



Electrical and Environmental Aging of Wind Turbine Generator Insulation: A Critical Review of Stress Mechanisms, Degradation, and Mitigation

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التقادم الكهربائي والبيئي لعوازل مولدات توربينات الرياح: مراجعة نقدية لآليات الإجهاد والتدهور
وسبل الحد منه

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Abstract:

Wind turbine generators are essential components of modern renewable-energy systems, and their operational reliability is strongly dependent on the performance and durability of their electrical insulation systems. These insulation systems are continuously exposed to interacting electrical, thermal, mechanical, and environmental stresses that may progressively reduce insulation performance, reliability, and service life. The increasing application of power electronic converters introduces additional electrical stresses, particularly rapid voltage transitions, repetitive impulses, and high-frequency components, while thermal cycling, vibration, humidity, water exposure, and salinity may further accelerate insulation degradation. Therefore, understanding the combined effects of these ageing mechanisms is important for improving the reliability and maintenance of wind turbine generators, particularly in demanding offshore environments.

This study aims to critically review and integrate the principal electrical, thermal, mechanical, and environmental ageing mechanisms affecting wind turbine generator insulation. It specifically examines converter-induced electrical stress, partial discharge, thermal ageing, mechanical degradation, humidity, water exposure, salinity, and the interactions among these mechanisms. The study adopts a descriptive and critical review methodology based on the analysis and synthesis of relevant technical and scientific literature. The reviewed evidence is comparatively examined to identify major degradation pathways, condition-monitoring indicators, insulation-protection measures, testing approaches, and maintenance strategies for both onshore and offshore wind turbine applications.

The findings indicate that insulation degradation is not generally attributable to a single stress factor but results from complex interactions among multiple ageing mechanisms. Partial discharge emerges as an important diagnostic indicator, although its interpretation requires consideration of operating and environmental conditions. The findings also demonstrate the practical importance of integrating insulation design, converter control, environmental protection, condition monitoring, and maintenance planning. In real-world applications, an integrated condition-assessment approach can support earlier detection of insulation deterioration, more informed maintenance decisions, reduced unexpected downtime, and improved generator reliability and service life. The study consequently provides a consolidated framework for understanding and managing electrical and environmental ageing in wind turbine generator insulation.

Keywords: Wind Turbine Generator Insulation; Electrical Ageing; Environmental Ageing; Electrical Stress; Insulation Degradation; Partial Discharge; Thermal Ageing; Mechanical Stress; Power Electronic Converters; Condition Monitoring.

المخلص

تعتبر مولدات توربينات الرياح مكونات أساسية في أنظمة الطاقة المتجددة الحديثة، وتعتمد موثوقيتها التشغيلية بشكل كبير على أداء ومثانة أنظمة العزل الكهربائي المستخدمة فيها. وتتعرض أنظمة العزل هذه باستمرار لمجموعة متفاعلة من الإجهادات الكهربائية والحرارية والميكانيكية والبيئية التي قد تؤدي تدريجياً إلى تدهور أداء العزل وموثوقيته وتقليص عمره الافتراضي. ويؤدي التوسع في استخدام محولات الطاقة الإلكترونية (power electronic converters) إلى نشوء إجهادات كهربائية إضافية، ولا سيما التغيرات السريعة في الجهد، والنبضات المتكررة، والمكونات عالية التردد، في حين قد تؤدي عوامل مثل الدورات الحرارية والاهتزاز والرطوبة والتعرض للمياه والملوحة إلى تسريع وتيرة تدهور العزل. ومن ثم، فإن فهم التأثيرات المشتركة لآليات التقادم هذه يُعد أمراً بالغ الأهمية لتحسين موثوقية مولدات توربينات الرياح وصيانتها، لا سيما في البيئات البحرية القاسية.

تهدف هذه الدراسة إلى إجراء مراجعة نقدية وتكاملية لآليات التقادم الرئيسية -الكهربائية والحرارية والميكانيكية والبيئية- التي تؤثر على عزل مولدات توربينات الرياح. وتتناول الدراسة على وجه التحديد الإجهادات الكهربائية الناجمة عن المحولات، والتفريغ الجزئي، والتقادم الحراري، والتدهور الميكانيكي، والرطوبة، والتعرض للمياه، والملوحة، والتفاعلات المتبادلة بين هذه الآليات. وتعتمد الدراسة منهجية المراجعة الوصفية والنقدية القائمة على تحليل وتوليف الأدبيات العلمية والتقنية ذات الصلة؛ حيث يتم فحص الأدلة المتاحة ومقارنتها لتحديد مسارات التدهور الرئيسية، ومؤشرات مراقبة الحالة، وتدابير حماية العزل، وأساليب الاختبار، واستراتيجيات الصيانة المناسبة لتطبيقات توربينات الرياح سواء البرية أو البحرية. وتشير النتائج إلى أن تدهور العزل لا يعزى عموماً إلى عامل إجهاد واحد، بل ينجم عن تفاعلات معقدة بين آليات تقادم متعددة. ويبرز "التفريغ الجزئي" كمؤشر تشخيصي هام، وإن كان تفسيره يتطلب مراعاة ظروف التشغيل والعوامل البيئية المحيطة. كما تظهر النتائج الأهمية العملية للتكامل بين تصميم العزل، والتحكم في المحولات، والحماية البيئية، ومراقبة الحالة، وتخطيط الصيانة. وفي التطبيقات العملية، يمكن لنهج متكامل لتقييم الحالة أن يدعم الكشف المبكر عن تدهور العزل، واتخاذ قرارات صيانة أكثر دقة واستنارة، وتقليل فترات التوقف غير المخطط لها، وتحسين موثوقية المولد وعمره الافتراضي. وبناءً على ذلك، تقدم الدراسة إطاراً شاملاً وموحداً لفهم وإدارة التقادم الكهربائي والبيئي في أنظمة عزل مولدات توربينات الرياح.

الكلمات المفتاحية: عزل مولدات توربينات الرياح؛ التقادم الكهربائي؛ التقادم البيئي؛ الإجهاد الكهربائي؛ تدهور العزل؛ التفريغ الجزئي؛ التقادم الحراري؛ الإجهاد الميكانيكي؛ محولات إلكترونيات القوى؛ مراقبة الحالة.

1. INTRODUCTION:

Wind energy has become an important component of modern electricity generation, with wind turbines increasingly deployed in both onshore and offshore environments. The generator is a key electrical component because it converts mechanical power from the rotating system into electrical power. Reliable generator operation is therefore essential for turbine availability, while deterioration of the insulation system can lead to electrical faults, reduced availability, and costly repair or replacement (Liu et al., 2024; Nunes et al., 2021).

Wind turbine generator insulation is exposed to a combination of stresses that can differ from those encountered in conventional electrical machines. Variable-speed operation and the increasing use of power electronic converters introduce rapid voltage transitions and repetitive impulses that can increase electrical stress on winding insulation and promote partial discharge. Previous studies have identified the relationship between converter switching, voltage stress, partial discharge, and insulation ageing as an important reliability consideration (Danikas & Karlis, 2011a; Danikas & Karlis, 2011b; Petri et al., 2022; Zou et al., 2024).

Electrical stress is only one component of the ageing process. Generator insulation may simultaneously experience thermal stress associated with winding losses and temperature cycling, mechanical stress caused by vibration and electromagnetic forces, and environmental stresses related to humidity, water, and salinity. These stresses may interact rather than act independently, particularly in offshore turbines where moisture and salinity can affect insulation behaviour (Afzal & Hassani, 2024; Ji et al., 2024; Malliou et al., 2016).

Partial discharge is an important indicator of insulation condition. Localized discharge can occur when the electric field within a defective or stressed region becomes sufficiently high, and repeated discharge activity may progressively damage the insulation. PD characteristics can therefore provide useful information for ageing assessment and condition monitoring (Altmann et al., 1998; Cruz et al., 2022; Danikas & Karlis, 2011b; Verginadis et al., 2021).

Recent reviews have examined insulation systems in electrical machines, including insulation design, testing, degradation mechanisms, and partial-discharge monitoring, while other studies have addressed wind turbine generator failures and condition-diagnosis methods (Afzal & Hassani, 2024; Cruz et al., 2022; Ji et al., 2024; Liu et al., 2024; Nunes et al., 2021; Zhang et al., 2025). These works provide important foundations, but a focused assessment of the combined electrical and environmental ageing of wind turbine generator insulation

remains useful, particularly regarding the interaction of electrical, thermal, mechanical, and environmental stresses.

The objective of this paper is to critically review the principal stresses affecting wind turbine generator insulation and their associated degradation mechanisms, with particular emphasis on converter-related electrical stress and its interaction with thermal, mechanical, humidity, water, and salinity effects. The review compares the main degradation processes and examines reported approaches for insulation protection, testing, condition monitoring, and mitigation. Practical considerations for onshore and offshore applications are also discussed, providing a technical framework linking stress, degradation, monitoring, and maintenance without relying on a specific experimental dataset or numerical simulation.

2. INSULATION SYSTEMS IN WIND TURBINE GENERATORS:

2.1 Main Insulation Components

The insulation system of a wind turbine generator consists of several components that provide electrical separation, mechanical support, and protection against operating stresses. Stator winding insulation is particularly critical because it must withstand electrical potential between the conductors and stator core while tolerating thermal cycling, vibration, and electromagnetic forces. Typical components include conductor enamel, turn-to-turn insulation, ground-wall insulation, slot insulation, and protective coatings or treatments (**Afzal & Hassani, 2024; Stone et al., 2014**).

In converter-fed generators, repeated voltage transitions produced by power-electronic switching introduce additional dielectric stress, particularly at winding terminals and between turns. The magnitude and distribution of this stress depend on converter characteristics, generator design, cable arrangement, and operating conditions (**Danikas & Karlis, 2011a; Petri et al., 2022; Zou et al., 2024**).

2.2 Insulation Materials

Electrical-machine insulation systems commonly combine polymeric, mica-based, resin, enamel, and composite materials. Material selection depends on thermal class, dielectric strength, mechanical properties, manufacturing requirements, and environmental exposure (**Afzal & Hassani, 2024; Stone et al., 2014**).

Modern insulation systems are generally multilayer structures, so degradation may occur within individual layers or at material interfaces. Voids, delamination, contamination, and local mechanical damage can produce regions of enhanced electric field and contribute to partial discharge or accelerated ageing (**Altmann et al., 1998; Danikas & Karlis, 2011b; Stone et al., 2014; Verginadis et al., 2021**).

2.3 Electrical Requirements

The primary function of generator insulation is to prevent unwanted current flow between electrically different winding components and between the winding and grounded stator core. It must therefore withstand normal operating voltage as well as temporary and repetitive overvoltage conditions (**Stone et al., 2014**).

Converter-fed generators require additional consideration because switching produces high-frequency components and rapid voltage changes. These conditions can create non-uniform electric-field distributions within the insulation, making converter-related electrical stress an important factor in insulation ageing (**Danikas & Karlis, 2011a; Petri et al., 2022; Zou et al., 2024**).

2.4 Thermal Requirements

Temperature strongly influences insulation lifetime. Winding losses generate heat, while variations in wind speed, electrical output, and loading produce changing thermal conditions during turbine operation. The insulation must remain within its specified thermal limits (**Barré & Napame, 2017; Stone et al., 2014; Zhang et al., 2025**).

Repeated temperature changes cause expansion and contraction of insulation components. Differences in thermal expansion between materials can generate stresses at interfaces and, over time, contribute to cracking, separation, and loss of mechanical integrity (**Munič & Miljavec, 2014; Stone et al., 2014; Zhang et al., 2025**).

2.5 Mechanical Requirements

Generator insulation must maintain mechanical integrity under vibration and cyclic loading associated with rotor rotation, electromagnetic forces, torque variations, and changing operating conditions. Inadequate winding support can lead to insulation movement, abrasion, or local damage (**Stone et al., 2014**).

Mechanical damage can also interact with other ageing mechanisms. Damaged regions may facilitate moisture penetration or partial discharge, while electrical and thermal ageing can further weaken mechanically affected areas. Insulation degradation should therefore be considered as an interacting process rather than as a set of completely independent mechanisms (**Altmann et al., 1998; Danikas & Karlis, 2011b; Munič & Miljavec, 2014; Stone et al., 2014**).

2.6 Environmental Requirements

Wind turbine generators may operate under humidity, condensation, dust, salt, temperature variations, and water ingress. These conditions are particularly demanding in offshore installations because of seawater exposure and airborne salt (Ji et al., 2024; Malliou et al., 2016).

Water and salinity can modify surface and dielectric behaviour and may promote leakage currents or surface discharge under suitable conditions. Environmental protection is therefore an integral part of insulation design and maintenance. Sealing, ventilation, surface protection, material selection, and appropriate maintenance can all influence insulation performance and service life (Ji et al., 2024; Malliou et al., 2016).

The overall relationship between the main stresses, degradation mechanisms, monitoring indicators, and maintenance considerations is illustrated in Figure 1.

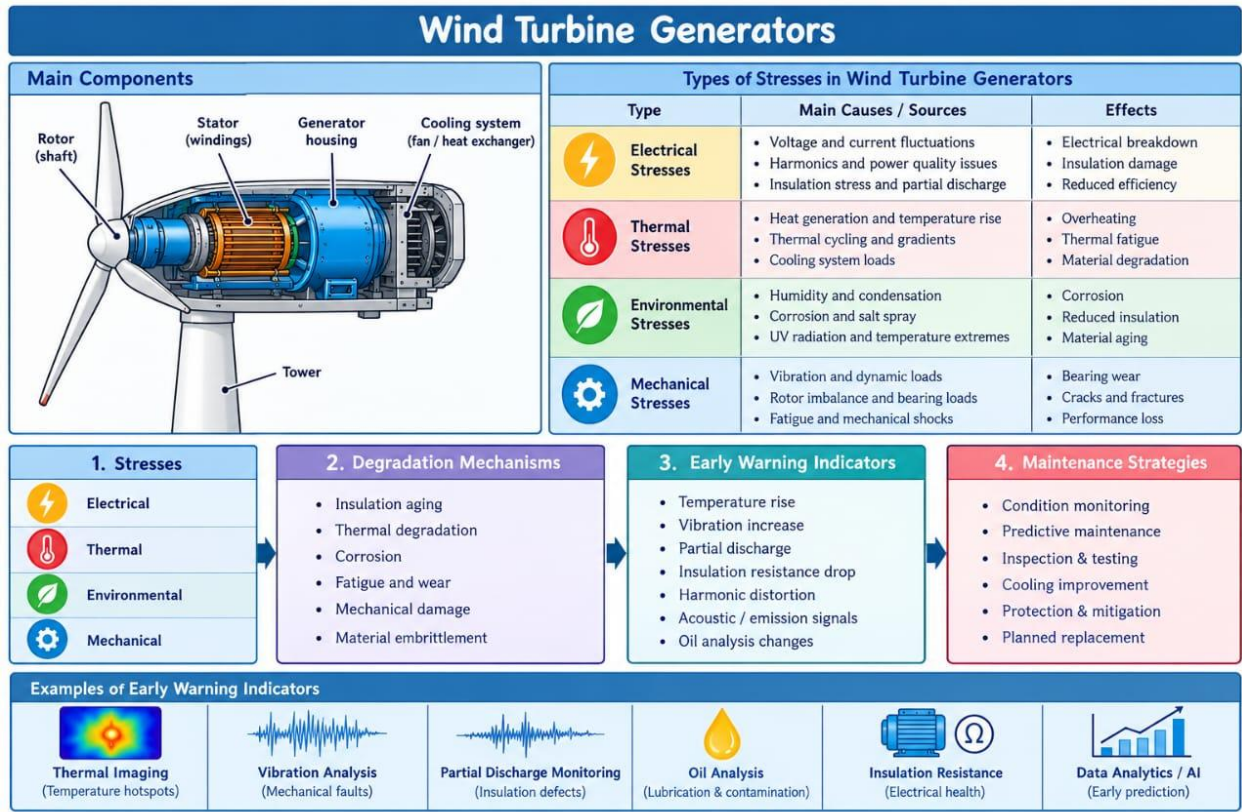


Figure 1. Integrated stress–degradation–monitoring–maintenance framework for wind turbine generator insulation.

3. ELECTRICAL STRESS AND CONVERTER-INDUCED INSULATION AGEING

Modern variable-speed wind turbine generators commonly employ power electronic converters to control generator speed and electrical power. Unlike approximately sinusoidal grid excitation, converter operation can introduce rapid voltage transitions, repetitive impulses, and high-frequency components. These phenomena impose additional electrical stress on winding insulation and can influence partial-discharge behaviour (Danikas & Karlis, 2011a; Petri et al., 2022; Zou et al., 2024).

3.1 Converter-Generated Voltage Stress

Pulse-width-modulated (PWM) converters produce voltage waveforms through high-speed switching. The resulting generator-terminal voltage depends on switching characteristics, cable parameters, converter topology, generator design, and operating conditions (Danikas & Karlis, 2011a; Petri et al., 2022; Zou et al., 2024). Rapid voltage transitions can produce a non-uniform voltage distribution along the winding, causing individual turns to experience stresses different from those expected under sinusoidal excitation. This is particularly important for turn-to-turn insulation, where localized electrical stress may develop even when the overall applied voltage remains below the conventional breakdown level (Danikas & Karlis, 2011a; Petri et al., 2022; Zou et al., 2024).

3.2 Effect of Voltage Rise Time

Voltage rise time strongly influences the electrical stress produced by converter switching. Shorter rise times generate steeper voltage gradients and can alter voltage distribution within the winding. Studies of inverter-fed winding insulation have reported lower partial-discharge inception voltages under faster repetitive impulses, indicating that sinusoidal-voltage testing alone may not fully represent converter-related electrical stress (Danikas & Karlis, 2011a; Nair et al., 2019; Petri et al., 2022; Zou et al., 2024).

PWM waveform characteristics, terminal overvoltage, and pulse repetition are therefore important considerations when assessing insulation ageing in converter-fed machines (Danikas & Karlis, 2011a; Zou et al., 2024).

The interaction among electrical, thermal, environmental, and mechanical stresses and their principal degradation pathways is illustrated in Figure 2.

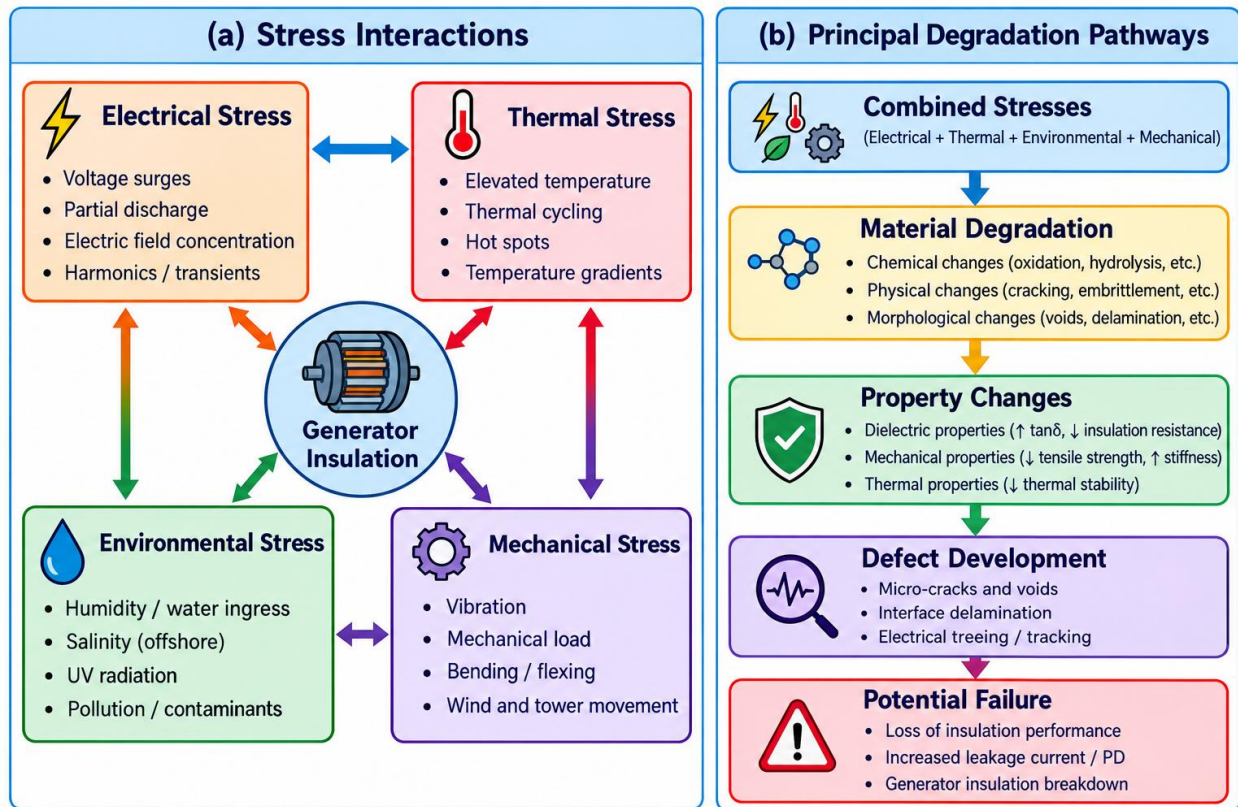


Figure 2. Interaction of electrical, thermal, environmental, and mechanical stresses in wind turbine generator insulation: (a) stress interactions and (b) principal degradation pathways.

3.3 Partial Discharge Under Converter Operation

Partial discharge (PD) is a localized electrical discharge that does not completely bridge the insulation between electrodes. In rotating-machine insulation, it may develop in voids, interfaces, cracks, or other regions of enhanced electric field (Altmann et al., 1998; Danikas & Karlis, 2011b; Stone et al., 2014; Verginadis et al., 2021).

Under repetitive impulse voltages, repeated PD activity can progressively modify and deteriorate insulation. In wind turbine generators, this process may be influenced by simultaneous thermal, mechanical, and environmental stresses. PD measurements can provide useful information about insulation condition; however, PD detection alone does not provide a universal prediction of remaining insulation life. Its interpretation depends on the insulation system, voltage waveform, defect characteristics, environmental conditions, and operating history (Altmann et al., 1998; Cruz et al., 2022; Danikas & Karlis, 2011b; Ji et al., 2024).

3.4 Turn-to-Turn and Ground-Wall Insulation

Converter-induced electrical stress affects different insulation regions differently. Turn-to-turn insulation is particularly sensitive to non-uniform voltage distribution caused by fast voltage transitions, whereas ground-wall insulation must withstand the voltage between the winding and the grounded stator core (Petri et al., 2022; Stone et al., 2014; Zou et al., 2024).

The relative importance of these regions depends on generator design, voltage level, winding arrangement, converter characteristics, and defect location. Generator insulation should therefore be assessed as a distributed and multilayer system rather than as a homogeneous structure (Afzal & Hassani, 2024; Stone et al., 2014).

3.5 Common-Mode Voltage and Associated Electrical Stress

Converter switching can also produce common-mode voltage (CMV), which interacts with parasitic capacitances in the generator and connected electrical system. This may result in shaft voltages and bearing currents and can therefore affect generator reliability (Petri et al., 2022; Zou et al., 2024).

Although CMV is not an insulation-ageing mechanism in the narrow sense, it illustrates how converter-generated electrical phenomena can affect several generator components simultaneously. Insulation reliability should consequently be considered within the complete converter-generator electrical system.

3.6 Mitigation of Converter-Induced Electrical Stress

Converter-related electrical stress can be reduced through appropriate control of voltage rise rates and terminal overvoltage, suitable converter topologies, output or common-mode filtering, optimized PWM strategies, converter-compatible insulation systems, and appropriate testing and condition-monitoring procedures (Danikas & Karlis, 2011a; IEC, 2019; IEC, 2020; Petri et al., 2022; Zou et al., 2024).

The most suitable approach depends on the converter and generator configuration. Mitigation may involve trade-offs among electrical stress, losses, cost, maintenance, and system complexity. It should therefore be considered as a system-level engineering decision rather than solely as an insulation-material selection problem.

4. THERMAL, MECHANICAL, AND ENVIRONMENTAL AGEING:

Electrical stress is only one component of insulation degradation in wind turbine generators. During operation, insulation is exposed simultaneously to temperature variations, mechanical loading, vibration, humidity, water, dust, and, particularly offshore, salt contamination. These stresses may act independently but can also interact, with degradation caused by one stress increasing the sensitivity of the insulation to others (Danikas & Karlis, 2011b; Ji et al., 2024; Malliou et al., 2016; Stone et al., 2014; Zhang et al., 2025).

4.1 Thermal Ageing

Temperature is a major factor influencing insulation lifetime. Heat generated by winding and magnetic losses varies with generator loading and wind conditions. Repeated temperature changes cause expansion and contraction of insulation components, and differences in thermal expansion between materials can generate stresses at interfaces. Over time, these stresses may contribute to cracking, delamination, loss of adhesion, and changes in dielectric performance (Barré & Napame, 2017; Munič & Miljavec, 2014; Stone et al., 2014; Zhang et al., 2025).

Thermal ageing is therefore influenced not only by maximum temperature but also by the duration, frequency, and magnitude of temperature excursions. This is particularly relevant to wind turbines because their operating conditions vary continuously (Zhang et al., 2025).

4.2 Thermal Cycling and Insulation Integrity

Thermal cycling can interact with electrical and mechanical ageing. Cracks or defects produced by repeated expansion and contraction may create localized regions of enhanced electric field and become sites for partial discharge. Conversely, degradation of insulation can reduce mechanical strength and increase its susceptibility to vibration and movement (Altmann et al., 1998; Munič & Miljavec, 2014; Stone et al., 2014; Zhang et al., 2025).

Thus, operation below the nominal thermal limit does not necessarily eliminate progressive ageing when repeated thermal cycling occurs together with other stresses.

4.3 Mechanical Stress and Vibration

Wind turbine generators experience mechanical forces associated with rotor rotation, electromagnetic forces, torque variations, and structural vibration. These conditions can cause insulation movement, abrasion, loosening, or damage at material interfaces, while vibration may amplify pre-existing defects (Altmann et al., 1998; Munič & Miljavec, 2014; Stone et al., 2014).

Mechanical deterioration can become more significant when insulation has already been weakened by thermal or environmental ageing. Mechanical stress can therefore act both as a direct degradation mechanism and as a factor that accelerates other ageing processes.

4.4 Humidity and Moisture

Humidity and moisture can enter generators through ventilation, condensation, inadequate sealing, or temperature changes between the machine and its surroundings. Depending on the insulation material and surface condition, moisture may reduce insulation resistance, modify surface electrical behaviour, and facilitate contamination-related surface conduction or surface discharge (Ji et al., 2024; Malliou et al., 2016).

The resulting effect depends on material properties, surface condition, and generator design. Repeated humidity cycles may therefore affect insulation differently from continuous exposure to dry conditions (Ji et al., 2024).

4.5 Water Exposure

Water exposure is more severe than ordinary atmospheric humidity and may result from condensation, leakage, inadequate sealing, or environmental ingress. It is particularly relevant to offshore wind turbines (Malliou et al., 2016).

Water can modify surface conductivity and create conditions favourable to leakage currents and surface discharge, especially in the presence of contaminants. Water protection and effective sealing should therefore be considered integral parts of the insulation reliability strategy (Malliou et al., 2016).

4.6 Salinity and Marine Exposure

Offshore wind turbines are exposed to high humidity, airborne salt, water droplets, and repeated wetting and drying. Salt contamination can increase surface conductivity, particularly when moisture dissolves deposited salts and forms a conductive surface layer. Under electrical stress, this condition may increase leakage current and promote surface discharge (Malliou et al., 2016).

Offshore generator insulation therefore requires particular attention to surface protection, sealing, contamination control, and inspection (Malliou et al., 2016).

4.7 Combined Environmental and Electrical Stress

Environmental, thermal, mechanical, and electrical stresses may interact rather than produce independent degradation. Moisture can modify surface conductivity while converter-generated transients provide repeated electrical excitation. Thermal cycling can create microscopic defects that become sites for partial discharge, while mechanical vibration may enlarge or propagate these defects (Altmann et al., 1998; Danikas & Karlis, 2011b; Ji et al., 2024; Malliou et al., 2016).

A useful conceptual degradation sequence is:

Environmental or thermal exposure → material/interface modification → defect formation → increased local electrical stress → partial discharge or leakage → progressive insulation deterioration.

This sequence is a conceptual framework rather than a universal failure path. Its purpose is to illustrate how different ageing mechanisms can interact and progressively reduce insulation reliability.

The conceptual interaction of these stresses and their progression toward insulation degradation is illustrated in Figure 3.

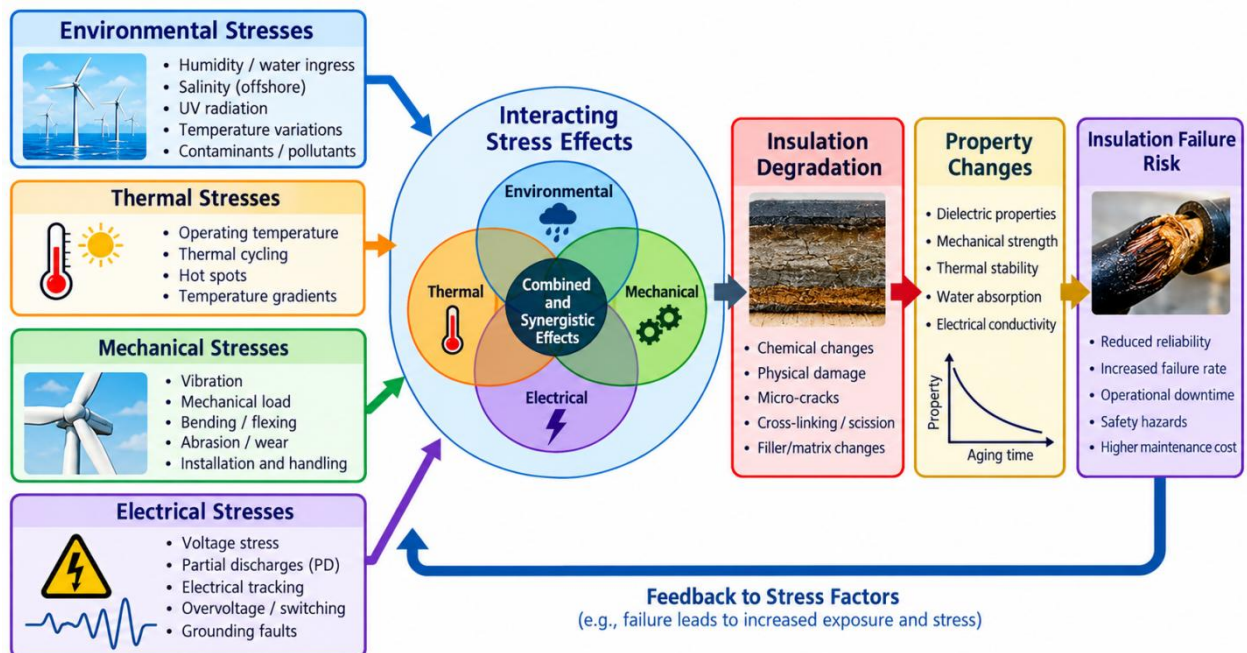


Figure 3. Conceptual interaction of environmental, thermal, mechanical, and electrical stresses leading to insulation degradation.

4.8 Interaction Between Ageing Mechanisms

The combined effect of multiple stresses is particularly important in wind turbine generators. Thermal ageing can weaken mechanical properties, mechanical damage can create defects, moisture can increase surface conductivity, and electrical stress can activate or accelerate degradation at these defects (Altmann et al., 1998; Danikas & Karlis, 2011b; Ji et al., 2024; Malliou et al., 2016; Munič & Miljavec, 2014).

Insulation assessment should therefore consider electrical operating conditions together with the thermal, mechanical, and environmental conditions experienced by the generator.

5. PARTIAL DISCHARGE AND INSULATION DEGRADATION:

Partial discharge (PD) is a localized electrical discharge that does not completely bridge the insulation between conductors or between a conductor and ground. In wind turbine generators, PD can develop in defects, voids, interfaces, cracks, or regions of high local electric-field strength (Altmann et al., 1998; Danikas & Karlis, 2011b; Stone et al., 2014; Verginadis et al., 2021).

Its importance is increased in converter-fed generators because repetitive voltage impulses and rapid voltage transitions produce electrical conditions that differ from conventional sinusoidal excitation. PD diagnostics have therefore been investigated as an important tool for assessing wind turbine generator insulation (Cruz et al., 2022; Danikas & Karlis, 2011a; Danikas & Karlis, 2011b).

5.1 Sources of Partial Discharge

PD can originate from imperfections within the insulation system, including:

- voids within solid insulation;
- cracks and delamination;
- weak interfaces between insulation layers;
- surface contamination;
- regions of excessive electric-field concentration; and
- defects associated with thermal, mechanical, or environmental ageing (Altmann et al., 1998; Danikas & Karlis, 2011b; Stone et al., 2014; Verginadis et al., 2021).

Discharge behaviour depends on the defect geometry and location, insulation material, voltage waveform, temperature, humidity, and operating conditions. Consequently, the same measured PD level does not necessarily indicate the same physical condition in different generators. Interpretation should therefore consider the insulation design and operating environment (Cruz et al., 2022; Danikas & Karlis, 2011b; Ji et al., 2024).

5.2 Partial Discharge Under Repetitive Impulses

Conventional insulation assessment often uses power-frequency voltage, whereas converter-fed wind generators may experience repetitive impulse voltages with short rise times (Danikas & Karlis, 2011a; Petri et al., 2022; Zou et al., 2024).

Under such conditions, the electric-field distribution can differ from that produced by sinusoidal excitation. Investigations of inverter-fed winding insulation have shown that impulse rise time can influence PD inception voltage, with shorter rise times potentially producing greater electrical stress and lower PD inception voltage (Danikas & Karlis, 2011a; Nair et al., 2019; Petri et al., 2022; Zou et al., 2024).

Therefore, power-frequency testing alone may not reproduce all electrical stresses experienced by converter-fed generators. This issue is also addressed by converter-fed rotating-machine insulation qualification standards (IEC, 2019; IEC, 2020).

5.3 Relationship Between Partial Discharge and Insulation Ageing

PD has two important roles in insulation assessment. First, it can act as a diagnostic indicator of existing defects or degradation. Changes in PD magnitude, phase distribution, repetition rate, and apparent discharge characteristics can provide information about insulation condition (Cruz et al., 2022; Danikas & Karlis, 2011b; IEEE, 2014).

Second, repeated PD activity can contribute to further deterioration by modifying the surrounding material and promoting additional defects. Depending on the insulation structure, this may involve erosion, chemical modification, electrical treeing, or enlargement of existing cavities (Altmann et al., 1998; Danikas & Karlis, 2011b; Verginadis et al., 2021).

However, PD activity cannot be directly interpreted as a universal measure of remaining insulation lifetime. High PD does not necessarily indicate immediate failure, while low PD does not guarantee long remaining life. Interpretation depends on the defect type, insulation system, voltage and waveform, temperature, and machine history (Cruz et al., 2022; Danikas & Karlis, 2011b; Ji et al., 2024).

5.4 PD Detection Techniques

PD can be detected using conventional electrical measurements, high-frequency current-transformer methods, high-frequency electromagnetic techniques, acoustic methods, and optical approaches (Cruz et al., 2022; Danikas & Karlis, 2011b; IEEE, 2014).

For large generators, online PD monitoring is particularly useful because it enables insulation condition assessment while the machine remains in service. The selection of a monitoring technique depends on sensitivity, installation requirements, electromagnetic interference, accessibility, cost, and whether the measurement is intended for laboratory testing or continuous online monitoring (Cruz et al., 2022; IEEE, 2014; Nunes et al., 2021).

5.5 Online and Offline Assessment

Insulation assessment can generally be performed using offline or online approaches. Offline testing provides controlled conditions and allows different diagnostic methods to be applied, but it requires the generator to be removed from service or electrically isolated and may not represent its actual operating conditions (IEEE, 2014; Stone et al., 2014).

Online monitoring enables insulation behaviour to be assessed during normal operation. This is particularly relevant to wind turbines because condition monitoring can reduce unnecessary shutdowns and support condition-based maintenance by identifying changes before severe deterioration occurs (Cruz et al., 2022; Nunes et al., 2021).

However, online measurements can be affected by converter switching, electromagnetic interference, operating noise, and changing load conditions. Reliable assessment therefore requires appropriate signal discrimination and interpretation of operating conditions (Cruz et al., 2022; IEEE, 2014).

5.6 PD and Environmental Conditions

Environmental conditions can significantly influence PD behaviour. Humidity and water can modify surface conductivity and local electric-field conditions, while salt contamination can further increase surface conductivity under wet conditions (Ji et al., 2024; Malliou et al., 2016).

This interaction is particularly relevant to offshore wind turbines. PD measurements should therefore be interpreted together with relevant operating and environmental conditions rather than considered as an isolated indicator of insulation condition (Ji et al., 2024; Malliou et al., 2016).

5.7 From PD Detection to Maintenance Decisions

The practical value of PD monitoring depends on how diagnostic information is translated into maintenance decisions. A useful assessment considers the sequence:

PD detection → trend analysis → defect interpretation → severity assessment → maintenance decision.

Trend analysis can provide more useful information than a single measurement because changes in PD behaviour over time may indicate progressive deterioration. However, universal PD thresholds are difficult to establish because wind turbine generators differ in design, insulation systems, voltage levels, converter configurations, and environmental conditions (Cruz et al., 2022; Danikas & Karlis, 2011b; Ji et al., 2024).

PD monitoring should therefore be considered as one component of a broader insulation condition-assessment strategy rather than as a standalone predictor of failure.

The conceptual pathway from PD monitoring to maintenance decision is illustrated in Figure 4.

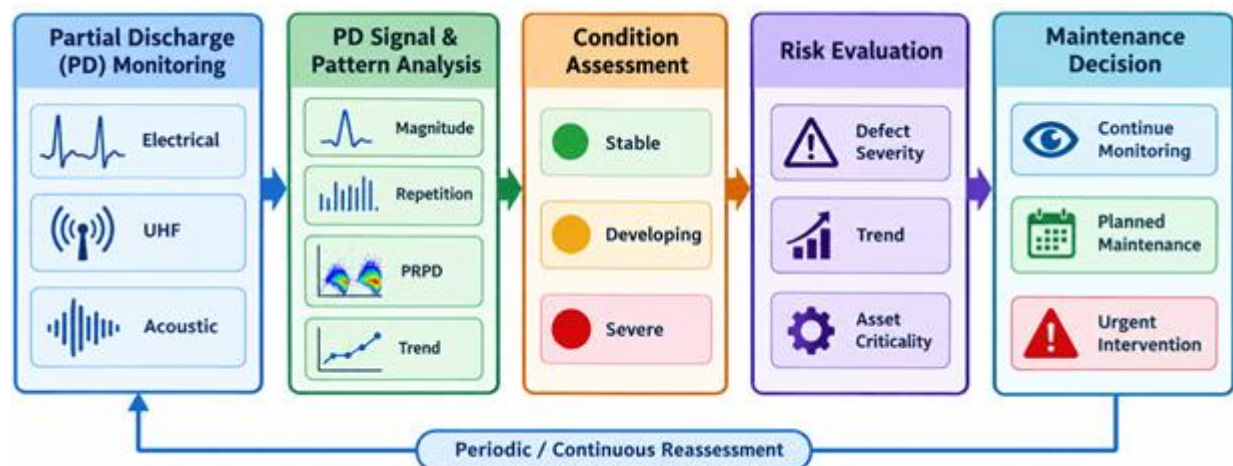


Figure 4. Conceptual pathway from partial-discharge monitoring to maintenance decision.

6. MITIGATION, MONITORING, AND MAINTENANCE STRATEGIES:

Insulation degradation can result from interacting electrical, thermal, mechanical, and environmental stresses. Mitigation should therefore address multiple levels, from insulation design and converter operation to environmental protection, condition monitoring, and maintenance (IEC, 2019; IEC, 2020; Ji et al., 2024; Nunes et al., 2021; Stone et al., 2014).

6.1 Insulation Design

Appropriate insulation-system design is the first level of protection. The selected system should provide adequate dielectric strength, thermal capability, mechanical integrity, and environmental resistance for the intended application (Afzal & Hassani, 2024; Stone et al., 2014).

For converter-fed wind generators, the design should also account for repetitive impulse voltages and rapid voltage transitions rather than relying exclusively on power-frequency dielectric requirements (Danikas & Karlis, 2011a; IEC, 2019; IEC, 2020; Petri et al., 2022).

6.2 Converter and Electrical-System Design

Converter-related electrical stress can be reduced through coordinated selection of converter topology, switching strategy, cable characteristics, filters, and generator insulation (Danikas & Karlis, 2011a; IEC, 2019; IEC, 2020; Petri et al., 2022; Zou et al., 2024).

Practical measures include controlling excessive voltage rise rates and terminal overvoltage, applying suitable filters, and selecting switching parameters that limit unnecessary electrical stress. These measures must also consider converter losses, control performance, and power quality.

6.3 Environmental Protection

Environmental protection is particularly important for offshore applications. Measures may include:

- improved sealing and protection against water ingress;
- contamination and humidity control;
- suitable surface treatments;
- corrosion-resistant components; and
- periodic inspection of exposed insulation surfaces (Malliou et al., 2016).

Such measures can reduce the contribution of environmental exposure to progressive electrical degradation.

6.4 Condition Monitoring

Condition monitoring can help detect progressive deterioration before it develops into a major failure. Relevant techniques include:

- partial-discharge monitoring;
- insulation-resistance measurements;
- temperature monitoring;
- vibration monitoring;
- electrical current and voltage monitoring; and
- visual inspection where accessible (Cruz et al., 2022; IEEE, 2014; Nunes et al., 2021).

The appropriate monitoring strategy depends on generator design and operating conditions. Combining complementary indicators can provide a more informative assessment than relying on a single diagnostic measurement (Cruz et al., 2022; Nunes et al., 2021).

6.5 Maintenance Considerations

Maintenance strategies can generally be classified as corrective, preventive, and condition-based approaches. Corrective maintenance is performed after failure, preventive maintenance follows predetermined intervals or operating criteria, and condition-based maintenance uses monitoring information to determine when intervention may be required (Nunes et al., 2021).

For wind turbine generators, condition-based maintenance can be particularly valuable because generator access may be difficult, especially offshore. Early identification of insulation deterioration can allow maintenance to be coordinated with other scheduled interventions and may reduce unnecessary downtime (Liu et al., 2024; Nunes et al., 2021).

However, monitoring results should not automatically trigger component replacement. Maintenance decisions should consider the severity and progression of degradation, operating history, and the consequences of continued operation.

Table 1. Main Insulation Ageing Mechanisms in Wind Turbine Generators

Ageing mechanism	Main effect	Key indicator
Electrical	PD and insulation erosion	PD activity
Thermal	Cracking and ageing	Temperature
Mechanical	Abrasion and damage	Vibration
Moisture	Surface conduction	Insulation resistance, PD
Salinity	Leakage and surface discharge	Surface condition, PD
Combined stresses	Accelerated degradation	Multiple indicators

7. COMPARATIVE ASSESSMENT OF INSULATION AGEING MECHANISMS:

The ageing of wind turbine generator insulation results from several interacting mechanisms rather than from a single source of stress. Electrical, thermal, mechanical, and environmental stresses can occur simultaneously during operation (Danikas & Karlis, 2011b; Ji et al., 2024; Malliou et al., 2016; Stone et al., 2014; Zhang et al., 2025).

A comparative assessment is useful for distinguishing the principal ageing mechanisms, their typical degradation effects, and the indicators that can support condition assessment. These mechanisms should not be interpreted as independent because thermal cycling, moisture, contamination, and mechanical damage can influence subsequent electrical degradation and partial-discharge activity (Altmann et al., 1998; Ji et al., 2024; Malliou et al., 2016; Zhang et al., 2025).

Operating conditions also vary continuously in wind turbines, so the insulation may experience different combinations of stress during different periods rather than a single constant ageing condition (Danikas & Karlis, 2011a; Danikas & Karlis, 2011b; Liu et al., 2024).

Table 2. Comparative Assessment of Insulation Ageing Mechanisms

Ageing mechanism	Main stress	Degradation effect	Key indicators
Electrical	Voltage impulses, overvoltage	PD and insulation erosion	PD activity
Thermal	High temperature, thermal cycling	Cracking and ageing	Temperature
Mechanical	Vibration, winding movement	Abrasion and mechanical damage	Vibration
Moisture	Humidity, water ingress	Surface conduction, insulation deterioration	Insulation resistance, PD
Salinity	Salt deposition, marine exposure	Leakage and surface discharge	Surface condition, PD
Combined	Multiple simultaneous stresses	Accelerated degradation	Multiple indicators

8. FRAMEWORK FOR INSULATION RELIABILITY:

Based on the mechanisms discussed above, insulation reliability can be considered through four interconnected stages (Cruz et al., 2022; Nunes et al., 2021; Stone et al., 2014).

Stage 1 - Stress Identification

Identify the principal stresses acting on the generator insulation, including electrical, thermal, mechanical, humidity, water, salinity, and combined stresses (Danikas & Karlis, 2011a; Danikas & Karlis, 2011b; Ji et al., 2024; Malliou et al., 2016).

Stage 2 -Degradation Assessment

Determine the relevant degradation mechanisms, such as partial discharge, cracking, delamination, contamination, reduced insulation resistance, thermal deterioration, and mechanical damage (Altmann et al., 1998; Danikas & Karlis, 2011b; Malliou et al., 2016; Stone et al., 2014; Verginadis et al., 2021; Zhang et al., 2025).

Stage 3 - Condition Monitoring

Select appropriate indicators according to the generator and operating environment. These may include:

PD + temperature + vibration + insulation resistance + visual/environmental inspection.

Because no single indicator necessarily provides a complete assessment, combining complementary indicators can provide a broader view of insulation condition (Cruz et al., 2022; Nunes et al., 2021).

Stage 4 - Maintenance Decision

Diagnostic information can then support an appropriate maintenance response:

Normal condition → continued operation

Early deterioration → increased monitoring

Progressive deterioration → planned maintenance

Severe deterioration → corrective intervention

This framework is particularly relevant to wind turbines because maintenance accessibility and downtime have practical consequences, especially offshore. Reliable condition assessment can therefore support timely maintenance and reduce the risk of unexpected generator downtime (Liu et al., 2024; Nunes et al., 2021).

9. RESEARCH GAPS AND FUTURE DIRECTIONS:

Although wind turbine generator insulation has been studied extensively, several issues remain important for further investigation (Afzal & Hassani, 2024; Danikas & Karlis, 2011a; Danikas & Karlis, 2011b; Ji et al., 2024; Liu et al., 2024).

9.1 Combined-Stress Assessment

A major challenge is understanding the interaction between different ageing mechanisms. Much existing work examines individual stresses under controlled conditions, whereas operating generators experience electrical, thermal, mechanical, and environmental stresses simultaneously (Danikas & Karlis, 2011b; Ji et al., 2024).

Future research should therefore place greater emphasis on combined-stress assessment and interaction effects rather than treating ageing mechanisms independently.

9.2 Converter-Related Insulation Stress

The continued use of power electronic converters makes converter-induced voltage stress an important research topic. Rapid voltage transitions and repetitive impulses can produce electrical conditions that differ from conventional sinusoidal operation (Danikas & Karlis, 2011a; Petri et al., 2022; Zou et al., 2024).

Further work is needed to clarify how converter characteristics interact with insulation design, operating conditions, and environmental exposure, particularly with respect to PD behaviour under different voltage waveforms and rise times (Danikas & Karlis, 2011a; IEC, 2019; IEC, 2020; Nair et al., 2019; Petri et al., 2022; Zou et al., 2024).

9.3 Environmental Effects

Environmental effects remain particularly relevant to offshore wind turbines. Humidity, water, and salinity can interact with electrical stress and influence surface conductivity, discharge activity, and insulation degradation (Ji et al., 2024; Malliou et al., 2016).

Further research should therefore address the combined influence of environmental exposure and electrical operating conditions under realistic service environments.

9.4 From Detection to Reliable Maintenance Decisions

An important challenge is converting evidence of deterioration into appropriate maintenance decisions. PD, temperature, vibration, and other diagnostic methods can provide valuable condition information, but reliable maintenance thresholds remain difficult to establish because generator designs and insulation systems differ (Cruz et al., 2022; Nunes et al., 2021).

A diagnostic indicator can demonstrate that degradation is occurring without necessarily providing an accurate estimate of remaining useful life (Cruz et al., 2022; Nunes et al., 2021; Zhang et al., 2025).

9.5 Standardization and Test Conditions

Differences in voltage waveforms, environmental conditions, measurement techniques, and ageing procedures make direct comparison between studies difficult (Danikas & Karlis, 2011a; IEC, 2019; IEC, 2020; IEEE, 2014; Petri et al., 2022).

More consistent relationships between laboratory test conditions and actual wind turbine operating conditions would improve the comparability and practical relevance of insulation ageing research.

9.6 Offshore Versus Onshore Reliability

Offshore wind turbines present a distinctive reliability challenge because environmental exposure and maintenance constraints occur simultaneously. The issue is therefore not only the severity of environmental stress

but also the practical consequences of insulation deterioration and limited maintenance accessibility (Liu et al., 2024; Malliou et al., 2016; Nunes et al., 2021).

Future insulation strategies should integrate material selection, environmental protection, condition monitoring, and maintenance planning.

10. CONCLUSIONS:

Wind turbine generator insulation operates under interacting electrical, thermal, mechanical, and environmental stresses that can progressively affect its reliability. Power electronic converters introduce additional electrical stresses, including rapid voltage transitions and repetitive impulses, while thermal cycling, vibration, humidity, water, and salinity can further contribute to insulation deterioration.

Partial discharge provides an important link between electrical stress and insulation degradation; however, its interpretation should consider the insulation system, operating conditions, and environmental exposure. Converter-induced voltage stress can interact with defects produced or accelerated by thermal, mechanical, and environmental ageing, thereby contributing to progressive insulation deterioration.

The comparison of the major ageing mechanisms demonstrates that insulation condition cannot be adequately described by a single stress factor or diagnostic indicator. Thermal ageing can weaken materials and interfaces, mechanical stress can create or enlarge defects, and environmental exposure can modify surface electrical behaviour and increase susceptibility to electrical degradation. These mechanisms may act simultaneously and reinforce one another throughout the generator's operating life.

For practical reliability assessment, an integrated approach is therefore required. Insulation design, converter operation, environmental protection, condition monitoring, and maintenance should be treated as interconnected elements of a comprehensive reliability strategy. Partial-discharge monitoring can provide valuable information about insulation condition, but it should be combined with complementary diagnostic indicators and interpreted in relation to operating history and environmental conditions.

Important research opportunities remain in understanding combined-stress ageing, converter-induced electrical stress, environmental effects, and the translation of diagnostic information into reliable maintenance decisions. Overall, wind turbine generator insulation reliability depends not only on appropriate material selection but also on understanding and managing the interactions among multiple ageing mechanisms throughout the generator service life. In practical applications, adopting an integrated assessment and maintenance approach can support earlier identification of insulation deterioration, improve maintenance planning, reduce unexpected downtime, and contribute to more reliable and sustainable wind turbine operation.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that they have no conflict of interest.

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