Technical Article

# 3-Level Strategy of Insulation Status Monitoring for Critical HV Motors and Generators

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# 3-Level Strategy of Insulation Status Monitoring for Critical HV Motors and Generators

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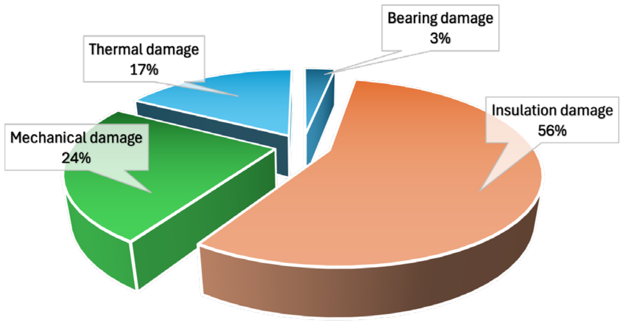
This article explains why electrical diagnosis of stator winding insulation status is a crucial part of the predictive maintenance program for critical HV motors and generators. Furthermore, it explains why a combination of periodic offline testing and online partial discharge monitoring is the most efficient strategy for condition-based maintenance of machine insulation throughout its lifecycle.

## I. Why electrical diagnosis of rotating machines?

Several studies about the causes of failures in HV motors and generators have been published. The survey of 1199 hydro generators carried out by CIGRE study committee SC11, EG11.02 [1] is an example. This not only identified the part of the machine that had failed but also provided a deeper insight into the failure mechanism. It gives detailed results for 69 incidents, of which 56% involved insulation damage. Other major types of damage were mechanical, thermal, and bearing (Figure 1a). The root causes which led to the damage are further divided into seven different groups (Figure 1b).

The results of the study clearly show that insulation deterioration is a significant and dominant root cause for failure of HV rotating machines. Other investigations, such as those detailed in a paper by Bruetsch et al. [2], have shown that the final failure of the epoxy mica insulation is usually caused by electric breakdown through a tree channel. The formation and propagation of trees in the insulation, therefore, reflect the ageing process of the insulation, and the treeing is accelerated by defects in the mica insulation, such as delamination, cracks, voids and wrinkled or damaged mica layers. These types of defects are either manufacturing imperfections or the result of ageing. The insulation ageing process is dominated by a combination of stress factors, of which thermal and mechanical wear are the most important. The ageing process is accelerated if the operating temperature exceeds the optimal temperature range substantially, i.e. is above 135 ° to 140 °C and/or if there are mechanical issues, like loose wedging of the bars. Loose wedging allows abrasion of the slot corona protection by the sharp edges of the laminated stator core, leading to partial discharge activity at the slot exit [2].

All of the failure and ageing mechanisms that have been described can be identified in their early stages by a suitable electrical diagnostic strategy, such as the one described in this article. The findings mentioned also explain why electrical diagnosis of the machine´s insulation status is a crucial part of a predictive maintenance program for HV motors and generators, and why relying purely on vibration analysis will detect only around 30% of all failure root causes.



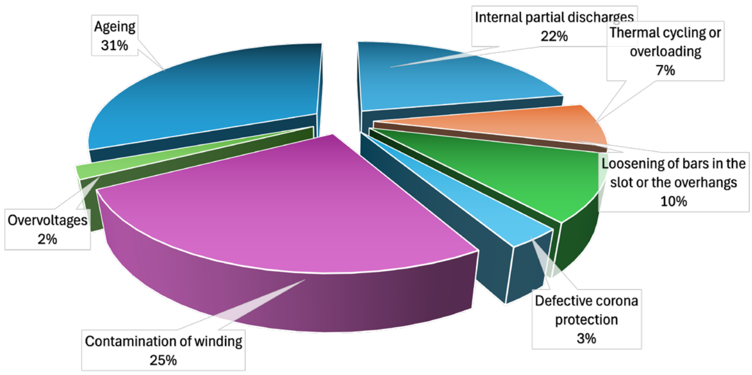




*Figure 1a and 1b: Result of CIGRE study committee SC11, EG11.02*

*Types of damage in hydro generators (top) and root causes of insulation damage (bottom) [3]*

## II. Is partial discharge testing and monitoring a suitable tool for condition-based maintenance, if PD is inherent for HV machine´s insulation systems?

The stator winding insulation in rotating machines is usually formed of mica tapes or flakes, and, in modern machines, epoxy resin is the usual choice for impregnating the mica layers. For large generators, traditional resin-rich impregnation is most often used and, for large motors in particular, vacuum impregnation of the entire stator coil has become increasingly popular in recent decades. These insulation systems are not PD free by design and are considered to be PD resistant in normal operating conditions. This is one of the reasons why no PD acceptance limits for the stator windings of HV rotating machines have so far been defined in standards.

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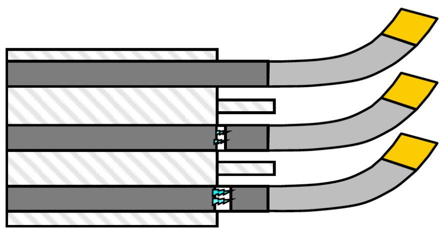
Nevertheless, the IEEE, for example, has provided a guide (IEEE Std 1434-2014) that outlines the Measurement of Partial Discharges in AC Electric Machinery and the available detection methods for online testing and offline testing of windings. This standard also covers quality control testing of individual stator coils and bars. (Other normative references are summarized in Table 1). As previously discussed, when exposed to so-called TEAM (Thermal, Environmental, Ambient, and Mechanical) stresses, insulation system degradation processes start, and all of these degradation processes result in partial discharge activity.

This makes partial discharge offline testing and online monitoring ideal tools for assessing the condition of a stator winding throughout its lifecycle with the proviso that because even a new machine may show PD activity, determining only the level of PD is insufficient. Trending of PD behavior against a base measurement obtained during a Factory Acceptance Test is crucial for HV rotating machine condition-based maintenance. In addition, analysis of Phase Resolved PD (PRPD) patterns allows identification of the type of failure mechanism, thanks to the unique PRPD "fingerprints" of each of the common degradation root causes. (See the examples of failure mechanisms and corresponding PRPD patterns in Figure 2a and 2b). The major advantage of high frequency measurement techniques, such as the PD measurement, is that they make it possible to detect winding defects and fault mechanisms in an early stage, which allows partial repairs to be made and often avoids the need of immediate rewinding.

| | |
|---|---|
| IEC 60034-27-1 | Rotating electrical machines- Off-line partial discharge measurements on winding insulation |
| IEC/TS 60034-27-2 | Rotating electrical machines- On-line partial discharge measurements on the stator winding insulation |
| IEC 60034-27-3 | Rotating electrical machines- Dielectric dissipation factor measurement on stator winding insulation |
| IEC 60034-27-4 | Rotating electrical machines- Measurement of insulation resistance and polarization index of winding insulation |
| IEC TS 60034-27-5 | Rotating electrical machines- Off-line measurement of partial discharge inception voltage on winding insulation under repetitive impulse voltage |
| IEEE Std 1434-2014 | IEEE Guide for the Measurement of Partial Discharges in AC Electric Machinery |

*Tab 1. Overview of some normative references for electrical testing of rotating machines.*

As it is shown in the following sections, PD testing and monitoring are an important part of a condition-based maintenance strategy for HV machines, but they should be combined with offline test methods to get the full picture of the insulation status throughout the asset´s life cycle.



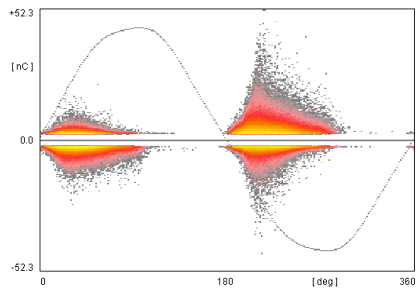
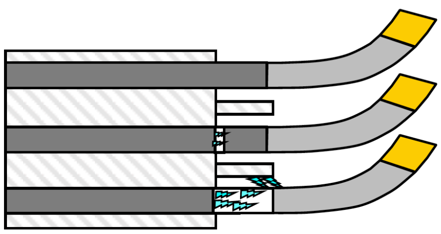



**Figure 2a: Slot- exit PD activity - initial stage**



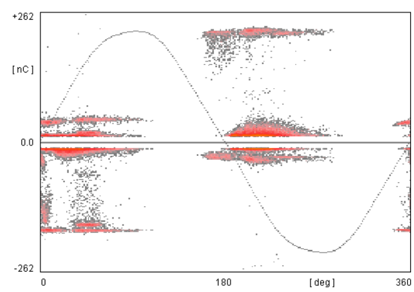



**Figure 2b: Slot- exit PD activity- final stage**

*Example of insulation failure mechanism and corresponding PRPD patterns:*

*Fig 2a: PD activity starts as soon as the semicon field grading tape at the slot exit is partially destroyed. The PD plot shows an asymmetrical pattern with higher activity in the negative half cycle. Later, surface discharges start between the semicon tape and the inner part of the stator bar, which leads to complete destruction of the field grading tape. At this stage, the activity progresses to that shown in Fig 2b. The pattern for the final stage of this failure mechanism shows floating potentials with significantly higher amplitudes (100 to 200 nC). At this stage, the dielectric strength to ground potential is lost and discharges to pressure fingers, plate or stator core occur. This is a highly critical insulation condition requiring immediate repair action.*

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## II. 3 level strategy of insulation status monitoring of HV rotating machines

The three-level strategy which follows reflects common best practice and represents the most effective condition-based maintenance strategy for the insulation status of HV rotating machines:

### LEVEL 0: Factory Acceptance Test

A Factory Acceptance Test (FAT) that includes the full range of tests detailed for Level 1 (see Table 2 below) is recommended. The FAT report will serve as a baseline measurement for future trending. The first offline inspection, including the full range of tests detailed in Table 2, should be performed within 12 months of on-site commissioning of the HV machine. A PD & TD test can also be carried out on single stator bars, which will deliver a good assessment of the production quality of the stator bar main insulation system after the manufacturing phase.

### LEVEL 1: Periodic Off-line Inspection

Offline inspection of the stator winding insulation status of critical HV machines is recommended at least every 2 years. The standard offline inspection procedure should consist of the following steps and tests:

| | Test | What do we inspect/ test? |
|---|---|---|
| 1. | Visual inspection of the overhang and the slot exit | Contamination, PD traces, status of field grading tape at the slot exit, corrosion |
| 2. | Winding resistance and Inductance | Balance between phases, connection issues |
| 3. | Insulation resistance and Polarization index | Ground wall insulation status, contamination |
| 4. | DC Step Voltage Test (up to 2Un + 1kV) | Ground wall insulation at higher stress, linearity of leakage current versus voltage |
| 5. | Surge test (up to 2Un + 1kV) | Turn to Turn and Phase to Phase insulation |
| 6. | Partial Discharge and Tan delta testing (up to Un) | Ground wall and phase to phase insulation deterioration in early stage with identification of failure mechanism; aging of insulation |

*Tab 2: Standard offline inspection and testing procedure for periodic insulation status assessment of HV stator windings*

Each of the individual tests in the above test procedure is important, as is the order of the tests. Only the complete sequence gives the full picture about the status of the whole stator winding insulation system. Each test in the sequence is performed only if the results of the previous test were within the pass/fail criteria. If the results of a test do not meet the pass/fail criteria, the root cause must be investigated before progressing further with the test sequence.

Tests 2 to 5 in Table 2 can be performed in one automated test sequence with a suitable static motor analyzer, such as the Megger Baker ADX (see Figure 3). The last two tests in the standard offline inspection sequence – PD and tan delta – can be performed simultaneously as a single procedure with the ICMflex portable PD and Tan Delta test set (see Figure 4) used in combination with an AC Hipot (or alternatively with a VLF test set, for countries and applications where VLF is accepted as an alternative to 50/60Hz testing).



*Figure 3. The ADX Static Motor Analyzer with the display showing a surge test in progress*

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Insulation resistance (Polarization index), DC Step voltage tests and PD/tan delta tests only detect deterioration of the main ground wall insulation and do not give any information about the status of the turn-to-turn, or phase-to-phase insulation. (An exception is windings with an accessible neutral connection, where PD testing can also detect phase-to-phase insulation deterioration, if each phase is tested individually).

Surge testing is the only test method that can detect turn-to-turn and phase-to-phase insulation weakness at an early stage – when the voltage at which arcing between turns occurs is still above nominal voltage. By injecting short rise time/low energy pulses with an amplitude of up to 2Un+1kV, a potential difference between turns is generated which simulates the voltage transients that the windings see in normal operation. (For the other tests previously mentioned, the test voltage is applied phase to ground and all turns are at the same potential). If a critical voltage is reached at which a turn-to-turn or phase-to-phase insulation weakness becomes evident, arcing between turns or phases occurs, which is detected and indicated by the static motor analyzer, thanks to analyzing the characteristic of the recorded surge wave (Figure 3). (When arcing between turns is present, the inductance of the winding decreases, which changes the frequency and shape of the surge wave). The surge test can be optionally expanded to include partial discharge detection. (This is PD at impulse voltage and must not be confused with the conventional PD testing with AC mentioned as point 6 of Table 2). This PD option at impulse voltage, as an even more sensitive detection method for turn-to-turn and phase-to-phase insulation weakness, has its main relevance for LV stator winding testing, especially with the Type 1 (PD free) insulation systems used in rotating machines fed from voltage converters (see IEC 60034-18-41; IEC TS 60034-27-5).

For tests 2 to 5, shown in Table 2, typical recommended pass/fail criteria are given, while for partial discharge and tan delta tests, evaluating the results involves trending them against the FAT report or previous offline inspection results and identifying any significant changes in PD inception voltage and PRPD pattern (which can give insights into an evolving failure mechanism and its position within the winding), as well as in tan delta tip up values. The typical sequence consists of 0,2Un voltage steps up to Un to determine the PD inception voltage (PDIV) while, at each voltage step, recording the tan delta value and a 60-second PRPD pattern. The same step sequence is typically applied with decreasing voltage to determine the PD extinction voltage (PDEV). Measurement conditions and setup can have an influence on the absolute PD level and tan delta values, therefore no recommended pass/fail criteria are defined, and care has to be taken to keep to a consistent measurement setup and methodology according to the relevant standards (IEC 60270; IEC 60034-27-1; IEC 60034-27-3). The possibility of measuring PD and tan delta in one simultaneous test sequence and presenting the results in a common test report not only saves time, but also makes it easier to evaluate the correlation between both sets of results (see Fig.4). As stated in EN 60034-27-3:2015 [3], the increase of dielectric losses with voltage can be caused by increasing partial discharge activity caused by cracks, voids, delamination, surface contaminations in the insulation structure, to name just a few failure mechanisms, as well as by losses in solid insulation (polarization, conductivity).

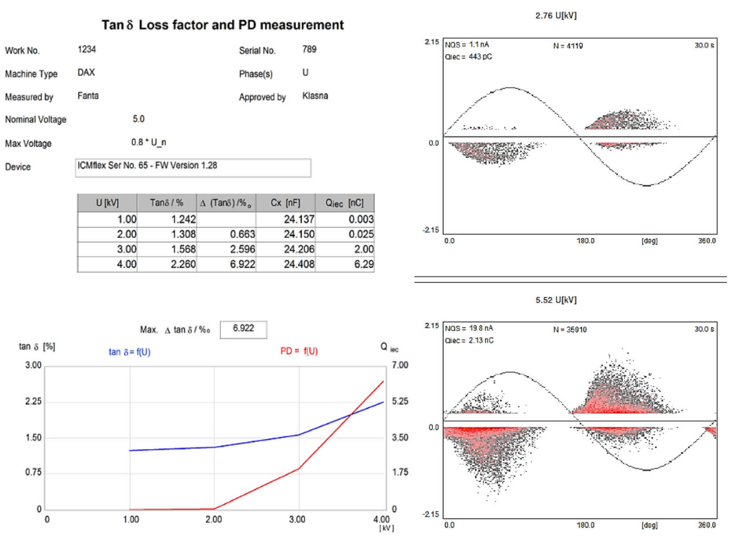


*Figure 4. ICMflex PD and Tan delta test set and example of test report*

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**LEVEL 2 (in combination with LEVEL 1): Online Partial Discharge Spot testing, or Temporary Monitoring with preinstalled coupling capacitors.**

On HV machines that are highly critical for the asset owners, such as generators and motors in industrial plants, online partial discharge monitoring is a very effective and useful addition to condition-based maintenance strategy. It serves as an early warning tool for deterioration and incipient failure mechanisms of the main ground wall insulation, and can also indicate other defect mechanisms and processes, such as contamination of the overhang with conductive dust, which invalidates control of the electrical field by the grading paint.

Another advantage of online monitoring (temporary or permanent) is that it allows the load dependance of the discharge activity to be studied, along with the influence of vibration in normal operational conditions [4]. If a PD fault mechanism develops at a critical position of the stator winding insulation system, the degradation process may cause severe problems in only a couple of months so, for highly critical machines, periodic offline testing every two years might not give a sufficient guarantee that no such process will be triggered between the inspections. PRPD analysis and online PD spot testing or monitoring can help to identify the failure mechanism and its position within the insulation system, which means that timely partial repairs can be carried out, potentially saving significant maintenance costs.

During a planned outage, coupling capacitors can be installed at the motor terminals or on generator busbars (see Figure 5). This will allow future periodic online PD spot testing or temporary online PD monitoring with a suitable portable PD testing/monitoring device without any downtime, although initial calibration of the measuring circuits will have to be performed after the installation of the couplers. Figure 6 shows a typical schematic for a HV rotating machine with preinstalled coupling capacitors and either a mobile device for periodic online PD spot testing/temporary monitoring, or a permanently installed monitoring system (see LEVEL 3).

Periodic offline testing as in LEVEL 1 and periodic online spot testing/temporary monitoring as in LEVEL 2, are complementary test approaches and should always be combined; neither fully replaces the other. However, thanks to using periodic online PD spot testing/temporary monitoring, for example, every 6 months, asset owners can afford to prolong the interval between planned outages for offline inspections from, for example, 2 years to 4 years. If any abnormality or suspicious trend is observed during periodic online PD spot testing, the asset owner can then decide to schedule the next offline inspection sooner.

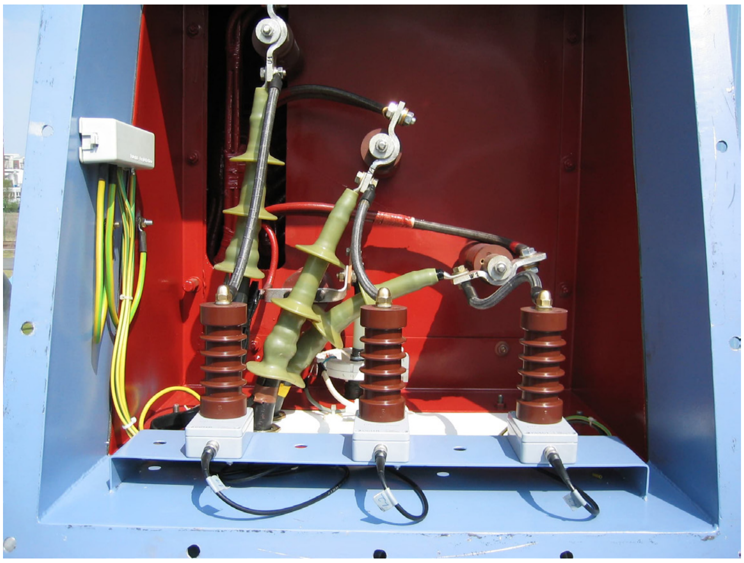

Figure 5. Example of preinstalled coupling capacitors on motor terminals (left) and on generator bus bars (right)

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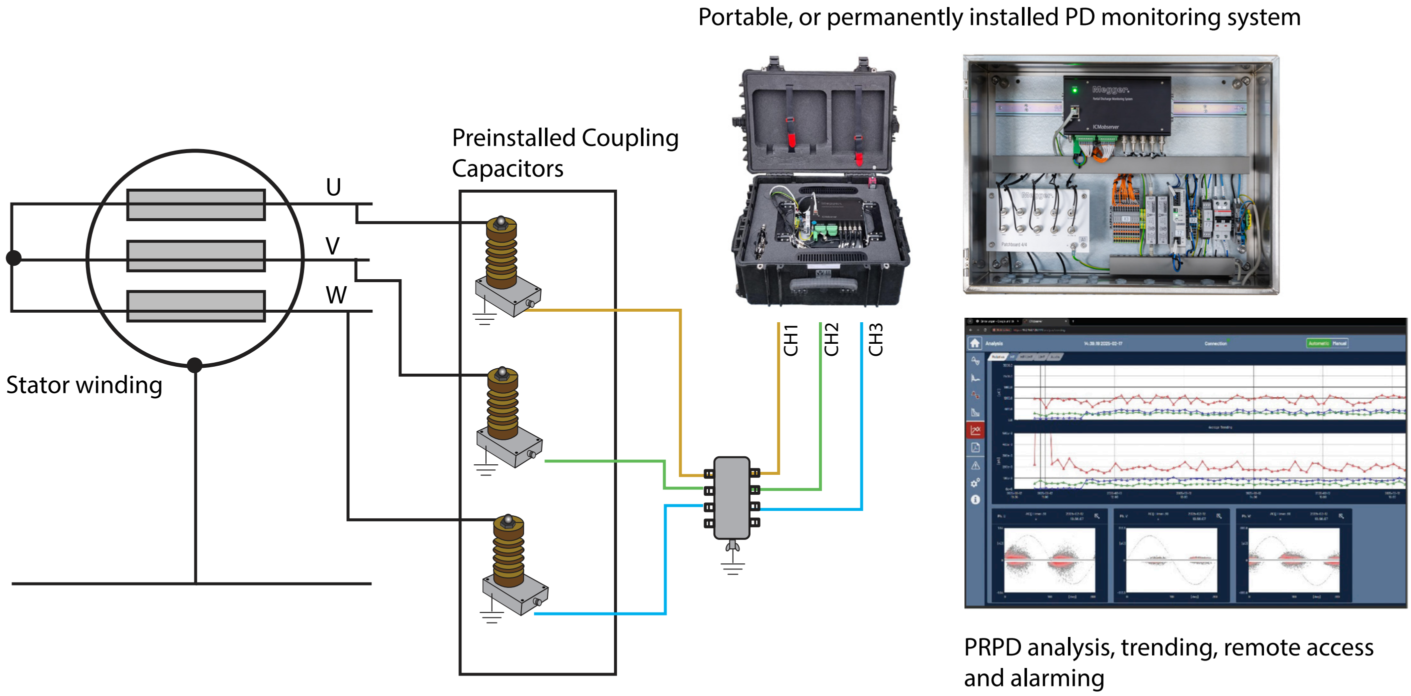


Figure 6. Schematic of a HV rotating machine with preinstalled coupling capacitors for online PD spot testing or monitoring

**LEVEL 3 (in combination with LEVEL 1, instead of LEVEL 2): Permanent Online Partial Discharge Monitoring**

Owners of highly critical and costly machinery, such as hydro generators, or critical motors for industrial processes, frequently prefer continuous online PD monitoring with remote access and automatic alarming if a threshold value is exceeded. This gives them the highest level of assurance that no critical and rapidly evolving failure mechanism will remain undetected and that they will be able to react with preventive measures at an early stage when partial repair is still possible and effective. Online PD monitoring is often also applied on aged machines with the objective of prolonging the life of the asset while having risk assessment under control 24/7. Online PD Monitoring can be augmented by monitoring other parameters, such as temperature and active power. To allow for this the ICM*observer* offers 4 analogue inputs 4-20mA.

The ICM*observer* system uses a web interface running directly on the device (Monitoring Webserver) and it can be remotely accessed through a LAN network or by using a LTE VPN router. This is a convenient solution for the user, as no desktop software license is necessary. It is also a safe solution from a cyber security point of view. Alarms can be forwarded through a dry alarm contact and the measured data for Qp (charge in pC, or mV) and NQS (average discharge current) can be forwarded together with the alarms into external systems through industrial protocols, such as IEC61850, Modbus, or DNP3.

## IV. Summary

The described "Three-Level Strategy" of combining regular offline inspections of stator winding insulation status with online partial discharge spot testing or monitoring appears to be the most effective predictive maintenance strategy for critical HV motors and generators. It not only allows costly failures and outages to be avoided, but also makes it possible to prolong the lifetime of these critical assets and to make condition-based informed decisions about their reliable operation.

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***Literature:***


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