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MICROGRID SEQUENCE OF OPERATIONS DOCUMENTATION

BY LUCAS MILLER, *Mayfield Renewables*

If you ask five people to describe a microgrid you might get five different answers. But one universally required function that cuts across all the nuances of what can make a microgrid a microgrid is the ability to "island" from the grid while continuing to serve onsite electrical loads. Islanding is the process of disconnecting and later reconnecting to the grid. It is complex and specific to each microgrid project.

A Sequence of Operations document that was developed to aid in system design clarifies how a microgrid is intended to behave. In this article, we define common modes of operation for solar-plus-storage microgrid systems, explain the transitions from one mode to another, and provide a short list of key questions to ask early in the development process.

DEFINING A MICROGRID

There is no universally accepted definition of a microgrid (Figure 1). Instead, three essential features distinguish a microgrid from the broader electrical grid.

1. **The microgrid has an easily identifiable boundary from the rest of the grid.** Electrically-powered assets within the boundary will remain active even when the rest of the grid outside the boundary loses power. The boundary could be a subset of circuits within a building, an entire building, a group of buildings, or an entire campus.

2. **Resources within the microgrid can be controlled together.** Sophisticated controls are an essential ingredient in a microgrid. A typical control system includes many distributed controllers and sensors and a central supervisory control and data acquisition (SCADA) system to collect data and distribute instructions. The software behind the controls can balance the load by increasing generation or decreasing demand elsewhere on the microgrid, maximizing renewable energy usage, and minimizing other electricity costs.

3. **The microgrid is capable of functioning whether or not it is actively connected to the rest of the grid.** In general, everything inside the microgrid boundary should operate normally without relying on grid power. However, the amount of time a microgrid can operate independently will vary based on the microgrid generation and storage capacity, the size of the microgrid loads, and local weather conditions, among other factors.

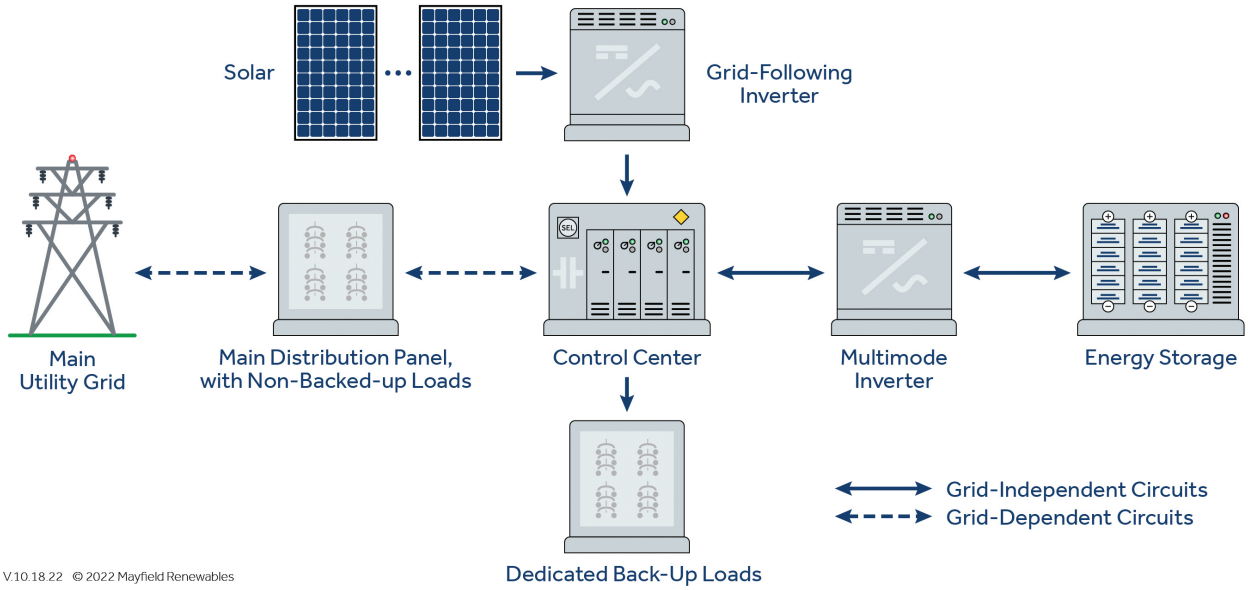


Figure 1: *This diagram shows a simplified example of an AC-coupled solar-plus-storage microgrid. The dashed lines indicate which circuits and loads will go offline during a grid outage. Solid lines show what will remain online, forming the boundary of the microgrid. The multimode inverter will become grid-forming during an outage, generating a 60-Hz sine wave for the solar inverter to follow. Only the loads in the Dedicated Back-up Loads panel will be operational during an outage.*

DEFINING MICROGRID SEQUENCE OF OPERATIONS

For the purposes of this article, let's consider a hypothetical microgrid consisting of a PV solar array and battery energy storage system (BESS) designed to meet resiliency goals by providing full backup during a grid outage and otherwise supply as many of the onsite loads as possible with electricity generated from the PV array. Based on the project goal (resilience) and equipment (solar array plus BESS) we can derive three main modes of operation:

Normal Operation

The microgrid (Figure 2) is connected to the grid, which operates within the expected voltage and frequency ranges. Since we want to be ready for a resiliency scenario, the energy storage system is programmed to maintain above a reserve state of charge. Any excess electricity generation from the PV array will be used to meet instantaneous loads, charge the BESS further, or export to the grid.

Grid Disconnection

The microgrid detects a grid outage (Figure 3) and undergoes the process of islanding. Once fully isolated from the grid, the solar array and BESS will become the primary power source for the microgrid. One of the BESS inverters will enter a grid-forming mode to provide a reference voltage and frequency for the entire microgrid system.

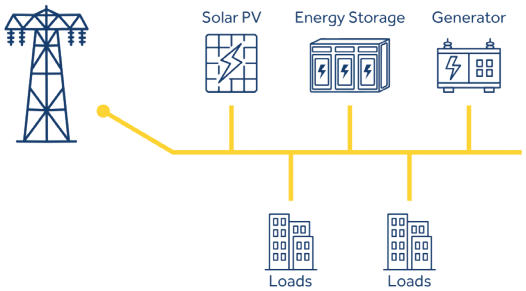


Figure 2: *Normal Operation*

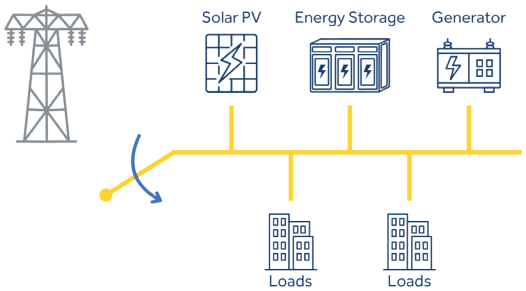


Figure 3: *Grid Disconnection*

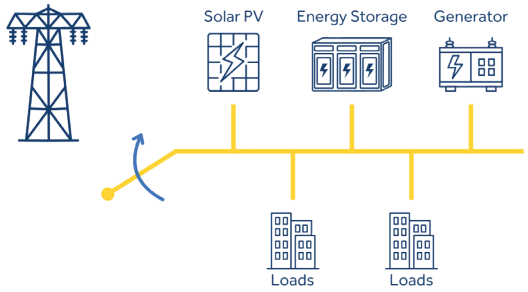


Figure 4: *Grid Reconnection*

Grid Reconnection

Grid power returns, and the microgrid transitions from being a self-sufficient energy island to a parallel connection to the broader electrical grid after detecting grid stability (Figure 4). The solar and BESS inverters all enter grid-following mode, relying on the grid as a voltage and frequency reference.

Starting with these three core operating modes, we can document how the components of the microgrid are intended to work together. This forms the basis of the sequence of operations (SO) document.

SEQUENCE OF OPERATIONS DOCUMENTATION

Microgrid development is highly collaborative. The end user and system owner should kick off the project by defining performance goals. The developer and engineer of record will determine the best path to meet those goals while also adhering to AHJ requirements and technical constraints. The best way to ensure goals are met — and any changes are addressed — is through documentation.



When we design a microgrid system, we assume the system will perform certain functions. Using a conceptual sequence of operations (CSOO) document, captures those functions to verify alignment between the designer, the client, and other project stakeholders. We begin using the CSOO document with the 30% preliminary design, the point at which major system components should all be specified. At later stages of the development process, the client may choose to share the CSOO document with the energy management system (EMS) manufacturer, who would review and revise the CSOO and program the EMS accordingly.

Returning to our hypothetical solar-plus-storage microgrid system, a CSOO for the three primary operating modes could include:

1. **Normal operation**. Export of excess PV to the grid vs. curtailment, routine BESS maintenance cycling, reserve state of charge for backup power requirements, and method of monitoring the grid signal for voltage and frequency anomalies.

2. **Grid disconnection**. Method of grid isolation, including whether the transition is closed or open (see next section); when the BESS inverter will enter grid-forming mode; and the energy storage state of charge reference points.

3. **Grid reconnection**. Method of detection of a stable grid; operations undertaken to reconnect to the grid.

ENGINEERING CONSIDERATIONS

Sequence of operations documents are customized to each microgrid project, but there are a few common variables to keep in mind.

Is an Open or Closed Transition Required?

In an open transition, the microgrid must fully break its connection to the grid before making a connection to other onsite generation sources. There will be a brief moment (on the order of a few milliseconds to a few seconds) during which the microgrid loses power during the transition. In contrast, in a closed transition, the microgrid establishes onsite generation sources as the primary power source (i.e., the BESS inverter enters grid-forming mode) before breaking

its connection to the grid.

A closed transition is seamless, but the equipment required is far more complex and expensive. Closed transitions are required for emergency backup loads. Open transitions are much more common for everyday backup loads because the equipment required is cheaper, easier to procure, simpler to program, and will not risk back-feeding between sources.

Are Any of the Backup Loads Considered Emergency Loads?

NFPA 70–2023®, *National Electrical Code®*, defines an emergency system as:

"…a system intended to supply, distribute, and control power and illumination essential for safety to human life."

If the backup loads for your microgrid fall into this category (e.g., lighting, heating, and cooling loads in a hospital), you must comply with more stringent code requirements, and your microgrid will require a closed transition to ensure power is never interrupted.

What Are the Microgrid Interconnection Requirements?

IEEE Std. 1547–2018, *IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces* sets baseline requirements for grid-interconnected distributed energy resources such as solar PV and BESS. Utilities can apply their own regulations on top of the IEEE 1547 standard, such as California's Electric Rule 21, *Generating Facility Interconnections*. All interconnection requirements must be adhered to during normal operation and must be factored into the grid disconnection and reconnection processes.

CONCLUSION

Microgrid sequence of operations documentation describes the common modes of operation and the methods by which the microgrid transitions between each mode. Using an effective conceptual sequence document ensures alignment between project stakeholders and acts as a basis for EMS programming. ■

REFERENCES

[1] NFPA 70–2023®, *National Electrical Code®*.

[2] IEEE Std. 1547–2018, *IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces*.

[3] California Public Utilities Commission. Electric Rule 21, Generating Facility Interconnections.



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FUTURE-PROOF FIBER NETWORKS REQUIRE THE HIGHEST QUALITY FIBER CABLES

BY JIM HENSCHEL, *Clearfield, Inc.*

New fiber-to-the-home (FTTH) networks are being built at a record pace. An integral part of any fiber network is the fiber jumper assemblies that help interconnect the systems, their branching devices, and fiber drops. Fiber network owners put a lot of emphasis on quality components to ensure a future-proof network with minimal maintenance and power costs that will last at least 15 years, and jumpers are one of those components.

There are cable assemblies, and then there are GR-326 approved cable assemblies. Some cable assemblies are also referred to as "designed to meet or exceed" cable assemblies. However, in this scenario, there is no mention of whether the assembly is Telcordia GR compliant.

Tier 1 and Tier 2 telcom provider networks are reaching further than ever before, which is key in closing the digital divide. To reach new and existing markets, it is vital to consider the elements each network is exposed to. For example, Alaska may see temperatures below –30° Celsius, while Puerto Rico might conversely be exposed to 65° Celsius with 97% relative humidity. This is not unique to these two specific markets. Customers across the globe require high-quality and high-performance cable assemblies to not only survive extreme temperatures, but also to maintain their performance through harsh conditions with minimal change in optical performance over a long period of time.

COMPONENTS

The rigorous design of a GR-326-certified cable assembly requires quality components.

Connectors

Many sources exist in the U.S. and dozens more offshore. When sourcing, look for well-known connector vendors that have a good reputation as well as accreditation for independent testing of their connectors. Be careful of the tested-to-GR-326 statement. Ask to see the certified test report. This will reveal who performed the tests, provide the actual insertion loss and return loss (IL/RL) results over temperature, and expose the baseline pre-test data vs. the post-test data.

Regarding the material itself, concentrate on the ferrule specifications. For example, a 125.5-µm inner diameter (ID) ferrule is recommended for high-performance single-mode (SM) connectors.

The next specification on the checklist is fiber hole concentricity. Use better than 0.5-µm concentricity. These specifications hold true for all SM Connectors with a 2.5-mm or 1.25-mm ferrule. The second component to examine is the connector strain-relief boot. These vary slightly in shape and size, so it is important to test all versions of a vendor's strain relief boot. Most vendors have at least two or three boot designs.

Cable

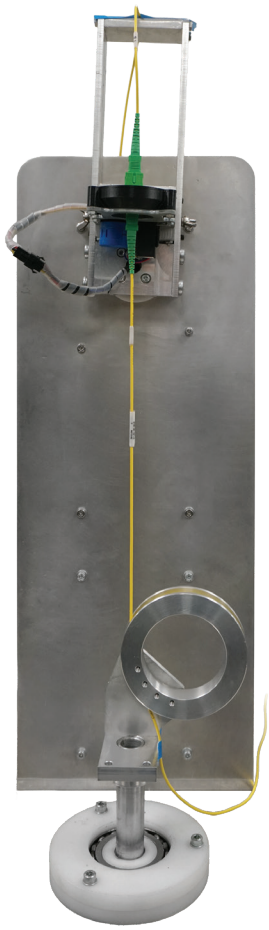
Generally speaking, it is commonplace to use a cable composed of top-tier single-mode glass. For cables with jackets ranging from a diameter of 1.6 mm to 3.0 mm, use a jacket material that offers a low (less than 5%) shrinkage rate. All indoor cables will have a certain amount of shrinkage, so to select the best fit, a round-robin approach can identify the right cable for the job. For 900-µm cable, be less concerned about shrink rates. That said, a tightly buffered 900 µm is best for this size of cable assembly.

Epoxy

This is likely the single most important component of the entire cable assembly. Without superior adherence between the glass and the ferrule, temperature cycling IL results would be very erratic. To start, look for a well-known local vendor. Make sure that the epoxy has an operating temperature that exceeds the GR-326 temperature requirements. Ensure the epoxy is rated for a glass transition temperature testing (Tg) of 100° Celsius or better. If a differential scanning calorimetry (DSC) analyzer is not available, many regional labs offer Tg testing.

Lapping Film/Rubber Pads

The accuracy and consistency of pad durometer, pad height, and pad life are instrumental in determining the desired result of the end-face geometry. This can usually be recommended by the machine manufacturer along with the lapping film. Diamond lapping film is required for efficient ferrule end-face shaping, and a silica dioxide final film is recommended for controlling the fiber height of the polish. Attributes such as grit size and density must be checked constantly.



Rigorous testing of flexibility and other aspects is required for fiber optic cables to meet the Telcordia GR-326 standard.

PREPARATION

Ferrules

Ferrules are often machined, which tends to leave some residue in the inside chamber of the ferrule hole from the machining and the ferrule hole itself. Many vendors clean their ferrules before shipment, but an additional cleaning step at the factory provides better results. This will help the adherence of the glass to the ferrule. An ultrasonic cleaner with an isopropyl mix or perhaps a detergent mixed into the water is best to use.

Cable

It is important to use the connector manufacturer's template for jacket and fiber strip lengths as well as Kevlar lengths. Be sure not to strip the 900-µm coating from the glass until the connector is ready

to be terminated. This will prevent the fiber from excessive exposure to air, which has been shown to leave fibers brittle. Once the fibers are stripped of their coating, cleaning the fiber with a lab wipe and acetone has been shown to result in the best performance when observing connector fiber heights over temperature. Once cleaned, the fiber should be immediately terminated to the connector.

Epoxy

Most epoxies used for GR-326 testing are a two-part epoxy (with the previously mentioned specifications). Removing air bubbles from the two-part mix is vital for a fully cured epoxy. This can be done using a centrifuge or a bell-jar-style vacuum. Epoxy with air bubbles can cause attenuation of the fiber over temperature, or even worse, cause a catastrophic failure. The other important factor is the mix ratio. If willing to go with a higher-priced epoxy, a pre-mixed and frozen (PMF) epoxy is a great option to ensure the epoxy is measured to the exact ratio for the two parts and excessive air bubbles are removed.

Polishing Machine

Select a machine vendor with very tight tolerances on their machines and polishing fixtures. The machine should have controls for downward pressure as well as platen speed. Use of a high-quality diamond lapping film is required for consistent geometry shaping of the ferrule end-face. Attributes like grit size and density must be checked constantly.

Fiber Buffer Stripper

The fiber stripper and epoxy are two of the main root causes for latent continuity issues. The desired epoxy specs have been mentioned above, so let's now focus on the fiber buffer stripper, which is needed to strip the 900-µm tight buffer from the 125-µm glass. The tool is an automated heat-and-strip tool. This is basically a buffer removal tool that uses heat as part of the process to ensure pristine glass, void of nicks or scratches. Lastly, the blades only penetrate a percentage of the buffer, which ensures the blade will never touch the glass.

Years ago (circa 1988), the use of mechanical strip tools was much cheaper and easier to replace. But these tools needed to be inspected every week, or even at a shorter duration, such as daily inspection. The test is quite easy to perform. All that is needed is a high-power microscope to inspect the whole length of the glass fiber to search for nicks and scratches. If any of these defects show up in the microscope, the fiber should be cut even with the buffer. Knicks and scratches are often overlooked.

Mechanical fiber buffer strippers that are calibrated to around 120 µm often cause these defects, which can lead to a nick or scratch to propagate into the cladding and/or fiber core. This would be classified as a catastrophic failure — one that could be avoided by using the automated heated buffer stripper.

Connector Curing Oven

Use of a high-capacity oven that allows the heating element to have direct contact with the ferrule is preferred. More economical ovens are available on the market that position the ferrules/connectors in a loose-fitting fixture, but this type of oven is not likely to achieve a full cure of the epoxy as recommended by the vendor. A Tg measurement is recommended to determine whether the cure time is too short due to the lack of heat transfer to the ferrule fiber hole.

Laser Cleaver

A laser fiber cleaver is recommended for its ability to make consistent cuts to the glass and also for reducing the epoxy bead removal step in the polishing process. The laser cleaver requires cleaning during the day, but has virtually no consumables to replace. Mechanical style cleavers have recently become more accurate and automated, so consider this as an alternative to laser cleaving.

Interferometer

This tool is crucial for the process design and as part of the manufacturing process for connector polishing. Most of today's interferometers will do the job, but using a well-known brand that offers regional customer support is ideal.

IL/RL TEST EQUIPMENT

It's common knowledge that laser and power meter (LPM) testing is the most accurate way to measure mated-pair-connector loss/reflectance. The equipment selected to perform insertion loss (IL) and return loss (RL) measurements should have good dynamic range, accuracy, and repeatability.

Choose a well-known test equipment vendor whose equipment offers a database and the ability to serialize and store IL/RL results. This is very important, as the GR-326 requires test results and component traceability.

PROCESS

This section outlines the process details and tips. Let's start with connector curing. If the epoxy vendor specifies a certain cure schedule, pick one and add either five degrees or another five minutes as a buffer for the cure schedule.

Polishing

The quality of the rubber pads the lapping film is placed on is just as important as the quality of the lapping film. Determining which rubber pad is needed requires a bit of process development, with ferrule pre-dome and ferrule hardness as the main variables in the equation. Empirical testing and a good-quality rubber pad can dial in the process as needed. Care in the maintenance of the rubber pad in manufacturing is of utmost importance. Ultraviolet (UV) light from ambient sunlight can cause the rubber to lose the durometer specified by the vendor.

Geometry

The current specification for ferrule radius is from 10 µm to 25 µm. Because there is a temporary deformation of the ferrule end face when mated and certain interferometers may have different tolerances, it is recommended to start with a geometry limit that is well within the GR-326 limit. For example, use an acceptable range of 12 µm to 22 µm, as opposed to accepting results that may be a few tenths of a micron inside of the limit.

Further, the geometries can be altered to reflect optimal performance, such as by using different durometer rubber pads and sometimes different pad heights, depending on the polish machine's manufacturer. Much like the radius requirements, the fiber height should have an internal control that is well inside the GR-326 limit. Because the post-cycling geometry limits for fiber height are +50 nm to -50 nm, pre-test fiber heights should be in the +10 nm to -40 nm range. Apex offset is usually a function of rubber pad quality and/or polish plate quality.

TESTING

For pretest IL and RL measurements, consider using an internal limit of better than 0.2 dB (objective) and 0.4 dB (requirement) to allow for some fluctuation that will certainly happen to some extent due to temp cycle/aging. The company can usually choose whether it uses a random mating process or a master test jumper for testing. This will need to be determined before environmental testing.

CONCLUSION

A good amount of empirical testing is required to fine-tune the GR-326 process. Consequently, this is the reason there are only a few Telcordia GR-326 approved cable assemblies. Beware of creative wording by the cable assembly vendors that imply they do Telcordia-witnessed or approved testing. In the end, it is an investment. Many Tier-1 providers require Telcordia-approved assemblies, and it follows that this is why GR-326-approved and accredited jumpers fetch a higher price. Quality is worth paying for, and some companies demand it. ■

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DISTRIBUTED ENERGY TRANSFORMER DISSOLVED GAS ANALYSIS STANDARDS DEVELOPMENT

HOWARD W. PENROSE, PhD, *MotorDoc LLC*

Wind turbine, solar, and battery storage — distributed energy resources (DER) — site transformers are generally excluded from dissolved gas IEEE and IEC standards for limits. The primary reason has to do with the unusually high levels of gassing that occur due to variable loads, harmonic content, resonance issues, and other conditions that are specific to DER applications. This has prompted American Clean Power (ACP), formerly American Wind Energy Association (AWEA), to task the DER standards group to develop gassing standards to assist balance-of-plant oil-filled transformer analysis. This is considered an urgent project as transformer failure rates are in the top five of major component failures on a DER site.

The first step was to combine the three internal standards groups involving wind, solar, and energy storage into a single group in 2024. The wind group is an ANSI-approved standards body with numerous best practices, notes, and standards under its belt. The other teams were recent additions with limited development. The groups were consolidated under the wind standards group, which primarily focused on such items as modification of IEC standards for structural and other similar mechanical systems, as well as some electrical.

In parallel, ACP's Balance of Plant Committee commissioned two projects. The first was a project with Doble that focused on mineral oil-immersed transformers. The second is an ongoing project associated with EPRI on synthetic oils that is planned for completion at some point in 2025. Each of these projects is reviewing populations of each type of transformer oil, gassing levels, and as-found conditions from a survey of primarily wind and solar sites. Battery storage (BESS) is assumed to be included, as these are generally built in as part of wind and solar projects and part of the balance of plant.

This article presents the basics related to the ongoing standards development, beginning with the first in-process standard on mineral oils co-chaired by Howard Penrose of MotorDoc and ACP standards Chair Chris Petrola of Enel and Kevin Alewine of Shermco. The second standard will kick off once the EPRI project is complete and will focus on synthetic oils.

MINERAL OIL STANDARD

The proposed title for the first standard is *ACP Guide for the Interpretation of Mineral Oil Gas Generation in Oil-Immersed Distributed Energy*



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Transformers. It is based on IEEE Std. C57.104–2019 (Revision of IEEE Std. C57.104-2008), *IEEE Guide for the Interpretation of Gases Generated in Mineral Oil Immersed Transformers* with its scope modified for DER systems. The Doble project, Transformer Risk Assessment and Mitigation Report, was performed for ACP in 2019 based on a March 2018 contract and is owned as a work-for-hire by ACP. Due to the transition of AWEA to ACP during that period, followed by COVID, little progress was made on the transfer of the data to a best practice or standard. In 2021, work and review were re-initiated based on the apparent need following the updates of industry standards that excluded DER transformers.

Initially, the idea was to incorporate the planned study on synthetic oils as part of a complete standard. However, during the March 2025 Balance of Plant and Standards Committee meetings, it was determined to do the same as other standards bodies and produce separate mineral oil and synthetic oil standards.

The Doble study was limited as it was performed while the organization was still AWEA, and the sole focus was on wind turbine transformer oil gassing. The study included three projects and deliverables:

- Review of dissolved gas analysis (DGA) data from populations of wind turbine transformers to determine norms for condition codes, gas, and combustible gas generation
- Review of failure reports and failure information to categorize primary failure modes
- Safety practices for oils with high concentrations of combustible gas

The data analyzed for the study consisted of over 20,000 DGA results from 5,172 transformers made by 16 manufacturers. The data was statistically analyzed and compared to a power industry study also performed by Doble. It was found that wind turbine applications, based upon gas, subject the transformers to more demanding operating conditions than were found in traditional power distribution applications.

The data used was compared to failed transformers from the population, where this is defined as being unable to return to service. The defects in which the gassing was correlated included the following:

- Arcing in the main tank
- Bushing failure
- De-energized tap changer
- Defective load break switch
- Internal faults identified by the manufacturer
- High DGA concentrations
- Failed electrical testing
- Mechanical defects
- Bulging of the main tank
- Converter
- Unknown failures
- Strategic replacement due to high gassing



Wind turbine applications, based upon gas, subject the transformers to more demanding operating conditions than found in traditional power distribution applications.

The prevalent gases found in the failed transformers include hydrogen, methane, ethylene, and acetylene, indicating issues such as partial discharge, high-temperature overheating of oil, and arcing conditions. It was noted that over 67% of the transformers exceeded IEEE C57.104 gas generation levels, which supports the concern that existing standards are not adequate for making DER transformer decisions based upon existing standards.

The primary causes were determined to be related to fluctuating loads, thermal cycling, harmonic conditions from tower inverters, and transient voltages. In addition, the transformers are often lightly loaded as the average USA capacity factor falls between 35%–40%. The result is that some turbine OEMs will make the transformer smaller than necessary for full load, resulting in gassing issues from overloads in addition to underloading. One significant issue is the high-order harmonics and core resonance from the inverter, whether the tower is an induction machine where the inverter is in series with the transformer or a doubly fed induction generator (DFIG) in which the inverter is in the rotor circuit.

The goal is to have the standard out for comment in early 2026 per the ACP ANSI process.

SYNTHETIC OIL PROPOSED STANDARD

Wind primarily uses mineral oils, but solar and BESS primarily use synthetic oils that have higher thermal ratings and gassing properties. The combination of oils used ranges from silicone to synthetic esters and natural esters (plant oil), each with thermal ratings well over mineral oils but with potentially drastically different gassing tendencies.

For silicone oils, IEEE C57.146, *IEEE Guide for the Interpretation of Gases Generated in Silicone-Immersed Transformers,* is referenced. Silicone oil exhibits unique gassing patterns with hydrogen, methane, and ethylene being the primary for electrical discharges. The generation of acetylene is less prevalent in arcing conditions.

For synthetic and natural esters, IEEE C57.155, *IEEE Guide for Interpretation of Gases Generated in Natural and Synthetic Ester-Immersed Transformers*, is used. Synthetic esters generally produce much lower concentrations of fault gases compared to mineral oils. However, their gas generation can vary based on the specific ester formulation and operating conditions. Natural esters, on the other hand, are primarily derived from vegetable oils and exhibit different gassing behaviors than mineral oils.

In the inverter applications associated with solar and BESS, the results are similar to wind transformers, where the gassing is different than in a standard application. The common oil as found in the EPRI work to date appears to be natural esters. Once the study is completed, a breakdown on how the results will be divided will be determined by the Standards Committee.

CONCLUSION

As DER step-up transformers are specifically excluded from industry standards for DGA purposes, it fell to the industry through ACP to develop a guide based upon industry experience. Because there are multiple oil types, similar to other utility industry transformer oils, standards are in development to provide guidance for each type based on the majority of use. The first, based on a study performed for ACP by Doble Engineering, will be mineral oils, which are primarily used in the wind industry. However, it is generally felt that the results should be considered for all mineral oil DER. The same will be developed once the EPRI study on esters and synthetics is complete. Overall, the result is expected to be a significant increase in DER step-up transformers. ■

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ADVANCEMENTS IN STATIONARY BATTERY TESTING FOR RENEWABLE ENERGY APPLICATIONS

BY SWAPNIL MARATHE, *Megger,* **and JOSEPH AGUIRRE,** *Spark Testing*

The global shift towards renewable energy, particularly solar power, is driving the clean energy revolution. However, solar energy's intermittent nature challenges grid stability and consistent supply. Stationary battery systems offer a crucial solution for energy storage and grid management, capturing excess solar energy during peak hours and releasing it when needed. These advanced systems smooth power fluctuations, provide backup during outages, optimize energy distribution, and build a more resilient and sustainable power infrastructure.

While large-scale stationary battery storage dominates current deployment, small-scale storage is also increasing. Various scenarios project the

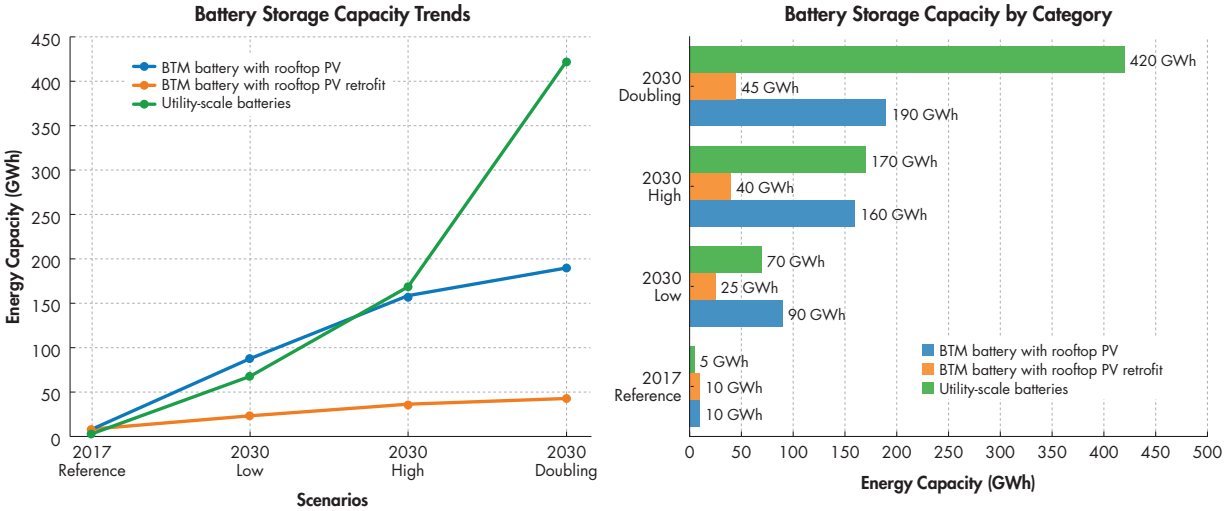


Figure 1: *Stationary Battery Storage Energy Capacity Growth, 2017–2030*
Note: GWh = gigawatt-hour; PV = photovoltaic; BTM = behind-the-meter SOURCE: IRENA, 2017[4]

adoption of battery storage by 2030, with the doubling scenario (Figure 1) showing increased stationary battery storage in response to the goal of doubling renewables in the global energy system by 2030.

In recent years, the renewable energy sector has witnessed remarkable growth, with photovoltaic (PV) systems, windmills, and other solar energy applications leading the charge towards a sustainable future. As these technologies evolve, so must the methods for testing and evaluating the stationary batteries that support them. This paper delves into the cutting-edge advancements in battery testing techniques specifically designed for renewable energy storage systems. We will explore innovative approaches that address the unique challenges posed by intermittent power sources, varying load demands, and the need for long-term reliability. By examining these developments, we aim to provide insights into how improved testing methodologies are enhancing the efficiency, safety, and longevity of stationary batteries in renewable energy applications.

CONVENTIONAL BATTERY (VLA/VRLA) TESTING

Impedance Testing

Impedance testing (Figure 2) shows a crucial method for assessing battery health in stationary

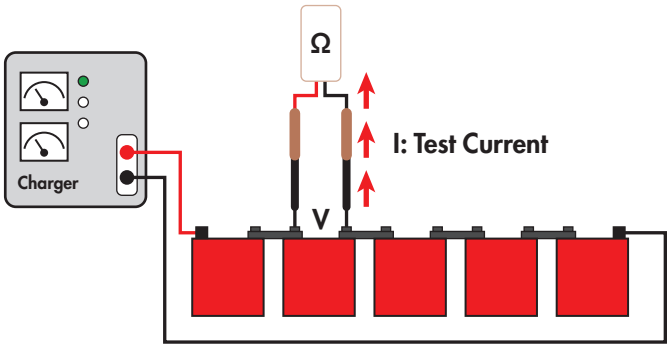
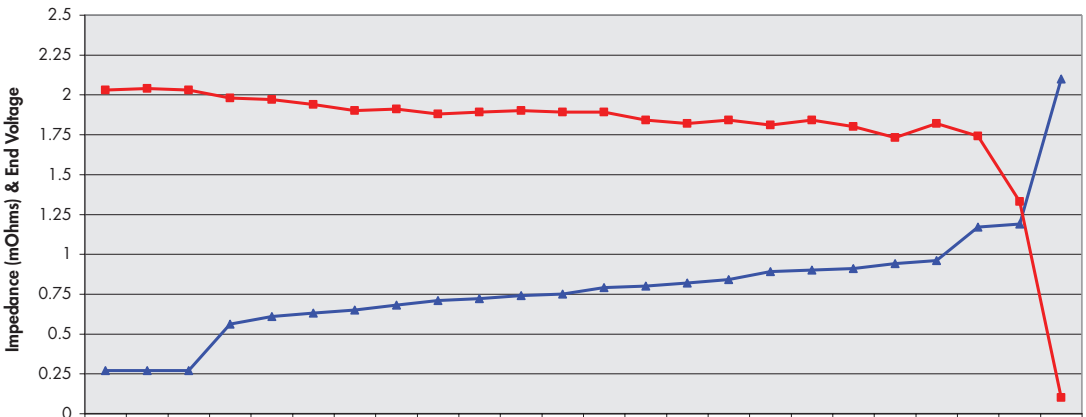


Figure 2: *Battery Impedance Test Setup*

applications. This non-invasive, online test utilizes a four-lead Kelvin measurement technique, where two leads inject AC current into the battery while the other two measure AC voltage. The internal impedance of each cell, comprising both resistance and capacitive reactance, is then calculated. This method is advantageous as it doesn't stress or load the battery during testing.

Ohmic Data Analysis

Ohmic testing, a relative assessment, compares current measurements to previous values or baselines to determine the battery's state of health (SOH). When analyzing data, voltage examination is critical, with tolerances typically within 1% of manufacturer-specified float voltages. Ohmic values can be analyzed through percent variation from the string average, percent deviation from baseline, and changes in inter-cell connection resistance. Key indicators of potential issues (Figure 3) include



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Imp	0.27	0.27	0.27	0.56	0.61	0.63	0.65	0.68	0.71	0.72	0.74	0.75	0.79	0.8	0.82	0.84	0.89	0.9	0.91	0.94	0.96	1.17	1.19	2.1
End V	2.03	2.04	2.03	1.98	1.97	1.94	1.9	1.91	1.88	1.89	1.9	1.89	1.89	1.84	1.82	1.84	1.81	1.84	1.8	1.73	1.82	1.74	1.33	0.1
Cell #	11	15	16	3	18	22	13	24	10	14	23	20	5	9	6	4	21	8	1	12	2	17	7	19

Figure 3: *Ascending Impedance with Corresponding End Voltage*

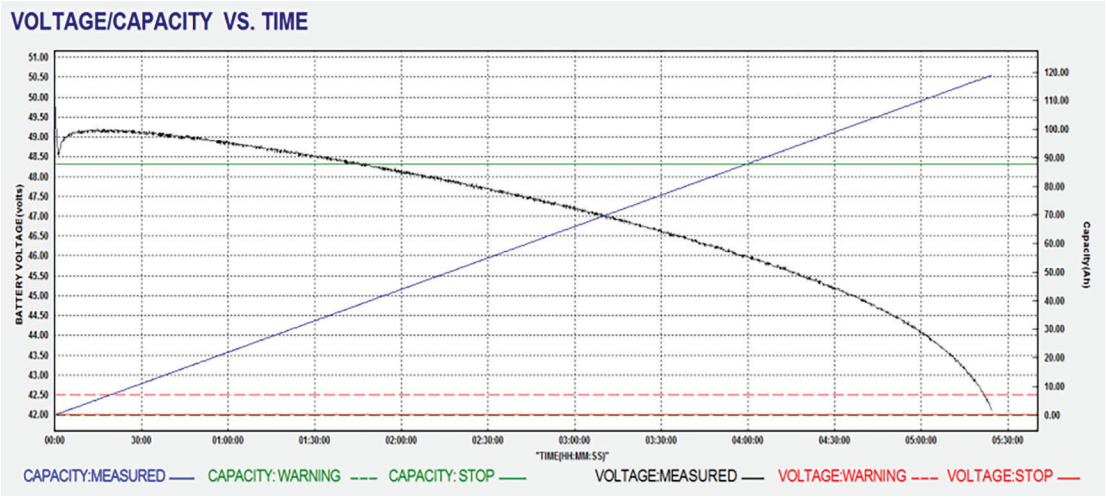


Figure 4: *Discharge Graph for a Discharge Test on Lead Acid Battery String*

batteries with 30–50% higher impedance than the string average, multiple batteries showing 30–50% change from baseline (signaling the need for a discharge test), and inter-cell connections with >20% resistance change (requiring torque checks and cleaning).

Discharge/Load Testing

IEEE Std. 1188-2005, *IEEE Recommended Practice for Maintenance, Testing, and Replacement of Valve-Regulated Lead-Acid (VRLA) Batteries for Stationary Applications,* outlines recommended practices for maintaining, testing, and replacing valve-regulated lead-acid (VRLA) batteries used in stationary applications (Figure 4). Two primary methods for capacity testing are described: the time-adjustment method (recommended for tests lasting over an hour) and the rate-adjustment method (for tests under an hour). Once a method is selected, it should be consistently used for all subsequent tests.

The time-adjustment method adjusts for temperature after testing and is preferred for acceptance and performance tests. Capacity is calculated using the actual test time, rated time, and temperature correction factor (KT). For tests using the rate-adjustment method, which suits shorter durations, the discharge rate may be adjusted for aging or kept at the full published rate. Temperature adjustments (using KC factors) ensure accurate capacity calculation.

Acceptance and Performance Tests

These tests require proper setup, maintaining discharge rates, monitoring cell voltages, and ensuring safety during weak cell bypassing. A service test simulates real-life duty cycles to verify battery adequacy. Batteries should be replaced when capacity falls below 80% of the manufacturer's rating, or if physical or performance characteristics indicate deterioration. Post-test procedures include restoring normal operations and safely recharging the system.



Ohmic testing, a relative assessment, compares current measurements to previous values or baselines to determine the battery's state of health (SOH).

EMERGING DIAGNOSTIC TECHNIQUES

Electrochemical Impedance Spectroscopy

Electrochemical impedance spectroscopy (EIS) is a powerful diagnostic tool used to measure the impedance, or resistance, within a battery.

Impedance measures a circuit's resistance to alternating current flow, varying with frequency unlike DC resistance. In EIS, the potentiostatic mode applies a voltage and measures the resulting current, while the galvanostatic mode does the opposite. The applied signal (E(t) or i(t)) and the response are phase-shifted and sinusoidal. Regardless of whether sinusoidal voltage E(t) is applied and current response I(t) is measured or vice versa, the response is phase-shifted relative to the input signal. Using complex notation and Euler's formula, impedance is expressed as:

$$Z = /Z/\, e^{j\phi} = Z_r + jZ_i$$

where:

- Z = *Total complex impedance*
- $/Z/$ = Magnitude of the impedance.
- $e^{j\phi}$ is Euler's formula representing the phase shift (in radians)
  where:
  j = Imaginary unit
  ϕ = Phase angle
- $Z_r + jZ_i$ is the rectangular form of the same complex impedance.
  where:
  Z_r = Real part (in phase) of the impedance (resistive component)
  Z_i = Imaginary part (out of phase) of the impedance (reactive component)

EIS experiments typically yield data including frequency, real and imaginary impedance components, magnitude, and phase angle. It assesses battery health by modeling the battery as a circuit with known elements and applying an AC signal across various frequencies to measure impedance response. This technique reveals information about electrochemical double-layer capacitance, charge transfer resistance, solution resistance, and diffusion processes. By analyzing changes in these parameters over time, EIS can detect electrode aging, electrolyte degradation, formation of solid-electrolyte interphase (SEI) layers, and changes in ion transport properties.

EIS data, typically presented as Nyquist or Bode plots (Figure 5), enables non-invasive, real-time monitoring of battery state of health (SOH) and can predict remaining useful life without complete knowledge of past operating conditions.

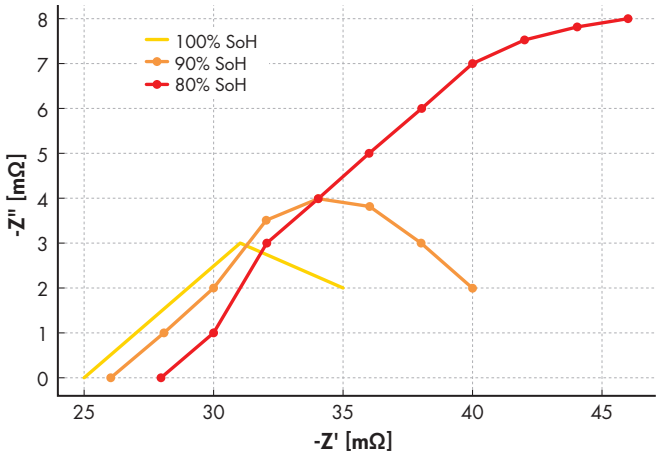


Figure 5: *Li-Ion Batteries with Unique Capacities Plotted Using EIS/Nyquist Plot*

Ultrasonic Tomography

Ultrasonic tomography is an advanced non-destructive testing (NDT) technique increasingly used for battery diagnostics, particularly in lithium-ion batteries. By transmitting high-frequency ultrasonic waves through a battery and analyzing how these waves are reflected or transmitted, researchers can create tomographic images that reveal the internal structure and condition of the cell.

Ultrasonic tomography involves placing transducers on or near the battery. These devices emit ultrasonic pulses (typically in the 0.1–15 MHz range) into the battery. As the waves encounter changes in material density, such as interfaces, defects, or gas pockets, part of the wave is reflected or altered in speed and amplitude. By collecting and analyzing these signals from multiple angles, it is possible to reconstruct detailed images of the battery's internal features, much like a medical CT scan.

Applications for Battery Testing

- **Defect detection.** Ultrasonic tomography can identify local microscopic defects such as metal impurities, voids, or dendrite formation, which are often invisible to electrical testing methods. Detecting these flaws early helps prevent catastrophic failures like internal short circuits or thermal runaway.
- **State-of-Health (SoH) and state-of-charge (SoC) monitoring.** Changes in the acoustic properties of battery materials correlate with

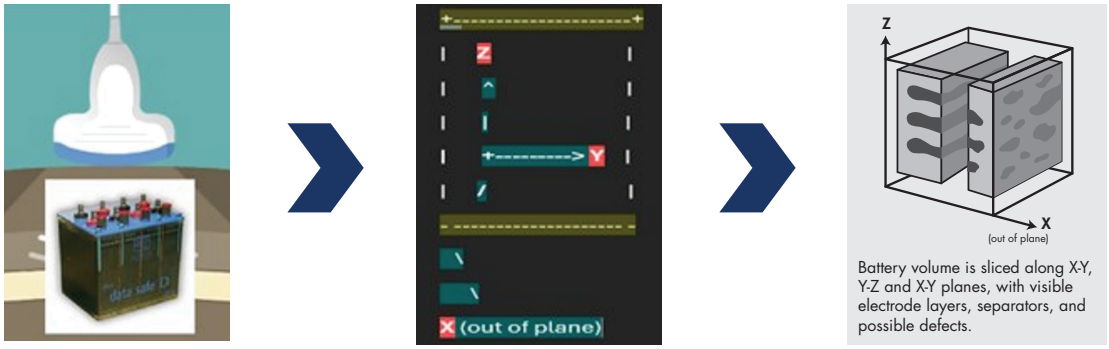


Figure 6: *Ultrasonic Battery Testing (Ultrasonic Waves > X-Y-Z Planes Plotting > Possible Defects)*

aging, degradation, and charge level. Ultrasonic data can be used to derive quantitative indicators of SoH and SoC, offering more accurate and real-time monitoring compared to traditional voltage or current-based methods.

- **Predictive maintenance.** Real-time ultrasonic monitoring enables proactive maintenance and enhances battery safety by providing early warnings of degradation or failure risks.
- **Quality control.** During manufacturing, ultrasonic tomography can be used to ensure internal consistency and detect manufacturing defects before batteries are shipped.

Future Potential

Ultrasonic tomography (Figure 6) offers a powerful, non-invasive method to enhance battery safety, reliability, and performance throughout the battery lifecycle. Advancements in transducer technology, signal processing, and machine learning are expected to further improve the accuracy and accessibility of ultrasonic tomography for battery diagnostics. Portable, cost-effective systems could soon enable widespread use in electric vehicles, grid storage, and consumer electronics.

Active Thermography

Active thermography is an advanced non-destructive testing (NDT) technique increasingly used in battery diagnostics, offering precise defect detection without compromising battery integrity. By applying a controlled thermal pulse — such as a flash of light or brief electrical excitation — and capturing the resulting heat diffusion with high-resolution infrared cameras, engineers can identify internal defects like delamination, voids, misaligned electrodes, weld inconsistencies, and early-stage internal shorts.

Unlike traditional inspection methods, active thermography visualizes hidden flaws by detecting localized anomalies in heat flow (Figure 7), making it suitable across all battery chemistries, including lithium-ion, LFP, solid-state, and nickel-metal hydride. In real-world applications, it plays a crucial role in R&D for design validation, in-line production testing for quality control, and module assembly checks to ensure uniform thermal behavior across cells. After installation, particularly in electric vehicles (EVs), energy storage systems (ESS), or backup power banks, active thermography serves as a predictive maintenance tool. Field technicians can use portable thermography units to monitor battery packs during operation, identifying subtle temperature anomalies that may indicate gas formation, separator degradation, or cell imbalance, long before failure symptoms appear in voltage or impedance. This allows operators to proactively isolate faulty units, prevent thermal runaway, and extend system life.

Applications for Battery Testing

For instance, EV fleet managers can incorporate routine thermal scans into service schedules to detect deteriorating cells, ensuring passenger safety and minimizing unplanned downtime. With its fast, contactless, and scalable nature, active thermography is proving to be an essential tool not just in manufacturing but throughout the operational life of modern battery systems.

Predictive Modeling

Predictive modeling is revolutionizing battery diagnostics by transforming raw building management system (BMS) data into actionable insights across electric vehicles (EVs), energy storage systems, and industrial backup applications. By applying machine



Figure 7: *Thermal Imagery Used to Illustrate Hot Points in Battery*

learning algorithms, such as random forests, linear regression, and long short-term memory (LSTM) neural networks, to real-time data like voltage, current, temperature, and charge/discharge cycles, predictive models can accurately estimate SoC, SOH, internal resistance, and aging rates.

Unlike traditional threshold-based diagnostics, these models recognize subtle patterns and forecast failures before they occur. A real-time example comes from a major EV manufacturer that deployed predictive analytics in its vehicle fleet: By continuously analyzing battery temperature rise during fast charging, the model flagged early signs of lithium plating in specific cells. Technicians were alerted through the fleet management platform, enabling preemptive cooling system adjustments and selective cell replacement, thereby avoiding expensive pack failures and recalls.

Similarly, in a utility-scale battery storage site, predictive modeling identified a cluster of modules with abnormal voltage decay during partial load cycles, prompting preventative maintenance weeks before alarms were triggered. After installation, these models continue learning and adjusting to operational conditions, detecting degradation under thermal stress, abuse cycles, or grid fluctuation.

Integrated with cloud platforms and digital twins, predictive modeling improves system-wide visibility, offers explainable diagnostics, and enables scalable anomaly detection across thousands of deployed assets. Ultimately, battery testing evolves from reactive checks to intelligent, real-time health monitoring, reducing downtime, enhancing safety, and extending asset life across all modern battery-dependent technologies.

Predictive modeling may be hindered by poor data quality, limited sensor coverage, model overfitting, lack of standardization, high computational demand, and difficulty adapting to new battery chemistries or unknown failure modes.

CONCLUSION

Traditional testing methods such as impedance testing, ohmic measurements, and standardized discharge tests have long served as the foundation for assessing battery state-of-health and performance consistency. These techniques, while essential, are increasingly being supplemented by more advanced diagnostic tools.

Emerging technologies such as active thermography, electrochemical impedance spectroscopy (EIS), and ultrasonic tomography enable non-invasive, real-time insights into internal battery conditions,

Table 1: *Cases Illustrating Active Deployment and Ongoing Research Using Predictive Modeling*

Implementation	Description	Outcome
NREL → SCE/ NextEra	Real-time physics-AI model for grid-scale storage	Optimized life expectancy and maintenance
EPRI + SRP	Module- and cell-level telemetry and analytics	Early detection of imbalance, standby loss
Academic PHM Studies	ML RUL predictions at substation scale	Forecasting within ±10 cycles

detecting early signs of degradation, material defects, or impending failures before they impact system performance.

Furthermore, predictive modeling powered by machine learning represents a paradigm shift in battery diagnostics. By analyzing real-time BMS data streams, predictive models can forecast failures, track aging, and recommend maintenance actions well before traditional metrics indicate issues. Such capabilities are essential not only for extending battery life but also for reducing downtime, avoiding catastrophic failures, and optimizing asset utilization across electric vehicles, grid storage, and critical infrastructure. ■

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Enhanced Bushing Assessment for Power Transformers

Transformer bushings are one of the most critical components of a transformer. Today, up to 22% of major failures on high-voltage transformers can be tracked back to bushings. Almost half of these failures result in catastrophic failures such as explosions, fires, or oil spills. The cost of these damages and the lost opportunity to deliver energy could be several hundred times higher than the price of a bushing.



Transformer Fire

Most modern power transformers will have two sets of bushings during their lifetime because transformers are expected to last 50 years, while bushings have an expected lifetime of 25 years. Experience suggests two points of failure within the lifetime of the bushings:

- The first failure point occurs between the ages of 10 and 13 years. This failure can arise from various factors, including design flaws, transformer operation, and potential quality issues, even though they are not aged out in life-cycle management terms.
- The second failure point occurs between the ages of 20 and 30 years. While bushings can fail before reaching this age, there are instances of transformers with bushings exceeding 50 years of age. Therefore, age alone cannot be the sole determining factor in bushing failure.

To prevent costly replacements of bushings based solely on age and without considering their actual condition, it is crucial to identify bushing failure mechanisms and causes. Bushing conditions are influenced by various operating conditions of the transformer, including overheating, load variations, frequent transient exposure, and intense pollution. Additionally, designs, types, and manufacturing processes can significantly impact the lifespan of bushings.

Moisture is a bushing's worst enemy. As a bushing ages, gaskets lose their ability to seal, thereby paving the most common way for moisture to enter the bushing. If moisture is allowed to enter the bushing, it will begin to break down the oil and paper insulation system. When this happens, the remaining concentric capacitors will have increased voltage stress across each capacitor.

As the breakdown goes unchecked and moisture continues to enter the bushing, the rate at which contamination is generated inside the bushing increases. This causes other layers to fail. At some point, there is a catastrophic failure of the bushing. Risk increases dramatically with age and voltage level. Bushings rated greater than 230 kV and older than 25 years fall into the highest risk category. The second highest risk category comprises bushings rated between 100 kV to 230 kV and older than 35 years.

While moisture ingress is the leading cause of bushing failures, the good news is that methods to assess the deterioration of a bushing's insulation system are available. Performing power factor measurements at multiple test frequencies helps identify compromised insulation. The power factor frequency sweep test involves performing power factor measurements at a series of various test frequencies (e.g., 15 Hz, 30 Hz, 45 Hz, 60 Hz, 150 Hz, 200 Hz, 300 Hz, and 400 Hz). As an oil-and-paper insulation system deteriorates, the frequency sweep trace typically becomes flat, or worse, decreases versus frequency.

Compromised insulation shows a distinct fishhook shape in the low-frequency range of the sweep (i.e., at frequencies below 60 Hz). If this occurs, the insulation system is considered questionable and warrants further investigation or increased testing frequency. One advantage of performing power factor frequency sweep measurements on the C1 insulation system of a bushing is that a bushing mounted on a power transformer has two or three similar-unit bushings that can be tested and compared to each other.

The frequency sweep traces should exhibit reasonably similar shapes when comparing similar-unit bushings. If the shape of the trace of one bushing deviates significantly from the shapes of the other similar-unit bushings, the dissimilar bushing should be investigated further or tested more frequently in the future.

In an effort to get the best indication of excessive moisture in a bushing, dielectric frequency response (DFR) should be considered in the testing process. For more information, access IEEE Std. C57.152, *Guide for Diagnostic Field Testing of Liquid-Filled Power Transformers, Regulators, and Reactors*, or call intellirent at 888-902-6111. ■

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How Third-Party Test Equipment Sourcing is Changing the Game for Electrical Teams

An Interview with Pam Stevenson, Director of Equipment Operations at TDS Equipment



With rising equipment costs, tighter project timelines, and increasing compliance demands, electrical teams are seeking smarter ways to access the necessary equipment without compromising quality or exceeding their budget.

That's why more professionals are turning to third-party equipment sourcing partners like TDS Equipment. Pam Stevenson, Director of Equipment Operations, explains how this shift is benefiting field teams and facility managers across the country.

Q: What's the biggest challenge you help your customers solve?

Pam: It comes down to keeping jobs on time and on budget. If a relay test set or hipot fails on-site, the clock starts ticking — and delays can get expensive fast. We step in with calibrated, reliable replacements, shipped immediately. Customers know that when they come to us, the gear will work the first time, every time.



Q: Most people might think of TDS Equipment as a rental company. What else do you offer?

Pam: Rentals are just one part of it. We also sell new and refurbished test equipment, provide full-service NIST-traceable calibration, and perform repairs. From megohmmeters and cable fault locators to temperature calibrators and IR cameras, we cover almost every category of test, measurement, and safety equipment.

Q: Why are more electrical professionals turning to third-party providers like TDS Equipment?

Pam: Because it's smart business. Managing and maintaining a fleet of specialty test gear is expensive. With third-party sourcing, you only pay for what you need, when you need it. That's a very cost-effective way to stay equipped with high-quality, job-ready gear, without tying up your capital. Plus, you're not worrying about calibration schedules or repair logistics. We handle all that for you.

More teams are moving away from owning everything outright. Instead, they're relying on trusted partners to supply calibrated, certified gear when and where it's needed.

Q: What makes your team and services stand out?

Pam: First, the depth of our inventory. Then there's our turnaround time — we move fast. But most of all, our people are experts. When a customer calls, they're not just talking to a sales rep; they're talking to someone who understands field conditions and can recommend the right tool for the job. And every item we ship is fully inspected and calibrated.

Q: Are there any trends you're seeing right now in the industry?

Pam: Definitely. More teams are moving away from owning everything outright. Instead, they're relying on trusted partners to supply calibrated, certified gear when and where it's needed. Documentation requirements are also increasing; customers want every piece of equipment to come with calibration records and traceability. We're already built to meet that standard.

Q: Any client stories that highlight how your team operates?

Pam: One utility called us in a panic when an unplanned outage hit over the weekend. We pulled the necessary equipment from our shelves, calibrated it, and shipped it the same day. By Monday morning, they were back online. That kind of service — and speed — is hard to find unless you have a third-party partner you can trust.

Q: What should new customers know about working with TDS Equipment as a third-party electrical testing equipment provider??

Pam: With TDS Equipment, the answer is always yes! We are the only vendor you need to call for all of your electrical testing equipment needs. We make it easy and economical. One PO can cover equipment from multiple manufacturers, and we offer competitive pricing and volume discounts. You get access to expertly maintained equipment, reliable turnaround, and responsive support. TDS Equipment is more than a supplier; we're a strategic partner for companies that depend on precision, performance, and safety.

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