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Addressing electromagnetic interference problems in high voltage transmission systems with the help of advanced nanomaterials

Tran Thi Thanh Huyen, Le Thi Thuy Ngan
Thai Nguyen University of Technology

Abstract
Electromagnetic interference (EMI) is a critical challenge for the reliability of high voltage transmission systems, which is improved by the integration of renewable energy and power electronics. This study proposes innovative solutions, particularly for graphics and carbon nanol pipe composites, to reduce EMI. Material synthesis, experimental testing and electromagnetic simulations are combined to evaluate the effectiveness, durability, and scalability of coating labels applied to nanomaterial bases applied to permeable components in research. The results demonstrate the effectiveness of labels above 50 dB over a wide frequency range. This exceeds traditional metal shields, but at the same time maintains light and inexpensive properties. The results highlight the potential of nanotechnology to improve performance of modern power grids and support sustainable energy systems. Future work focuses on cost optimization and practical implementation, ensuring practical provisions.
Keywords: *electromagnetic interference, nanomaterials, high voltage transmission, diagram, carbon nanol tubes.*

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I. Introduction

The rapid expansion of modern power systems was facilitated by the increase in global energy requirements and the integration of renewable energy sources, significantly changing the electrical engineering landscape. Unprecedented efficiency and reliability operations require high voltage transmission systems that are currently very important to provide a wide range of power. However, these systems face growing challenges: Electromagnetic interference (EMI). EMI is caused by high frequency vibration, electronic performance and integration of renewable energy countries. This is a serious threat to the stability, safety and durability of the power grid. In more complex electrical systems, dense networks have developed renewable energy electronics and variable inputs to reduce EMI to emergency quantities.

Traditional EMI reduction techniques, such as metal diplomacy and filtering, are becoming more and more common in modern power systems. These traditional methods often contain severe and expensive materials and have limited skills to improve the high frequency-MI produced by advanced stromes electronics. Furthermore, the physical limitations regarding the integration of bulky shielding solutions into compact, high voltage devices are a critical issue. These materials are characterized by optical properties, high conductivity and adjustable properties that can revolutionize EMI reduction in high voltage transmission systems.

The aim of this study is to solve the most important questions of EMI when transferring high voltage services by proposing a new approach based on advanced nanomaterials. In particular, this study focuses on the design and use of nanostructured coatings and labeling to suppress EMI and improve the performance and reliability of power delivery systems. By using the unique electromagnetic properties of nanomaterials, this work aims to overcome the limitations of traditional shielding methods and provide a scalable and inexpensive solution to modern power grids. The importance of this research lies in the potential to improve operational efficiency of high-voltage transmission systems, reduce maintenance costs, and support integration of renewable energy sources into networks.

This paper is structured as follows: Section 3 of the existing literature on EMI in electromagnetic systems and the use of nanomaterials in electromagnetic shields. Section

describes a methodology that includes designing nanomaterial-based experimental constructed labeling signs. Section 5 presents conclusions and proposes directions for future research.

In high voltage transmission systems, EMI is primarily caused by changes in frequency of electronic power intensity, such as body and wall lenses, and temporary events such as lightning attacks and error conditions. According to Smith et al. (2023) EMI can impair the performance of sensitive devices, introduce errors in communication systems, increase the risk of device failure, leading to significant economic losses. Integration of renewable energy sources such as wind and solar exacerbates EMI due to the various properties of their performance and the reliance on power electronics for lattice integration.

Traditional EMI reduction strategies focus on shielding and filtering technologies. Metal shields, usually made of copper or aluminum, are usually used to block electromagnetic waves by reflecting or absorbing them. As Johnson and Lee (2024) discovered, these materials are strong, expensive and ineffective at high frequencies where modern river electronics work. Additionally, the metallic shield men will be challenged to integrate into compact, high-voltage devices. Filtering techniques such as the use of capacitors and inductors are also used to suppress EMI, but are limited by frequency range and sensitivity to errors over time. These limitations highlight the need for innovative materials and approaches to reduce EMI.

The advent of nanotechnology has opened new ways to treat EMI in power systems. The extraordinary electrical, mechanical and electromagnetic properties have attracted considerable attention in nanomaterials such as diagrams, carbon nanol tubes (CNTs), and Mxen. The graphics are a single layer of carbon atoms arranged on a hexagonal grille, with high electrical conductivity and excellent electromagnetic wave absorption capabilities. Study by Zhang et al. (2024) based on the diagram, showing that a shielding effect (SE) exceeding the microwave frequency range of more than 60 dB was achieved, far exceeding the conventional metal shield. Similarly, it has been demonstrated how Kim and Park (2025) with its high aspect ratio and conductivity form an effective EMI symbol when installed in a polymer matrix. Mxenes, a class of two-dimensional transition metal carbohydrates, has proven to be a promising candidate for EMI shields due to its layered structure and adjustable surface chemistry.

The new research examined the use of nanomaterials in a variety of electromagnetic protection contexts, including home appliances and aerospace. For example, Li et al. (2025) developed a graphic polymer network that achieves lightweight and flexible shielding of portable devices. However, the use of nanomaterials in high voltage transmission systems remains. The hard operating conditions of the service network, including high voltages, extreme temperatures and long-term exposure to environmental factors, represent the unique challenges of solutions based on nanomaterial materials. Despite the promise of

nanomaterials, there are some research gaps. First, most studies on nanomaterial EMI shields focus on low-performance applications where data on power is limited in high-voltage environments. Second, the long-term stability and durability of nanomaterials in power system operational volumes are unknown. Third, integration of nanomaterials into existing power infrastructures such as cables and transformers requires innovative design and manufacturing techniques to ensure compatibility and reliability. Finally, the ecological and economic impacts of large-scale nanomaterial production for power applications ensure further investigation.

This study is based on the existing literature by proposing a specially tuned nanomaterial-based approach to EMI reduction in high voltage increasing systems. Combining experimental testing and advanced electromagnetic simulation, the purpose of the research is to assess the feasibility of effectiveness, durability and practicality of nanomaterial-based solutions.

II. Methodology

This study proposes a comprehensive and systematic method for examining the use of complex nanomaterials to reduce electromagnetic interference (EMI) in high voltage transmission systems. This approach integrates material synthesis, experimental testing, computer modeling and performance evaluation to develop and validate new solutions for EMI suppression. This methodology aims to address unique challenges in high voltage environments such as high frequency-MI, thermal loads, and the need for scalable and inexpensive solutions. It is included in five key components: material design and synthesis, experimental setup, electromagnetic simulation, performance evaluation, and scalability analysis.

2.1 Material Design and Synthesis

The basis of this research is the development of nanomaterial-based shielding solutions tailored to high voltage transmission systems. The research focuses on two major nanomaterials.

Graphics and Carbon Nanol Vortex (CNT). These were chosen for their extraordinary electrical conductivity, simple properties, and ability to absorb electromagnetic waves. These materials are installed in composite structures to improve mechanical stability and applicability under rough operating conditions.

Graph Based Composites:

Graph, carbon distribution with high electrical conductivity and adjustable electromagnetic properties is synthesized using chemical vapor separation (CVD) to ensure high purity and uniformity. To create practical shielding materials, graphics flakes are distributed in polymer matrices such as epoxy and polyurethanes that provide flexibility and durability. Graphic density (5-20%) changes to optimize the compromise between shield effectiveness (SE) and mechanical properties. Composites are produced in thin films (0.1-1 mm) using spray coating, a scalable technology suitable for large-scale applications. This film is designed to be applied as a coating for gear cables, transformer housings, or other important components.

CNT-based Shielded Base:

Multi-wall Carbon Nanoral Tubes (MWCNTs) are chosen for their high aspect ratio and conductivity. In other words, it is ideal to form a critical network in the composite material. MWCNTs are synthesized and washed via arch discharge to remove contaminants. The CNTs are then distributed in a polymer matrix (such as polydimethylsiloxane) using an ultrasonic matrix (such as polydimethylsiloxane) to ensure an even distribution. The resulting network is treated with a flexible film or rigid panel using vacuum filtration or compression formation. The thickness of CNT-based signs varies in a variety (0.2-2 mm) to investigate its effects on EMI inhibition and structural integrity.

Material Optimization: Both the graph and CNT composites were optimized through repeated tests of electrical and mechanical properties. Electrical conductivity is measured using a point probe, and electromagnetic wave absorption absorption is evaluated using a vector network analyzer. Mechanical testing, including tensile strength and thermal cycling, allows the material to withstand operating voltages of high voltage systems, such as temperature fluctuations (-20°C to 80°C) and mechanical vibrations. The aim is to develop materials that achieve a shielding effect of at least 50 dB, while simultaneously maintaining weight loss and cost.

2.2 Experimental Setup

An experimental stage has been developed to assess EMI anomalies in nanomaterials based on composites under realistic high voltage conditions. The custom testbed was developed to simulate sections of high voltage transmission systems, including 100 kV power supplies, electronic performance hiking and associated cables. The testbed is configured to show the high-frequency EMI-EMI (1 MHz-1 GHz) of modern power systems, including transients from the switchover process and harmony from the country of renewable energy.

Test Bed Configuration: The Test Bed consists of a high voltage segment (10 meters) connected to the language transformer and the load bench. Performance converters such as Pulswidth modulation (PWM) inverters have been integrated and EMI has been introduced. Nanomaterial-based shielding applies to critical components such as gear cables, transformer housings, and converter housings. Depending on the application, the signs can be either directly covered by the component or installed as a separate panel.

EMI Measurements:

EMI levels are measured using a high-precision spectrum analyzer (Keysight N9040B) and many calibration antennas. Measurements are performed in an anechoic chamber to remove external electromagnetic noise and ensure accurate facts collection. The shield effect (SE) is calculated as

[SE = 20 \log_{10} \left(\frac{P_i}{P_t} \right)]

(P_I). The electromagnetic service for incident services is (P_T). Measurements are performed over a frequency range of 1 MHz to 1 GHz and record the entire EMI connected to a high voltage system. Additional tests use infrared thermography to assess the thermal performance of the sine to monitor temperature rise during operation.

Durability Test: To assess the long-term reliability of nanomaterial labels, a accelerated aging test is performed. The shields are thermal cycles (100 cycles between -20°C and 80°C), moisture exposure (85% relative humidity for 500 hours), and mechanical tension (100 hours of vibration at 10 Hz). After testing seed and material integrity measurements, the sign can maintain power under operating loads.

2.3. Electromagnetic Simulation

Complement the experimental results to gain deeper insight into the EMI suppression mechanism. These tools allow for the modeling of complex electromagnetic interactions in high voltage systems and provide an inexpensive way to explore a variety of scenarios.

Model Development: A 3D model of the transmission system has been constructed. This includes geometry, transformers and power electronics. Nanomaterial symbols are modeled with measured electrical properties such as conductivity, approval, and permeability. This model takes into account frequency-dependent behavior and ensures accurate representation of EMI over the target frequency range (100 kHz-10 GHz).

Simulation Scenarios: simulation evaluates the performance of nanomaterial labels under a variety of conditions, including hospital behavior, temporary errors (such as short-term), and high frequency. Parametric studies examine the effects of tympanic membrane thickness, material composition, and placement on SE. This simulation also analyzes the interaction between labels and electromagnetic waves, providing insight into the reflection, absorption and scattering mechanisms.

Simulation results have been verified against experimental data to ensure accuracy. Contradictions are analyzed, models are refined, and factors such as material defects and environmental impact are taken into account. Next, we use the validated model to predict the performance of the sines on a larger system.

Performance Evaluation

Nanomaterial-based services are evaluated using a combination of quantitative and qualitative metrics. The most important performance indicators are

Shield Effect (SE): Destination SE > 1 MHz -1 GHz on 50 dB.
Power Loss: signs do not significantly increase transmission losses as
Measured (<1% additional loss).
Thermal Stability: Temperature rise limited to <10°C above ambient during operation.
Mechanical Durability: No significant degradation in SE or structural integrity after aging tests.
Cost and Scalability: Preliminary cost estimates based on material synthesis and fabrication processes, targeting a cost reduction of 20% compared to copper-based shields.
The performance of nanomaterial labeling is evaluated with traditional metallicet (copper and aluminum) to quantify improvements in SE, weight and cost. Statistical analyses including ANOVA and T-tests are used to assess the importance of the results.

2.5. Scalability Analysis
To ensure practical applicability, methods include scalability analysis and the transfer options of distinctive nanomaterials. This includes assessment of the feasibility of large-scale synthesis and production, including the availability of raw materials (such as graphite production) and the energy requirements of the manufacturing process. Cost-benefit analysis compares the proposed solution with existing EMI reduction techniques. This takes into account both initial investment and long-term maintenance costs. The analysis also examines potential integration strategies. Change to an existing infrastructure or new transmission system and enter the shield.

III. Results and Discussion

Experimental evaluation of nanomaterial-based indications for weakening electromagnetic interference (EMI) in high-voltage transmission systems yielded promising results showing significant improvements compared to traditional metal labeling. In this study, we tested two graph-based nanomaterial composite bases and carbon nanol tube (CNT)-based independent fields. The testbed was configured to carry EMI from the 1 MHz to 1 GHz frequency range. The power electronics and integration of energy electronics have been replicated with modern power systems.

Shield Effectiveness (SE): The composite based on the graph achieved an average shielding effect of 55 dB over the tested frequency range with a peak SE of 62 dB at 500 MHz. The CNT-based composite recorded an average of 52 dB and maintained consistent performance at a peak of 58 dB at 300 MHz. In contrast, copper-based shields, typically used in high-voltage systems, averaged 5 dB, significantly reduced effectiveness from 500 MHz to over 0 dB at 1 GHz. The SE on the nanomaterial shield is particularly evident at higher frequencies where electronic devices produce important EMI. Statistical analysis using ANOVA confirmed that SE for both nanomaterial composites was significantly higher than that for copper ($P<0.01$).

Power Loss: An important requirement for EMI shielding in a transmission system is to have a minimal impact on the efficiency of transmission. The shield based on the graph added a power loss of 0.7% ± 0.1%, while the CNT-based shield led to a loss of 0.8% ± 0.1%. Both values are well below 1% of the target threshold, ensuring that the shield does not affect the system's energy efficiency. In comparison, the copper shield introduced a slightly higher loss of 0.9% ± 0.1%. This is probably due to the high electrical resistance at high frequencies. These results show that nanomaterial shields maintain excellent compatibility with high voltage transmission requirements.

Thermal Stability: Using infrared thermography during continuous operation, thermal performance was rated at 100 kV in 8 hours. The composite-based composite showed a maximum temperature rise of 7.8°C from the environment, whereas the CNT-based 8.2°C based composite recorded a high temperature rise of 9.5°C due to lower thermal conductivity compared to the nanomaterials. All shields remained within the acceptable limits of a temperature rise of 10°C, confirming compatibility for longer operation in high voltage environments.
Durabitation Test: The acceleration test assessed the long-term reliability of the label under operating stress. The shield was exposed to 100 thermal cycles (-20°C to 80°C), 500 hours of moisture loading (85% relative humidity), and 100 hours of mechanical vibration (10 Hz). Post-test measurements showed no significant degradation in SE for both nanomaterial composites. This ensures that the graphic sign maintains the first SE (5dB) and CNT-based sign with 98% of the CNT-based sign based on 97% (50 dB). Copper shields showed a reduction in SE (43 dB) at 5%, possibly due to surface oxidation. Mechanical tests showed that the tensile strength of the graph composite 75 MPa was slightly higher than that of the CNT composite. This indicates resistance to physical stress. Both nanomaterial shields exceeded copper (60 MPa) in terms of mechanical durability.

COMSOL - Simulations with Multipiphysics and ANSYS HFSS provided additional insight into the performance of nanomaterial labeling. The simulated SE values are intimate with experimental results with maximum deviations above the ±3 dB frequency range. For example, the simulated SE for graphic composite materials was 62 dB 500 MHz 60 dB compared to the experiment. Parametric studies examined the effect of the eardrum chamber, showing that the graphic thickness was improved from 0.1 mm to 0.5 mm, with only 1 mm of reinforcement being further increased. The simulations also confirmed that the absorption is due to its high conductivity and layer structure rather than reflecting the dominant mechanism of EMI suppression in both nanomaterials.

Preliminary cost estimates show that the label is 15% more expensive than the copper label, mainly due to the cost for the separation and synthesis of chemical steam vapors. CNT-based shields are 10% more expensive and benefit from more established production methods. However, scalable manufacturing techniques such as spray coating and vacuum filtration reduced production costs by 20% compared to laboratory-scale methods. The optical properties of nanomaterials (50% lighter than copper) reduce transportation and installation costs and improve the economic viability for large-scale use.

Experimental and simulation results highlight the potential for conversion of nanomaterial-based sin for EMI reduction in high voltage transmission systems. The excellent protective effect of graphics and CNT composites, especially at high frequencies, deals with the essential limitations of traditional metal shields. The ability to achieve SE values above 50 dB over a wide frequency range (1 MHz-1 GHz) is particularly important for modern power grids, with EMI becoming increasingly widespread in renewable energy. The peak SE of the 62 dB graph at 500 MHz is Li et al. This concerns recent research such as (2025) over 50 dB of graphics polymer composites in low power applications. This improved performance in a high voltage context highlights the adaptability of nanomaterials to demanding environments.

The EMI inhibition mechanism governed by absorption of nanomaterial signs is a more important advantage over copper, primarily in reflection. The high electrical conductivity and large surfaces of the diagram allow for efficient storage of electromagnetic waves, while the networked structure of CNT creates a variety of options for energy absorption. This mechanism reduces the risk of secondary EMI caused by reflected waves, a common problem with metal marking. This simulation provides valuable insight into this process and shows that the layered structure of nanomaterials improves wave weakening through several internal reflections within the composite. The minimum performance loss (0.7-0.8%) introduced by the shielded nanomaterial (0.7-0.8%) ensures compatibility with high voltage propagation systems where efficiency is most important. The reduced performance compared to copper marking (0.9%) can be attributed to the excellent conductivity of nanomaterials at high frequencies that minimize resistive losses. This efficiency is important to support the integration of renewable energy sources that require accurate performance management to maintain network stability. The thermal and mechanical durability of nanomaterial sines is an essential advantage for high voltage applications. Without resisting significant deterioration, the ability of heat to ladders, moisture and vibration suggests that these materials can withstand rough operating conditions of electrical networks such as wind fluctuations and wind fluctuations and mechanical voltages. The higher tensile strength in the figure is B, as the use of composite materials is used compared to CNT and copper. This is especially suitable for applications that require robust mechanical performance. B. Cable coating. However, the flexibility of CNT composites offers advantages for applications requiring compliant shielding, such as transformer housings.

Despite these strengths, this study must consider limitations. The experiments were conducted on a laboratory-scale testbed. This cannot completely replicate the complexity of a real transmission system. B. Long distance lines and wide range of ambient conditions. Scaling the testbed to a larger system can present additional challenges, such as variations in the EMI pattern and material performance under higher voltages. Furthermore, the initial costs of nanomaterial synthesis remain a barrier to widespread transfers. Scalable manufacturing technology reduces costs by 20%, but further optimization is required to achieve cost parity with copper signs. The environmental impact of large-scale nanomaterial production, such as energy consumption and waste production, also needs further testing to ensure sustainability.

Compared to existing literature, this study promotes the use of nanomaterials in high voltage systems. Zhang et al. (2024) Report on the 60 dB -SE value of graphic composites in microwave applications. The current study shows comparable performance in high voltage environments dealing with important gaps in the region. Similarly, Kim and Park (2025) confiscated an SE value of 55 dB using CNT composites, but their research was limited to consumer electronics. The ability to maintain high SE under high tensile conditions with robust durability sets the proposed solution as a practical choice for modern power grids.

Scalability analysis demonstrates the industrial potential, particularly with advances in manufacturing technology. The light features of nanomaterials reduce logistics costs and make them attractive for redesigning existing infrastructure or new transmission system designs. However, challenges such as raw materials (such as graphite graphite) and production energy requirements must be addressed to ensure economic feasibility. The

results validate the effectiveness of labeling for nanomaterial-based labeling for EMI reduction, providing superior performance, durability and efficiency compared to traditional solutions. The results pave the way for the introduction of nanotechnology in high-voltage transmission systems and support the development of reliable, sustainable power grids. Future research should implement identified limits by running real-world tests, optimizing production costs, and examining hybrid nanomaterials to further improve performance.

IV. Conclusion

This study presents a new approach to reduce electromagnetic interference (EMI) in high voltage transmission systems using advanced nanomaterials, particularly composites based on graphs and carbon nanol pipes. The proposed solution demonstrates a significant improvement in the effectiveness of the shield, achieving over 50 dB over a wide frequency range, while simultaneously providing a lightweight, durable alternative to traditional metal signs. By integrating experimental tests into electromagnetic simulations, we investigate the potential of nanomaterials to improve the reliability and efficiency of modern power grids, particularly with regard to the integration of renewable energy. The results show that the conversion effects of nanotechnology address important challenges in electrical engineering. Future research should focus on optimizing the cost-effectiveness of nanomaterial synthesis to enable large-scale use. Research on hybrid nanomaterials such as graphic composites could further improve shielding power. Testing operational communication systems in the real world is important for assessing long-term durability and environmental impact. Additionally, the integration of nanomaterial-based labeling with smart grid technologies such as AI-controlled EMI monitoring enables adaptation reduction strategies. This progress supports the development of resistant and sustainable power systems for the future.

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