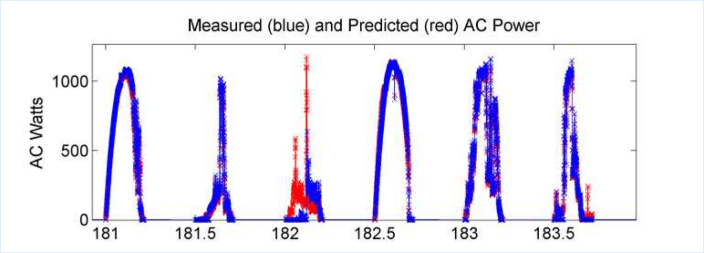
New and Novel Methods

5a. PV fault detection/monitoring system using learning algorithms

- After commissioning, a learning algorithm is trained to estimate power production based on meteorological data (irradiance, temperature, wind speed)
- This prediction is compared to the actual power to detect various faults.
- Current research is focused on distinguishing different fault signatures
- No module/inverter parameters needed!



In one example, a neural network was used for the model.
- Model accuracy +/-3%
- Smaller problems and degradation were difficult to detect.

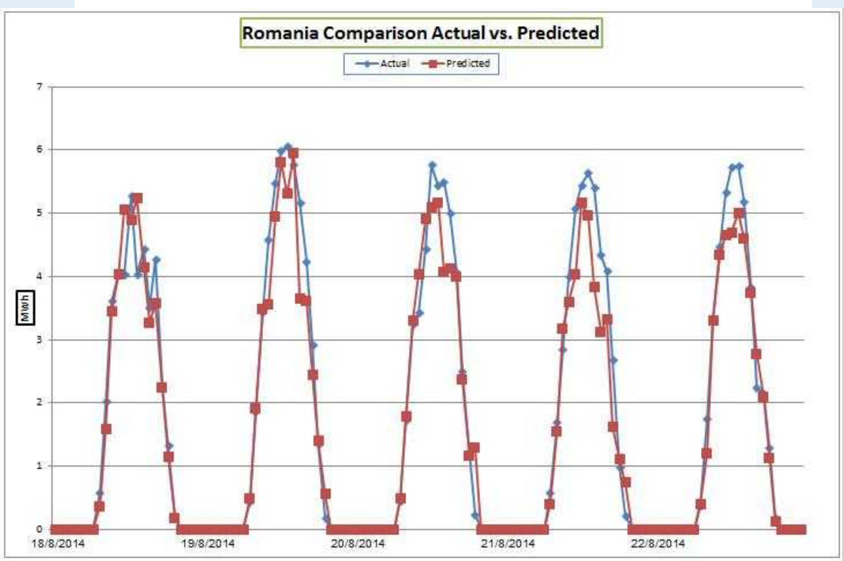


- D. Riley and J. Johnson, "Photovoltaic prognostics and heath management using learning algorithms," 38th IEEE PVSC, Austin, TX, 5 June, 2012.
- J. Johnson and D. Riley, "Prognostics and Health Management of Photovoltaic Systems," US Patent Application 14/023,296, Filed 16 Aug, 2013.

5b: Predicting next day's production, comparing end of day values with predictions

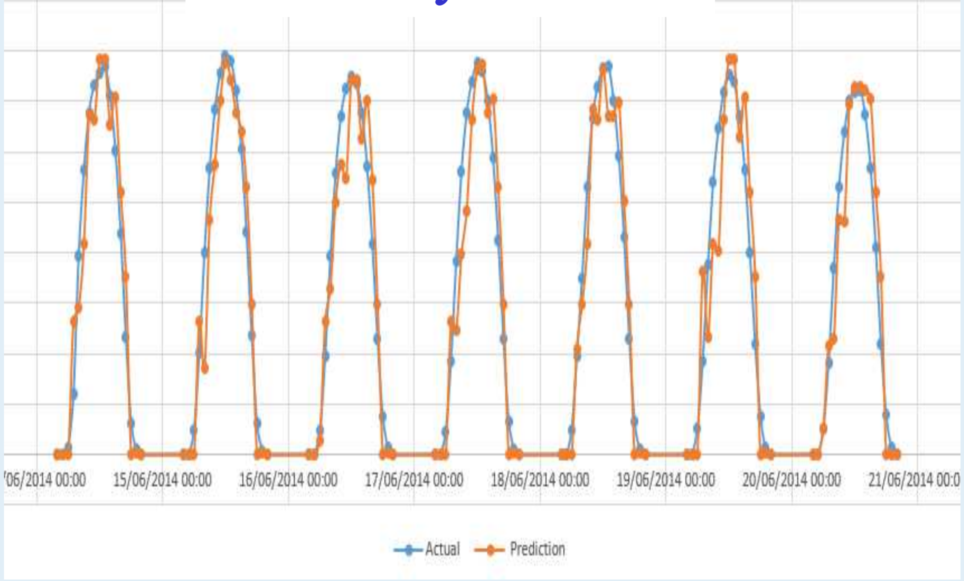
- M.G. Lightning is using a machine learning algorithm and weather service data (no irradiance!) from the day before to forecast PV production for the next day.
- System is still being developed but preliminary results are encouraging!

Partly Cloudy Day Results



Data from Romania

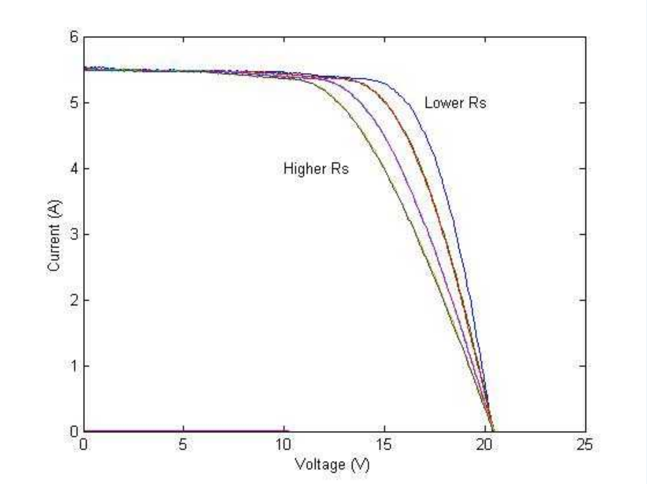
Clear Day Results

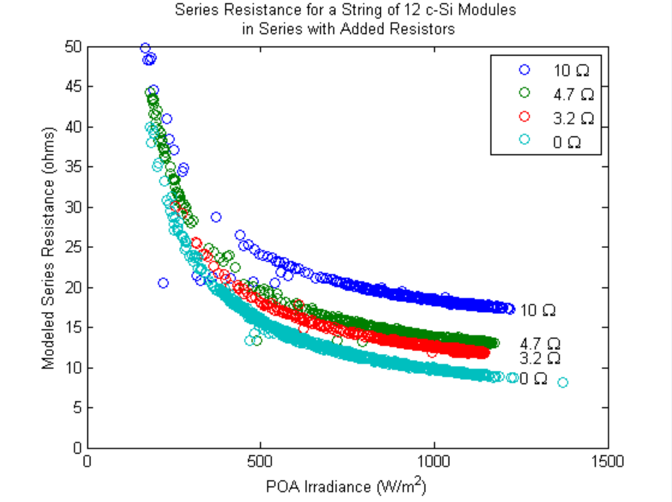


Data from Israel

6a: Monitoring DC Array Health – Series Resistance

- Low and stable series resistance (Rs) is a good proxy for PV module and array health.
- Rs is typically calculated from IV curves.
- Sandia and Draker developed a new empirical method to measure Rs changes without IV curves (uses Imp, Vmp, and Voc).
- Method still requires periodic measurements of Voc.
- Sandia is investigating low-cost hardware and software solutions to automatically measure Voc.
- In parallel, Sandia is also helping to develop low cost automated IV tracers.



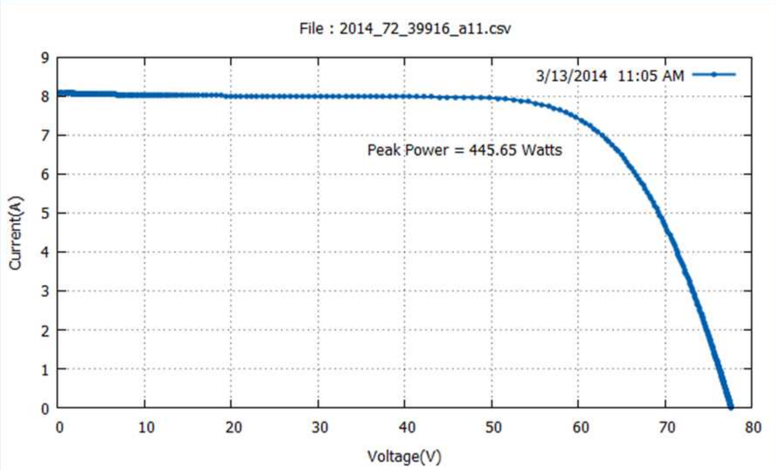


- **Stein, J.S., S. McCaslin, et al. (2014), "Measuring PV System Series Resistance Without Full IV Curves", IEEE PVSC, Denver, CO.**

6b: Monitoring DC Array Health – Autonomous IV Curves

- Analysis of IV curves on modules or strings is a powerful way to detect and identify performance issues.
- Collecting this information is expensive in both labor and equipment.
- Sandia is working with industry to develop low cost IV tracers that can automatically and briefly disconnect modules or strings from an inverter, trace an IV curve and then reconnect.
- Sandia is working with Stratasense (right) to improve prototype units at the module scale.
- Sandia is also working to develop a string solution to be embedded into a smart combiner box.
- We believe that availability of low-cost IV curves could revolutionize PV system monitoring (e.g., LFM model).

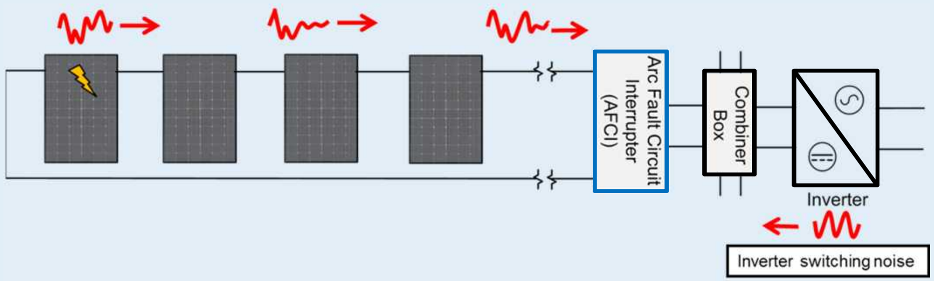
Stratasense prototype IV tracer



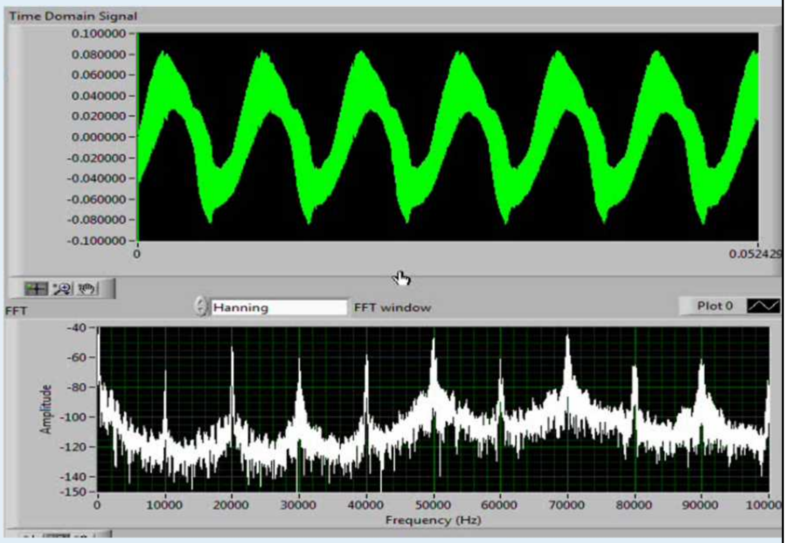
7a. Arc-Fault Detection

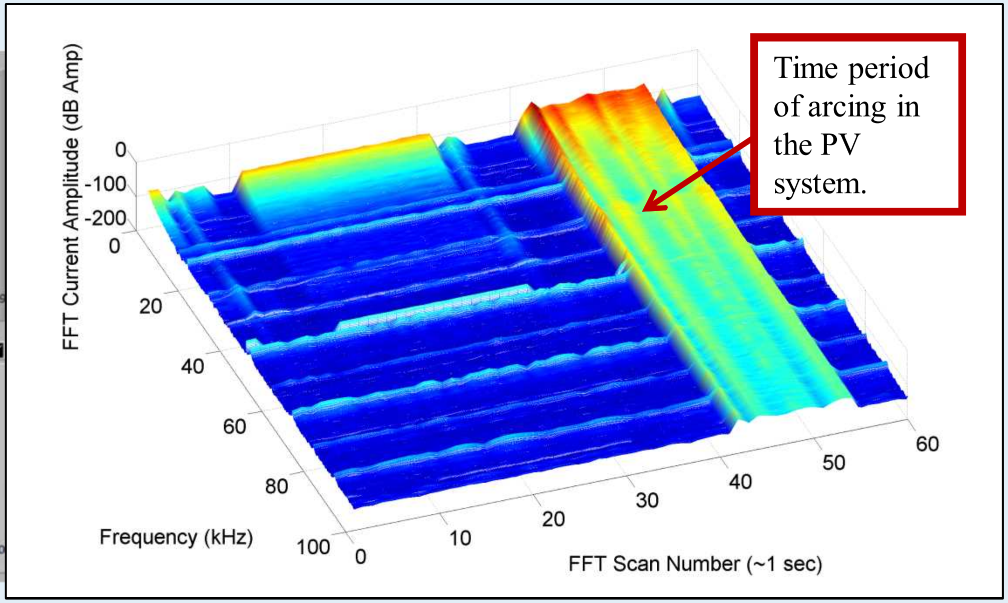
The AC noise on the DC conductors is often used to identify when series arcing occurs in PV systems.

Series arcing noise propagating through the array



Arcing noise propagating through the array



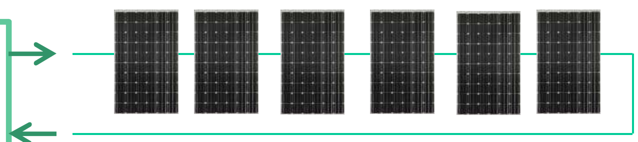


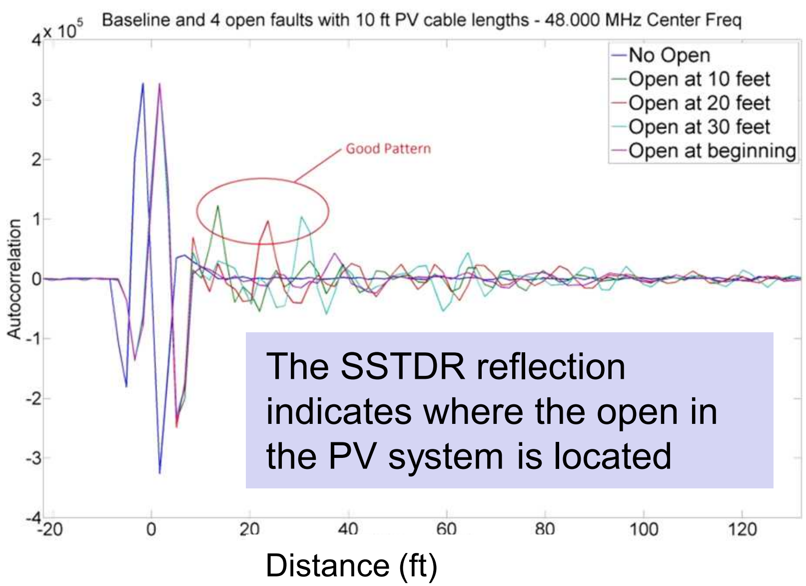
7b. Locating Arc-Faults in Real-Time

Two different methods are being investigated.

Spread Spectrum Time Domain Reflectometry

Sine-modulated pseudo-random pulses

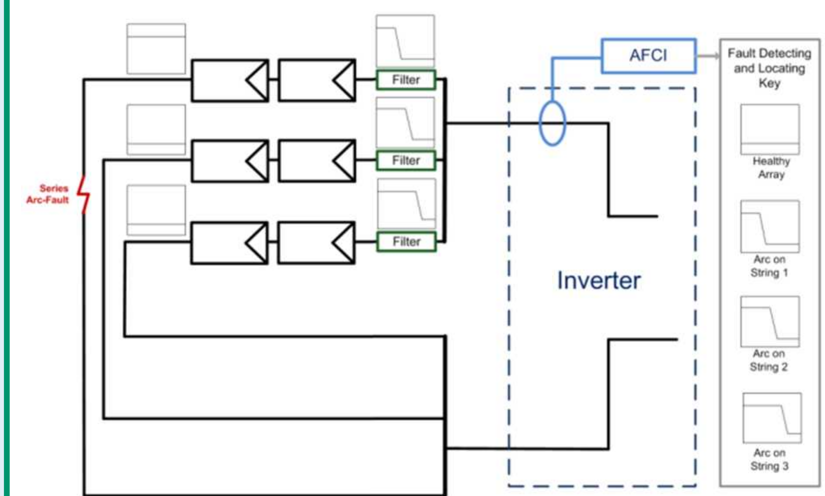




M. K. Alam, F. H. Khan, J. Johnson, and J. Flicker, "PV Arc-Fault Detection Using Spread Spectrum Time Domain Reflectometry (SSTDR)", IEEE Energy Conversion Congress and Exposition (ECCE), Pittsburgh, PA, 14-18 Sept, 2014.

Current Spectrum Filters

- The arc-fault generates wideband noise in the PV system.
- Low-pass filters with staggered cutoff frequencies would indicate in which string the fault was located.

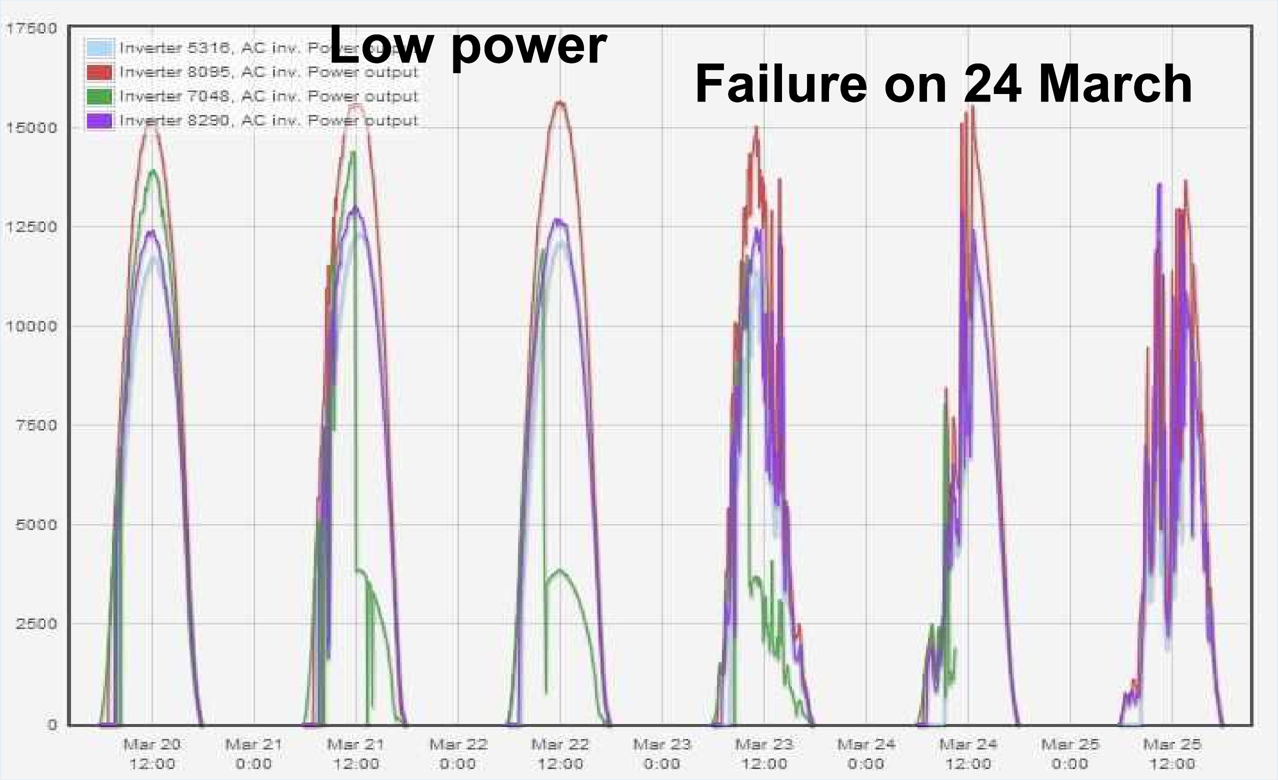


J. Johnson, "Detection Of Arcing Location On Photovoltaic Systems Using Filters," Provisional Patent No. 61/972,247, March 27, 2014.

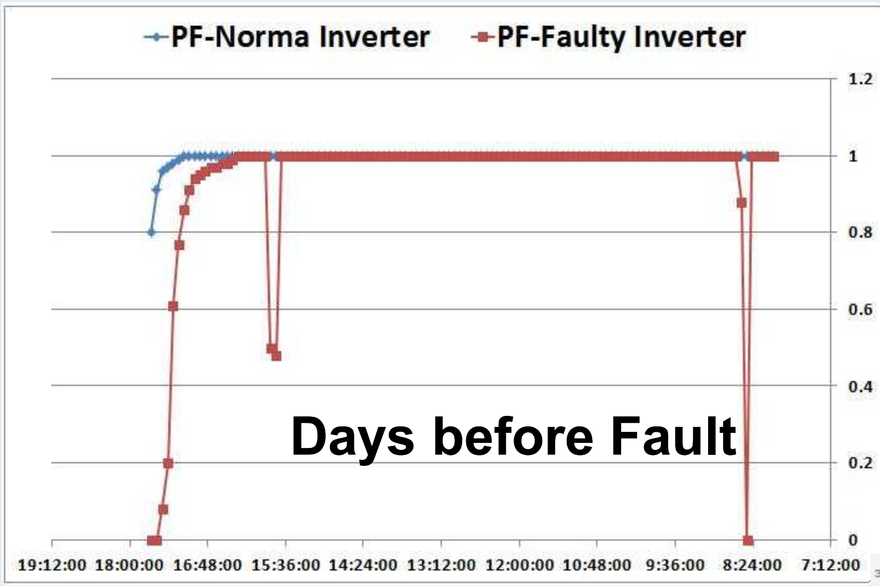
8. Predicting faults using machine learning algorithms

Under development, being studied in Task 13 Activity 2.2

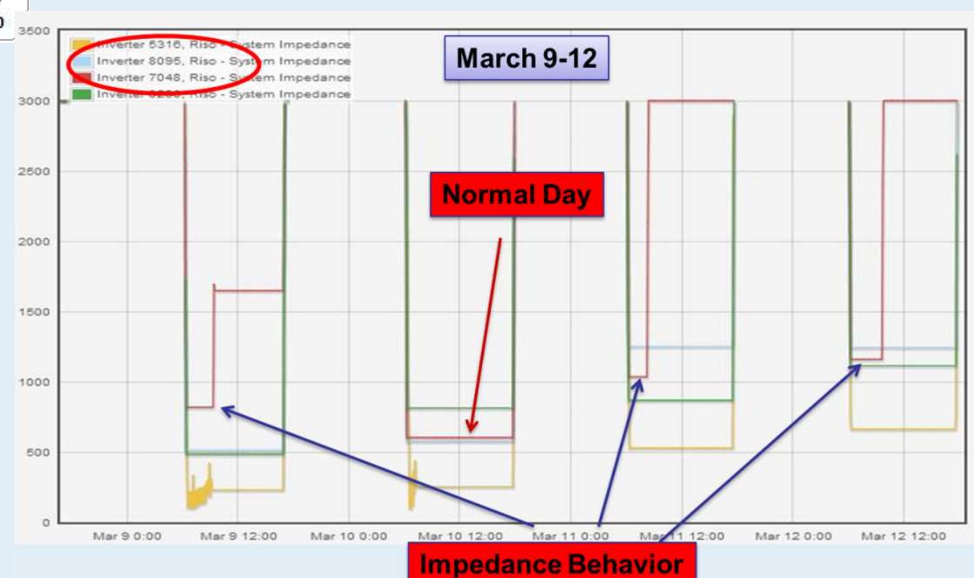
Under the assumption that all inverter parameters behave the same under normal conditions, when the normal behavior changes, a fault is on the way.



8. Predicting faults using machine learning algorithms



Several days before Fault



Faulty inverter began exhibiting abnormal behavior several days prior to failing.

PV Monitoring "Holy Grail"

Prognostics and Health Management

- Low cost sensors with embedded and central data processing is used to monitor system performance and predict current and future problems (e.g., engine check/service light).
- Little to no energy is lost from unplanned outages
- O&M activities are optimized to maximize availability.
- Monitoring system costs are low enough to justify investment.

Summary and Conclusions

- New methods to monitor PV systems are actively being developed.
  - Machine learning algorithms
  - New applications of DC monitoring
  - Fault detection and location
  - Prognostics
- Data collection is not enough.
- Rapid, automated, and integrated analysis methods are needed to derive intelligence on system performance and health.
- Monitoring systems of the future will be seamlessly integrated into operations and maintenance activities.