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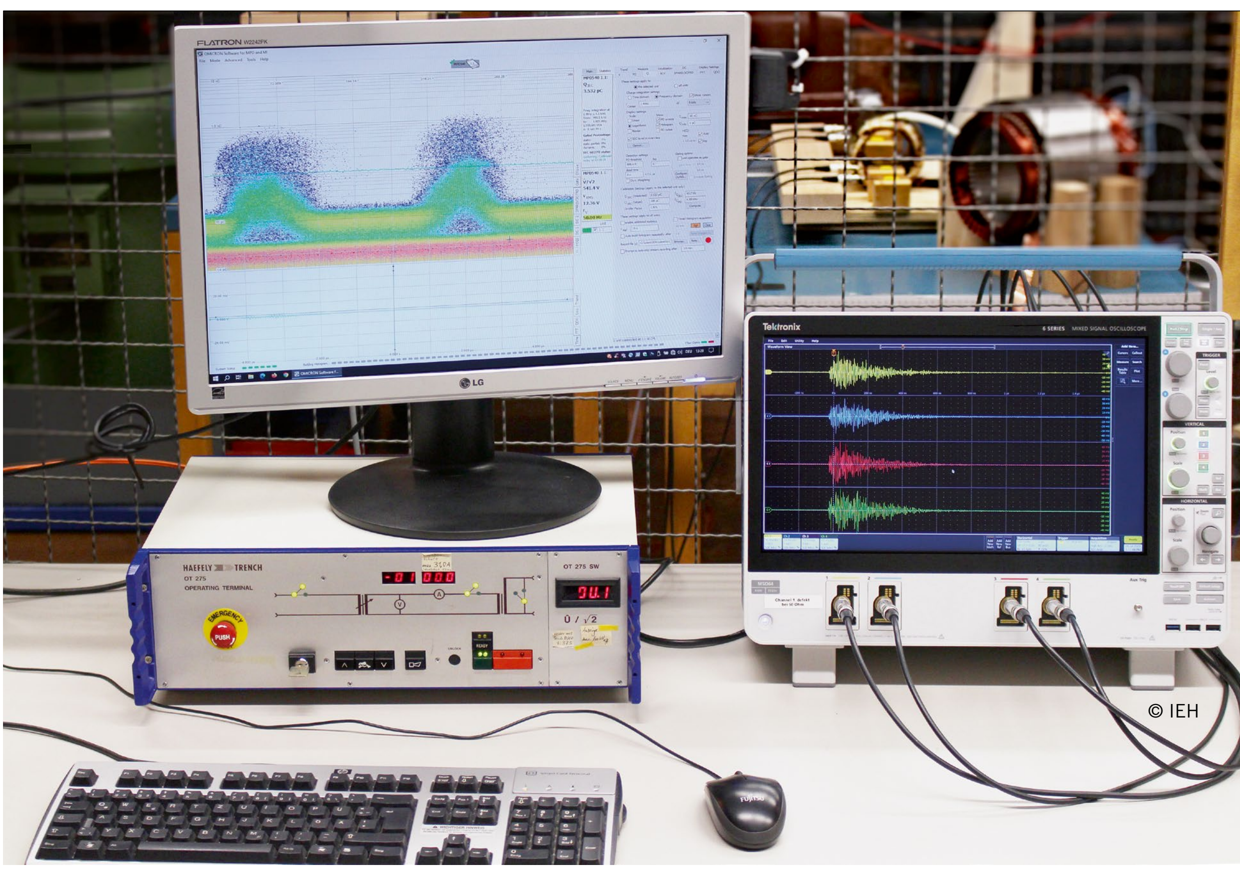
Reliability Assessment for Failure Mechanisms in Complex Electrified Systems

Decarbonization and electrification determine the further development of complex technical systems. Sustainability goals are the central motivation drivers. The success of a product is determined by its reliability, which must also be ensured against unknown damage mechanisms. In the FVV project "Lifetime Model Winding Insulation" (no. 1441), researchers at the University of Stuttgart investigated how this can be achieved for electric motors powered by silicon carbide power semiconductors.



1 MOTIVATION

For several years, the automotive industry has been captivated by the shift towards electric propulsion [1]. However, the development of the electric drivetrain is far from being complete: the desire for further efficiency improvements, particularly concerning the range of electric mobility solutions, places significant demands on the innovation capacities of the automotive industry [2]. To address these demands, the utilization of Silicon Carbide (SiC) based power semiconductors has been employed. They enable shorter switching times, reducing switching losses, and consequently enhancing the efficiency and range of battery-electric systems. In consequence, the damage mechanism of Partial Discharge (PD) must be examined more closely, especially in the insulation of the stator windings, which are usually designed as so-called hairpins in the automotive sector [3-5]. In the FVV research project, it was investigated which physical influences affect the PD sensitivity of hairpins in electric motors. Around a dozen industrial partners from the fields of electromobility and PD measurement technology took part in the project, which was carried out at the Institute of Machine Components (IMA) and the Institute of Power Transmission and High Voltage Technology (IEH) of the University of Stuttgart.

2 DAMAGING MECHANISM

The best-known type of failure of electrical insulation is electrical breakdown, which occurs when the breakdown voltage is exceeded, bypassing the insulation entirely. PDs, on the other hand, do not entirely bypass the insulation, but damage it locally. If the so-called Partial Discharge Inception Voltage (PDIV) is exceeded, PDs occur until the Partial Discharge Extinction Voltage (PDEV) is undercut, **FIGURE 1**. This is particularly the case with slew rates substantially greater than 1 V/ns. The energy converted locally during PD leaves behind an initially small damage (mostly due to carbonization of the insulator), which leads to increased electric conductivity. The PDIV is reduced and thus promotes further PD [5-7]. This can increase the defects in the insulation and lead to complete breakdown and thus to a failure of the electric motor winding. Therefore, it is reasonable to use the PDIV as an indicator for the insulation condition.

First, it must be clarified which physical conditions favor the occurrence of PD and to what extent. **FIGURE 2** provides a categorized overview of the influencing factors considered in the research project. Furthermore, it is essential to determine the service life that the examined hairpins can achieve before reaching a critical PDIV level, which is a fundamental question in reliability engineering [8].

PDs are a stochastically occurring and highly scattering phenomenon. There is currently no established model or comprehensive phenomenological description of the PD damaging mechanism within the scientific community. It is therefore unclear which physical parameters exert a relevant influence on the reduction of PDIV.

3 HEURISTICS

The application-orientated design of electric motors is becoming more complex due to the requirements for sustainability and economic efficiency. These challenges can be met appropriately using statistical Design of Experiments (DoE) methods [9]. Beyond the exemplary use case of the PD occurrence, this structured approach also enables reliability statements to be made for unknown damaging mechanisms.

The first step is to delimit and describe the system under consideration and the relevant damaging mechanism as precisely as possible, considering all available knowledge, literature sources, and related systems. In the case of PDIV degradation, for example, assumptions based on the known behavior of other electrical damaging phenomena can be made that, in addition to the voltage gradient, temperature has a relevant influence on the service life. Preparatory tests confirm this hypothesis. **FIGURE 3** shows the respective comparison: The absolute PDIV and its degradation speed depend on the maximum temperature. This systematic difference is superimposed by the measurement error (±1 σ error bars) and the production variation of the hairpins (recognizable from the initial values). Due to the chemical composition of the hairpin insulation, it is reasonable to assume that the humidity of the ambient air is also one of the influencing parameters. Nevertheless, this parameter can be neglected, since it is known that the hairpins are encapsulated in the stator and thus are not exposed to air humidity fluctuations.

Most technical systems are subject to wear. The insulation is assumed to experience degradation not only due to PD, but also during PD-free operation [5, 6]. Consequently, it is not necessary to conduct tests until failure. Measuring the PDIV at defined inter-

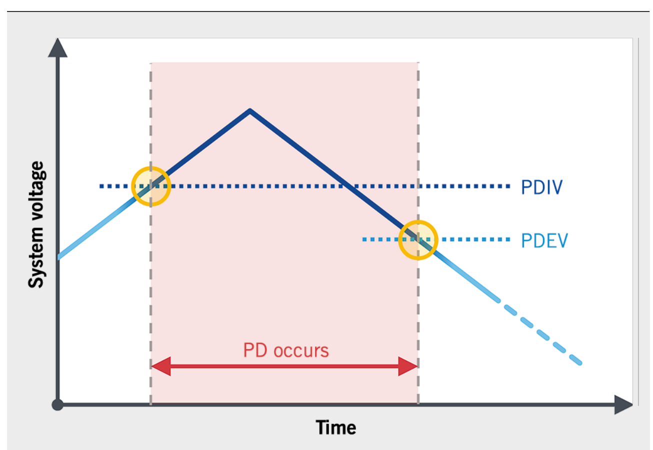


FIGURE 1 Schematic representation of the occurrence of PD (© IMA)

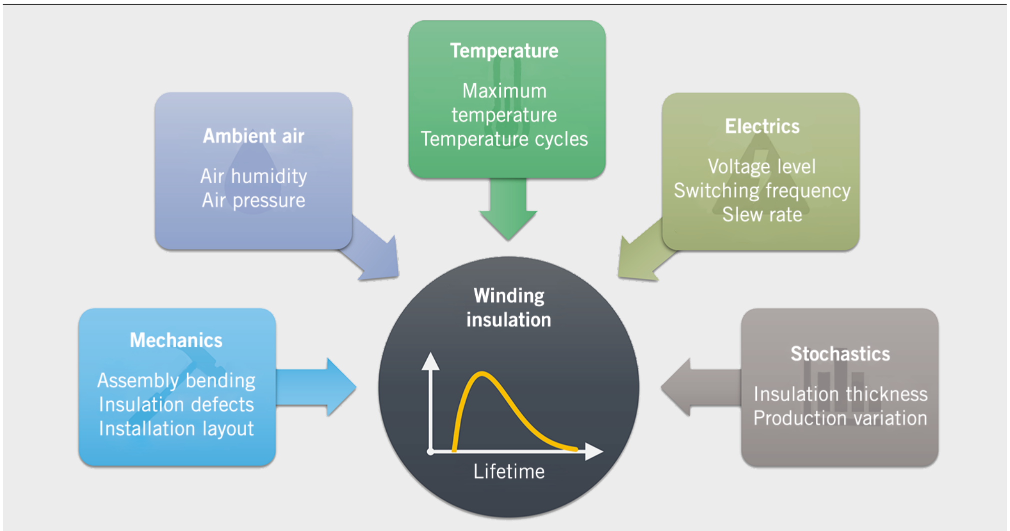


FIGURE 2 Categorized potential influencing parameters for the degradation and the lifetime of the winding insulation (© IMA)

vals allows the extrapolation to the time of failure. With that in mind, the experimental effort can be reduced by applying accelerated degradation tests, which is a well-investigated aspect of reliability engineering [6, 8].

4 MEASUREMENT METHOD

PDIV is a challenging measurand not only due to its strong inherent scattering, but also because of the lack of a standardized measurement method in the considered case of pulse-width modulated voltage, for which only proposals exist [7]. Additional scattering is particularly problematic and cannot be avoided in practice. However, even when uncontrollable overlaid variations occur, quantifying them can optimize subsequent data analysis. Therefore, a measurement system analysis prior to the experiments and monitoring of reproducibility during the test execution are necessary. This includes addressing differences between multiple measurement setups that may arise, for example, in parallelized experiments.

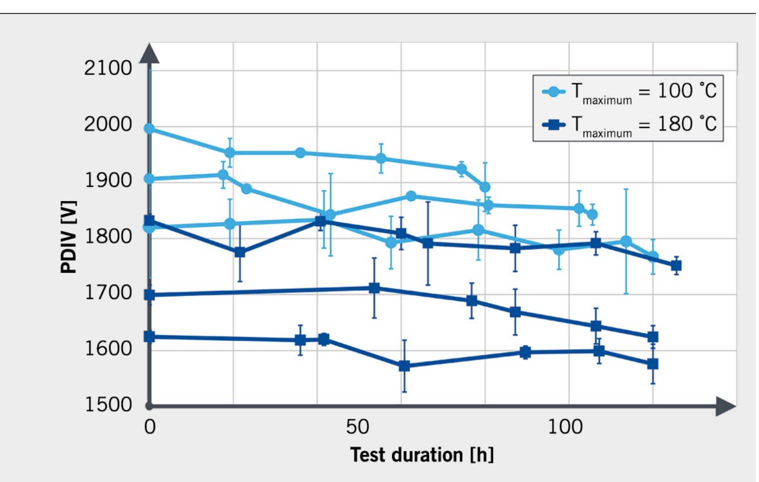


FIGURE 3 Degradation tests for different maximum temperatures (© IMA)

In the presented use case, the measurement was repeated ten times at each measurement point and then averaged. Outlier values and drifting data were detected and removed using defined statistical criteria and Artificial Intelligence (AI). From the replicated measurements, it was possible to quantify the development of the measurement repeatability over the test time.

5 MULTI-STAGE EXPERIMENTAL DESIGN

To be able to make statements about the service life of a product within a short period of time, the load is increased compared to the field level. When considering more than one individual load variable, an experimental design systematically derived through DoE becomes essential [9]. If there are more than three potential influencing factors, a parameter screening is recommended. A significantly shortened preparatory experimental plan is used to check which parameters can be considered negligible. Each parameter that does not need to be varied in the main tests reduces the workload and frees up capacity to analyze relevant parameters in more detail. This improves the accuracy of the results.

FIGURE 4 outlines the test plan, with which the number of parameters in the investigation of PDIV degradation could be significantly reduced. Initially, certain parameters were assessed based on pragmatic considerations, such as production variations, which were represented close to reality. Based on the results of the screening, other parameters were identified as non-significant, or corrections were made with regard to their influence [6]. Consequently, only four parameters are varied in the main tests instead of the original twelve. The number of parameter combinations to be tested is thus reduced from over 160 to an affordable level of 20.

6 UNBIASED EVALUATION

In the case of complex systems and unknown damaging mechanisms, the assumption that all data correspond to the intended failure mechanism must be critically reviewed. Competing failure causes can be identified, for example, by deviating damage patterns, which are often limited to a sub-area of the experimental space [8].

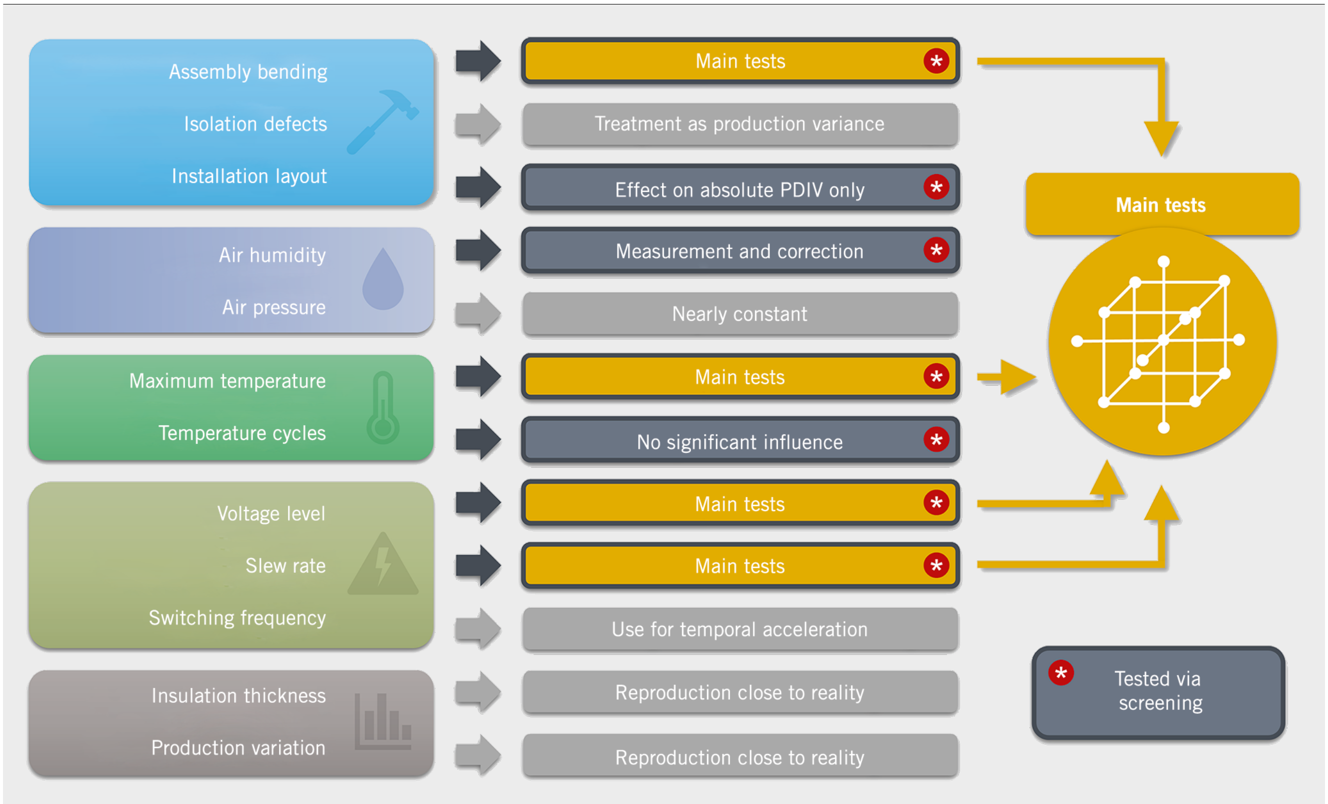


FIGURE 4 Treatment of the previously categorized potential influencing variables and assignment to screening tests or main tests (© IMA)

In the presented research project, early failures occurred, which did not belong to the intended damage mechanism, but do hold practical significance. Beyond identifying the sought-after cause of failure, this has led to the generation of additional knowledge about the previously poorly understood system.

7 OUTLOOK

Especially for complex or not fully understood systems, efficient investigation is possible only when the scope extends beyond traditional reliability methods to encompass DoE. As the experiments approach their conclusion, empirically grounded predictions can be made to ensure the reliability of the systems. The application example of PD susceptibility in electric motor winding insulation demonstrates how the testing effort can be reduced and how the probability of failure can be determined in a structured manner.

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