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Generator Early Warning System Based on Partial Discharge & Operation Parameters to Prevent Catastrophic Failure*

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Abstrak

Generator merupakan komponen penting dalam industri pembangkitan listrik yang bertanggung jawab dalam menjaga pasokan listrik yang kontinu dan andal. Menjaga kondisi generator tetap prima sangat krusial untuk menghindari waktu henti yang mahal dan kegagalan sistem yang bersifat katastropik. Penilaian kesehatan secara konvensional yang dilakukan secara *offline* cenderung menunda deteksi dini terhadap potensi permasalahan dan sering kali tidak memberikan diagnosis yang akurat. Analisis *Partial Discharge* (PD) telah menjadi alat yang berharga dalam mengidentifikasi kerusakan isolasi pada stator generator melalui pengukuran besaran pelepasan muatan listrik. Namun, meskipun teknologi PD telah diterapkan, kegagalan besar tetap terjadi, yang sebagian besar disebabkan oleh kurangnya pemahaman terhadap analisis PD dan tidak adanya sistem peringatan dini yang efektif. Untuk mengatasi permasalahan tersebut, telah dikembangkan sistem peringatan dini daring (*online*) yang inovatif dengan memanfaatkan *Digital Signal Input Module* (DSIM) yang terhubung dengan *Program Vision* untuk pengumpulan data secara waktu nyata dan analisis PD. Sistem ini secara signifikan meningkatkan kemampuan diagnosis, tidak hanya dengan memantau tren besaran PD, tetapi juga dengan membandingkan parameter operasional untuk mengidentifikasi secara cepat sumber terjadinya anomali. Pembuatan *dashboard* pemantauan daring yang komprehensif, yang mengintegrasikan seluruh parameter operasional generator, memungkinkan penilaian kondisi secara waktu nyata dan memberikan wawasan yang dapat ditindaklanjuti oleh operator, sehingga memperbaiki strategi perawatan dan secara drastis mengurangi risiko kegagalan mendadak. Sistem yang ditingkatkan ini memberdayakan operator untuk secara proaktif menangani potensi masalah, memastikan keandalan generator yang lebih tinggi, serta meminimalkan gangguan operasional.

Kata kunci: peringatan dini, belitan stator, generator, *partial discharge*.

Abstract

Generators are essential components in the power generation industry, responsible for maintaining a continuous and reliable electricity supply. Ensuring their health is critical to avoid costly downtime and catastrophic failures. Traditional offline health assessments delay the detection of potential issues and may not provide accurate diagnostics. Partial Discharge (PD) analysis has become a valuable tool for identifying insulation faults in generator stators by measuring discharge magnitudes. However, despite the implementation of PD technology, catastrophic failures still occur, often due to a lack of understanding of PD analysis and the absence of an effective early warning system. To address these issues, an innovative online early warning system has been developed, utilizing Digital Signal Input Modules (DSIM) connected to Program Vision for real-time data collection and PD analysis. This system significantly enhances diagnostic capabilities by not only monitoring PD magnitude trends but also incorporating operational parameter comparisons to swiftly identify the source of any anomalies. The creation of a comprehensive online monitoring dashboard, which integrates all generator operational parameters, enables real-time health assessments and provides operators with actionable insights, thereby improving maintenance strategies and drastically reducing the risk of unexpected failures. This enhanced system empowers operators to proactively address potential issues, ensuring greater generator reliability and minimizing operational disruptions.

Keywords: *early warning, stator winding, generator, partial discharge.*

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1. INTRODUCTION

Generators are critical components in power generation systems, playing a vital role in maintaining continuous electricity production. Any failure in a generator can have significant repercussions, directly affecting the generation of kilowatt-hours (kWh) and disrupting the overall operation of the power plant. The restoration process after a failure can be lengthy and complex, further exacerbating the risk to the plant's operational readiness, as reflected by the Equivalent Availability Factor (EAF) and the Equivalent Forced Outage Rate (EFOR) (Sarjiya, 2016).

A notable example occurred at the Pelabuhan Ratu power plant in 2015, where a generator failure in Unit 1 led to a production loss of 1,561,662 MWh. The incident involved a stator winding earth fault, necessitating a six-month recovery period to replace the stator coil. This event underscores the critical importance of preventive maintenance and rigorous monitoring to minimize the risk of disruptions.

Traditionally, generator health assessments have been conducted during scheduled overhauls, primarily when the equipment is offline. However, these offline assessments may not accurately reflect the generator's condition during actual operation, given the differences in cooling provided by hydrogen and cooling water systems. This discrepancy can lead to uncertainty in decision-making regarding the generator's operational integrity.

To address these challenges, there is a growing need for real-time, online monitoring systems that provide continuous insights into generator health. Such systems, particularly those based on partial discharge analysis and operational parameters, can detect early signs of deterioration and prevent catastrophic failures. By integrating these advanced monitoring technologies, power plant operators can enhance the reliability and resilience of their infrastructure, ensuring uninterrupted electricity generation and minimizing the impact of potential failures.

2. METHODOLOGY

The methodology for developing a Generator Early Warning System (EWS) based on partial discharge (PD) and operational parameters to prevent catastrophic failures involves several key steps. This process ensures that the system effectively monitors the health of the generator and provides timely alerts to prevent potential failures. The methodology is divided into the following stages:

2.1. System Design and Architecture

The first step involves the installation of sensors and data acquisition systems on the generator. This includes partial discharge sensors to detect electrical discharges within the insulation system, and sensors to monitor key operational parameters such as temperature, vibration, pressure, and load.

Data Integration: The acquired data from the sensors is integrated into a central monitoring system. This system is designed to handle real-time data flow, ensuring that all critical parameters are continuously monitored without delay.

Data Storage and Management: A database is established to store historical data, which is essential for trend analysis and long-term monitoring. The data storage system is designed to handle large volumes of data and ensure data integrity and accessibility.

2.2. Partial Discharge Analysis

PD Signal Processing: The raw PD signals are processed using advanced signal processing techniques to extract meaningful information. This includes noise filtering, pulse counting, and waveform analysis. The objective is to accurately detect and quantify partial discharges within the generator's insulation system.

PD Pattern Recognition: The processed PD data is analyzed to identify patterns that correlate with specific insulation defects. Machine learning algorithms, such as support vector machines or neural networks, may be employed to improve the accuracy of defect identification. These patterns are then correlated with historical failure data to predict potential points of failure.

2.3. Operational Parameter Monitoring

Parameter Threshold Setting: Thresholds for critical operational parameters (e.g., temperature, vibration, pressure) are established based on manufacturer specifications and historical data. These thresholds serve as benchmarks to identify abnormal conditions.

Real-time Monitoring: The operational parameters are continuously monitored in real-time. Any deviations from the established thresholds are flagged, and alerts are generated. The monitoring system is designed to prioritize alerts based on the severity of the deviation and its potential impact on the generator's performance.

2.4. Integration of PD and Operational Data

Correlation Analysis: The partial discharge data is correlated with the operational parameters to identify relationships between the insulation condition and the generator's operational state. This correlation helps in understanding how different operational stresses impact the insulation system and in predicting potential failures.

Risk Assessment Model: A risk assessment model is developed that combines both PD analysis and operational parameter monitoring. The model assigns risk levels to different operating conditions, providing a comprehensive view of the generator's health status.

2.5. Early Warning System Implementation

Alert Generation: The EWS is configured to generate alerts when certain risk thresholds are exceeded. These alerts are categorized based on urgency—ranging from warnings that require routine inspection to critical alerts necessitating immediate shutdown and intervention.

Decision Support System: The EWS is integrated with a decision support system that provides recommendations for corrective actions based on the type and severity of the detected anomalies. This system aids operators in making informed decisions to prevent catastrophic failures.

2.6. Validation and Testing

System Calibration: The EWS is calibrated using data from controlled experiments and historical failure data to ensure its accuracy and reliability.

Field Testing: The system is deployed in a real-world environment, and its performance is monitored over a defined period. Any issues identified during this phase are addressed, and the system is fine-tuned for optimal performance.

Continuous Improvement: Based on the results of the field tests, the EWS is continuously improved. Feedback loops are established to refine the algorithms, thresholds, and alert mechanisms.

2.7. Implementation and Deployment

System Deployment: After validation, the EWS is fully deployed across the power plant's generator units. Training is provided to the plant operators on how to use the system effectively.

Routine Monitoring and Maintenance: Regular maintenance of the EWS is conducted to ensure its long-term reliability. The system is monitored continuously to ensure that it is providing accurate and timely alerts.

2.8. Reporting and Documentation

Report Generation: The system is configured to generate regular reports on the health status of the generators, highlighting any potential issues detected and the actions taken to mitigate them.

Documentation: Comprehensive documentation of the EWS, including its design, implementation, and operating procedures, is maintained. This documentation is essential for troubleshooting, system upgrades, and operator training.

In addition to maintenance activities, assessments are crucial for determining the health of generator systems. When evaluating electrical machinery, a critical step is conducting equipment condition assessments. This process involves in- depth analysis, and recommendations based on a comprehensive assessment of the electrical machinery's condition, with a focus on key components. We assign weight to each component based on assessment results, testing, and evaluation. Determining this weightage is crucial as it significantly influences the final assessment outcome. Therefore, the process of assigning weightage requires careful analysis and expert evaluation.

Table 1. Failure Data For Rotating Machinery Related To Electrical Failures

IEEE Study		EPRI Study	
Failure Contributor	%	Failed Component	%
Persistent Overloading	4.2	Stator Ground Insulation	23.0
Normal Deterioration	26.4	Turn Insulation	4.0
		Bracing	3.0
		Core	1.0
		Cage	5.0
Total	30.6		36.0

Key parameters considered in generator condition assessments include visual condition, age, installed technology level, operational limitations, and electrical testing results on the stator and rotor as in Table 1 (Renforth *et al*, 2013). The results of testing on the stator and rotor are crucial and depend on the accuracy of calibrated equipment following manufacturer guidelines. However, it is equally crucial to note that testing can only take place when the machine is not in operation. Waiting for the machine to stop operating can present its own challenges, necessitating meticulous planning to ensure effective testing. However, it's crucial to remember that testing during the machine's inactivity might not accurately reflect its condition during active operation.

In power generation operations, the reliability of generators is a key focus due to their significant contribution to the overall reliability of the power plant. Online partial discharge (PD) measurement is invaluable in accurately monitoring and evaluating the insulation quality of machines under actual operating conditions. In relatively new generators or motors, low-level PD activity is a common and unavoidable phenomenon resulting from imperfect fabrication processes and designs. Partial discharge refers to the occurrence of electrical sparks within insulation (either within voids or on surfaces) due to high potential differences within the insulation. PD events occur when a "defect/void" area within the insulation, containing "gas pockets," cannot withstand electrical stress and breaks down. (Condition Assesment Manual, 2012).

When insulation becomes damaged, the number and magnitude of PD events increase. This is because the breakdown strength of air/hydrogen (3 kV/mm peak) is much lower than that of solid insulation (around 300 kV/mm peak). The breakdown of gas and air within these "pockets" generates small voltage pulses that can be detected and measured, hence enabling PD activity monitoring (S. Gaidhu *et al*, 2023).

Monitoring PD in rotating machines, such as generators, is essential to observe the degradation occurring in stator winding insulation. The degradation process in stator winding insulation is slow due to the application of discharge-resistant materials (e.g., mica). Failures in the insulation of the stator winding can be caused by switching surges, problems with the synchronization process, load rejections, winding vibrations, bad materials, and other things. Therefore, periodic monitoring is necessary to help determine the condition of stator winding insulation.

The monitoring of partial discharge (PD) activity at the Palabuhanratu coal-fired power plant using the Bus Trac II system manufactured by IRIS Power is a continuous process aimed at assessing the insulation condition within the plant's electrical equipment. This system provides real-time data storage of PD magnitude (Qm) and quantity pulse signals (NQN numbers). The sensors utilized in this system are capacitive couplers designed to meet specific requirements, including:

1. Capacitance: 80 pF + 4 pF in compliance with the requirements outlined in IEC 60034-27-2.
2. Coated with high-grade cyclo-epoxy resin to enhance tracking resistance, ensuring superior performance and durability even in demanding operational environments.
3. Directly connected to high-voltage terminals and bus bars, facilitating efficient and reliable data collection directly from critical points within the electrical infrastructure.

The Bus Trac II system can effectively detect and monitor PD activity by using capacitive couplers with these specifications, as seen in Figure 1. This enables the prompt implementation of proactive maintenance measures, thereby enhancing the overall reliability and safety of the power plant's electrical systems.

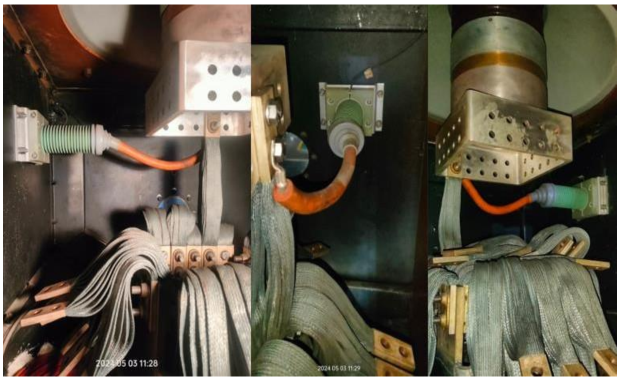

Figure. 1 The Installation of Partial Discharge (PD) Sensors on Generator.

In monitoring trend analysis, it's crucial to consider several parameters that can influence the readings of PD data, including voltage, load, power, stator winding temperature, gas pressure, and humidity. If the values of these parameters tend to remain consistent with previous measurements, a direct data comparison can be made. A robust trend analysis involves using data from the same parameters consistently.

The primary objective of online PD testing of machines is to assist asset managers in determining when maintenance of stator windings would be advisable to prevent in-service failures. Practical guidance on this matter in standards often revolves around monitoring changes in Qm over time. Clause

11.5 in IEEE 1434-2014 suggests that a "doubling of the Qm in 6 to 12 months may indicate rapid aging-insulation condition change".

Despite the installation of online PD monitoring systems, the provision of guidelines, and the establishment of certain limitations, generator failures still occur frequently. Various factors, including operator negligence in diligently observing changes, could be responsible for this. Hence, there is a need for an online monitoring system that enhances vigilance in monitoring online PD to maintain the health of generator systems. Expanding this monitoring system can help detect potential issues more quickly and accurately, enabling timely corrective actions or maintenance interventions, reducing the risk of generator system failures, and enhancing overall operational efficiency.

3. RESULT & DISCUSSION

PI Vision is an intuitive web-based visualization tool that provides quick, easy, and secure access to all data within the PI System. With PI Vision, users can effortlessly conduct ad hoc analysis, uncover insights, and share findings with others. Online Qm data, both positive and negative, can be accessed using the Bus Trac II equipped with the Digital Signal Input Module (DSIM) option. The DSIM module facilitates the retrieval of Modbus data, enabling PI Vision to directly access PD results from the plant system on the same network, as seen in Figure 2. The PI Vision interface can seamlessly retrieve and monitor data using the provided address range (S.R. Campbell, 2006).

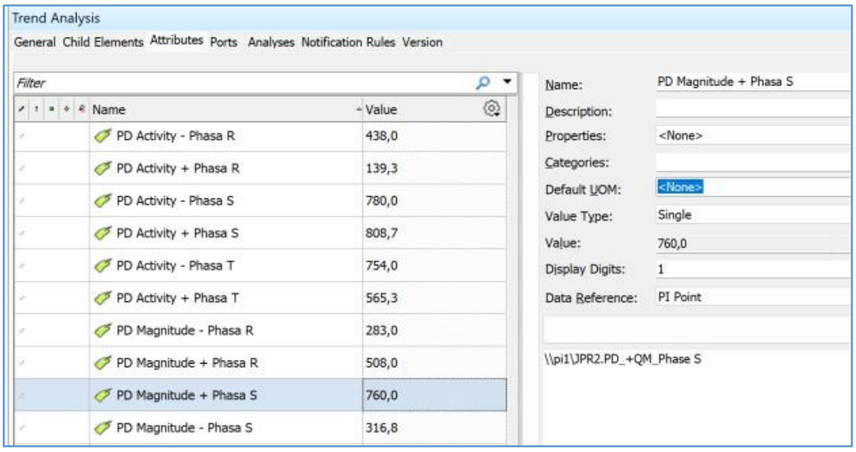

Figure. 2 PD Magnitude and Activity Values in PI System Explorer.

The values that have emerged can be analyzed through algorithms continuously developed with guidance provided by IRIS Power via the "Interpretation of Partial Discharge Result" book. In line with IEEE 1434, which suggests that doubling the Qm value within 6 to 12 months (short-term analysis) may indicate rapid aging of insulation, this logic is incorporated into PI Vision by averaging all measurements over a one-week period for the past 6 months compared to the average of the most recent week of the current month, as seen in Figure 3.

The use of the tagavg function is one of the expression functions available in the PI System Explorer software (Osisoft dan LLC, 2009-2019). The tagavg function above provides the average value of the past 6 months within a weekly range, compared to the current actual value, which is also compared within the average weekly range. This is used to calculate the PD increase value according to the explanation in the previous paragraph.

QmRP	Abs(((TagAvg('PD Magnitude + Phasa R','*-12W','*-11	40,059	40,135	JPR 2 ST QmRP	⊗
	Abs(((TagAvg('PD Magnitude + Phasa R','*-12W','*-11W')-TagAvg('PD Magnitude + Phasa R','*-1W','*'))/TagAvg ('PD Magnitude + Phasa R','*-4W','*-3W'))*100)				
QmSP	Abs(((TagAvg('PD Magnitude + Phasa S','*-12W','*-11	24,70	24,71	JPR 2 ST QmSP	⊗
QmTP	Abs(((TagAvg('PD Magnitude + Phasa T','*-12W','*-11	21,73	21,72	JPR 2 ST QmTP	⊗
QmRN	Abs(((TagAvg('PD Magnitude - Phasa R','*-12W','*-11	25,69	25,71	JPR 2 ST QmRN	⊗
QmSN	Abs(((TagAvg('PD Magnitude - Phasa S','*-12W','*-11	0,62	0,65	JPR 2 ST QmSN	⊗
QmTN	Abs(((TagAvg('PD Magnitude - Phasa T','*-12W','*-11	13,52	13,55	JPR 2 ST QmTN	⊗

Figure. 3 The Equation used in The PI Vision Value.

In order to simplify the process of monitoring and constructing monitoring and warning systems, it is essential to classify the alarm statuses effectively. This involves assigning distinct categories based on the magnitude of change in the monitored parameters. Specifically, we identify instances of doubling or experiencing a 100% increase, as well as those within a range of 75%, as the highest priority category and highlight them in red. Following this, a 50–75% increase is designated as the next level of concern and marked in orange (Osisoft dan LLC, 1992-2019). Subsequently, any changes falling within a range of a 25% increase are denoted in yellow, while those indicating a lower level of change are highlighted in green. This categorization scheme aids in swiftly identifying and responding to varying degrees of deviation from normal operating conditions.

Name	Expression	Value at Evaluatio	Value at Last Trigg	Output Attribute	
RasioVab	Abs(((TagAvg('Voltage AB Generator','*-12W','*-11W'	1,16	1,16	JPR2 OC Rasio Vab	⊗
RasioVbc	Abs(((TagAvg('Voltage BC Generator','*-12W','*-11W'	1,23	1,23	JPR2 OC Rasio Vbc	⊗
RasioVCA	Abs(((TagAvg('Voltage CA Generator','*-12W','*-11W'	1,08	1,08	JPR2 OC Rasio Vca	⊗
ResultRasioV	if RasioVab >= 2.5 or RasioVbc >= 2.5 or RasioVCA >	2	2	JPR 2 Result Rasio V	⊗
DescResultRasioV	Type an expression	-	-	Map	⊗
RasioMW	((TagAvg('MW Generator','*-12W','*-11W')-TagAvg('M	29,00	29,00	JPR2 OC Rasio MW	⊗
ResultRasioMW	if RasioMW >=10 then 1 else if RasioMW <=-10 then 6	1	1	JPR 2 Result Rasio MW	⊗
DescRsltRsioMW	Type an expression	-	-	Map	⊗
RasioMVAR	((TagAvg('MVAR Generator','*-12W','*11W')-TagAvg('M	19,70	19,70	JPR2 OC Rasio MVAR	⊗
ResultRasioMVAR	if RasioMVAR >=10 then 1 else if RasioMVAR <=-10 th	1	1	JPR 2 Result Rasio MVar	⊗
DescRsltRsioMVar	Type an expression	-	-	Map	⊗
RasioH2Press	Abs(((TagAvg('H2 Pressure','*-4W','*-3W')-TagAvg('H	0,89	0,89	JPR2 OC Rasio H2 Press	⊗
ResultRasioH2Press	if RasioH2Press >=1.5 then 1 else 2	2	2	JPR2 Result Rasio H2	⊗

Figure. 4 Early Warning Based on Short-Term Trend Analysis.

The established warning system naturally requires validation through operating parameters and phase comparison. As of the time of writing, no alternative has been found for phase comparison, but its relationship with changes in stator winding temperature will be studied further. Operating parameters are utilized to generate recommendations based on increases in PD magnitude and changes in operational parameters. This validation process ensures the effectiveness and reliability of the warning system in accurately identifying potential issues and providing timely recommendations for corrective actions based on real-time data analysis, as seen in Figure 4.

The foundation of Short-Term Analysis lies in comparing the current test results with previous test outcomes (Osisoft dan LLC, 2019). The Qm value plays a crucial role in comparing machines or monitoring trends over time. However, this trend comparison must also consider voltage, load, winding temperature, and gas pressure in relation to previous test results. To ensure proper comparison of tests, it is recommended to maintain operational conditions within a specific range according to the guidelines provided in PD Interpretation. This approach ensures that any observed changes in PD activity are accurately assessed in the context of variations in operating conditions, allowing for more informed decision-making regarding maintenance and asset management strategies.

Table 2. Operating Condition Parameters

Variable	Value	Description
Voltage	± 2.5%	PD increases with voltage, so variances in voltage can lead to fluctuations in PD levels.
Load	± 10%	If a machine has PD that is mechanically dependent, such as loose coils or connections, then it is likely the PD levels will change with load.
Real Power	± 10%	
Reactive Power	± 10%	
Stator Temperature	± 10%	Operating temperature affect the volume of internal voids, with change PD magnitudes.
Hydrogen Pressure	± 5 psi-g ± 35 kPa ± 0.35	Gas pressure impacts the electrical breakdown stress and therefore levels of PD.
Humidity	unknown	Humidity can impact surface PD, especially PD at the end winding or on ring busses.

In accordance with the provided instructions, any percentage increase detected in the short-term analysis falling within the range of 25–50% will be subject to investigation (Osisoft dan LLC, 2014-2019). This investigation encompasses several parameters, as outlined in Table 2. Furthermore, algorithms for these parameters are integrated into PI Vision to ensure that the system warning can promptly pinpoint potential issues. This approach streamlines the process of addressing potential problems by directing attention to areas where significant deviations from normal operating conditions are observed, thereby facilitating timely corrective actions, as seen in Figure 5.

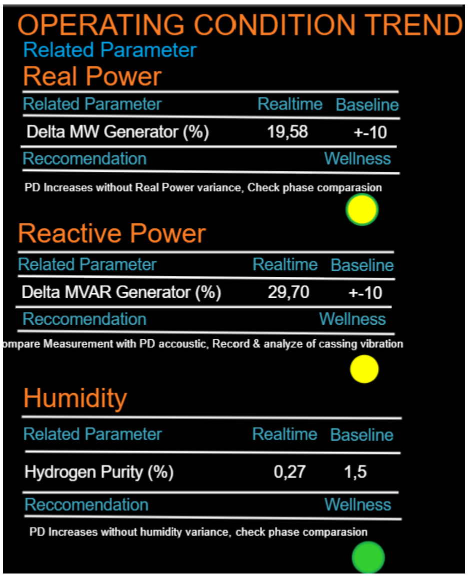

Figure. 5 Operation Parameters in PI System Explorer.

The constraints utilized in formulating this equation adhere to the guidelines provided in the interpretation instructions. These constraints are then applied to the data, and the resulting values are compared with the PD increase. If there is no increase in PD observed with parameters changing within the specified constraints, a recommendation to inspect the respective parameter along with its measuring instrument will be displayed in PI Vision, as seen in Figure 6.

Similarly, recommendations are generated when there is an increase in PD alongside a change in operational parameters, no increase in PD despite changes in parameters, and no increase in PD with parameters remaining unchanged. This systematic approach ensures that relevant recommendations are provided based on the observed patterns, facilitating proactive maintenance actions and minimizing the risk of potential equipment failures.

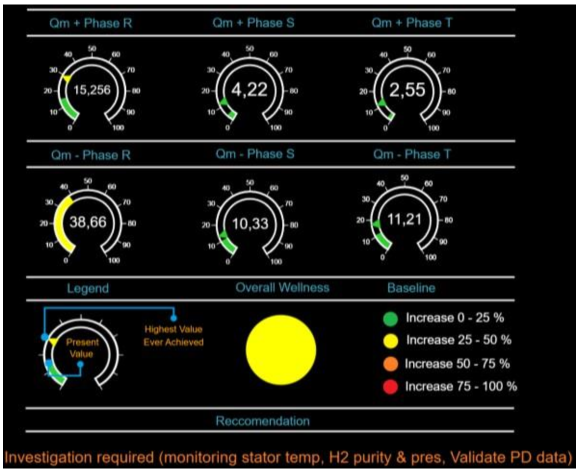

Figure. 6 Operation Parameters based on Trend Conditions.

The warning system established for operational parameters is designed with two colors: green and yellow. Green indicates normal levels of PD increase, while yellow is used to signify PD increases above 25%. This color-coded system allows for quick visual identification of the severity of PD changes in operational parameters, enabling operators to prioritize actions and responses accordingly.

4. CONCLUSION

The reliability of power generation systems hinges on the seamless operation of generators, the backbone of electricity production. As the demand for uninterrupted power supply continues to grow, the stakes have never been higher for ensuring the health and longevity of these critical assets. Traditional offline assessments often fall short, leaving potential issues undetected until it's too late. This challenge underscores the urgent need for a more proactive and real-time approach to generator monitoring.

1. Enhanced Monitoring Capabilities: The integration of PD-Online monitoring provides a continuous and robust solution for assessing the condition of stator windings by tracking partial discharge magnitudes in real-time.
2. Innovative Early Warning System: The newly developed online warning system, powered by Digital Signal Input Module (DSIM) connectivity to PI Vision, dramatically improves real-time monitoring and early detection capabilities.
3. Effective Trend Identification: By utilizing the Tag- Average equation configured according to data interpretation guidelines, the system effectively identifies and tracks rising trends in discharge magnitudes, allowing for early intervention.
4. Rapid Source Identification: The system enables quick comparison of operational parameter data, facilitating the rapid identification of the sources of partial discharge symptoms and providing actionable recommendations for timely maintenance.
5. Comprehensive Real-Time Dashboard: The creation of an integrated online monitoring dashboard consolidates all operational parameters, streamlining real-time health assessments and enhancing overall monitoring efficiency.

In a world where every second of power production counts, the implementation of this online early warning system marks a significant advancement in generator maintenance strategies. By shifting from reactive to proactive monitoring, power plants can not only prevent catastrophic failures but also optimize the reliability and efficiency of their operations. This system not only fortifies the resilience of power generation infrastructure but also ensures that the lights stay on, uninterrupted, for the communities and industries that depend on them. The future of power generation is not just about generating electricity; it's about doing so with the assurance of continuous, reliable performance.

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