EPRI



2024 White Paper

# Enhancing PV Inverter Reliability Through Predictive Maintenance: Insights from Retrofitting of PV Inverters



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# INTRODUCTION

Photovoltaic (PV) systems have emerged as a pivotal solution in the global transition toward environmentally friendly and sustainable energy generation. Inverters serve as the vital link connecting solar panels to the grid, which is crucial in transforming the direct current (DC) power produced by solar panels into the alternating current (AC) energy essential for household and industrial applications. Inverters also optimize energy output, ensuring maximum efficiency even in harsher environmental conditions. Their ability to effectively synchronize with the electrical grid enables solar energy to supply the broader energy demand. Moreover, inverters improve monitoring and safety features by rapid shutdown and anti-islanding, enhancing safety and system reliability.

However, despite their key role, inverters have been pinpointed as the primary cause of corrective maintenance and operational disruptions in large-scale PV plants. The literature survey conducted by P. Hacke et al. shows that about 70% of all operations and maintenance (O&M) events in utility-scale PV plants are due to inverters, as shown in Figure 1 [1]. Inverter failures can impact overall system performance significantly. Common causes of inverter malfunctioning include overheating, electrical surges, component degradation, and other defects. Such failures can disrupt energy production, leading to substantial system downtime and significant financial losses. Thus, addressing inverter reliability has become crucial to improving the performance and long-term reliability of solar PV plants.

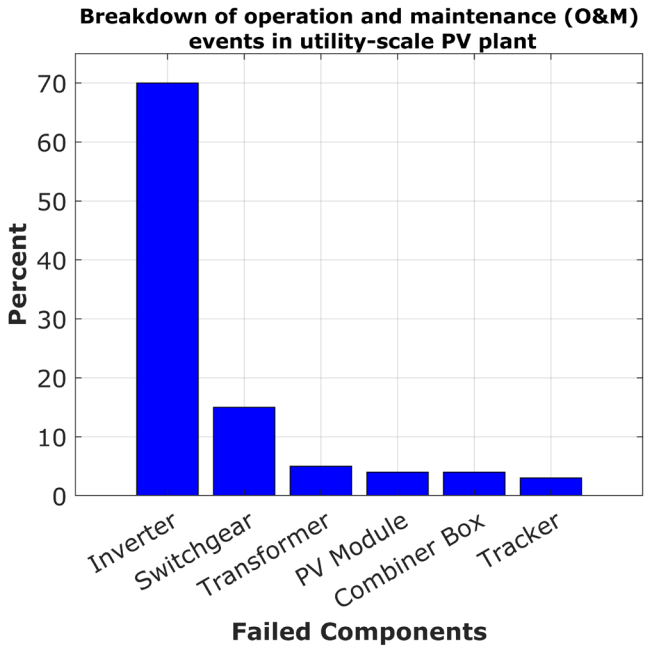



***Figure 1.*** *Breakdown of O&M events in utility-scale PV plants (P. Hacke et al. [1]) .*

Gaining additional insights on the reliability of PV inverters requires delving into the specific components within PV inverters that are prone to failures. The literature survey conducted by EPRI suggests that specific components with higher failure rates include cards/boards, contactors, fans, IGBTs (insulated gate bipolar

transistors), fuses, and capacitors, as shown in Figure 2 [2, 3]. The main cause of this type of component failure could be overheating due to electrical stress, degradation over time, environmental effects, or manufacturing defects.

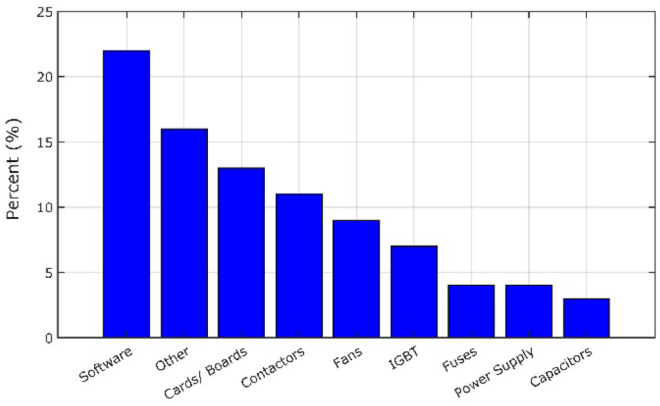



***Figure 2.*** *Frequency of failure of components of solar inverter (source: EPRI literature survey [2, 3])*

In another study by EPRI, 40 failed string inverters from a utility-scale PV plant were analyzed, as shown in Figure 3. Components such as current and voltage transformers (CT&VT), inductors, contactors (AC), IGBTs, capacitor banks, and communication boards failed the most, consistent with the findings of the literature review mentioned earlier [2]. Therefore, it is essential to adopt a predictive maintenance approach by monitoring the components. This proactive strategy allows for corrective actions to be taken in time to prevent actual failures.

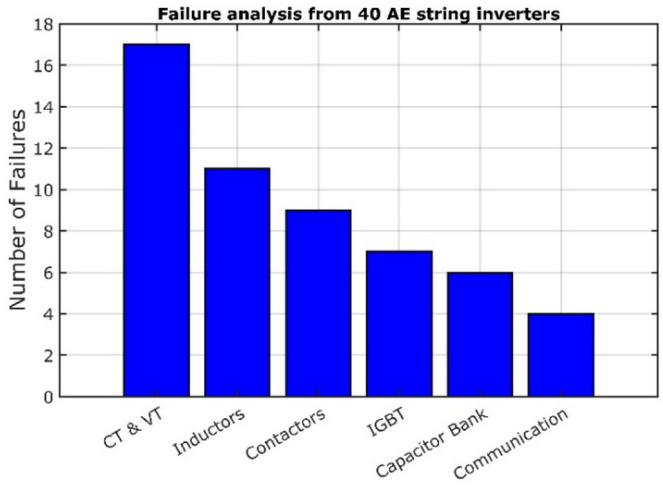



***Figure 3.*** *Frequency of failure of components inside string inverter (source: visual examination study by EPRI)*

The predictive maintenance strategy monitors system parameters and inverter components to collect specific data on operational reliability and performance changes in the system. The inverter's existing sensors might not be sufficient to fully capture the operational reliability of individual components. Therefore, additional sensors can be installed in the inverter to monitor the performance of individual components. The primary aim of retrofitting an existing inverter with new sensors is to improve the reliability of its components, thereby enhancing overall efficiency and performance. This modification both addresses predictive maintenance needs and monitors frequently failed components to increase their service lifetime.

This research also surveyed EPRI members and other industry professionals to understand the status quo and to obtain insights from owners and operators regarding inverter preventive maintenance and retrofitting at large-scale PV plants. The survey revealed that industry experience with inverter predictive maintenance is limited, and adoption of predictive maintenance through retrofitting of inverters with additional sensors is nonexistent. This is due in part to 1) these plants being relatively new for large-scale generation; 2) agreements between PV plant owners and third-party O&M teams, or O&M strategy employed by the PV plant owners; 3) contractual arrangements with original equipment manufacturers (OEMs) that may limit what changes are permitted; and 4) limited resource availability. The goal of analyzing this cumulative industry experience is to identify common themes, gaps, needs, and opportunities for improvement that can impact PV system reliability, with a focus on inverter reliability. This is of particular importance since extending component lifetime and improving inverter reliability through retrofitting and predictive maintenance may introduce new challenges.

## CURRENT STATUS OF PREDICTIVE MAINTENANCE AND RETROFITTING

Most existing experience in predictive maintenance and retrofitting stems from laboratory-scale endeavors, and there are challenges when attempting to apply these insights to utility-scale PV plants [2]. Several laboratory-scale methodologies may be excessively complex for practical use in real-world contexts. However, there are some promising techniques for failure prediction. To achieve broad acceptance and applicability, these techniques need additional validation and refinement through comprehensive field testing at utility-scale PV plants.

Contemporary inverter designs by various OEMs facilitate an array of data points via the communication module, allowing for the monitoring of component-level temperature and electrical signals. However, only a limited number of O&M teams overseeing utility-scale PV plants are currently leveraging these signals for predictive maintenance purposes. The prevailing approach predominantly utilizes performance data and a sparse set of alarm points. This approach provides information only on whether the inverter is operational, not on whether certain of its internal components are functioning. The limited set of alarm points can generate false positives, leading the O&M team to neglect these alerts when directing their activities.

To enhance predictive maintenance practices for solar PV inverters, a crucial step is refining the alarm system by strategically categorizing alerts and addressing the challenges of false positives and false negatives. Creating well-defined alarm points is essential to prevent the potential decline in vigilance over time that results from unnecessary alerts due to false positives. By categorizing alarms based on severity and urgency, operators can prioritize responses and allocate resources more efficiently. On the other hand, false negatives can be reduced by incorporating additional sensors and diverse sensing technologies. This multifaceted, more comprehensive monitoring system reduces the likelihood of overlooking potential issues. By carefully balancing the sensitivity of the alarm system and implementing a diverse range of sensors, solar PV inverter maintenance teams can significantly enhance the accuracy of predictions, minimize false alarms, and ultimately optimize the overall reliability of solar PV plants.

There is a noticeable trend among PV inverter customers toward adopting predictive maintenance. This trend is driven by the desire for newer inverters, which offer more inbuilt sensor capabilities. These advanced inverters allow for the collection of detailed component-level data, such as the temperature of specific components, through supervisory control and data acquisition (SCADA) systems. This component-level data helps make predictive maintenance more accurate, enhancing the overall reliability and efficiency of the PV systems. However, fully integrated implementation remains elusive. Addressing common failure modes is the main goal of the companies. In considering sensors and components, the focus shifts toward the thermal model and software responses to power and temperature, rather than relying on specific sensors.

Understanding failure prediction models becomes crucial, particularly in scenarios where the impact of IGBT failures varies. This impact hinges on factors such as current, diode status, and the presence of temperature sensors. The thermal model's response to over-temperature is identified as a potential source of issues. Temperature and hot spots, influenced by design disparities among manufacturers, play a pivotal role in overall system performance. Precise thermal monitoring and modeling with a margin are highlighted as key elements for effective predictive maintenance. Hence, predictive maintenance strategies should prioritize the management of power and temperature issues, encompassing self-protection logic and voltage waveform reduction to mitigate damage.

Inverter testing laboratories have encountered inconsistent reliability among inverters produced by the same manufacturer. Upon investigation, it was discovered that inverters with a range of AC ratings may share identical power electronics components. Consequently, there is a higher likelihood of a reduced lifespan for inverters with higher power ratings produced by the same OEM, particularly within a specific range of AC power ratings. For instance, an OEM manufactures string inverters ranging from 25 to 50 kW. The power electronics devices used in the 25-kW and 50-kW models are the same, resulting in the 25-kW inverter being more reliable than the 50-kW model. This disparity in reliability underscores the importance of a nuanced examination of AC and power ratings of individual components to optimize the performance and longevity of inverters from a given manufacturer.

Overall, the review of the literature and expert opinion on the current status of predictive maintenance and retrofitting highlighted challenges in current maintenance approaches, the impact of geographical factors, and the need for addressing specific failure modes and their consequences.

# PREDICTIVE MAINTENANCE AND RETROFITTING: CASE STUDIES

## Predictive Maintenance Utilizing Existing Sensor

Utility-scale PV plant owners are utilizing the inbuilt sensors of inverters to conduct predictive maintenance activities. This use of advanced inverters, which collect detailed component-level data, enhances predictive maintenance accuracy and improves the overall reliability and efficiency of PV systems.

In a case study presented by a utility at an EPRI workshop, the utility is actively tracking inverter temperature data from different components, including coolant, cabinet, reactor, and busing temperatures, as shown in Figure 4. These temperature data channels are integrated into the data historian system, in this case, Maximo. The data historian helps store and manage historical data, providing a basis for analysis and predictive maintenance. The observations derived from the temperature data are then used to provide feedback to the O&M team.

In another case study by DNV GL and GreenPowerMonitor, an anomaly detection system was trained on historical data to create baseline models for analyzing new operational data of an inverter [4]. The system successfully identified a sustained anomaly in the inverter's behavior lasting over two months. A daily log pinpointed the top four features responsible for the anomaly. Through an analysis of this log, the frequency of occurrence for each feature was calculated, revealing that inverter power and heatsink temperature had the most significant impact. The inverter produced less power and operated at a higher temperature, indicative of potential issues, such as a filter requiring servicing. While operators might not have detected the anomaly manually due to its duration, the anomaly detection system could have facilitated early detection, identification of influential data channels, and implementation of corrective measures to enhance inverter performance and production.

While many owners and operators of PV plants lack experience in predictive analytics, certain PV plants have demonstrated confidence in leveraging sensor data from inverters for predictive analytics. For instance, at a National Renewable Energy Laboratory (NREL) inverter workshop in April 2024, an independent power producer (IPP) showcased its ability to detect IGBT issues early and execute repairs within approximately 2 hours of downtime, potentially avoiding several days of downtime resulting from IGBT failure [5]. Figure 5 shows the IGBT temperature during the days of normal and critical operation; the temperature is elevated during the days of critical operation.

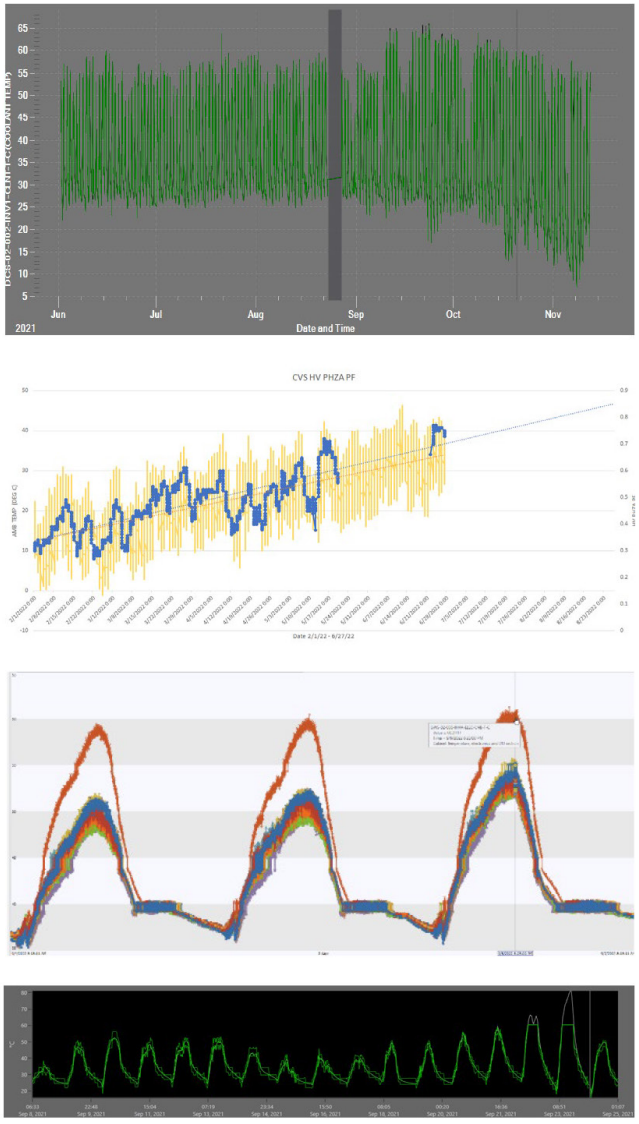



***Figure 4.*** *Tracking temperatures of different components of the central inverter of a utility-scale PV plant through SCADA*

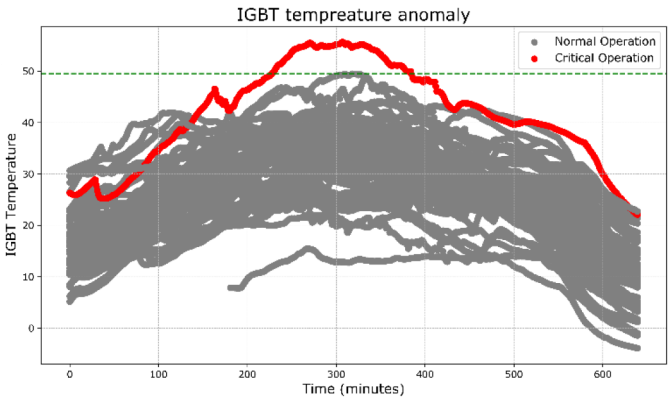



***Figure 5.*** *Anomaly detection on IGBT temperature through comparison of daily IGBT temperature profiles*

The O&M team has categorized the inverters in the company's portfolio into four groups—low, medium, mid, and high data—based on the data channels accessible through the inverters. It is apparent that modern PV inverters offer an increased number of data channels that can facilitate predictive analytics. Furthermore, the O&M team is progressing toward retrofitting inverters that have expired warranties to acquire additional data for predictive analytics. The project is currently conducting levelized cost of energy analysis before the retrofitting. This example underscores the industry's advancement in enhancing inverter reliability through the monitoring of component-level failures via predictive analytics.

To extract useful information and enhance the effectiveness of the predictive maintenance system, several key steps are required, such as fine-tuning temperature models and standardizing data and methods. The temperature models associated with different components need refinement to ensure prediction accuracy. Fine-tuning involves adjusting parameters and algorithms within the temperature models to better reflect the specific conditions of the solar inverter system. Achieving consistent and standardized data across different temperature channels is crucial for meaningful analysis. Standardization involves establishing uniform data formats, units, and methodologies for collecting and processing temperature data. This ensures that comparisons and analyses are reliable and meaningful.

## Retrofitting Case Study

The majority of retrofitting experience to date is at laboratory scale. Moreover, most of this retrofitting has been performed to study reliability prediction for particular components inside an inverter. These projects pose unique engineering challenges when implemented at the utility-scale PV plant.

EPRI conducted a retrofit case study at a utility-scale PV plant with a 23-kW string inverter (OEM A). The repowering of this inverter was necessary due to its market obsolescence and an annual failure rate of 5–10%. Retrofitting was also performed on two repowered inverters—OEM B (25 kW) and OEM C (25 kW). Hence, three inverters of each OEM were retrofitted in this study.

The inverters have been instrumented with four distinct types of sensors. The initial type, a thermistor, is utilized to monitor the temperature of critical components within the inverters, including IGBTs, capacitors, and inductors. Incorporating a humidity sensor allows monitoring of humidity levels within the inverter cabinet. Acoustic sensors have also been installed to detect fluctuations in switching frequency preceding IGBT failure and to monitor the noise emitted by the inductors prior to failure. Additionally, electrical sensors have been implemented on AC and DC sides to measure high-frequency electrical signals originating from the inverters. The instrumentation, showcasing the integration of different sensors across three diverse types of inverters, is illustrated in Figure 6.

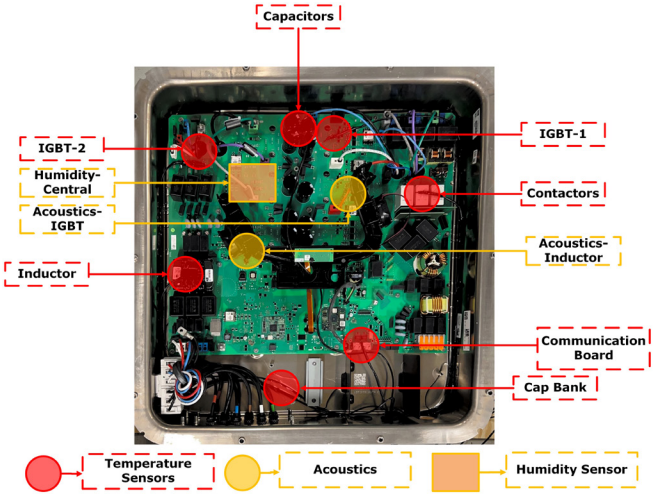



***Figure 6.*** *Retrofitting of 25-kW string inverter with temperature, humidity, acoustics, and electrical sensors*

Furthermore, a data monitoring package has been developed for continuous monitoring of the signal from the retrofitted sensors. The data monitoring system consists of a PQube meter for power quality monitoring, a data acquisition system for recording temperature and humidity signals, and a myRIO device for recording acoustics signals, as presented in Figure 7. The nine retrofitted inverters, three from each OEM, along with the monitoring package, have been deployed in the field at the commercially operated PV plant in North Carolina. The same number of retrofitted inverters are undergoing accelerated lifetime testing in the lab.

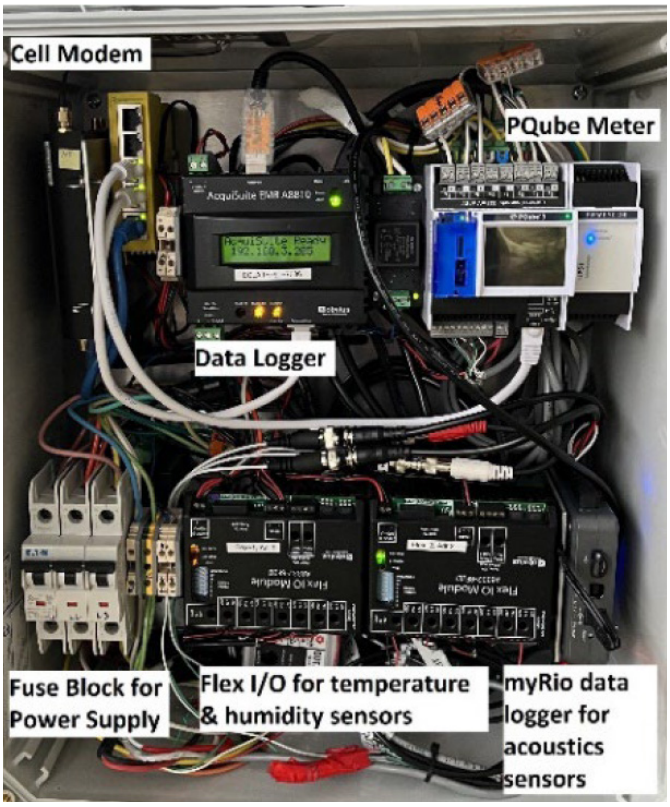



***Figure 7.*** *Data monitoring box with installed data logging devices for temperature, humidity, acoustics, and electrical sensors*

The inverters from all three OEMs are being tested under the same stress conditions, and one of the OEM A inverters failed prematurely. The root-cause analysis revealed that the failure was due to the degradation of the electrolytic capacitors (Figure 8). It was found that the extended storage without power before operation likely led to this issue. The failure appears to have been caused by a combination of higher ripple currents in the circuit block and increased leakage and heating from the capacitor's dielectric degradation. This suggests that the limited shelf life of the unit's electrolytic capacitors and the deterioration of the oxide dielectric layer, coupled with the high charge/discharge rate of the output topology, were the primary factors behind the failure.

During the same test sequence, OEM B observed a fan failure after 98 cycles (350 minutes per cycle), and the inverter failed within 1 cycle after the fan failed, with a noticeable amount of power derating. Data from different sensors have been analyzed, and the real-time anomaly has been detected. It can be seen clearly in Figure 9 that the rise in capacitor temperature during pre-failure operation (120 minutes before actual failure) is higher than during normal




***Figure 8.*** *Vented electrolytic capacitor, side and top views*

operation (gray plots). After doing post-failure analysis, it has been found that the fan failed during exactly this time. The capacitor temperature then increased exponentially above 100° C, and suddenly the electrolytic capacitor failed, causing the entire inverter failure.

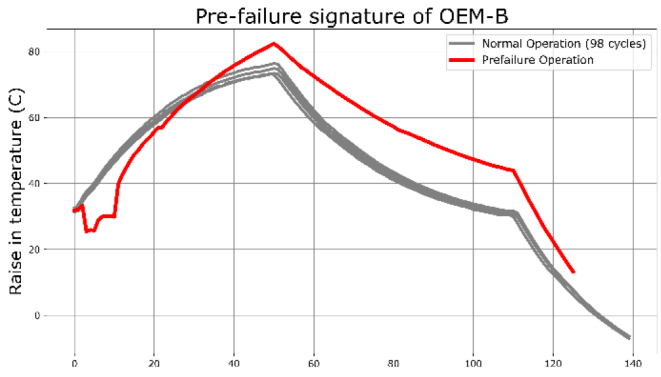



***Figure 9.*** *Rise in capacitor temperature during pre-failure operation*

Apart from the temperature data, the electrical data from the PQube were analyzed. As shown in Figure 10, the total harmonic distortion current (THDi) rises suddenly during pre-failure operations. Since the current injection to the grid is constant, the sudden increment of THDi serves as the pre-failure signature of AC harmonic filters or electro-

lytic booster capacitors. As shown in Figure 10, the THDi pre-failure remains above 4.9%, which is beyond the OEM's data sheet of normal operation. The frequency analysis and data from other sensors are currently being analyzed.

Retrofitting PV inverters at various case study locations involves navigating distinct challenges, emphasizing the importance of conducting a comprehensive site assessment through on-site visits before initiating the retrofitting process. Selection of appropriate equipment is also crucial. This study serves as an insightful illustration of the retrofitting procedure, focusing on an existing 23-kW string inverter alongside three different inverters of capacities 25 kW and 36 kW. The primary concern for PV plant owners and operators during inverter retrofitting revolves around the reliability of the chosen equipment. This investigation underscores the feasibility of retrofitting with three distinct inverter types of varying physical dimensions, a cost range with the highest cost nearly double the lowest, diverse electrical designs, and differing reliability profiles.

The dimensions and shape of the inverters emerge as key determinants for minimizing rework and adhering to guidelines for effective cooling and ground-level mounting position. Optimal performance in retrofitting is achieved by selecting an inverter with the highest possible maximum power point tracking (MPPT) number based on the available input strings. It is crucial that the designated inverter's capacity exhibit minimal deviation from the existing one, preventing overloading or underloading of other electrical components. A comprehensive analysis of the new system configuration is, therefore, essential before finalizing the inverter selection.

The integration of advanced technologies, such as machine learning and sensor networks, holds promise for enhancing predictive maintenance practices. However, the industry must overcome hurdles such as standardization of data and methodologies, as well as addressing false positives and false negatives in alarm systems, to fully realize the potential benefits. Additionally, the observed inconsistencies in reliability among inverters from the same manufacturer underscore the importance of thorough examination and optimization of individual components to maximize performance and longevity.

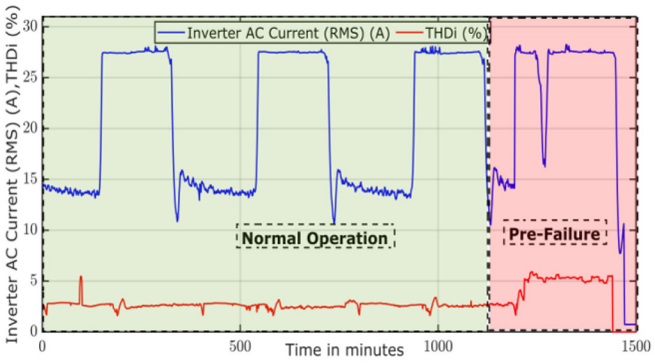



***Figure 10.*** *Deviation of THDi value over threshold during pre-failure operation of inverter*

## TAKEAWAYS

In conclusion, predictive maintenance represents a promising pathway in the solar industry, offering substantial opportunities to enhance the reliability and efficiency of solar power systems. Numerous applications and case studies underscore its potential benefits, particularly in optimizing the maintenance of crucial components such as inverters. By leveraging predictive analytics, maintenance teams can shift from reactive to proactive approaches, identifying anomalies in real time and addressing them before they escalate into costly failures. The empirical evidence from pilot studies and ongoing research highlights the effectiveness of predictive maintenance systems, emphasizing the need to balance sensitivity and specificity in detecting failures while considering operational and environmental variables.

The application of condition-based or predictive maintenance in the PV inverter industry is still relatively nascent. Many PV inverter customers are only beginning to explore the potential of predictive maintenance, driven by the increasing availability of advanced sensor technologies in newer inverters. The transition from reactive to predictive maintenance represents a significant shift in the industry, promising improved reliability and reduced downtime. However, many operators are still in the process of understanding and integrating these technologies into their maintenance strategies.

Predictive maintenance has been demonstrated to be effective in various case studies, including those conducted by Silicon Ranch, Southern Company, DNV, and EPRI. These studies show that predictive maintenance can significantly optimize performance, reduce unexpected failures and

extend the lifespan of PV inverters. By utilizing advanced data analytics and continuous monitoring, operators can identify potential issues before they lead to costly failures. This proactive approach not only enhances the operational efficiency of PV systems but also provides a more reliable energy supply.

Modern PV inverters come equipped with a variety of inbuilt sensors that can be leveraged for preventive maintenance. These sensors provide critical data on key parameters such as temperature, voltage, and current, enabling real-time monitoring and early detection of potential issues. For many operators, retrofitting existing systems with additional sensors may not be necessary, if the inbuilt sensors are utilized effectively. By maximizing the use of existing sensor data through SCADA systems, operators can implement predictive maintenance strategies without significant additional investment. However, this approach's efficacy should be validated on a case-by-case basis to ensure it meets specific operational needs.

For older PV inverters, retrofitting with new sensors is often necessary to implement predictive maintenance effectively. These legacy systems may lack the advanced sensor technologies found in newer models, making them more susceptible to unexpected failures. Retrofitting them with modern sensors can provide the necessary data for condition-based monitoring and predictive analytics. However, the business cases for retrofitting should be evaluated individually, considering factors such as the cost of retrofitting, the remaining lifespan of the inverters, and the potential benefits of improved reliability and reduced maintenance costs. Each case requires a thorough analysis to determine the most cost-effective approach.

Despite the proven benefits of predictive maintenance, there are still research gaps in understanding which sensors are most effective in detecting various failure modes while being economical for different types of inverters, both old and new. Current research focuses on identifying the optimal sensor configurations that can provide reliable data for early fault detection without incurring excessive costs. Further studies are needed to evaluate the performance and cost-effectiveness of different sensors across a range of inverter models and operating conditions. Addressing these gaps will be crucial in advancing the adoption of predictive maintenance and ensuring it delivers maximum value to PV inverter operators.

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