



Reliable and Cost-Effective Solar System Operations and Maintenance



This material is based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Solar Energy Technologies Office Award Number 38458.

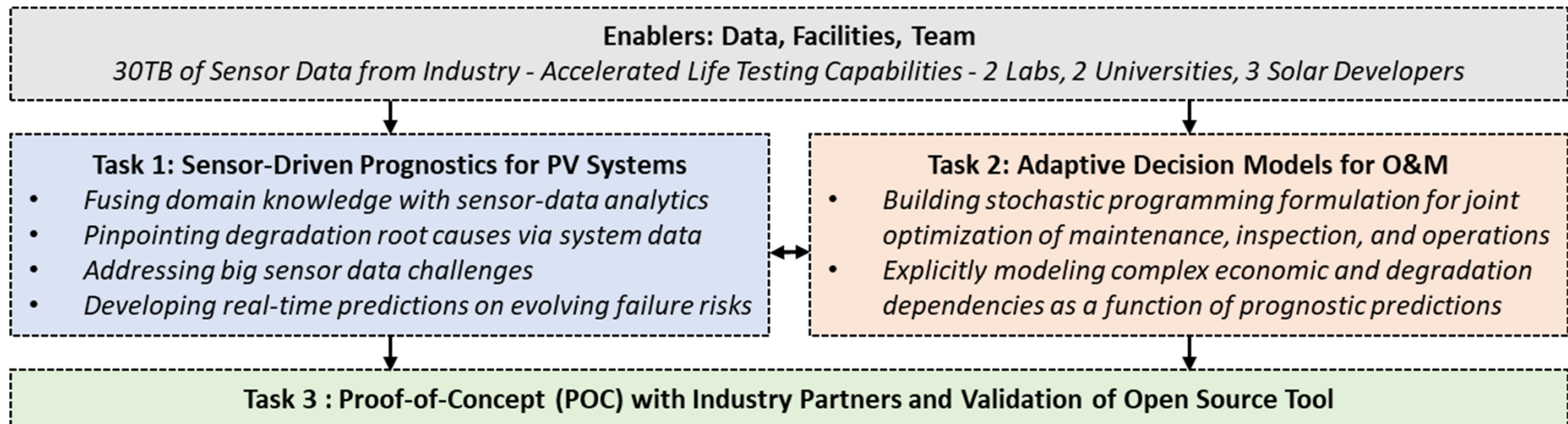
SETO's Programs and Perspectives



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ANL-38458 Project Overview

Project Overview



ANL-38458 Project Overview

Project Objective

To provide a new generation of prognostics-driven O&M approaches that will

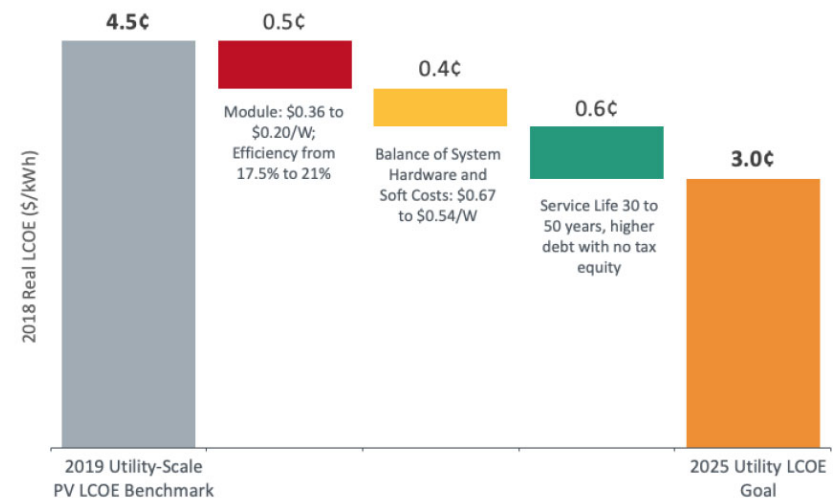
- Reduce maintenance costs (through the accurate determination of inverters in need of service, optimizing opportunistic maintenance)
- Enhance inverter service life (by replacing them efficiently before onset of failure, rather than relying on a set schedule),
- Reduce inverter unavailability (by minimizing failures and modeling economic dependencies).

ANL-38458 Project Overview

Project Background

Our focus: inverters

- Inverter reliability is one of the larger opportunities to improve the overall performance of PV systems
- Root cause for 43% of PV system failures
 - Aim to reduce BOS hardware and soft costs
 - Aim to increase inverter reliability performance



ANL-38458 Project Overview

Project Background

O&M Policies

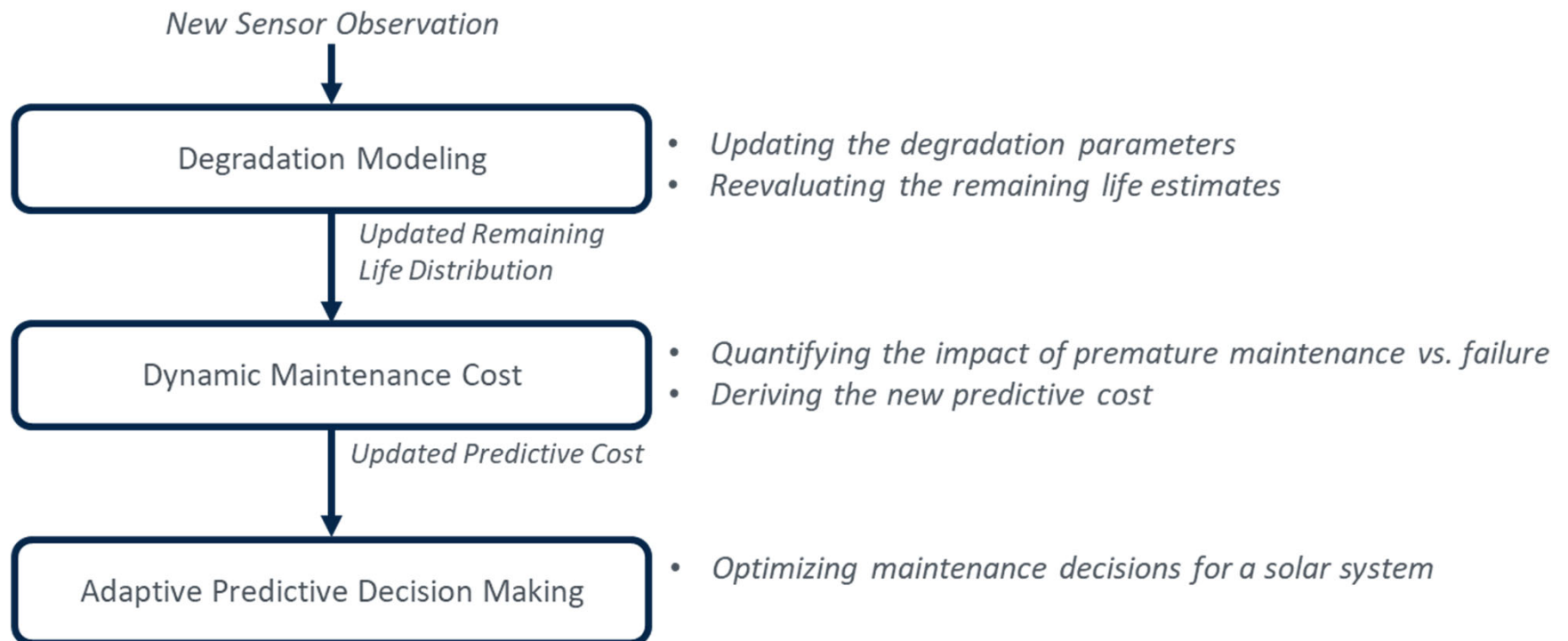
- Periodic
- Diagnostics
- Prognostics

Implementation	Simple-to-Implement Industry Standard	Rule-Based Triggers Emerging Technology	Complex Models Industry Access via this Project
Approach	Periodic Maintenance	Diagnostics-Based Maintenance	Prognostics-Based Maintenance <i>(Proposed Method)</i>
Limitations	Based on population-specific degradation characteristics	Does not predict future degradation Not amenable to proactive O&M	Requires detailed stochastic formulations to model degradation

	Leveraging OEM reliability database	Discovering Imminent Failure Risks	Estimating Early Signs of Degradation	Predicting Asset's Time-to-Failure	Connection to Decision Making
Periodic	✓	✗	✗	✗	✓
<i>easy-to-implement maintenance policies – often over-conservative</i>					
Diagnostics-Based O&M	✗	✓	✗✓	✗	✗✓
<i>policies focusing on process control – not-stable, ad-hoc connection to decision making</i>					
Prognostics-Based O&M	✓	✓	✓	✓	✓
<i>sensor-driven policies that integrate time-to-failure predictions with O&M optimization</i>					

ANL-38458 Project Overview

Technical Framework



ANL-38458 Project Overview

Benefits to Industry

- Cut maintenance cost by improving asset risk assessments and decision-making capabilities introduced through prognostics-based O&M policies proposed in this project.
- Extend lifetime of PV components, reduce unexpected failures and interruptions during operation.
- Integrate the open-source tool developed in this project into existing software and/or enhance this tool for further commercialization.
- Energy equity - Democratizing access to condition monitoring and advanced O&M technologies.



Data analytics for industrial data stream

Zhaoyu Wang

**Professor
Iowa State University**

Industrial Dataset Collections

Dataset Overview

Category	Solar Inverter Dataset (BP1-Q4)	Solar Inverter Dataset (BP1-Q5)
Site number	443	443
Inverter number	751	751
Inverters with failures	85	98
Percentage of Inverters with failures	11.3%	13.1%
Number of total failure events	103	140
Number of failure data points for degradation modeling	~5 million	~7 million
Dataset size	22 GB	24 GB
Earliest installation time	2013	2013

Industrial Dataset Collections

Dataset Overview

Solar Inverter Dataset

Basic Information

- Installation Time
- Geographic Information
- Equipment List
- Replacement Records
- ...

Operational Dataset

- DC Voltage
- AC Voltage
- AC Current
- Temperature
- ...

Weather Dataset

- Temperature
- Wind Speed
- Precipitation
- Extreme Events
- ...

Alert Records

- Inverter production issue detected
- DC Isolation
- Inverter not producing energy - low voltage
- Residual current device
- Inverter - production issue detected (status error)
- External Fan fault

Alert Type	Percentage
Inverter production issue detected	48%
DC Isolation	13%
Residual current device	12%
Inverter - production issue detected (status error)	12%
External Fan fault	7%

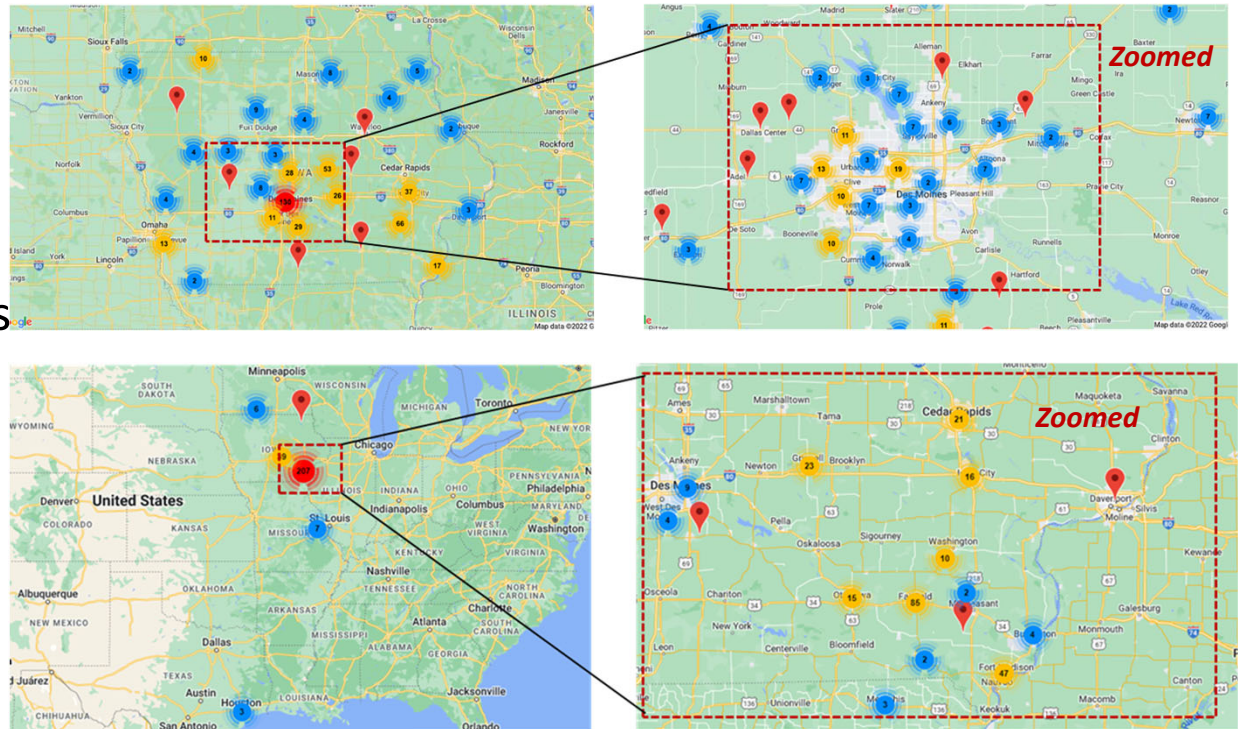


Industrial Dataset Collections

Geographic Information

Geographic Distribution of Inverters

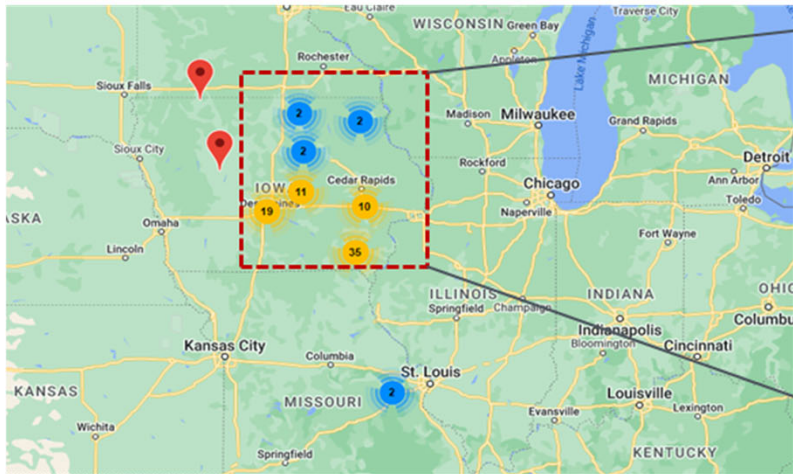
- The inverters in the dataset are located in several states, including IA, MI, MO, and TX, which provides us with various characteristic samples and increases the diversity of the analysis.



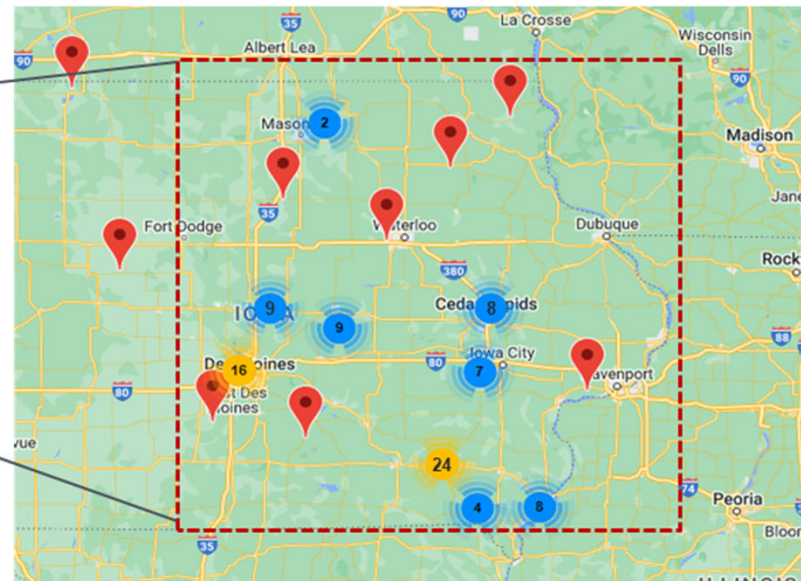
Industrial Dataset Collections

Geographic Information

- The geographic locations of 98 inverters with changing records are shown below.



Locations of 98 inverters with changing records

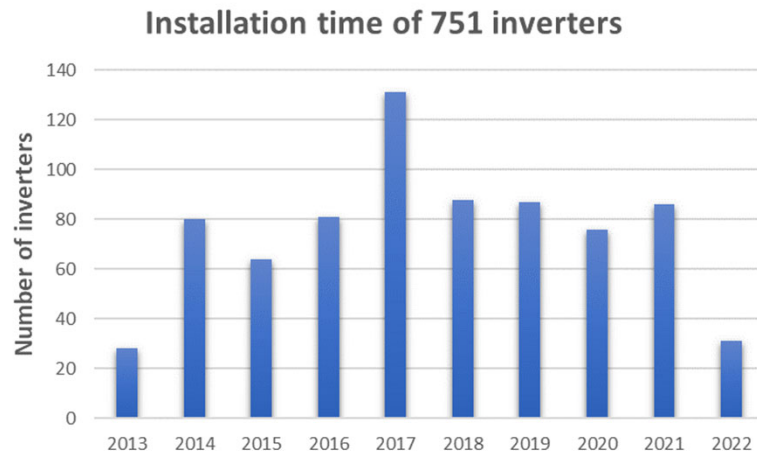


Partial area zoomed

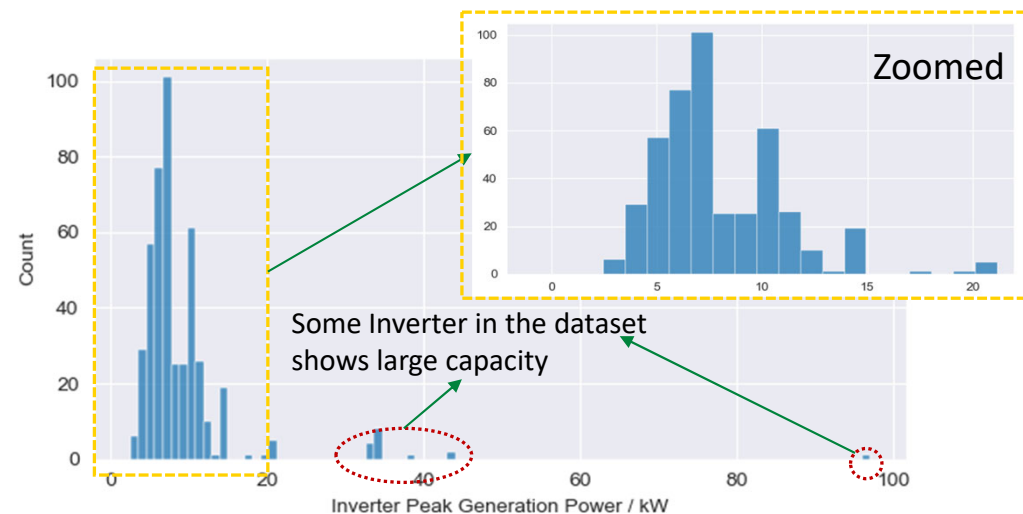
Industrial Dataset Collections

Installation Time and Inverter Peak Generation

- The installation time of 751 inverters in the dataset is shown below.



- Most distributed PV systems are residential cases. Large commercial PV systems are also included in the dataset.



The histogram of actual peak generation data from inverters

Industrial Dataset Collections

Inverter Alert Codes

- Multiple types of Inverter alert codes are recorded in the monitoring system, providing sufficient information for faults and anomaly analysis.

Inverter Alert Codes

- Inverter not producing energy - low voltage
- Inverter production issue detected
- Inverter shutdown by Sense Connect
- Module Voltage Mismatch
- Production issue inverter overheated
- Residual current device
- System overload
- Temperature warning on AC terminal
- Temperature warning on DC terminal
- Inverter - production issue detected (status error)
- AC SPD failure
- Auto transformer overheated
- Internal circuit breaker tripped
- Critical temperature on AC terminal
- Critical temperature on DC terminal
- DC Isolation
- DC SPD failure
- High temperature on the optimizer output connector
- Internal com fault - inverter is not producing
- Internal fan fault

Alert Type	Impact	Opened	Status	Component
Inverter production issue detected	High	03/18/2022 10:34	Open	Inverter 3
Inverter production issue detected	High	08/23/2022 10:19	Open	Inverter 4
Inverter production issue detected	High	09/08/2022 10:42	Open	Inverter 4
Inverter not producing energy - low voltage	High	09/10/2022 14:53	Open	Inverter 4
Grid voltage	High	09/12/2022 08:37	Open	Inverter 4
Inverter not producing energy - low voltage	High	07/28/2022 20:10	Open	Inverter 1 (Unit
Grid voltage	High	08/25/2022 16:34	Open	Inverter 2
Inverter production issue detected	High	08/26/2022 10:19	Open	Inverter 2
Residual current device	High	08/30/2022 08:26	Open	Inverter 2
Inverter production issue detected	High	08/12/2022 14:43	Open	Inverter 1 (Unit
No communication - string	High	09/01/2022 21:25	Open	String 2.1
No communication - string	High	09/15/2022 20:27	Open	String 2.2
No communication - string	High	09/10/2022 20:29	Open	String 1.1
No communication - string	High	09/04/2022 21:26	Open	String 2.0
No site communication	High	12/09/2021 19:26	Open	Zahradnik
No communication with the Power Optimizer	High	08/11/2022 21:27	Open	Panel 1.2.8

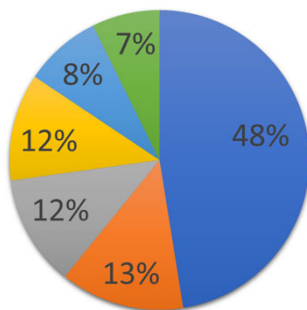
Inverter Alert Codes Recorded in the dataset

Industrial Dataset Collections

Inverter Alert Codes

- As of December 31, 2022, the dataset has recorded around 2300 alerts related to inverter failures. By combining the operational data of the corresponding inverter, further insights can be uncovered in future analysis.

- Inverter production issue detected
- DC Isolation
- Inverter not producing energy - low voltage
- Residual current device
- Inverter - production issue detected (status error)
- External Fan fault

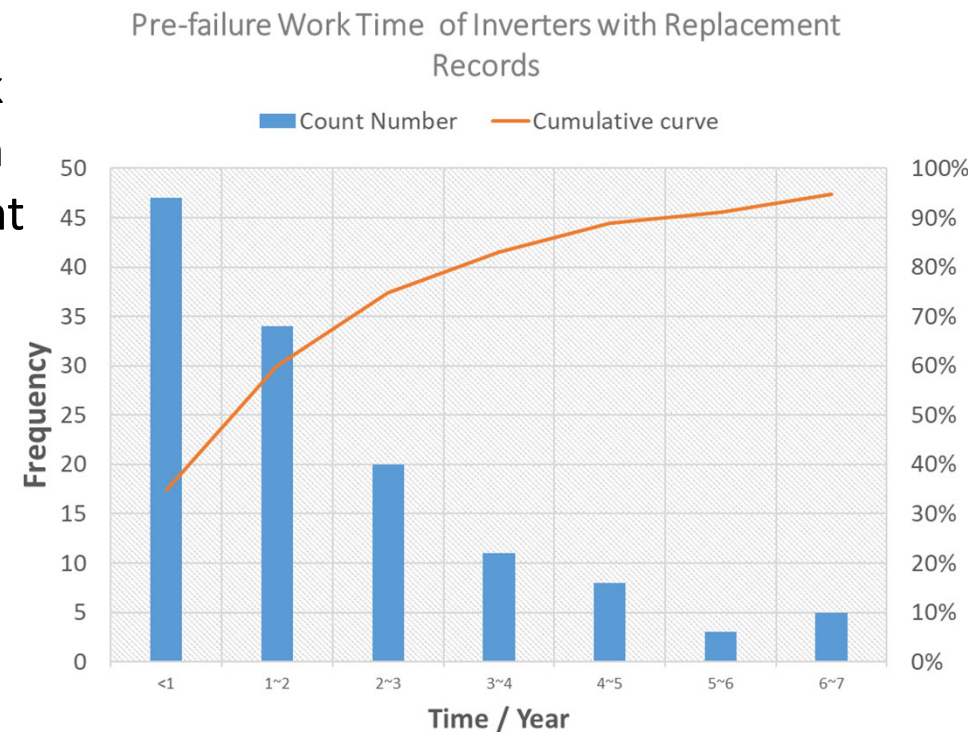


Alert Types	Descriptions
Inverter - Production issue detected	<i>Inverter - Production issue detected</i>
Low voltage (Inverter is not producing energy)	<i>The inverter's voltage is low; The inverter is not producing energy</i>
Residual current device	<i>High residual current has been detected by the inverter</i>
Inverter - production issue detected (status error)	<i>Inverter - production issue detected (status error)</i>
External Fan fault	<i>One of the inverter's external fans is not working</i>
DC Isolation	<i>DC current leakage to ground has been detected by the inverter</i>

Industrial Dataset Analysis

Inverter Failure Cases—Pre-failure work time

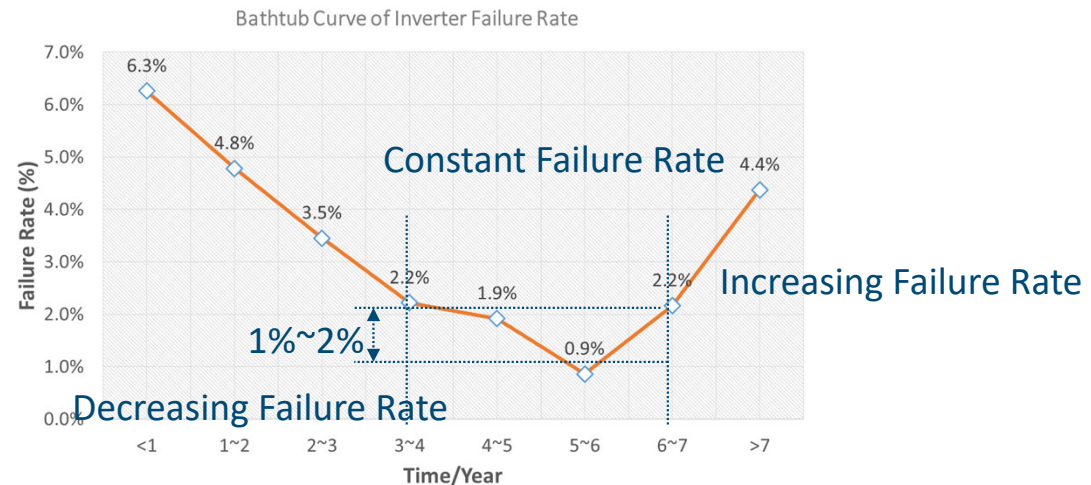
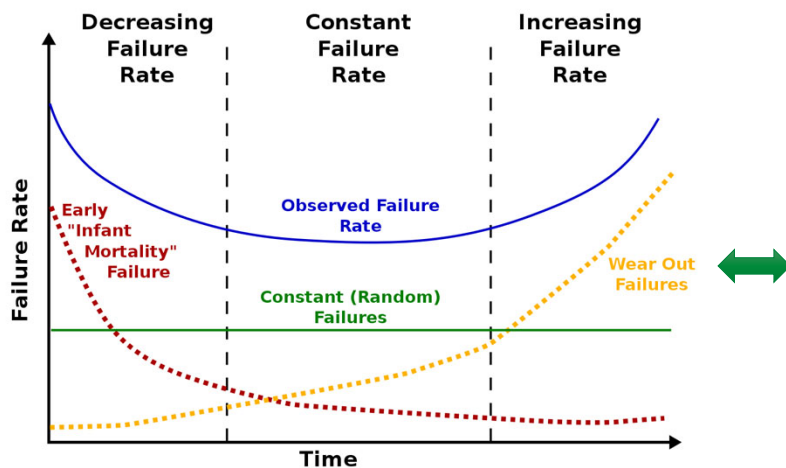
- The bar chart presents the pre-failure work time of total replaced inverter cases, which shows that most inverters with replacement records failed within the first four years.
- After reaching the lowest number in “5~6 years”, the failure number grows again as time goes on.



Industrial Dataset Analysis

Typical “Bathtub” Shape of Inverter Failure Rates

- The typical “bathtub” shape shown in the trend of inverter failure rates exhibits that *our industrial inverter failure dataset has enough failure cases needed* by the deterioration modeling, promising a reliable dataset for the prognosis analysis.

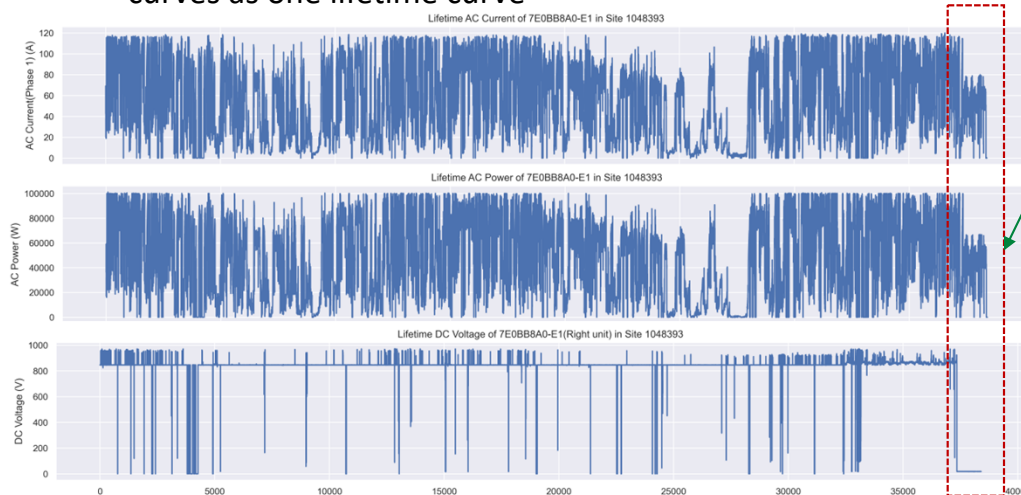


Industrial Dataset Analysis

Industrial Data-Driven Degradation Analysis

Case 1 : Health Indicator-Based Degradation

- The AC current, AC power, and DC Voltage (one of the three units) curves of Inverter 7E0BB8A0-E1 over its lifetime, starting from July 21st, 2019, to Sep. 27th, 2021, are shown below.
 - The inverter was installed on **Mar. 26th, 2019**, and replaced on **Oct. 19th, 2021**.
 - We only clip the **time slot from 10:00 am to 2:00 pm** for daily curves and combine modified curves as one lifetime curve



9/14/2021 to 9/27/2021

Low voltage (Inverter is not producing energy)	6	09/14/2021 19:08
Inverter - Production issue detected	7	09/16/2021 13:48
RCD	6	09/27/2021 10:48
Inverter - production issue detected (status error)	1	09/27/2021 12:43

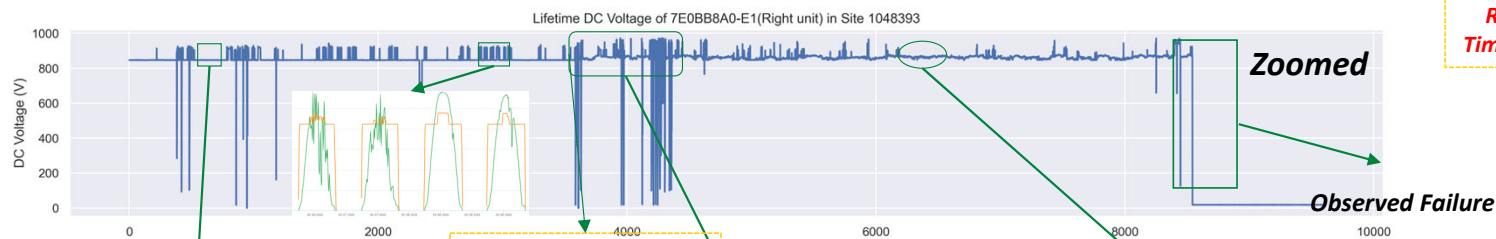
Low voltage: The inverter's voltage is low; The inverter is not producing energy
RCD: High residual current has been detected by the inverter

Industrial Dataset Analysis

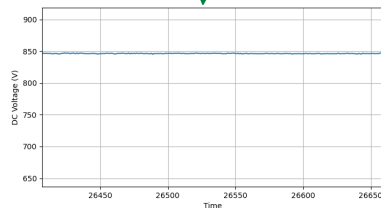
Industrial Data-Driven Degradation Analysis

Case 1 : Health Indicator-Based Degradation

- The inverter 7E0BB8A0-E1 was installed on 3/26/2019. Failure emerged on 9/5/2021, and it was replaced on 10/19/2021.



Normally working condition: DC voltage curve is flat, and the value almost stays constant.

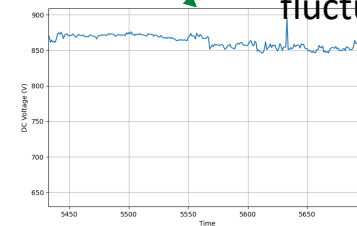


Start Time: 5/25/2021

Change point: Large shock occurred in the PV system, and the DC voltage showed sharp fluctuation.

<input type="checkbox"/>	Inverter production issue detected	2	05/16/2021 14:23
<input type="checkbox"/>	Inverter not producing energy - low voltage	2	05/17/2021 20:13
<input type="checkbox"/>	Residual current device	1	05/25/2021 12:53
<input type="checkbox"/>	Residual current device	1	05/25/2021 12:53
<input type="checkbox"/>	Residual current device	1	05/25/2021 12:53
<input type="checkbox"/>	Residual current device	1	05/25/2021 12:53
<input type="checkbox"/>	Residual current device	2	05/26/2021 08:58
<input type="checkbox"/>	Residual current device	2	05/26/2021 08:58

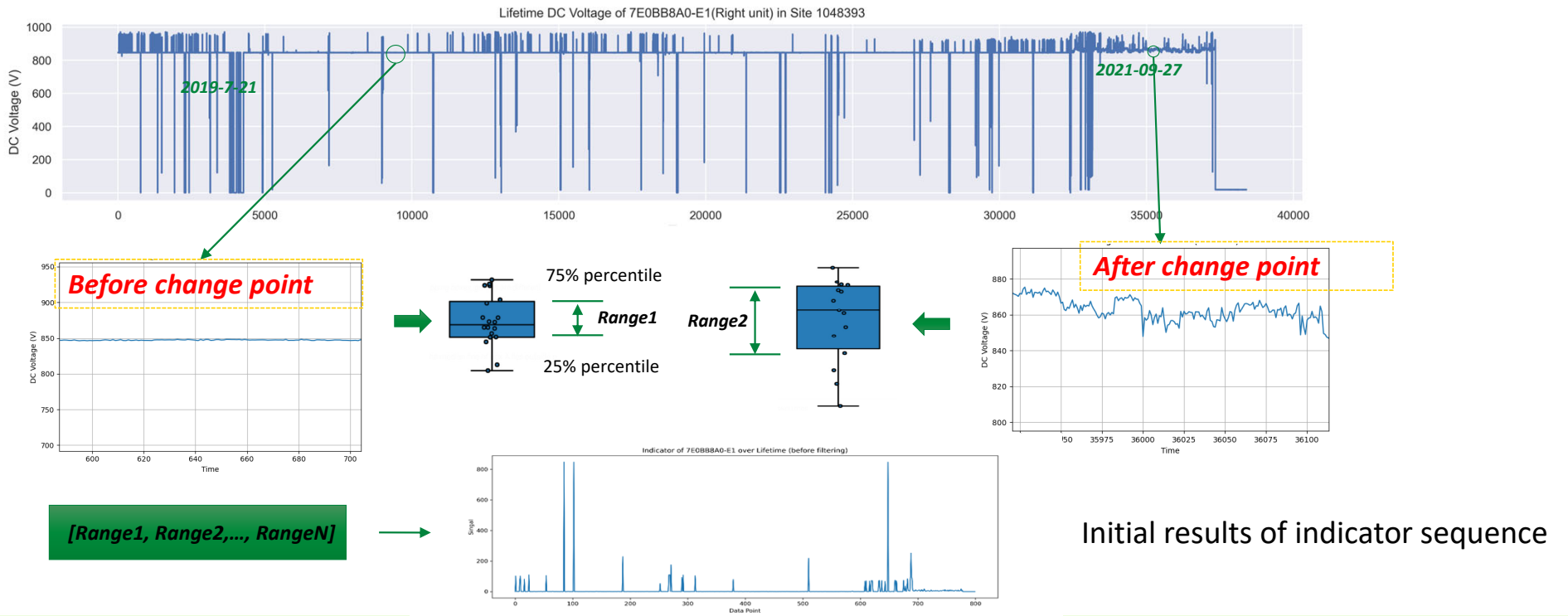
Degradation: After the change point, DC voltage started to fluctuate



Industrial Dataset Analysis

Industrial Data-Driven Degradation Analysis

Case 1: Health Indicator-Based Degradation

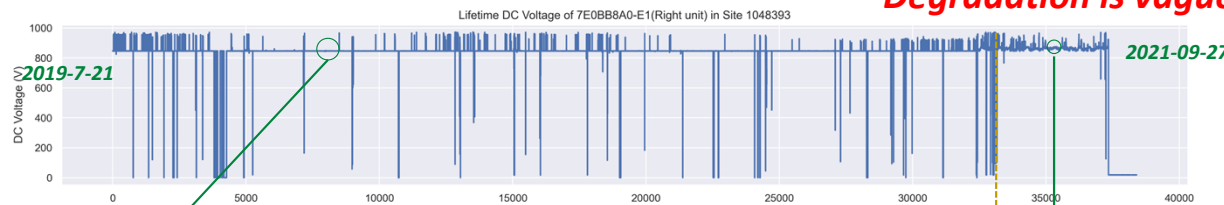


Industrial Dataset Analysis

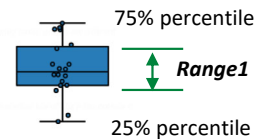
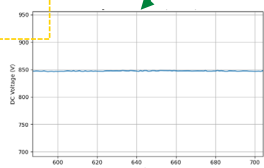
Industrial Data-Driven Degradation Analysis

Case 1: Health Indicator-Based Degradation

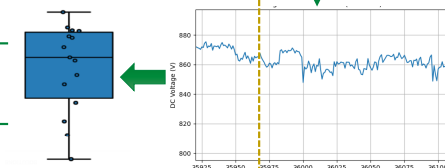
Degradation is vague in original curve



Before change point



Range2

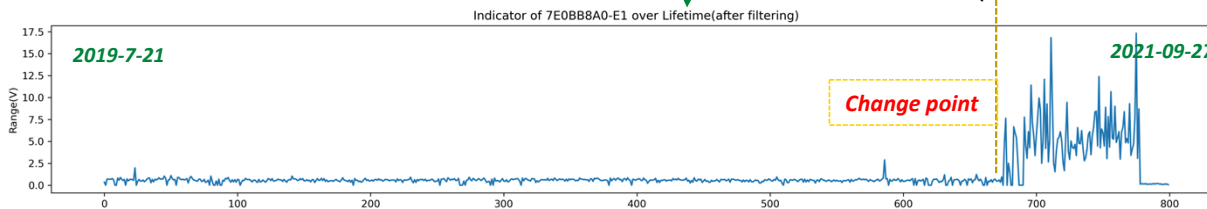


After change point

[Range1, Range2, ..., RangeN]

Threshold Filter

We filter the results by removing the data points larger than the Threshold (Threshold set as 30V).



Change point

Clearer in indicator curve

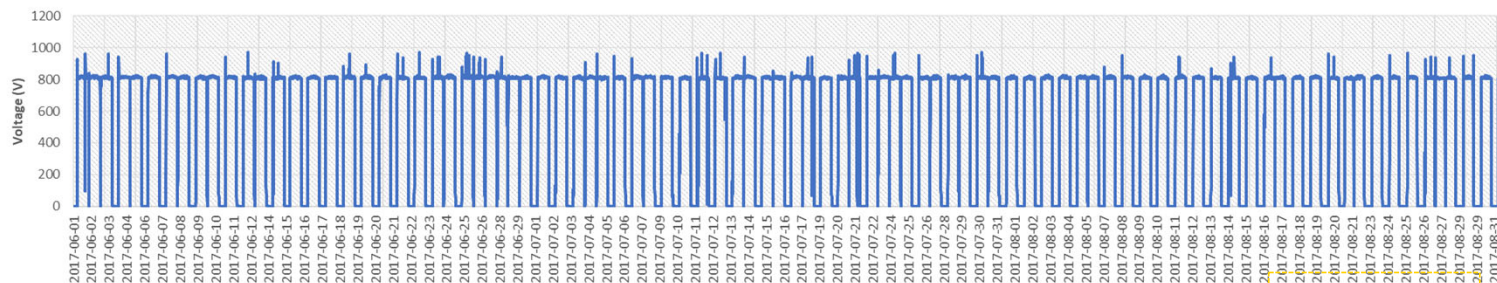
Industrial Dataset Analysis

Industrial Data-Driven Degradation Analysis

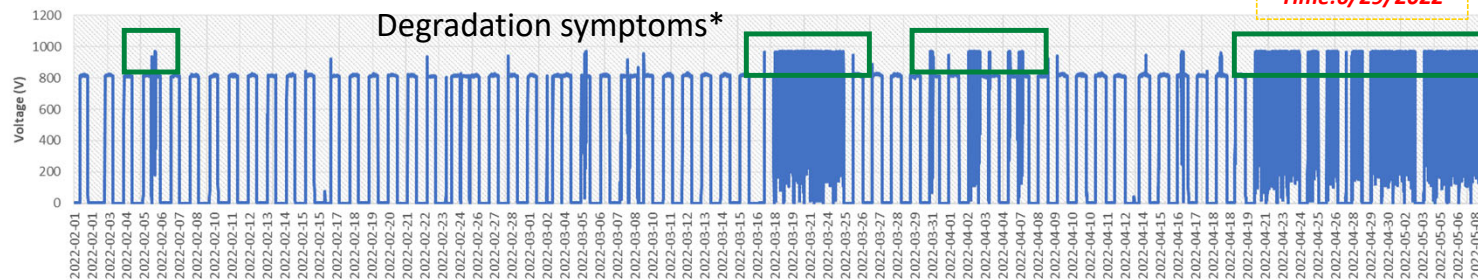
Case 2: Anomaly Events-Based Degradation

- The inverter BE101AB7-9F was installed in 5/30/2017 and observed failure on 4/20/2022.

DC Voltage of BE101AB7-9F from 6/1/2017 to 8/31/2017



DC Voltage of BE101AB7-9F from 2/1/2022 to 5/25/2022



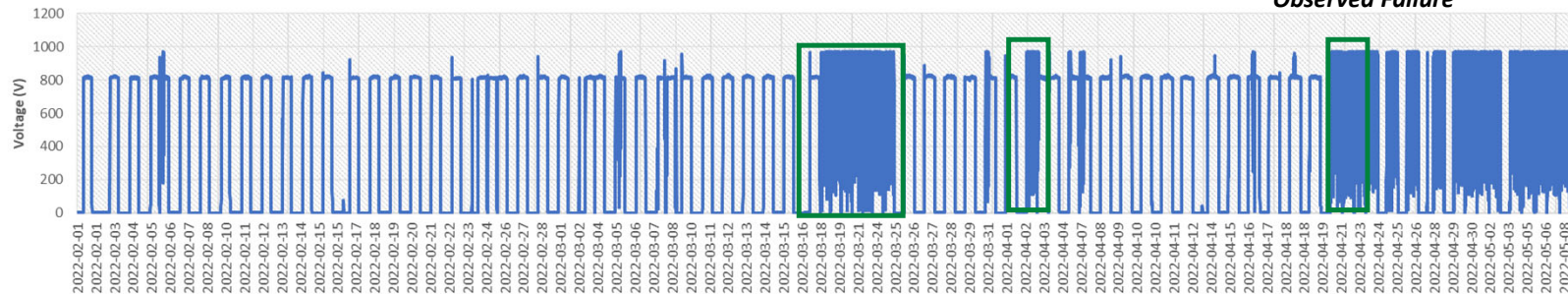
*Only partial samples are marked to show the degradation symptoms.

Industrial Dataset Analysis

Industrial Data-Driven Degradation Analysis

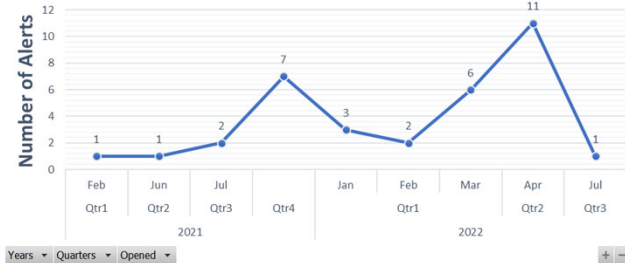
Case 2: Anomaly Events-Based Degradation

DC Voltage of BE101AB7-9F from 2/1/2022 to 5/25/2022

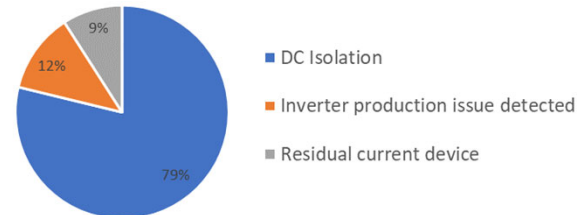


Count of Alert Type

Number of alerts detected in BE101AB7-9F



- Total 33 failure related alerts observed including: ***Inverter production issue detected***, ***Residual current device***, and ***DC Isolation***.

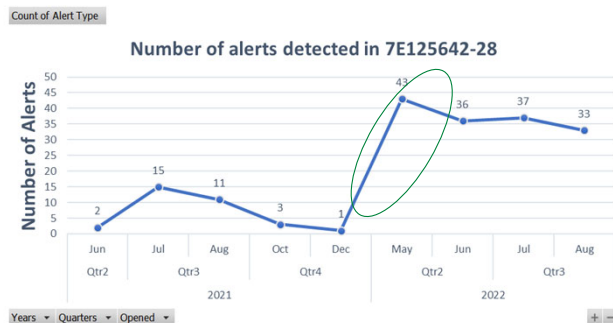


Industrial Dataset Analysis

Industrial Data-Driven Degradation Analysis

Case 2: Anomaly Events-Based Degradation—Preliminary Application

- The inverter 7E125642-28 was installed on 11/18/2016 and has lost data updates since 8/30/2022.



- Total 180 failure related alerts observed including: **Inverter production issue detected, Residual current device, and DC Isolation.**

