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A Review of Insulation Stress and Partial Dischargein Medium-Frequency Transformers Under Fast Repetitive Voltage Pulses

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Abstract. The use of wide-bandgap power devices in solid-state transformers enables higher switching frequencies and power densities, but it also exposes medium-frequency transformer insulation to fast repetitive voltage pulses. Short rise times, high dv/dt, high repetition frequencies, and harmonic content can produce nonuniform winding voltages, local field enhancement, and partial discharge. This review examines the resulting insulation stress, discharge mechanisms, detection methods, relevant IEC standards, and design approaches. The reviewed studies show that partial discharge inception and insulation lifetime depend on voltage amplitude, rise time, repetition frequency, polarity, temperature, and residual charge. They also show that power-frequency test results cannot be transferred directly to pulse-width modulation service. Reliable insulation assessment therefore requires complete waveform reporting, interference-resistant sensing, and product-specific test procedures. The resulting evidence should then guide an insulation design that combines electric-field control and thermal management while accounting for parasitic parameters and manufacturing tolerances. Future work should establish common test waveforms and relate discharge activity to long-term material damage under representative operating duty.

Keywords: solid-state transformer, medium-frequency transformer, fast repetitive pulses, partial discharge

1. Introduction

Solid-state transformers use power electronic conversion to transform voltage, provide electrical isolation, and control bidirectional power flow. Wide-bandgap devices, particularly silicon carbide devices, allow medium-voltage converters to operate at higher frequencies and switch more rapidly. Prototypes have demonstrated direct medium-voltage conversion, high power density, and fast dynamic response [1]. Medium-frequency transformers provide isolation and transfer energy in these systems. They are much smaller than power-frequency transformers, but their windings must still provide medium-voltage isolation and withstand transient overvoltages. Insulation performance therefore places a primary constraint on system power density and reliability [2].

Conventional transformer insulation is designed mainly for power-frequency sinusoidal voltages, lightning impulses, and switching impulses. In a solid-state transformer, the insulation experiences

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pulse-width-modulated square-wave voltages for long periods. These waveforms have short rise times, high rates of voltage change, high repetition frequencies, and substantial high-frequency harmonic content. The harmonics may excite resonances associated with parasitic elements in the winding. Local turn-to-turn voltages may then exceed values estimated from the terminal voltage [3]. Fast voltage transitions also generate strong electromagnetic interference. The interference pulses can overlap partial discharge pulses in time and occupy similar frequency ranges, which makes detection and calibration difficult [4]. Tests also indicate that discharge behavior and insulation lifetime vary with pulse frequency, rise time, voltage amplitude, and temperature [5]. Recent studies further examine discharge development and measurement under high-voltage pulse-width modulation stress [6].

This review evaluates insulation risk in medium-frequency transformers subjected to fast repetitive voltage pulses. It compares published studies on waveform parameters, partial discharge behavior, detection methods, the scope of existing standards, and engineering design. The analysis examines the limits of applying power-frequency test results to converter operation. It also considers how waveform-based assessment can support test selection, condition monitoring, and coordinated electrical and thermal design. The review aims to identify the test information and design factors needed to reduce the risk of overlooking local insulation stress in solid-state transformers.

2. Insulation stress under fast repetitive pulses

2.1. Operating conditions in solid-state transformers

A solid-state transformer typically includes a medium-voltage AC/DC stage, a DC/DC stage with high-frequency isolation, and a low-voltage output stage. The medium-frequency transformer operates in the isolated conversion stage, and a semiconductor bridge supplies its primary voltage. A higher switching frequency allows smaller cores and windings, but it also increases switching losses, dielectric losses, parasitic effects, and electromagnetic interference. Studies of 10 kV-class silicon carbide converters show that high-voltage insulation, high dv/dt, thermal management, and protection must be considered together [1]. Insulation analysis must therefore consider more than the rated root-mean-square voltage. It must also include waveform peaks, rise time, pulse width, repetition frequency, common-mode voltage, and fault conditions.

2.2. Voltage distribution within windings and electric field concentration

At power frequency, a winding can often be represented mainly by its inductance. During a fast voltage transition, turn-to-turn, layer-to-layer, and winding-to-core capacitances interact with leakage inductance and shape the transient response. Using a high-frequency model, Cremasco et al. showed that short-rise-time voltages produced by wide-bandgap devices may excite internal resonances in medium-frequency transformers [3]. Electrical stress can therefore vary among turns even when the terminal voltage remains unchanged. The electric field tends to concentrate at the winding entrance, conductor edges, shield ends, and triple junctions where a conductor, solid insulation, and air meet. A design based only on the average electric field may underestimate the stress near local defects.

As summarized in Table 1, pulse amplitude and timing determine the basic electrical stress, while parasitic capacitance and leakage inductance control how that stress is distributed within the winding.

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Table 1. Fast repetitive pulses, insulation stress factors, and required test information [3, 7]

Waveform or structural factor	Main electrical effect	Possible insulation effect	Required test information
Peak voltage	Sets the basic electric field at a defect.	May initiate partial discharge or cause direct breakdown.	Peak value, polarity, and overshoot
Rise time and dv/dt	Increase displacement current and high-frequency content.	Increase local electric-field stress and measurement interference.	10%-90% rise time and maximum dv/dt
Repetition frequency	Reduces the time available for charge dissipation.	Promotes residual-charge accumulation and more discharges per unit time.	Switching frequency, pulse count, and voltage application time
Duty cycle and dead time	Change the duration of voltage application and reversal.	Change charge memory and heat accumulation.	Duty cycle, dead time, and modulation method
Parasitic capacitance and leakage inductance	Produce resonance and internal overvoltage.	Create nonuniform turn-to-turn or layer-to-layer stress.	Terminal and internal winding waveforms and model bandwidth

3. Partial discharge behavior and insulation lifetime

3.1. Effects of waveform parameters on partial discharge



Figure 1. Processes leading from wide-bandgap switching to insulation damage under fast repetitive voltage pulses [3-6]

Partial discharge is a localized electrical breakdown within insulation or along its surface that does not completely bridge the insulation between electrodes. Under pulse-width-modulated voltage, the instantaneous voltage alone does not determine discharge behavior. Surface charge, space charge, and metastable species left by the preceding pulse also affect the next discharge. Guo et al. tested medium-frequency transformer specimens on a high-frequency pulse-width modulation platform. Their measurements showed that repetitive partial discharge inception varied with frequency, voltage amplitude, and dv/dt [4]. Wang et al. later used a high-frequency current transformer (HFCT) and an ultrahigh-frequency (UHF) antenna to examine insulation under high-voltage pulse-width modulation stress. They studied the effects of triple junctions and residual charge from earlier discharges [6]. These findings show that a power-frequency partial discharge

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inception voltage should not be transferred directly to pulse-width modulation service as a safe operating limit. Figure 1 summarizes the sequence from fast switching to cumulative insulation damage.

3.2. Partial discharge thresholds under repetitive pulses

Studies of fast repetitive pulses commonly distinguish partial discharge inception voltage (PDIV), partial discharge extinction voltage (PDEV), and repetitive partial discharge inception voltage (RPDIV). PDIV is the voltage at which a discharge is first detected as the applied voltage increases. PDEV is the voltage at which the discharge ceases as the voltage decreases. RPDIV is the threshold for recurring discharges under a specified pulse count and repetition condition. In tests with unipolar repetitive square waves, Naderiallaf et al. found that polarity, frequency, rise time, and previous voltage application affected these quantities [7]. Their specimens were insulated wires for inverter-fed motors, but the definitions and waveform effects also inform test methods for medium-frequency transformers. Reports of inception voltage should therefore include the complete waveform and the criteria used to identify discharge inception.

3.3. Partial discharge and reduced insulation lifetime

Partial discharges produce local heating, charged particles, ultraviolet radiation, and pressure impulses. One discharge may release little energy, but a high repetition frequency can greatly increase the number of discharges per unit time. Agarwal et al. tested medium-frequency transformer winding specimens under pulse-width modulation conditions up to 50 kHz and 60 V/ns and related the discharge measurements to endurance tests [5]. Their results show that voltage rise time and repetition frequency cannot be treated as secondary parameters. Recent tests under high-voltage pulse-width modulation stress also indicate that the number of insulation layers, voltage amplitude, frequency, and rise time jointly affect discharge patterns [6]. Voltage-lifetime curves obtained at power frequency may therefore be insufficient to describe damage accumulated during converter operation. Lifetime models should include electric field, pulse repetition frequency, and temperature at a minimum.

4. Detection methods and the scope of standards

4.1. Partial discharge detection under switching interference

Conventional electrical detection measures apparent charge through a coupling capacitor and measures impedance. Its calibration procedures are well established. Under pulse-width modulation excitation, however, switching edges produce large displacement currents and common-mode interference. A high-frequency current transformer detects broadband current pulses in a grounding conductor or circuit, while an ultrahigh-frequency antenna receives electromagnetic radiation emitted by discharges. Both methods can support noncontact or minimally intrusive measurements. Because sensor bandwidth and installation position affect the measured amplitude, results from different platforms may not be directly comparable. Chen et al. used time-frequency reassignment to extract discharge pulses from repetitive pulse interference [8]. Such processing can improve signal separation, but reports should still provide raw waveforms, noise conditions, sensor bandwidth, and threshold settings.

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As shown in Table 2, no detection method is suitable for every test condition. A reliable measurement plan should combine the method's sensitivity and calibration needs with the expected interference and access constraints.

Table 2. Comparison of partial discharge detection methods under fast repetitive voltage pulses [4, 6, 8-10]

Detection method	Main advantages	Main limitations	Suitable applications
Coupling capacitor and measuring impedance	Supports calibrated apparent-charge measurement under established procedures.	Sensitive to displacement current and switching pulses.	Offline reference tests
HFCT	Easy to install and detects broadband current pulses.	Measured amplitude depends on circuit layout, bandwidth, and sensor position.	Grounding-circuit detection and pulse timing
UHF antenna	Isolated from the main circuit and suppresses low-frequency interference.	Sensitivity depends on shielding and propagation paths.	Noncontact detection and multisensor localization
Optical or ultraviolet detection	Insensitive to electromagnetic interference and can assist localization.	Requires an optical path or viewing window and has limited coverage in current standards.	Laboratory studies of discharge mechanisms
Digital time-frequency separation	Uses pulse-shape differences to separate discharge signals from switching interference.	Results depend on algorithm settings, training data, and thresholds.	Post-processing under complex noise conditions

4.2. IEC TS 61934 and IEC 60270

IEC TS 61934:2024 specifies basic requirements for offline electrical partial discharge measurement under repetitive voltage impulses with short rise times generated by power electronic devices. The current edition updates the pulse generator and waveform parameters to reflect developments in wide-bandgap devices [9]. IEC 60270:2025 addresses charge-based partial discharge measurement and mainly covers AC tests at frequencies up to 500 Hz and DC tests [10]. The difference in scope means that power-frequency test procedures cannot be applied without modification under high-frequency pulse-width modulation conditions. IEC TS 61934 does not cover optical or ultrasonic detection, and specific transformer products may require additional procedures. A remaining research need is to develop product-specific tests that preserve waveform traceability, quantify noise, and allow results from different sensors to be compared.

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5. Insulation design and risk reduction

5.1. Electric field control and structural optimization

Insulation design should first reduce electric fields at conductor edges and triple junctions. Common measures include increasing critical clearances, optimizing edge radii, adjusting interlayer insulation thickness, changing the winding arrangement, and adding electrostatic shields. Guillod et al. showed that electrical shielding can change the common-mode electric-field distribution in medium-voltage, medium-frequency transformers subjected to high dv/dt [11]. Yi et al. optimized insulation distances and structures by finite-element analysis and considered the tradeoffs among size, heat dissipation, and insulation margin [12]. For 13.8 kV grid applications, Chen et al. proposed a shielded insulation structure for high-frequency transformers and verified it through impulse and partial discharge tests [13]. Additional shielding does not always improve the overall design because it can increase parasitic capacitance, dielectric loss, and coupling between windings. These effects must be assessed together with the converter topology.

5.2. Coordinated insulation and thermal design for high power density

Increasing insulation thickness generally reduces breakdown risk, but it also increases leakage inductance, winding-window requirements, and thermal resistance. Reducing spacing improves power density but raises local electric fields. Guo et al. optimized a 200 kW medium-frequency transformer subject to constraints on the core, windings, losses, thermal behavior, and insulation [14]. A separate 100 kW prototype used potted windings and a 3D-printed bobbin with heat-dissipation features. The prototype achieved a peak PDIV of 20 kV, and the authors also reported its efficiency and power density [15]. These results show that high insulation performance can be combined with high power density. However, the result depends on the materials, waveform, temperature, and manufacturing quality. Clearance values from one prototype should not be copied directly into another design. Each design iteration should combine electromagnetic analysis, electric-field analysis, thermal design, manufacturing-tolerance analysis, and experimental verification.

6. Discussion

Comparison across test platforms remains difficult because equal peak voltages do not imply equal insulation stress. Published studies use unipolar or bipolar pulses with different rise times, dead times, duty cycles, repetition frequencies, and specimen geometries. The relationship between discharge indicators and remaining life is also incomplete. PDIV marks the onset of detectable discharge, but it does not describe the rate of damage accumulation. Future databases should therefore retain raw voltage waveforms, sensor transfer functions, background noise, ambient temperature, specimen geometry, discharge count, pulse amplitude, and temperature rise. Endurance tests should use waveform sequences that represent actual converter duty instead of one fixed frequency and duty cycle.

A second challenge is the difference between controlled offline tests and online monitoring. Laboratory tests can use shielded rooms, short connections, and specimens with known defects. Operating converters contain gate-drive pulses, parasitic oscillations, grounding loops, and several radiation sources. Online systems should record gate signals and terminal voltages together with outputs from more than one discharge sensor. These synchronized records can help distinguish a

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discharge from switching interference. Evaluation of detection algorithms should report missed-detection probability, false-alarm behavior, and uncertainty in addition to classification accuracy.

Product-specific acceptance criteria remain another important gap. Existing technical specifications provide a measurement basis for repetitive pulses, but they do not set one acceptance limit for all medium-frequency transformers. Topology, rated voltage, insulation structure, cooling method, and manufacturing variation change the actual stress. A practical qualification process should proceed in stages. A high-frequency equivalent model should first identify the locations at greatest risk. Specimen tests should then measure RPDIV and endurance under thermal cycling. The final stage should verify the complete converter under rated operation and credible fault conditions. This sequence would connect material behavior, component design, and system-level reliability without treating any single test result as conclusive.

7. Conclusion

This review shows that power-frequency PDIV values and voltage-lifetime curves are not sufficient for assessing medium-frequency transformer insulation in solid-state converters. Fast repetitive pulses have short rise times, high dv/dt, and substantial high-frequency content. These features can distort the voltage distribution within a winding, increase local electric fields, and change partial discharge behavior. Residual charge, repetition frequency, polarity, temperature, and insulation geometry also affect discharge inception and cumulative damage.

The review links waveform characterization, interference-resistant detection, standards, and insulation design within one assessment process. This connection is important because it allows engineers to interpret a discharge result in relation to the actual electrical and thermal stress. HFCT and UHF sensing, supported by time-frequency processing, can improve detection under pulse-width modulation excitation. IEC TS 61934:2024 provides a useful measurement basis, but product-level qualification must also include field control, thermal design, manufacturing tolerances, and complete-system verification.

This review is limited by the small amount of long-term field failure data and by differences among published test platforms. Future work should establish common waveform descriptions, quantify the relationship between discharge activity and insulation lifetime, and validate online detection across laboratories and converter designs. Shared data should include raw waveforms, environmental conditions, sensor characteristics, and operating duty. These steps can support comparable test results and provide a stronger basis for reliable, high-density solid-state transformer design.

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