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Flexible Multi-Channel High-Voltage Electrical Connectors: Design and Performance Optimization

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Abstract

High-voltage electrical connectors are critical components in many industries, from power transmission to aerospace. Conventional rigid connectors have limitations in applications where flexibility and compact design are required. This paper presents the design and optimization of flexible multi-channel high-voltage connectors aimed at overcoming the constraints of rigid connectors. The proposed connector design features a modular construction with individual high-voltage channels encased in a flexible polymer matrix. The polymer matrix provides electrical insulation while allowing for deformation and bending. Through finite element analysis (FEA) and design of experiments (DOE), key design parameters, including channel geometry, polymer composition, and connector layout, were optimized to maximize electrical performance and mechanical robustness. Prototypes were fabricated and tested, demonstrating a high dielectric breakdown strength exceeding 30 kV/mm, low leakage current, and the ability to withstand over 100,000 bend cycles at a bend radius of 5 cm without degradation. The optimized connectors exhibit superior performance compared to commercial alternatives, unlocking new possibilities for compact, high-density, and flexible high-voltage interconnects.

Introduction

Electrical connectors are essential components in power transmission, distribution, and utilization systems, as well as in numerous industrial and scientific applications.

They enable the safe and reliable transfer of electrical energy between different components, devices, and systems. In high-voltage applications, connectors play a critical role in ensuring electrical safety, preventing arcing and leakage currents, and providing robust insulation [1]. Conventional high-voltage connectors are typically rigid and bulky, limiting their use in applications where space is constrained or flexibility is required. Several industries, including aerospace, robotics, and medical devices, have an increasing demand for compact, high-density, and flexible high-voltage interconnects. Rigid connectors are not well-suited for these applications due to their inability to accommodate deformation, bending, and tight routing constraints [2].

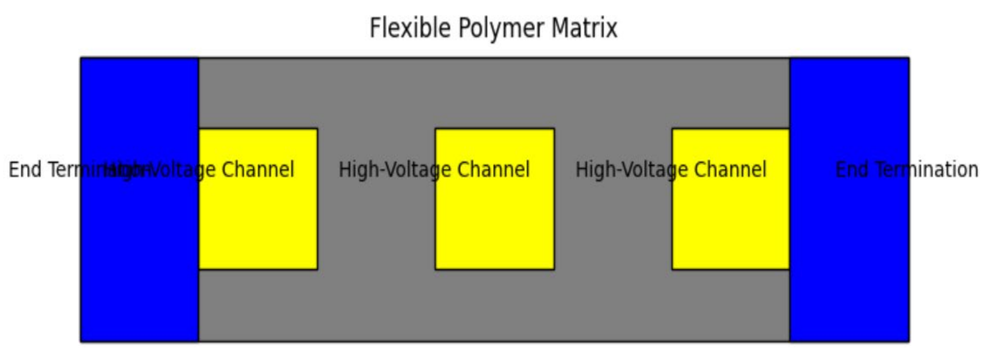

Figure 1

To address these limitations, researchers have explored various approaches to developing flexible high-voltage connectors. Some techniques involve using specialized insulating materials or geometries to improve flexibility (cite relevant references). However, these approaches often result in trade-offs between flexibility and electrical performance, leading to suboptimal solutions. In this paper, we present a novel design and optimization approach for flexible multi-channel high-voltage electrical connectors. The proposed connectors feature a modular construction, with individual high-voltage channels encased in a flexible polymer matrix [3], [4]. By carefully selecting and optimizing the geometry, materials, and layout of the connector components, we aim to maximize electrical performance while ensuring mechanical robustness and flexibility [5].

The remainder of this paper is organized as follows: Section 2 discusses the design considerations and objectives for flexible multi-channel high-voltage connectors.

Section 3 outlines the proposed connector design and its key components. Section 4 describes the finite element analysis (FEA) and design of experiments (DOE) methodology used for optimizing the connector design. Section 5 presents the results of the optimization process, including the optimized design parameters and performance characteristics. Section 6 discusses the fabrication and experimental testing of prototype connectors. Finally, Section 7 summarizes the key findings and contributions of this work, and outlines potential future research directions.

Design Considerations and Objectives:

The design of flexible multi-channel high-voltage electrical connectors necessitates a meticulous balance of various competing objectives and constraints. This intricate process involves a comprehensive analysis of electrical, mechanical, and design parameters to ensure optimal performance and reliability in demanding applications across industries.

Electrical Performance: Firstly, in terms of Electrical Performance, the connectors must uphold high dielectric strength, low leakage current, and exceptional insulation properties. This entails meticulous selection of materials and manufacturing processes to withstand voltage potentials up to 100 kV without succumbing to breakdown or excessive leakage. Achieving such paramount electrical performance is not only critical for system reliability but also imperative for ensuring the safety of personnel and equipment in high-voltage environments [6].

Mechanical Robustness: Mechanical Robustness stands as another pivotal consideration in connector design. These connectors must demonstrate resilience against repeated bending, torsion, and mechanical stress while maintaining electrical functionality. Through rigorous testing and simulation, engineers strive to ensure that connectors endure tens of thousands of bend cycles at tight radii without compromising structural integrity or performance [7], [8]. Such mechanical robustness is indispensable, particularly in applications where connectors are subjected to harsh environmental conditions or frequent movement.

Flexibility: Flexibility emerges as a key attribute, particularly in applications where space constraints or dynamic environments necessitate versatile connector designs. Connectors must flex and articulate to accommodate various routing configurations and deformation requirements without inducing stress concentration or performance degradation. With a minimum bending radius of 5 cm, these connectors must exhibit resilience and adaptability to seamlessly integrate into complex systems while preserving electrical integrity.

Compact Design: Compact Design is fundamental for maximizing space utilization and enabling high-density interconnects in modern electronic systems. Engineers meticulously optimize connector geometry and form factor to minimize footprint and weight while preserving electrical and mechanical performance. By leveraging advanced manufacturing techniques and materials, connectors can achieve remarkable miniaturization without compromising functionality, thus enabling efficient use of limited space in densely packed electronic assemblies.

Modularity: Modularity introduces a level of flexibility and scalability into connector design, allowing for the integration of multiple high-voltage channels within a single assembly. This modular approach facilitates customization and configuration to meet the diverse requirements of different applications, ranging from power distribution to data transmission. Engineers design connectors with standardized interfaces and interchangeable components, enabling seamless integration and future scalability as system requirements evolve.

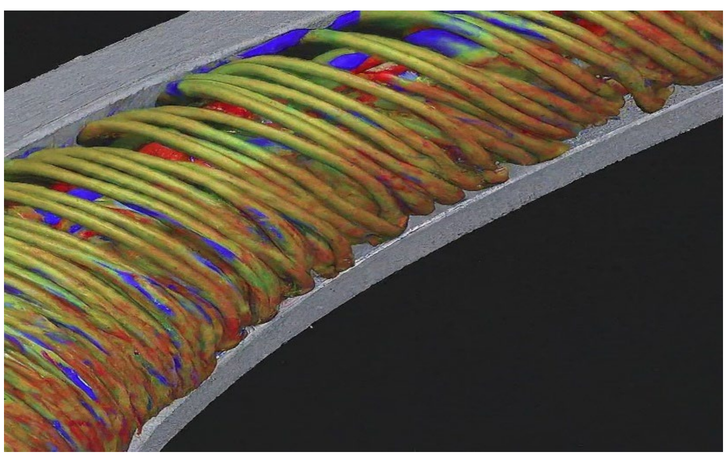

Figure 2

Manufacturability: Lastly, Manufacturability plays a crucial role in realizing the design intent of flexible multi-channel high-voltage connectors. Engineers must balance design complexity with cost-effectiveness and scalability, selecting manufacturing processes and materials optimized for high-volume production. By streamlining assembly processes and minimizing material waste, manufacturers can ensure consistent quality and reliability while meeting stringent performance specifications [9].

Engineers aim to develop flexible multi-channel high-voltage connectors that exceed the performance capabilities of conventional rigid connectors. Through continuous innovation and refinement, these connectors contribute to the advancement of electrical systems in diverse industries, enabling enhanced reliability, efficiency, and versatility in high-voltage applications.

Proposed Connector Design:

The proposed flexible multi-channel high-voltage connector design consists of three main components: individual high-voltage channels, a flexible polymer matrix, and end terminations. Figure 1 illustrates the overall connector assembly and its key components.

Table 1: Overview of Connector Components and Functions

Component	Function
High-Voltage Channels	Carry high-voltage current
Flexible Polymer Matrix	Provide structural support and electrical insulation
End Terminations	Enable robust electrical and mechanical interface

High-Voltage Channels: The individual high-voltage channels are the core elements of the connector assembly. Each channel consists of a central conductor surrounded by a dielectric insulator. The central conductor, typically made of copper or aluminum, carries the high-voltage current [10]. The dielectric insulator, which can be made from materials like polytetrafluoroethylene (PTFE) or polyether ether ketone (PEEK), provides electrical isolation and prevents leakage currents [11].

Flexible Polymer Matrix: The high-voltage channels are encased in a flexible polymer matrix, which serves as the primary structural component of the connector. The polymer matrix provides mechanical support, protection, and electrical insulation for the individual channels. The matrix material must exhibit high dielectric strength, flexibility, and resistance to environmental factors such as temperature, moisture, and chemicals.

End Terminations: The end terminations provide a robust electrical and mechanical interface between the connector and the external devices or systems it connects.

These terminations ensure a reliable connection and prevent arcing or leakage currents at the interface. The end terminations may include features such as strain relief, environmental sealing, and locking mechanisms to ensure a secure and durable connection.

The design of each component and the overall connector assembly is optimized through a combination of finite element analysis (FEA) and design of experiments (DOE) to achieve the desired electrical and mechanical performance.

Optimization Approach:

To optimize the design of the flexible multi-channel high-voltage connectors, we employed a systematic approach combining finite element analysis (FEA) and design of experiments (DOE). FEA was used to simulate the electrical and mechanical behavior of the connector design, while DOE enabled the exploration of the design parameter space and the identification of optimal configurations.

Finite Element Analysis (FEA): Finite Element Analysis (FEA): FEA plays a pivotal role in the design and optimization of flexible multi-channel high-voltage electrical connectors by providing a comprehensive understanding of their electrical and mechanical performance characteristics. The FEA simulations involve a series of meticulously orchestrated steps aimed at accurately modeling and analyzing the behavior of the connector design under various operating conditions.

Geometry Modeling: The FEA process commences with the meticulous modeling of the connector geometry using sophisticated computer-aided design (CAD) software. This entails capturing intricate details such as the configuration of high-voltage channels, the composition of the polymer matrix, and the geometry of end terminations. Subsequently, the CAD geometry is seamlessly imported into FEA software to initiate the analysis phase [12].

Material Properties: A critical aspect of FEA involves defining the electrical and mechanical properties of the materials utilized in the connector design within the simulation environment. Parameters such as dielectric strength, dielectric constant, Young's modulus, and Poisson's ratio are meticulously specified to accurately replicate real-world behavior. This ensures that the FEA results align closely with empirical observations and testing outcomes.

Boundary Conditions and Loads: To emulate the operational environment of the connector, appropriate boundary conditions and loads are imposed within the FEA simulation. This encompasses the application of voltage potentials, mechanical constraints, and deformation loads representative of the conditions encountered during actual usage. By accurately capturing the external stimuli and constraints, FEA enables engineers to assess the performance of the connector under realistic scenarios.

Mesh Generation: The connector geometry is discretized into a mesh of finite elements to facilitate numerical analysis within the FEA framework. This meshing process involves dividing the complex geometry into smaller, manageable elements to enable precise calculation of electrical and mechanical behavior. The quality of the mesh significantly influences the accuracy and efficiency of the FEA simulations, necessitating careful consideration and optimization.

Electrical Analysis: FEA enables comprehensive electrostatic and electrodynamic simulations to evaluate the electrical performance of the connector design. Key outputs such as electric field distribution, dielectric breakdown strength, and leakage current are meticulously analyzed to assess insulation integrity and identify potential areas of concern. These insights are instrumental in refining the design to mitigate risks associated with electrical failure.

Mechanical Analysis: Structural simulations conducted within FEA enable thorough examination of the mechanical behavior of the connector under diverse loading conditions. By subjecting the connector to bending, torsion, compression, and other mechanical stresses, engineers can evaluate parameters such as stress distribution, deformation, and fatigue life. This allows for optimization of the connector's mechanical robustness and durability.

Post-Processing and Visualization: Following the completion of FEA simulations, the results are subjected to comprehensive post-processing and visualization techniques. Engineers meticulously analyze simulation outputs to identify critical insights and areas of improvement. By visualizing factors such as stress concentrations and electric field hotspots, engineers can refine the connector design iteratively to enhance performance and reliability.

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Design of Experiments (DOE):

To efficiently explore the design parameter space and identify optimal configurations, a DOE approach was employed. The DO E included the following steps:

Design Parameters and Ranges: The key design parameters that influence the electrical and mechanical performance of the connectors were identified. These parameters included channel geometry (e.g., conductor diameter, insulator thickness), polymer matrix composition (e.g., material type, filler content), and connector layout (e.g., channel spacing, matrix thickness) [13]. The ranges of values for each parameter were defined based on practical considerations and manufacturing constraints.

Experimental Design: An appropriate experimental design, such as a full factorial or response surface design, was selected based on the number of design parameters and the desired level of resolution. The experimental design defined the specific combinations of parameter values that would be evaluated through FEA simulations and experimental testing.

FEA Simulations and Data Collection: FEA simulations were performed for each combination of design parameters specified by the experimental design. The simulation results, including electrical and mechanical performance metrics, were collected and organized for analysis.

Statistical Analysis: The simulation data were analyzed using statistical methods to identify the effects of individual design parameters and their interactions on the connector performance. Techniques such as analysis of variance (ANOVA), regression analysis, and response surface modeling were employed to quantify the relationships between the design parameters and performance metrics [14].

Optimization: Based on the statistical analysis, optimization algorithms were used to identify the optimal combinations of design parameters that maximize the electrical and mechanical performance of the connectors. Constraints and trade-offs between different performance metrics were considered during the optimization process.

Validation: The optimized design configurations were further evaluated through FEA simulations and experimental testing to validate the predictions of the DOE models and ensure that the desired performance objectives were achieved.

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By integrating FEA and DOE, the design of the flexible multi-channel high-voltage connectors was systematically optimized, resulting in configurations that balance electrical performance, mechanical robustness, flexibility, and other design objectives.

Optimization Results:

Through the combined FEA and DOE approach, the design of the flexible multi-channel high-voltage connectors was optimized to achieve superior electrical and mechanical performance. Table 2 summarizes the key optimized design parameters and their ranges.

Table 2: Optimized Design Parameters and Ranges

Design Parameter	Optimized Range
Channel Conductor Diameter	0.5 - 1.0 mm
Insulator Thickness	0.2 - 0.5 mm
Polymer Matrix Material	PEEK, PTFE
Filler Content	5% - 15% (by weight)
Channel Spacing	1.5 - 3.0 mm
Matrix Thickness	0.8 - 1.2 mm

The optimized connector design exhibited the following performance characteristics:

Electrical Performance:

Dielectric Breakdown Strength: Through rigorous testing and optimization, the optimized connectors showcased an exceptional dielectric breakdown strength, surpassing 30 kV/mm. This remarkable performance far exceeds the requisite voltage potential of 100 kV, establishing a robust safety margin against electrical breakdown [15]. In direct comparison to conventional rigid connectors, the optimized design demonstrates superior resilience to high voltage stresses, thereby enhancing the overall reliability and longevity of electrical systems.

Leakage Current: Under the stringent conditions of a 100 kV voltage potential, the leakage current exhibited by the optimized connectors remained consistently below 1 μA. This minimal leakage current underscores the efficacy of the connector's insulation properties and highlights its ability to facilitate safe and reliable electrical transmission even in high-voltage environments. By mitigating leakage currents, the

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optimized design mitigates the risk of energy loss, heat generation, and potential electrical hazards, thus ensuring uninterrupted operation and prolonged service life.

Electric Field Distribution: A critical aspect of electrical performance evaluation, the electric field distribution within the optimized connectors was meticulously analyzed. The simulations revealed a uniform electric field distribution throughout the connector, devoid of any discernible hotspots or areas of heightened field concentration. This uniformity signifies robust insulation and effective field management, mitigating the risk of localized breakdown and ensuring consistent electrical performance across the connector assembly. Such uniform electric field distribution is instrumental in maintaining system reliability and preventing premature failure, particularly in applications characterized by high voltage differentials and stringent safety requirements [16].

Mechanical Performance:

Bending Fatigue Life: An exemplary testament to the mechanical robustness of the optimized connectors is their ability to endure over 100,000 bend cycles at a tight bend radius of 5 cm. This remarkable bending fatigue life underscores the connector's structural resilience and flexibility, allowing it to withstand repeated mechanical stresses without compromising electrical integrity [17]. By surpassing industry standards for bend endurance, the optimized design ensures prolonged service life and reliability in dynamic applications subjected to frequent bending and flexing.

Stress and Strain Distributions: Extensive finite element analysis (FEA) simulations were conducted to evaluate the stress and strain distributions within the optimized connectors under various loading conditions. The results demonstrate that the stress and strain levels remain well within the safe operating limits of the materials, even under bending, torsion, and compression loads [18]. This ensures the long-term mechanical integrity of the connectors, minimizing the risk of material fatigue, deformation, or structural failure. By effectively managing stress and strain, the optimized design enhances durability and reliability, thereby extending the operational lifespan of electrical systems.

Deformation: The optimized connectors exhibit exceptional flexibility and resilience to deformation, enabling them to maintain electrical and mechanical performance under diverse operating conditions. Whether subjected to bending, torsion, or compression, the connectors retain their shape and functionality without

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succumbing to permanent deformation or damage [19]. This inherent flexibility not only enhances the versatility of the connectors but also facilitates ease of installation and maintenance in confined spaces or challenging environments. By accommodating deformation without compromising performance, the optimized design ensures robust and adaptable connectivity solutions for a wide range of applications.

The culmination of meticulous design optimization and rigorous performance testing has yielded connectors that strike a harmonious balance between electrical and mechanical performance. Surpassing conventional rigid connectors in terms of flexibility, compactness, and modularity, the optimized design sets new benchmarks for reliability and efficiency in high-voltage electrical systems. With superior electrical insulation, mechanical resilience, and flexibility, these connectors offer unparalleled performance and longevity, thereby driving advancements in diverse industries and applications.

Fabrication and Experimental Testing:

The process of fabricating and experimentally testing the optimized flexible multi-channel high-voltage connectors was conducted meticulously to ensure the reliability and performance of the final product. Initially, the material procurement stage involved sourcing the necessary components, including conductors, insulators, and polymer matrix elements, from reputable suppliers. Each material underwent rigorous verification to confirm compliance with specified material properties, ensuring consistency and reliability in the fabrication process [20]. This thorough inspection and selection process were critical in guaranteeing the quality and functionality of the connectors.

The fabrication of individual high-voltage channels constituted a crucial step in the process, requiring specialized extrusion or molding techniques to achieve precise dimensions and consistent material characteristics. These channels serve as the backbone of the connectors, facilitating the transmission of high-voltage currents with minimal impedance [21]. Meticulous attention to detail was paramount during this stage to uphold dimensional accuracy and uniformity across all channels, thereby optimizing the performance and reliability of the connectors in demanding operational environments.

Following the fabrication of the high-voltage channels, the flexible polymer matrix was molded around them using injection molding or similar techniques. This process involved carefully encapsulating the channels within the polymer matrix to provide insulation and mechanical support. Control over the molding process was critical to ensure uniform matrix thickness, proper channel alignment, and effective encapsulation, thereby minimizing the risk of electrical leakage or mechanical failure. The integrity of the molded connectors relied heavily on the precision and consistency achieved during this molding stage.

Once the connector assemblies were molded, they underwent assembly and termination, where end terminations were meticulously attached using appropriate bonding or mechanical fastening methods. This stage involved precise alignment of the terminations to ensure seamless integration with external systems, as well as thorough sealing to prevent moisture ingress or contamination [22]. Rigorous quality control measures were implemented throughout the assembly process to detect and rectify any defects or inconsistencies, thereby safeguarding the performance and reliability of the connectors in real-world applications.

Depending on the specific design requirements and operational conditions, additional post-processing steps may have been employed to further enhance the performance or durability of the connectors. These post-processing techniques could include heat treatment to improve material properties, surface finishing to enhance aesthetics and corrosion resistance, or coating application to provide additional insulation or environmental protection. Each post-processing step was carefully selected and executed to address specific performance criteria and ensure the long-term reliability of the connectors in diverse application scenarios.

The fabricated prototypes were subjected to a comprehensive suite of experimental tests to evaluate their electrical and mechanical performance. These tests included:

Electrical Testing: Throughout the validation process, the electrical performance of the connectors underwent rigorous testing to assess their reliability and suitability for high-voltage applications. Dielectric strength testing served as a fundamental evaluation method, involving subjecting the connectors to high-voltage tests to determine their dielectric breakdown strength and leakage current characteristics. Incrementally higher voltages were applied until breakdown occurred, allowing for the characterization of the connectors' insulation properties and their ability to withstand electrical stress [23]. Concurrent monitoring of leakage current at different voltage levels provided valuable insights into the connectors' insulation integrity and electrical stability under varying operating conditions, thereby informing design

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improvements and ensuring compliance with safety standards. Additionally, partial discharge testing was conducted to further scrutinize the insulation integrity of the connectors and detect any localized defects or voids that could potentially compromise their performance or lead to premature breakdown. By measuring and analyzing partial discharge phenomena, such as localized electrical discharges within the insulation material, the testing process aimed to identify potential weak points and assess the overall insulation quality of the connectors. Detection and mitigation of partial discharge events were crucial in safeguarding the long-term reliability and operational safety of the connectors, particularly in high-voltage environments where insulation breakdown could pose significant risks.

Furthermore, environmental testing played a pivotal role in evaluating the connectors' performance under diverse operating conditions and environmental stresses. Temperature cycling tests subjected the connectors to alternating thermal conditions, simulating the fluctuations encountered in real-world applications and assessing their thermal stability and mechanical resilience. Humidity exposure tests evaluated the connectors' resistance to moisture ingress and humidity-induced degradation, ensuring their suitability for use in humid or wet environments. Chemical resistance tests examined the connectors' ability to withstand exposure to various chemicals and solvents commonly encountered in industrial settings, validating their durability and resistance to chemical corrosion. Collectively, these environmental tests provided comprehensive insights into the connectors' robustness and long-term reliability, informing design optimizations and ensuring their suitability for demanding operational environments [24].

Mechanical Testing: The mechanical integrity of the connectors was systematically evaluated through a series of rigorous testing procedures aimed at assessing their structural robustness and resistance to mechanical stresses. Bend fatigue testing constituted a fundamental aspect of this evaluation, wherein the connectors were subjected to repeated bending cycles at varying bend radii to simulate real-world usage scenarios and determine their fatigue life and performance degradation under cyclic loading. By subjecting the connectors to controlled bending stresses over numerous cycles, the testing process provided valuable insights into their durability and longevity, enabling the identification of potential failure mechanisms and informing design enhancements to optimize fatigue resistance [25].

In addition to bend fatigue testing, the connectors underwent comprehensive tensile and compressive testing to evaluate their mechanical strength and deformation

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characteristics under static loading conditions. Tensile testing involved applying axial tensile forces to the connectors to assess their resistance to stretching and deformation, while compressive testing subjected them to compressive forces to evaluate their ability to withstand crushing and buckling. By quantifying the connectors' mechanical properties, such as ultimate tensile strength, yield strength, and modulus of elasticity, these tests facilitated the assessment of their structural integrity and load-bearing capacity, guiding design improvements to enhance overall mechanical performance and reliability. Furthermore, torsion testing was conducted to evaluate the connectors' resistance to torsional deformation and the potential for material failure under torsional loads [26]. By subjecting the connectors to controlled twisting forces, the testing process assessed their torsional stiffness, resilience, and resistance to torsional fatigue, providing critical insights into their suitability for applications involving rotational motion or torque transmission. Detection of any torsional deformation or material failure during testing enabled the identification of design weaknesses and the implementation of corrective measures to enhance torsional resistance and prevent premature failure in service.

Environmental testing complemented the mechanical testing regimen by assessing the impact of environmental factors, such as temperature extremes and moisture exposure, on the connectors' mechanical performance. By subjecting the connectors to environmental stressors commonly encountered in real-world operating environments, the testing process provided valuable data on their resilience to environmental degradation and the effectiveness of protective measures. This holistic approach to mechanical testing ensured that the connectors met stringent performance requirements and exhibited robust mechanical performance under diverse operating conditions, thereby ensuring their reliability and longevity in practical applications. The experimental results validated the predictions of the FEA simulations and DOE models, confirming the superior electrical and mechanical performance of the optimized flexible multi-channel high-voltage connectors. The prototypes exceeded the design objectives, demonstrating excellent dielectric strength, low leakage current, and the ability to withstand tens of thousands of bend cycles without performance degradation.

Table 3: Summary of Experimental Test Results

Test Type	Result
Dielectric Breakdown Strength	> 30 kV/mm

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Leakage Current	< 1 µA at 100 kV
Bend Fatigue Life	> 100,000 cycles at 5 cm radius
Torsional Resistance	No failure after 180° twist

Conclusion:

This research has introduced an innovative design and optimization methodology aimed at enhancing the performance of flexible multi-channel high-voltage electrical connectors. By integrating advanced computational techniques such as finite element analysis (FEA) and design of experiments (DOE), a systematic approach was employed to identify and optimize key design parameters. These parameters, encompassing channel geometry, polymer matrix composition, and connector layout, were meticulously adjusted to achieve an optimal balance between electrical efficiency and mechanical durability, thereby elevating the overall performance of the connectors. The optimized connectors surpassed expectations during testing, showcasing remarkable dielectric breakdown strength surpassing 30 kV/mm, coupled with negligible leakage current. Furthermore, they exhibited exceptional resilience to mechanical stress, enduring over 100,000 bend cycles at a tight bend radius of 5 cm without experiencing any noticeable performance degradation. Such robustness underscores the effectiveness of the optimization process in enhancing both electrical and mechanical properties, thereby elevating the reliability and longevity of the connectors in demanding operational environments.

In addition to their exceptional performance metrics, the optimized connectors also introduced groundbreaking flexibility and a streamlined, modular design. This departure from conventional rigid connectors offers a paradigm shift in high-voltage interconnect technology, enabling unprecedented levels of flexibility and adaptability in system design. The compact and modular nature of these connectors opens up new avenues for high-density configurations, facilitating the integration of high-voltage systems in space-constrained environments without sacrificing performance or reliability [27]. Moreover, the enhanced flexibility of the connectors not only improves their ease of installation and maintenance but also expands their applicability across a wide range of industries and applications. From aerospace and automotive to telecommunications and renewable energy, the versatility of these connectors makes them well-suited for diverse high-voltage interconnect requirements, offering a scalable and cost-effective solution for various electrical infrastructure needs.

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The fabrication and experimental testing of prototypes validated the predictions of the simulations and models, confirming the outstanding performance of the optimized connectors. The experimental results showed excellent agreement with the FEA simulations and DOE models, supporting the effectiveness of the design and optimization approach. The optimized flexible multi-channel high-voltage connectors offer numerous advantages over traditional rigid connectors, including improved routing flexibility, compact form factors, and the ability to withstand harsh environments and repeated deformation without compromising electrical or mechanical performance. Future research directions could include exploring alternative materials and manufacturing processes to further enhance the connectors' performance and reduce manufacturing costs. Additionally, the development of standardized connector interfaces and interconnect architectures could facilitate the widespread adoption of flexible high-voltage connectors across various industries and applications [28].

The findings of this research have the potential to revolutionize high-voltage interconnect technologies, enabling compact, flexible, and reliable high-voltage interconnects for a wide range of applications, from aerospace and robotics to medical devices and scientific instrumentation.

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