How Renewable Energy Stresses Power Equipment, Leading to Failure

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Abstract

The transition to wind and solar power has led to significant changes in the way electrical power is generated, transmitted, and distributed. Large scale integration of wind and solar generation into the power grid has altered power system dynamics. The grid stability we once took for granted may suddenly be disrupted by voltage disturbances, harmonics, and other power quality issues creating stresses on high voltage power equipment that didn't exist before. Harmonics, for example, exacerbate the thermal and electrical stresses on power transformers, bushings and the medium voltage collection systems. Harmonics can also induce voltage waveform distortion which can complicate signal interpretation from online monitoring systems resulting in increased false alarm rates. This paper evaluates the impact renewable generation can have on equipment failure rates and investigates how online systems can be used to detect failure modes early, thereby preventing catastrophic equipment failure. Case studies will be used to demonstrate online monitoring's effectiveness in improving equipment reliability as well as driving the change from preventative and corrective maintenance to predictive maintenance and failure prevention.

Introduction

Large-scale wind and solar integration have fundamentally changed power grids. The shift from a rotating machine-based generation to wind and solar based generation has shifted the power grid from a physics-based grid to a control-system based grid. Traditional rotating machine-based power systems offered stable and reliable power grids with very few power quality issues. The inertia of these systems helped to minimize frequency and voltage deviations. When events occurred, the inertia of the generating systems helped to stabilize the system until the system fault could be cleared or the event subsided. Wind and solar generation utilize power electronics-based systems which do not offer the same level of stability we have come to expect. Power electronics-based invertors on their own do not provide inertia and offer little support to ride through system events. As a result, the same fault on a transmission or distribution system supplied by renewable generation, will result in much greater and faster voltage and frequency swings. While renewable providers continue to develop ways to manage these issues, the complexity of these systems means they are more prone to failure and adverse reaction to other parts of the system. Without the inertia provided by rotating machine-based generation, transmission and distribution systems may experience larger frequency swings, higher frequency rates of change, and greater voltage fluctuations during system events and switching.

Due to the high stress these assets are exposed to, many renewable providers are turning to continuous online monitoring to better manage their high voltage electrical assets and to prevent failures.

Transformer Failure Rates

"Warnings by both the Federal Energy Regulatory Commission (FERC) and the North American Electric Reliability Corp. (NERC) nearly 10 years ago that transformer failures pose insidious vulnerabilities to the nation's economy, public health, and security issues somewhat rattled the federal government into action." [1] While this has prompted increases in manufacturing capacity, the rapid expansion of the grid continues to outpace the supply which is prompting users to turn to online monitoring to increase visibility, prevent failures, and extend the life of their existing fleet.

Figure 1 lists the failures by component for power transformers, reactors and GSU's based data collected from CIGRE members. [2]

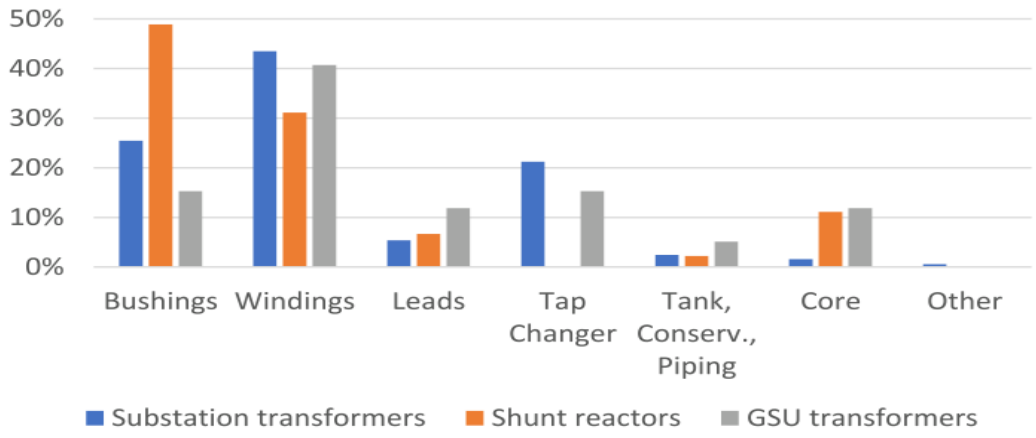

Figure 1 - Transformer Failures by Component

While these failure rates are for the industry as a whole and do not separate out failures in wind and solar applications, most industry working groups suspect the failure rates of transformers in wind and solar applications are higher due to the conditions they are exposed to. At this time, industry statistics are not available due to insufficient failure data. Understanding the types of failures, and the stresses which drive those failures can help with the selection of monitoring equipment to help prevent those failures.

Impact of Inverter-Based Generation on Transformers

Inverter-based generation is often associated with frequent switching, load swings, thermal cycling, harmonics, and voltage/frequency fluctuations which can degrade the health of electrical assets over time. While single events have little impact, the repeated stress these events have on transformers, bushings, URD cables, and pad mount transformers and can degrade their insulation systems quickly.

Over-voltages, Voltage and Frequency Deviations, and Switching Transients

Over-voltages are a growing concern with renewable generation because wind and solar plants are often connected through long underground cable systems into relatively weak grids. Long

URD cables increase system capacitance which reduces natural damping. During periods of high-generation, the capacitance of the line can drive a steady-state voltage rise (Ferranti effect). Since inverter-based resources have limited ability to absorb reactive power reactive, the voltage control margin is reduced which can result in over-voltages. Transformers in renewable applications can also be subjected to excessive overvoltage caused by extremely fast reactive power compensation. Due to the fast nature of these over-voltages, the OLTC in the transformer cannot operate quickly enough to provide relief. Thus, the voltage can rise above the dielectric ratings of the insulation resulting in failures. [3] [4] [5]

Unlike rotating-machine based systems, inverter-based systems lack the inertia to maintain system voltage and frequency during system events; hence they rely on power electronics-based controls to rapidly respond to changes in frequency and voltage. Rapid rates of change in voltage and frequency can create magnetic stress in the core by driving changes in the magnetizing current and stray flux. This can result in vibration in the core which over time can damage the winding insulation. In addition, during rapid changes in frequency, the controls will often inject reactive power which can result in overvoltage conditions discussed previously.

However, over-voltage is not the only concern. Most of the collector system in wind and solar applications are protected by vacuum breakers. When vacuum breakers operate, they can generate steep front high frequency transients. These transients can damage transformer windings, bushings and URD cables. In addition, during fault clearing, the low short-circuit ratio of URD cables in the collector systems can cause amplified temporary over-voltages. The result is greater cumulative insulation stress on GSUs, the collector equipment (URD cables and padmount transformers), and increased arrester duty.

An investigation of wind farm pad-mount transformer failures found that winding failures due to transients, pre-strikes, restrikes, and resonance/ferro-resonance were the leading cause of URD cable and pad mount transformer failures. The transients were the result of the open/close operations of vacuum circuit breakers serving wind farm collector systems. While the investigation focused on URD cables and pad mount transformers, power and GSU transformers, are also exposed to these transients and can be damaged over time. [3]

Figure 2 shows a comparison of a typical switching transient from a rotating-machine based system vs. an inverter-based system.

- Conventional (rotating-machine) system transient
  - Lower oscillation frequency
  - More gradual voltage rise
  - Better natural damping

- Inverter-based system transient
  - Higher frequency oscillations
  - Steeper front (higher dv/dt)
  - Faster initial decay but sharper peak stress

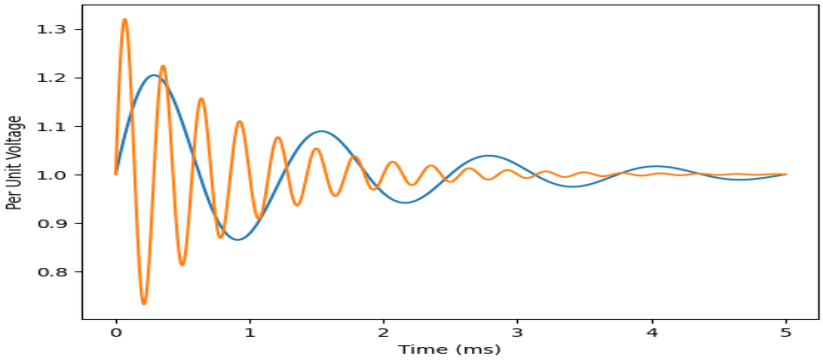

Figure 2 - Switching Transient Comparison: Machine-Based vs Inverter-Based Generation

During high frequency, steep front waveforms, stress is concentrated in the first few turns of the winding which greatly increases cumulative dielectric insulation aging. Arrester duty is also much higher with this type of waveform which can result in premature arrester failure, placing even greater stress on the transformers and bushings. [2] [3] [5]

Transient and steady state over-voltages and frequency deviations can cause:

- Dielectric failures
- Increased core flux density
- Saturation
- Heating
- Audible noise
- Partial discharge
- Elevated dissolved gases

Monitoring transients, over-voltages, and partial discharge can help to raise awareness of the stress the transformer has been exposed to over time and can help to identify whether the arrestors and power-electronics based controls are working properly to prevent failures.

Through Faults

It is well known that external short-circuits faults are responsible for a significant portion of transformer failures. In wind and solar applications, each URD cable and padmount transformer failure puts the GSU at risk. During a fault, the transformer windings are exposed to severe mechanical stresses and thermal heating proportional to the I^2t of the fault. With inverter-based generation, the output of the inverter is current limited, with maximum values of 1.1-1.3p.u. Hence the majority of the fault current will flow from the transmission system through the GSU to the fault. The level of fault current will be dependent on the strength of the grid at that location.

Investigation into the impact repeat fault events have on transformers has found that repeat electromagnetic forces have a cumulative impact on the windings and result in clamping stress relaxation. Even at lower fault magnitudes, repetition matters for mechanical aging. [2] [6] The number of faults, combined with additional stress which occurs due to the higher transient

recovery voltages and frequency deviations due to the invertor controls response to the fault can significantly increase the stress the GSU sees during through faults. Monitoring the fault history can provide valuable insights into the mechanical health of the GSU.

Fault Data 0

Dual CT Plus XV X1 & XV X3

Input 1 (XV X1)		Input 2 (XV X3)	
Total Fault Count	4	Total Fault Count	4
Total Accumulated Fault Current (I2t)	10616.412 pu	Total Accumulated Fault Current (I2t)	999.562 pu
Current	1700 A	Current	1908 A
Historical Peak Current	4216 A	Historical Peak Current	4168 A
Fault Current Alarm Threshold	3465 A	Fault Current Alarm Threshold	3465 A
Fault Current Alarm	On	Fault Current Alarm	On

Date	Fault Current (A)	Accumulated Fault Current (I2t pu)	Duration (ms)	Date	Fault Current (A)	Accumulated Fault Current (I2t pu)	Duration (ms)
2022-07-22 21:18:47:670	3972.00	3342.43	2967	2022-06-22 21:18:40:706	3500.00	387.88	617
2022-09-25 11:39:42:428	3740.00	7860.12	65535	2022-10-22 21:18:42:160	3584.00	2090.28	2833
2023-08-25 11:40:26:437	4216.00	454.08	351	2023-08-25 11:40:40:125	4168.00	846.16	876
2023-08-25 11:40:30:416	4184.00	2302.21	1785	2023-08-25 11:40:54:539	3472.00	153.40	317

Figure 3 - Dynamic Ratings DR-E3 Fault Current Monitoring

Harmonics

Inverter-based generation systems generate harmonics when converting direct current (DC) to alternating current (AC). The rapid switching of the transistors in the inverter creates non-linear current waveforms leading to harmonic distortion in the current and voltage being supplied to the transmission/distribution system. The pulse width modulated techniques used produce harmonics at multiples of the fundamental frequency resulting in a complex harmonic profile.

Harmonics in electrical systems can significantly impact power transformers, generator step-up (GSU) transformers, bushings, and underground cables by causing overheating and increased insulation aging. In bushings, harmonic-induced vibrations can contribute to mechanical stress in addition to the thermal stress resulting in premature aging of insulation materials.

Harmonics can also have a significant impact on PD activity. High-frequency components can cause multiple PD pulses per cycle, increasing discharge repetition rates. The waveform distortion caused by the harmonics often has steeper voltage gradients, especially near the zero-crossings, which can enhance the electric field in the insulation intensifying PD in the voids and defects. Analyzing partial discharges in the presence of harmonics can also be very challenging since the PD characteristics and phase resolved data patterns are significantly different when harmonics are present. [7]

Figure 4 shows the harmonic voltage distortion which was recorded during the bushing monitoring case study discussed below. The total harmonic distortion for both voltage and current were greater than 7%, exceeding the allowable levels recommended in IEEE 519.

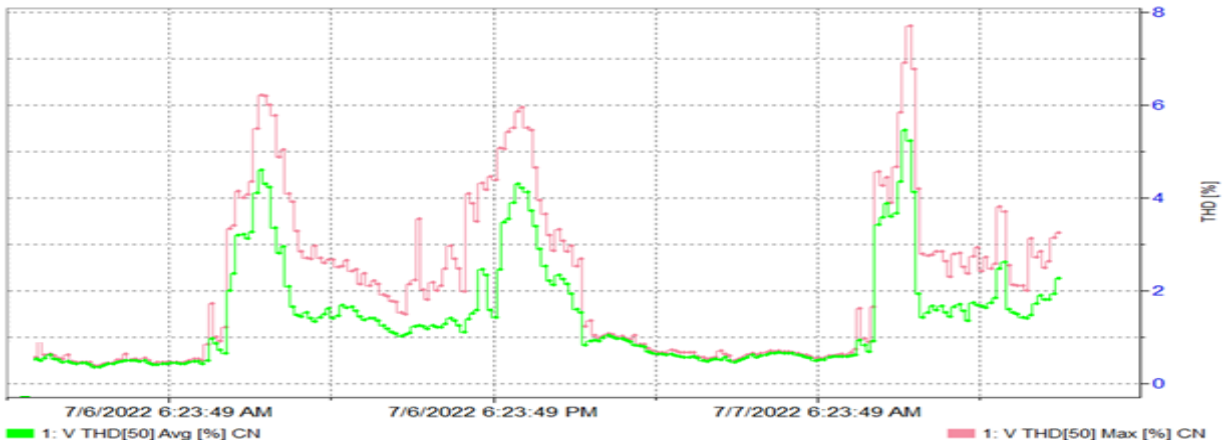

Figure 4 - Total Harmonic Voltage Distortion Recorded at a Wind Farm GSU

Due to the significant damage harmonics can cause, monitoring is critical to ensure that the filtering deployed is adequately managing the harmonics being produced by the inverter.

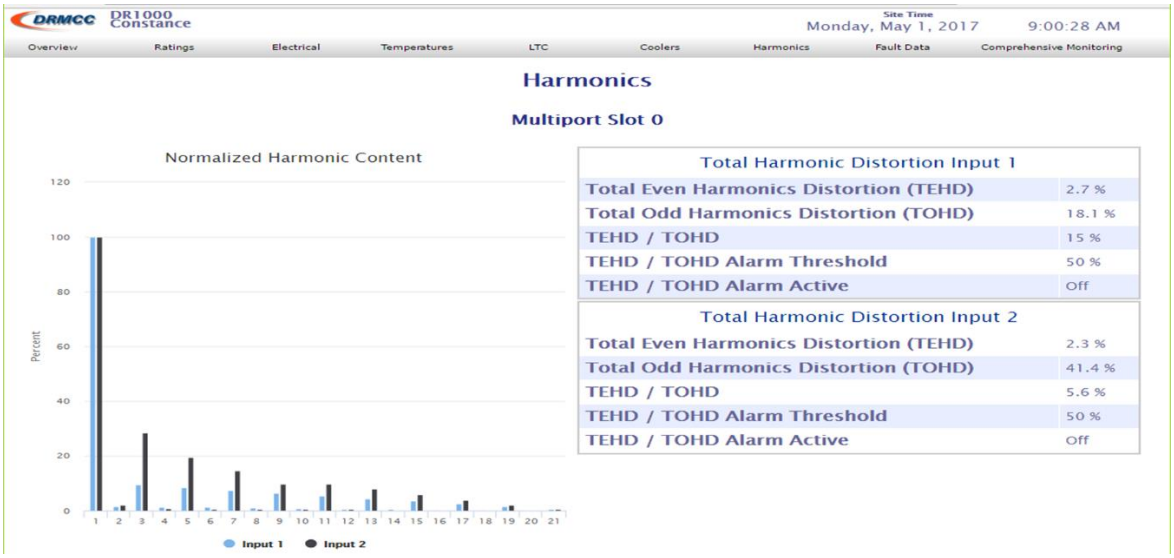

Figure 5 - DR-E3 Harmonics Monitoring

Temperature and Load Cycling

In wind and solar plants, transformers experience more frequent temperature and swings than in traditional baseload generation which can result in increased aging. Unlike large synchronous units that run near steady output, inverter-based resources will ramp up and down based on irradiance and wind variability. These variances combined with daily start/stop cycles results in repeated top-oil and winding hot-spot temperature fluctuations. These thermal cycles drive mechanical expansion and contraction of windings and clamping structures, accelerating insulation aging (per Arrhenius behavior), increasing the risk of winding movement, and contributing to loosening of structural components over time. Elevated ambient temperatures at solar sites can further raise hot-spot temperatures, reducing insulation life. Additionally,

harmonic currents from inverters can increase stray and eddy losses, resulting in localized heating. Overall, compared to conventional rotating-machine plants, renewable GSUs tend to see higher cumulative thermal fatigue stress and more variable loading profiles.

Temperature cycling can also adversely affect bushings. As temperatures rise, the materials and insulating fluid in the bushings expand and later contract as the temperature drops. Rapid temperature changes can occur when generation is suddenly switched on or off. The frequent temperature fluctuation stresses the sealing gaskets and will fatigue them over time. Once the seal is broken, moisture ingress will occur leading to increases in power factor and capacitance. During drops in pressure, partial discharge activity can increase which will further degrade the bushings. The role pressure plays in partial discharge activity in bushings was documented by BC Hydro in field investigations which were later verified by laboratory testing. [8] Similar concerns were raised in the ABB service advisory documenting the risk of failure of OIP bushings immediately following heat run tests. [9] This partial discharge activity will damage the capacitive layers of the bushings over time increasing the risk of failure. Due to the large number of bushing failures renewable providers have experienced, many are turning to online bushing monitoring to detect degraded bushings at an early stage and prevent failures.

Case Study – Bushing failure on a 230/34.5kV solar farm step up transformer

Following a series of bushing failures on the step-up transformers wind farms, a renewable energy provider decided to install online bushing monitoring to monitor the health of the bushings on one of the large GSUs. Shortly after installing the system, the customer began receiving alarms for the 34.5kV bushings whenever the wind farm was generating power. Figure 7 shows the trend of the sum of the bushing currents and the polar chart for the high and low side bushings. While the sum of currents for the high voltage bushings was low and stable, the sum of currents for the low voltage bushings was high and erratic, often exceeding the warning and high alarm set points. No pattern could be identified to indicate which phase was experiencing problems.

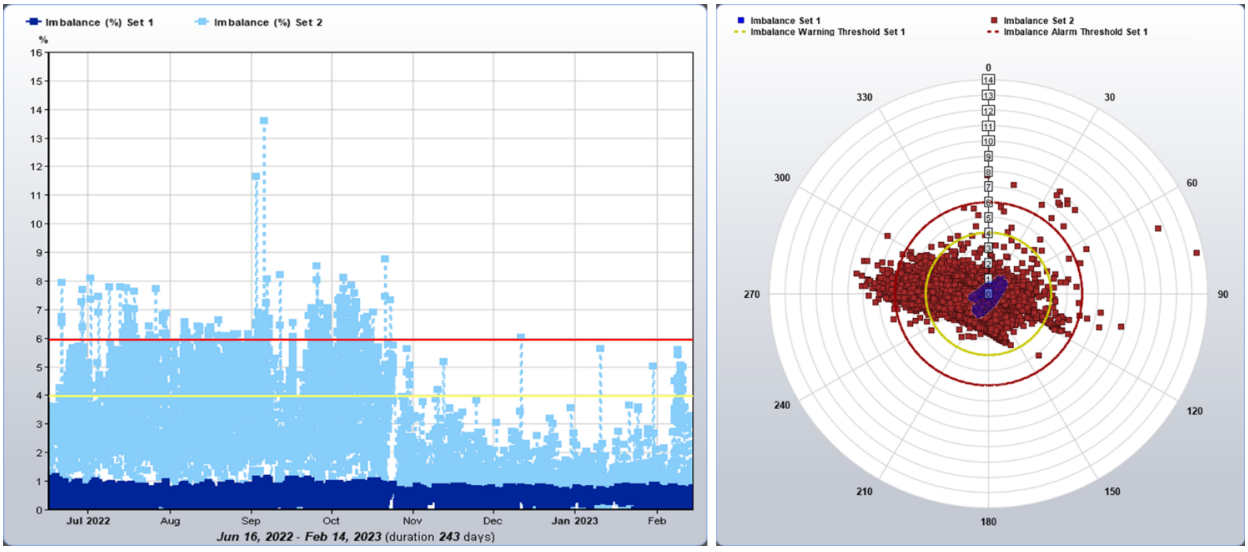

Figure 6 – Imbalance Trend and Polar Chart of High and Low Side Bushings

A detailed analysis of the data was performed and frequent deviations in all three bushing leakage currents were noticed. Since it is very unusual to see significant deviations in the bushing leakage

currents in all three bushings at the same time, power quality data was requested from the customer to see if there was any system correlation to the data.

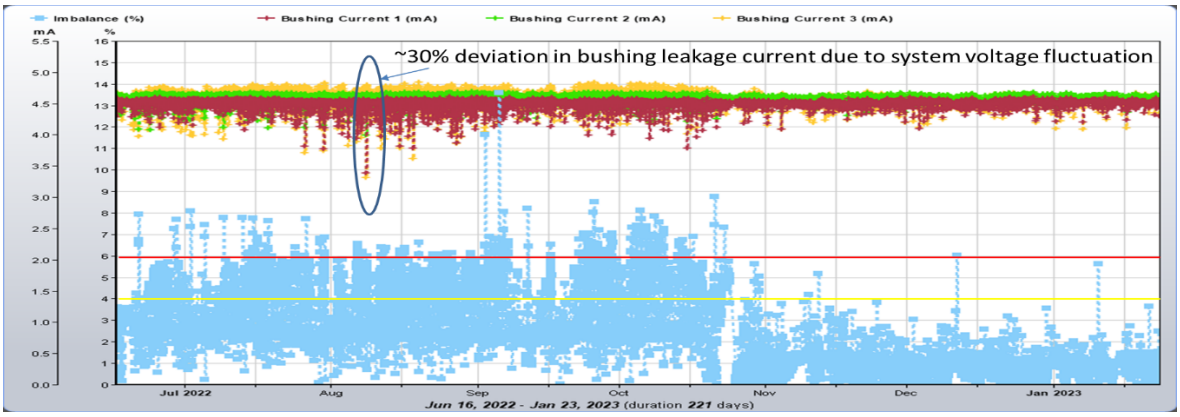

Figure 7 – Trend of Imbalance Current and Bushing Leakage Currents

The power quality data provided showed regular single phase voltage fluctuations similar to the fluctuation shown in figure 8. These fluctuations would explain the large deviations being measured by the bushing monitoring system.

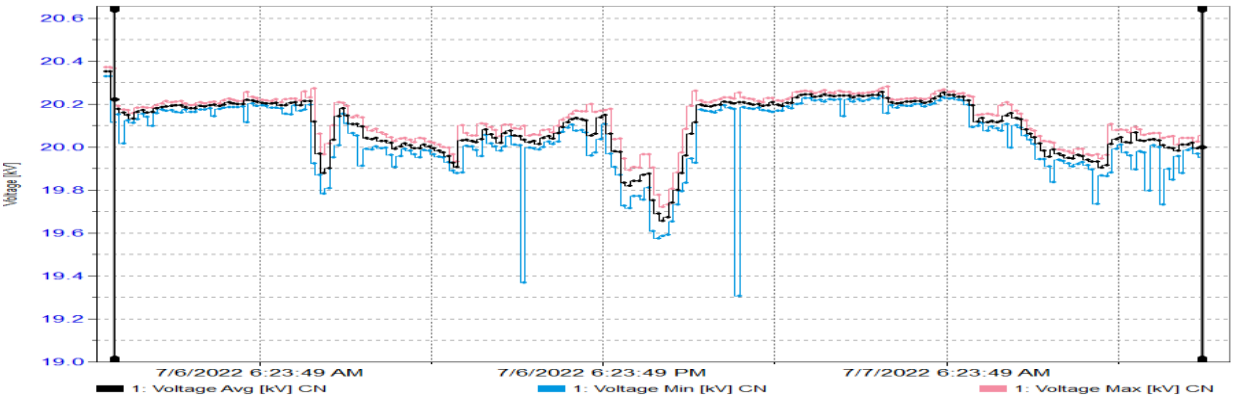

Figure 8 - System Voltage Fluctuations

In addition, figure 9 shows system power factor fluctuated based on the state of the generation; 1) it was a leading power factor when the wind turbines were starting up and shutting down, 2) lagging power factor when the wind turbines were running, and 3) unity power factor when the wind turbines were offline. The system voltage imbalance was also different in each of these states.

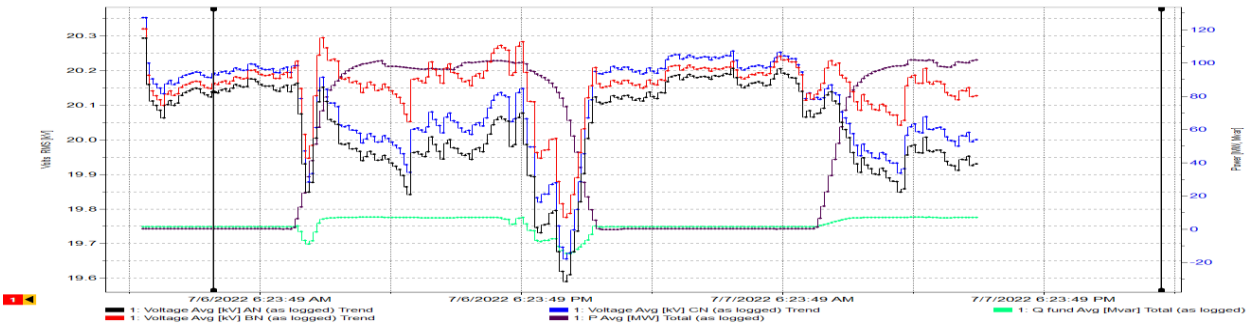

Figure 9 – System Power Factor Based on Generator Status

Since the system conditions changed depending on the status of the wind turbines, the data from the bushing monitor was separated to see if any trends could be identified in the data. Figure 10 shows the data from the bushing monitor when the generators were offline. By separating the data, it was clear that one of the low side bushings was degrading.

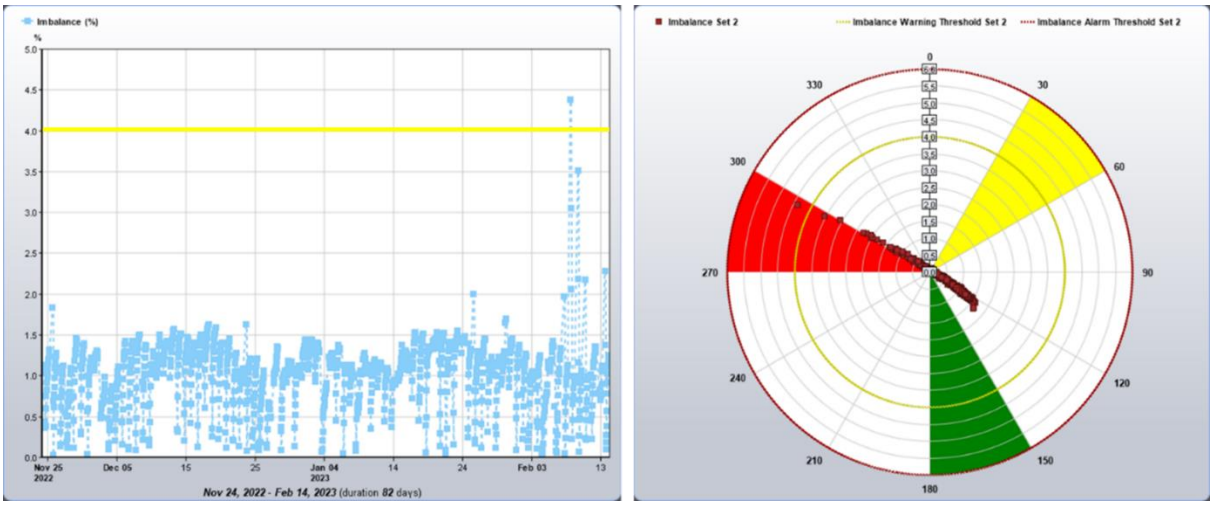

Figure 10 – Bushing Imbalance Data When the Generator is Offline

The trend of the imbalance current and the top oil temperature in figure 11 shows a large temperature dependency indicating a change in power factor and capacitance in one of the bushings.

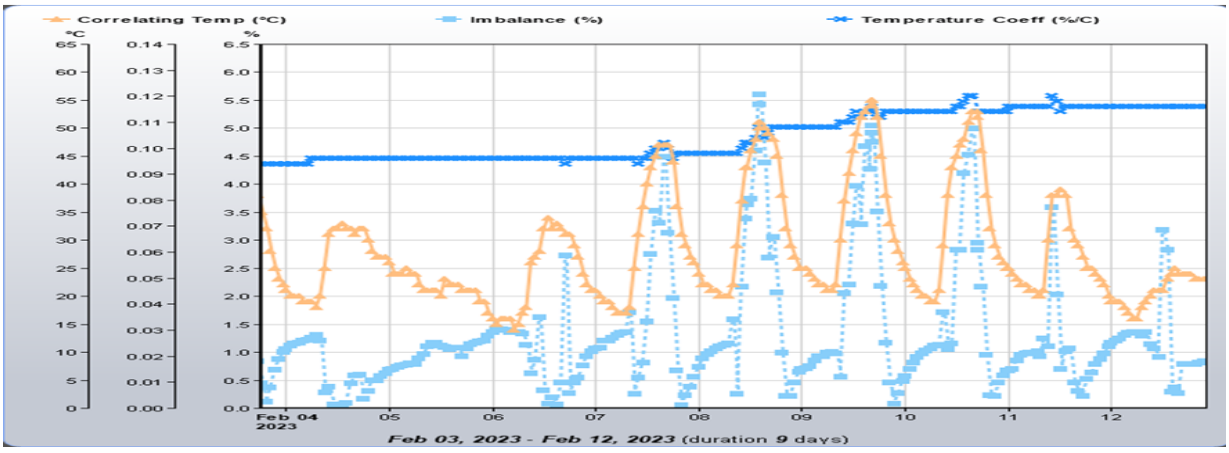

Figure 11 - Trend Chart Showing the Correlation Between Imbalance Current and Top Oil Temperature

Based on the data from the bushing monitoring system, the customer was able to schedule the replacement of the bushing during the scheduled outage to maintain the wind turbines.

Conclusion

The rapid expansion of wind and solar generation has fundamentally changed the operating environment for high-voltage power equipment, introducing new electrical, thermal, and mechanical stresses that were far less prevalent in traditional rotating-machine power systems. Inverter-based resources contribute to harmonics, switching transients, voltage and frequency deviations, and erratic

thermal cycling—all of which accelerate insulation aging, increase failure rates, and complicate asset diagnostics. As these stresses accumulate across transformers, bushings, underground cable systems, and other critical components, the industry can no longer rely solely on preventative or corrective maintenance strategies. Instead, continuous online monitoring has become essential for detecting early-stage failure modes, improving situational awareness, and extending asset life. By embracing these technologies and adopting predictive maintenance practices, utilities and renewable operators can better safeguard system reliability, reduce unplanned outages, and navigate the evolving challenges of a modern, inverter-dominated grid.

“Only by innovating, by taking a new approach and changing the way they plan, engineer, operate, and in particular, manage their systems, can utilities get both the system and financial performance they need.” [10]

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Prior to his present position, Mark was a Construction & Maintenance Supervisor at We Energies. During his 19 years at We Energies, he led the implementation of many of condition based monitoring programs for substation equipment.

Mark is an active member of the IEEE Transformers Committee and is a registered professional engineer in the State of Wisconsin.