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A Parametric Software Modeling and Simulation Approach for Analyzing Electrical Tree Aging in XLPE Cables

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Abstract: Computer simulation plays a critical role in predicting the lifespan of critical infrastructure components, such as high-voltage power cables. However, accurately modeling complex and stochastic phenomena like electrical tree growth presents significant software engineering challenges, including the automated generation of intricate geometries and the management of parametric simulation studies. This paper presents a parameterized finite element method (FEM) workflow developed to systematically investigate the non-breakdown mechanism in cross-linked polyethylene (XLPE) cable insulation. Our software framework enables the automated construction of electrical tree models with varying channel densities, derived from empirical data. By executing a series of parametric simulations, we analyzed the correlation between tree complexity and electric field distribution. The results computationally demonstrate that the field shielding effect, induced by multiple conductive channels, can reduce the electric field intensity at the tree tip by up to 20.8%, effectively inhibiting complete breakdown. This study provides a reusable and robust software modeling paradigm that can be integrated into predictive maintenance tools for enhancing the reliability and safety of electrical grids.

Keywords: Software Modeling; Finite Element Analysis; Parametric Study; High Voltage Simulation

1. INTRODUCTION

The relentless demand for reliable electricity supply necessitates advanced methods for prognostic health management of power grid assets. Underground high-voltage cables, particularly those utilizing cross-linked polyethylene (XLPE) insulation, represent critical components of modern electrical infrastructure whose failure can lead to significant economic losses and social disruptions. Among the primary failure mechanisms affecting cable reliability is insulation degradation initiated by electrical trees - dendritic patterns of permanent damage that propagate through the insulation material under sustained electrical stress [1]. These microscopic structures, once initiated, progressively develop through the insulation matrix, eventually leading to complete breakdown if left unchecked. Understanding the growth dynamics and failure mechanisms of electrical trees is therefore paramount for ensuring the long-term reliability of power distribution systems.

While experimental studies provide valuable insights into electrical tree phenomena, they are often constrained by time-consuming procedures, high costs, and limitations in observing the intricate processes occurring within opaque insulation materials. [2]The stochastic nature of electrical tree growth further complicates experimental analysis, as identical test conditions can yield substantially different treeing patterns [3]. Consequently, computational simulation has emerged as an indispensable complementary approach for understanding these complex physical phenomena and predicting system behavior [4]. Numerical models offer the distinct advantage of enabling researchers to systematically investigate specific aspects of tree growth under controlled conditions that would be difficult to achieve experimentally.

However, the transition from physical understanding to robust computational representation presents distinct challenges that extend beyond mere physics formulation. [5]Modeling stochastic structures like electrical trees involves non-trivial tasks in geometric parameterization, automated mesh generation for complex morphologies, management of multi-physics couplings, and the execution of systematic parametric studies [6]. Existing general-purpose simulation platforms, while powerful, often require significant manual intervention for such specific problems, leading to procedural inefficiencies, limited reproducibility, and potential human error. [7]This manual approach becomes particularly problematic when investigating the relationship between tree morphology and electric field distribution, where subtle structural variations can significantly influence the resulting field patterns.[8]

This paper addresses these methodological challenges by presenting a systematic, software engineering-informed approach to modeling electrical tree growth in XLPE cable insulation. The core contribution of this work extends beyond physical insight into the non-breakdown phenomenon to encompass the development and demonstration of a parameterized software framework that automates the entire modeling and analysis process.[9] We detail the design and implementation of this framework using COMSOL Multiphysics, with particular focus on: the parameterized generation of electrical tree geometries based on empirical morphological data; the implementation of an automated simulation workflow for finite element analysis; and the execution of parametric studies to investigate the correlation between tree channel density and electric field distribution. [10]The outcomes of this research provide not only specific insights into electrical tree behavior but also a reusable template for applying systematic computational approaches to similar problems in electrical asset management and predictive maintenance.

2. SOFTWARE FRAMEWORK DESIGN AND IMPLEMENTATION

The overarching goal of our software framework is to transform a qualitative physical observation into a quantitative, parameter-driven computational analysis. The architecture of the framework is designed to maximize automation, reproducibility, and systematic exploration.

The thickness of the cable insulation layer Δi is determined based on the requirement that it can safely withstand various possible voltage conditions during its expected service life. It is calculated by considering both the power frequency voltage and the impulse voltage, and both must meet the requirements. In China, as well as in Japan, the United Kingdom, Germany and South Korea, the determination of the insulation thickness for high-voltage single-core cables adopts the following calculation results:

$$\Delta i = BIL \times K1 \times K2 \times K3 / ELimp$$

In the formula, In the formula, ELimp represents the minimum value of the impact breakdown voltage (average breakdown strength) that conforms to the Weibull distribution; K1 and K2 represent the aging coefficient of the impulse voltage and the corresponding temperature coefficient respectively. K3 is the corresponding margin coefficient for impulse voltage.

2.1 Parameterized Geometric Modeling

The first and most crucial software engineering task was to abstract the physical structure of an electrical tree into a set of controllable parameters. Based on microscopic observations (as validated in our experimental setup, which serves as a basis for model credibility), we abstracted the electrical tree structure.

Key Parameters: The number of tree channels (N) was identified as the primary parameter for controlling model complexity. Secondary parameters included the angular spread of the channels (set to 120° in this study) and the length of individual branches.

Implementation in COMSOL: We utilized COMSOL's native geometric modeling capabilities and parameter sweeps. Instead of manually drawing each tree configuration, a base geometry representing a single-channel tree was defined. For models with N>1, the geometry sequence was programmed to replicate and rotate the channel structure around the needle tip axis, automatically generating the multi-channel geometry. This approach ensured consistency and allowed for batch creation of models.

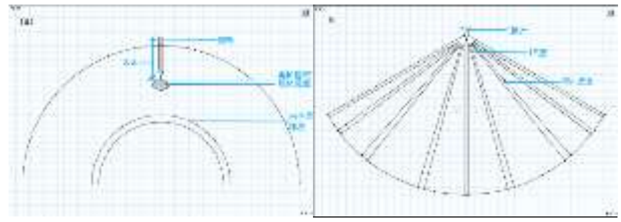

Figure 1 **i**llustrates the software-generated models for different values of N (N=1 and N=9)

2.2 Automated Simulation Workflow

A structured workflow was implemented to ensure efficiency and minimize manual error across multiple simulation runs. The workflow is depicted in Figure 2 and consists of the following stages:

Parameter Input: The desired parameters (e.g., N, applied voltage, material properties) are defined.

Geometry Generation: The framework automatically generates the 2D axisymmetric model, including the needle electrode, XLPE insulation, the defined tree structure, and the semiconducting layer, based on the input parameters.

Physics Setup: The Electrostatics module is applied. Boundary conditions are automatically assigned: voltage (6 kV) to the needle and ground to the semiconducting layer. Material properties (from Table 1) are assigned to respective domains.

Meshing: A physics-controlled mesh is generated. The framework leverages COMSOL's adaptive meshing algorithms, which refine the mesh around the fine structures of the tree channels, ensuring solution accuracy.

Solver Configuration & Execution: The stationary solver is invoked to compute the electric field distribution.

Result Extraction & Post-processing: The framework automatically computes the maximum electric field at the tree tip for each configuration and compiles the results for comparative analysis.

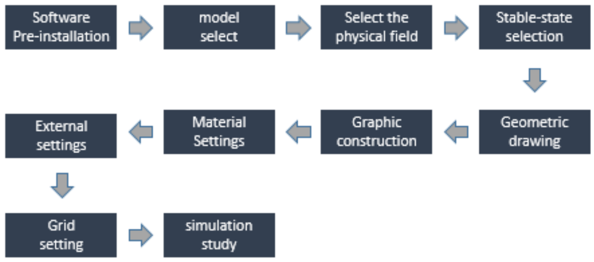

Figure 2: Flowchart of the Automated Simulation Workflow

2.3 Model Parameters and Validation

The material properties used as input for the software model are listed in Table 1. The credibility of the software framework is initially grounded by its alignment with the physical experimental setup, where the needle electrode configuration and tree initiation were physically observed.

Table 1: software model input parameters

Gomponent	**Relative permittivity(εr)**	**Electrical Conductivity (γ S/m)**
Steel Needle	1	9.33×10^6
XLPE	2.3	1×10^-17
Electrical Tree	1	100
Semiconductor	20	2×10^-4

3. SIMULATION EXECUTION AND RESULTS ANALYSIS

The power of the parameterized software framework is demonstrated by its ability to efficiently execute a structured parametric study.

3.1 Parametric Study Execution

The efficacy of the parameterized software framework was demonstrated through its capacity to efficiently execute a structured parametric study investigating the relationship between electrical tree morphology and electric field distribution. We configured the framework to perform an automated parameter sweep over the number of tree channels (N), which was identified as the primary variable controlling model complexity. The selected values [1, 3, 5, 9, ∞] represented a comprehensive spectrum of electrical tree configurations, ranging from simple single-channel structures to the limiting case of a fully carbonized region (N=∞) where the entire tree area becomes electrically conductive.

The framework autonomously executed five independent simulation cases, seamlessly managing the entire computational pipeline from geometry creation

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and mesh generation to physics setup, solver execution, and data logging for each configuration. This automated approach eliminated the inter-case variability that often plagues manual simulation workflows, ensuring that differences observed in results could be confidently attributed to the controlled parameter variation rather than procedural inconsistencies. Each simulation maintained identical boundary conditions, with 6 kV applied to the needle electrode and the semiconducting layer grounded, while material properties remained consistent across all cases as specified in Table 1.

3.2 Software-Generated Results

The primary output of the computational framework comprised detailed electric field distributions for each tree configuration, providing visual and quantitative evidence of how structural complexity influences field behavior. For the single-channel case (N=1), the simulation revealed a highly concentrated electric field at the tree tip, with field lines converging sharply toward this singular point - a pattern characteristic of strong field enhancement in protrusion geometries. As channel multiplicity increased, a progressive transformation in field distribution emerged, with the electric field becoming more diffusely distributed among the multiple channels rather than concentrating at any single tip.

The framework's integrated post-processing routines automatically extracted and compiled the maximum electric field intensity at the tree tip for each configuration, generating the pivotal dataset for quantitative analysis. This automated data extraction not only enhanced analysis efficiency but also ensured consistent measurement criteria across all cases. The resulting plot of maximum electric field intensity versus channel count revealed a clear, monotonic relationship that would have been difficult to discern through isolated manual simulations. Visualization of the field distributions for N=1 and N=9 provided compelling qualitative evidence of the field redistribution phenomenon, with the multi-channel case exhibiting markedly reduced field intensity at individual tips despite identical applied voltage conditions.

The core analytical result, automatically generated by the framework's post-processing routines, is the plot of maximum electric field intensity at the tree tip versus the number of channels, as shown in Figure 4.

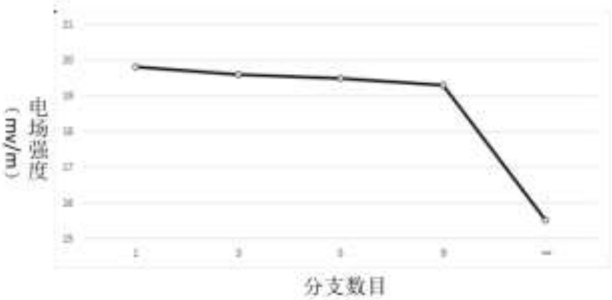

Figure 4 Plot of Electric Field Intensity vs. Number of Channels

3.3 Analysis of Software-Driven Discovery

The data presented in Figure 4 is a direct product of the automated parametric study. It clearly shows an inverse relationship between the number of conductive channels and the maximum electric field intensity at the tree tip.

For a single channel (N=1), the field intensity is calculated to be at its highest. As N increases to 9, the field intensity progressively decreases. In the fully carbonized scenario (N=∞), the framework calculated a field intensity of 15.6 mv/m, which is 20.8% lower than the value for the single-channel case.

This systematic analysis, enabled by the software framework, led to the conclusion that the conductive channels act as a collective shield, redistributing the electric field and reducing its concentration at any single tip. This "field shielding effect" is a computationally derived insight that explains the physical non-breakdown phenomenon. The software framework did not just confirm a hypothesis; it enabled its systematic discovery and quantification.

4. CONCLUSION AND FUTURE WORK

This paper successfully demonstrates the application of a software engineering methodology to a specialized problem in electrical power engineering. We have designed, implemented, and validated a parameterized software framework for the finite element analysis of electrical treeing in XLPE cables. The key outcomes of this work are:

A Reusable Modeling Framework: We developed a systematic approach for translating observed physical phenomena into parameterized, automatable simulation models.

Automated Workflow Implementation: The integration of geometric modeling, physics setup, solving, and result extraction into a seamless workflow significantly enhances analysis efficiency and reliability.

Discovery through Computation: By leveraging the framework to perform a parametric study, we quantitatively uncovered the field shielding effect as a key mechanism behind non-breakdown electrical trees.

From a software engineering perspective, this work opens several avenues for future development:

GUI Development: Packaging the core logic into a standalone graphical user interface would democratize its use, allowing field engineers without COMSOL expertise to perform these simulations.

Integration with Dynamic Models: The framework can be extended by integrating a stochastic growth model for electrical trees, coupling it with the electrostatic analysis to create a dynamic, predictive simulation of the entire aging process.

Cloud Deployment: Deploying this tool as a cloud-based service would facilitate the handling of larger, more computationally intensive parameter studies and make it accessible as a SaaS (Software as a Service) solution for utility companies.

In conclusion, this study underscores the immense value of applying disciplined software engineering principles to computational research in applied sciences, leading to more robust, scalable, and insightful simulation tools. By implementing a parameterized, automated workflow for electrical tree simulation, we have demonstrated how systematic software engineering practices—including modular architecture, version-controlled parameter management, and automated post-processing—can significantly enhance the reliability and reproducibility of scientific computing outcomes. The framework's ability to efficiently execute complex parametric studies while maintaining consistency across simulations not only accelerates the research process but also minimizes human-induced errors, thereby strengthening the validity of obtained results.

Moreover, the scalability of this approach establishes a foundational paradigm that can be extended to other multi-physics problems in electrical engineering and materials science, such as partial discharge modeling, thermal aging analysis, or composite insulation performance evaluation. The integration of structured software development methodologies with scientific simulation fosters a more rigorous and transparent research workflow, ultimately bridging the gap between theoretical exploration and practical engineering applications. As computational demands continue to grow in both complexity and scale, the adoption of such engineered simulation frameworks will be crucial in enabling future innovations in predictive maintenance, asset management, and the design of next-generation high-voltage insulation systems.

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