The Scientific Temper (2025) Vol. 16 (spl-1): 83-95
E-ISSN: 2231-6396, ISSN: 0976-8653
Doi: 10.58414/SCIENTIFICTEMPER.2025.16.spl-1.12
https://scientifictemper.com/
ORIGINAL RESEARCH PAPER

Field-effect limits and design parameters for hybrid HVDC – HVAC transmission line corridors

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Abstract

The scientific evaluation of extra-high voltage (EHV) and ultra-high voltage (UHV) hybrid transmission lines presents essential research demands for power transmission systems' efficiency. The high-capacity transmission lines need proper electric and magnetic field (EMF) management because public concerns about environmental and health risks keep rising. The relationship between power grid lines and surrounding areas needs thorough study to fulfill health-related requirements and earn public trust in power projects. The experiments demonstrated in Figure X show that strategic grounding with clever conductor placement effectively reduces EMF exposure, which results in enhanced performance and social acceptance of transmission lines in urban environments. In EHV/UHV lines, the Right of Way (ROW) is fundamental in establishing these power systems' operational efficiency and safety. The need for broader corridors stemming from EMF considerations and corona discharge concerns requires designers to achieve ideal solutions between effectively using land space and maximizing electrical system efficiency. The design optimization needs to integrate technological innovations for future energy growth because this will reduce environmental impacts throughout the design process. Combining design strategies is crucial for protecting power transmission systems against upcoming energy requirements and regulatory changes. Evaluating corona effects influences the complete functional performance and design strategies for these power transmission lines. The environmental conditions that trigger corona discharge, especially when combined with ice accumulation, result in power losses and environmental damages, thus requiring designers to grasp its impact on lines thoroughly. Many publications present effective laboratory methods for studying icing phenomena that affect severe weather areas. The research discoveries help reduce power losses and simultaneously support the secure integration of EHV/UHV systems into existing electrical networks. This investigation addresses multiple elements in depth to create better design procedures that promote efficiency with safety and environmental sustainability.

Keywords: Hybrid Transmission Line, EHVAC, HVDC, EMF, Corona Effect

Introduction

Hybrid power system applications combining the extra high voltage alternating current (EHVAC) transmission lines with high voltage direct current (HVDC) technology can improve energy sector efficiency and reliability. The combined solution enables AC and DC conductors to run a standard tower or Right of Way (ROW). Many countries have recently launched the Hybrid Transmission Line concept, which justifies the feasibility of placing AC and DC conductors on the same tower or sharing the same Right of Way with benefits of increased reliability and efficiency along with reduced cost benefits for tower infrastructure (Artuso, M., Ayad, R., Bukin, K., Efimov, A., Boulahouache, C., Dambasuren, E., ... & Smith, A., 2005). The newly introduced Hybrid Transmission Line concept, which facilitates the feasibility of placing AC and DC conductors on the same tower or sharing the same Right of Way, offers improved grid reliability, efficiency, and cost benefits for tower infrastructure." [COA Paper] (Manan Pathak) Because the generated EMF affects human health evaluations and environmental sustainability assessments, the idea requires complete research on how electrical components respond to environmental elements. ROW optimization extends beyond engineering needs, such as interaction with society and economy, and extensive research, particularly regarding spatial restrictions.

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How to cite this article: Pathak, M., Trivedi, D. (2025). Field-effect limits and design parameters for hybrid HVDC – HVAC transmission line corridors. The Scientific Temper, **16**(spl-1):83-95.

Doi: 10.58414/SCIENTIFICTEMPER.2025.16.spl-1.12

Source of support: Nil

Conflict of interest: None.

Received: 13/04/2025 **Accepted:** 11/05/2025 **Published** : 21/05/2025

The models for hybrid transmission lines that represent how EMF interacts with different materials when they are in contact with residential areas need to be of their advanced mathematical nature. Conducting objects makes understanding the electric field distribution around them easier by diagrams illustrating these field patterns. During transmission line design, premium materials are applied, which lowers electromagnetic side effects and ensures the environment remains in harmony while meeting today's energy consumption needs (Bernier, David et al., 2021). This makes possible the development of designs satisfying EMF exposure standards and facilitating the proper increase in energy systems density. The mechanisms to reduce the effects caused by corona discharge due to natural phenomena on the infrastructure of efficient energy transfer through EHV/UHVAC-HVDC hybrid transmission lines are evaluated. Power losses generated by the corona effects lead to audible sound and radio interference and thus affect the system's performance integrity. Corona and environmental conditions are evaluated to decide how to specify tower spacing and design to minimize operating costs. The system performance and reliability changes brought on when using alternate wire arrangements to shield a particle detector are supported through visualizations (Brown, Valerie., 2022). Comprehensive optimization techniques can assure the engineering field that modern power transmission systems are technologically advanced, environmentally sustainable, and economically sustainable.

A Framework of EHV/UHVAC-HVDC hybrid transmission lines

A significant innovation in power transmission in this particular field is the integration of extra-high voltage (EHV) and ultra-high voltage (UHV) alternating current (AC) with high-voltage direct current (HVDC) systems. This hybrid approach optimizes energy transmission efficiency for long-term transmission with minimal power conversion and transmission losses (Chen, Z., Huang, X., & Li, W., 2020). The contemporary electric power transmission system necessitates reevaluating theory and practice, grounded in innovative concepts that facilitate the optimal utilization of existing transmission infrastructure without compromising system availability and security." (Gollapalli Vinod Kumar, Grandhi Ramu). Using EHV, UHVAC, and HVDC systems strategically enhances grid stability and fulfills the increasing demand for renewable energy sources, creating a need for creative transmission lines to adjust to the changing landscape (Fofana, I., & Brettschneider, S., 2022). The complexity of these systems necessitates careful design and analysis for optimal performance and reliability. Determination of the electric and magnetic field (EMF) distribution is of prime importance in designing and implementing EHV/UHVAC-HVDC hybrid transmission lines. The potential environmental impacts of EMF have to be evaluated in populated areas to ensure the system's safety and acceptability. A practical design must consider parameters such as conductor configuration, ROW, and distance to minimise adverse effects on nearby communities. For example, electric fields within a conductor can be studied extensively to determine the height and arrangement of a conductor in such a way that optimizes the spatial configurations that align with the regulatory laws and the public tension on safety issues. An EMF effect evaluation is also made in connection with the fluctuation of electric field strength as a function of conductor positioning, as shown in, which underscores the importance of such factors in transmission line design (Ghosh, S., Das, B., & Kumar, P., 2021). In addition, EHV/UHVAC-HVDC lines exhibit significant differences in the right of way (ROW) requirements, which affects land use and public planning decisions. The long-term success and public acceptance of EHV / UHVAC HVDC hybrid transmission lines will ultimately hinge on a well coordinated approach to overcoming these challenges.

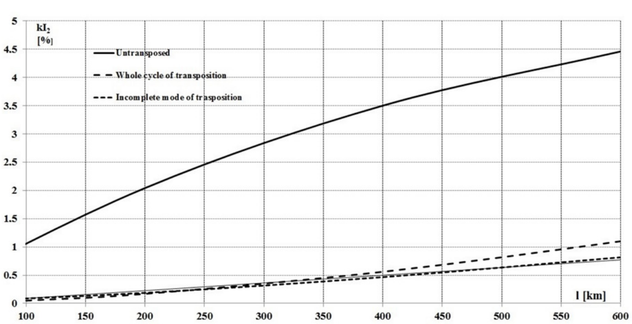

Figure 1: Variation of Voltage Imbalance (kI) with Line Length under Different Transposition Modes

Significance of Operational Analysis

The reliability and efficiency of EHV/UHVAC-HVDC hybrid transmission lines can be analyzed through performance analysis (Table 1). Engineers can rigorously assess performance metrics, i.e., electric or magnetic field distributions, to identify infrastructure weaknesses in multiple atmospheric conditions and operational modes. These variables are significant and knowing them directly affects the efforts to design and optimize to minimize losses and mitigate the risk of electrical faults (Huang, J., Tang, T., Hu, G., Zheng, J., Wang, Y., Wang, Q., ... & Peng, X., 2013). The need to establish performance standards in HVDC transmissions promptly arises as the demand for high-capacity transmission grows. Consequently, such performance analyses help improve the operational capabilities of hybrid systems and serve as the basis for devising new means of meeting future energy needs. Such analyses are very important for the long-term sustainability of the electrical networks. Another critical factor of performance analysis is the right of way (ROW) for transmission lines. This evaluation shows that the

Table 1: EHV/UHVAC-HVDC Hybrid Transmission Lines: Key Characteristics and Performance Metrics

Voltage level	*Voltage range (kV)*	*Transmission type*	*Typical applications*	*Advantages*
Extra High Voltage (EHV)	345–765	Alternating current (AC)	Transmission of electricity over extensive distances, incorporation of renewable energy sources	Reduced line losses, improved system stability
Ultra High Voltage Alternating Current (UHVAC)	Above 765	Alternating Current (AC)	Massive power transmission over long distances	Enhanced capacity, reduced transmission losses
High Voltage Direct Current (HVDC)	Above 500	Direct Current (DC)	Interconnection of asynchronous grids, long-distance bulk power transmission	Lower line losses, ability to control power flow, integration of remote renewable energy sources
EHV/UHVAC-HVDC Hybrid	Combination of EHV/ UHVAC and HVDC levels	Hybrid of AC and DC	Enhanced power transmission capacity, improved system reliability, integration of diverse power sources	Optimized transmission efficiency, flexibility in power flow control, reduced environmental impact

transmission line installation and maintenance adhere to its legal and environmental standards and, most importantly, optimizes land use. They also use performance assessments to find the most efficient roads to minimize land acquisition costs and efficiently conduct electricity transmission. In addition, engineers can determine how electric fields affect surrounding landscapes and wildlife and develop better management strategies to impact ecology (Khaligh, A., & Onar, O. C., 2022). For example, the electric field graph indicates how variation in lateral distance is quantitatively related to electric field intensity, which provides vital information for planning a ROW somewhere between excessive operational effectivity and insensitivity to the environment. To understand and mitigate phenomena such as corona discharge causing operational issues in transmission lines, performance analysis has proven to be important. By understanding the impact of coronal effects on energy loss and acoustic emissions, engineers can be better prepared to design mitigations on the system level to improve a system's resilience and performance. Researchers can, therefore, simulate icing effects using empirical data, and in turn, designers can use this data to anticipate and counteract how icing effects can affect transmission efficiency under adverse weather conditions (Lesnicar, A., & Marquardt, R., 2003). In addition, performance maps, including the real-life operational scenario, such as the UHV grid outline, are employed to contextualize the electrical infrastructure's capability and aid in understanding the need and criteria for future expansion and upgrade. Overall, careful monitoring, combined with adaptive design, is paramount to innovative, proactive engineering and performance analysis form the cornerstone of high-capacity transmission systems.

One of the key objectives of this paper is to investigate the performance optimisation of Hybrid transmission lines using Extra High Voltage (EHV), Ultra High Voltage Alternating Current (UHVAC), and High Voltage Direct Current (HVDC) (Table 2). This investigation focuses on the effect of electric and magnetic fields on a conductor's energy loss minimization as it relates to energy loss during transmission. The paper attempts to create such a framework by analyzing the interaction of these factors so rigorously as to guarantee the safe and reliable distribution of energy while at the same time not impacting the environment or public health (Liu, W., Xiang, Y., & Zhao, H., 2019). This paper aims to analyze the performance of EHV/UHVAC-HVDC hybrid transmission lines, considering the effects of electric and magnetic fields, right of way, and corona discharge. (A. Carvajal, V.R. Garcia-Colon). This graphical representation of an electric field with conductor dimensions will serve as a comprehensive analysis to determine optimized configurations of conductor geometry that can achieve high transmission efficiency while satisfying these important electromagnetic considerations. The second one is the study of the right of way (ROW) requirements for EHV/UHVAC-

Table 2: Performance Analysis of EHV/UHVAC-HVDC Hybrid Transmission Lines

Parameter	*Value*
Insulation Specifications	Reduced from 27 to 21 disc insulators for 400 kV lines
Live Metal Clearance	Decreased from 2600 to 2400 mm
Cost Savings per Line	7–9% reduction
Right-of-Way (ROW) Requirements	Reduced due to optimized design
Operational Challenges	Insulator quality issues, bird activity, and design margins
Adverse Weather Impact	Tripping issues during foggy winter periods

HVDC transmission lines. The fact that ROW specifications directly affect land use and environmental impacts is significant for project viability. The focus of this essay is an in-depth analysis of spatial and regulatory parameters that govern the planning of ROW. The last part of this essay discusses the significance of corona discharge phenomena on the performance and design of hybrid transmission systems (Madigan, G., Lee, C., Cetois, A., Dixit, A., Zhong, X., Knight, A., ... & Ashworth, P., 2023). Energy losses from corona effects and the audible noise it generates can cause operational integrity problems with transmission lines. The study seeks to implement methodologies for designing better systems, which are directly correlated with the technical requirements of high voltage environments through assessing various shielding strategies and their ability to reduce the impact of corona in the environment. The application of these techniques in the real world was shown in the example of the experimental setup described, which allows us to see how high-voltage conductors interact with the surroundings (Nguyen, Q., Etingov, P., & Elizondo, M. A., 2023, January). The essay proposes to provide valuable and accessible knowledge for the future evolution and optimisation of HVDC and hybrid systems in energy supply by dealing with these problems.

Methodology

Efficient hybrid AC-DC transmission line design depends on joining electromagnetic field theory science with simulation modelling and real-life specs for EHV and UHV power lines. Our strategy needs to handle the EMF complexities of hybrid transmission lines by monitoring results against safety standards and boosting operational efficiency in environmentally friendly ways. Case of 400 kV EHVAC and 500 kV HVDC Hybrid Delta Transmission Line are considered.

Theoretical framework: Establishing electromagnetic and transmission line models

The framework starts with a complete theory based on electromagnetic field science combined with transmission line information about hybrid networks. When studying hybrid transmission configurations, the exact behavior between electric and magnetic fields needs proper

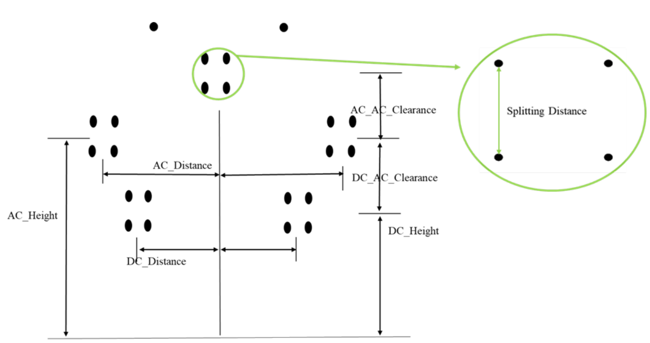

Figure 2: Schematic Diagram Showing AC and DC Clearance and Splitting Distance Parameters

modeling alongside ROW factors, corona emission processes, and natural surroundings (Table 3).

Maxwell's equations must solve transmission line specifications, including line geometry properties, to determine an EMF's spatial characteristics and behavior.

- The transmission line's physical shape and groupings determine the number of conductors.
- Electromagnetic coupling effects between AC and DC lines (Figure 2)

Table 3: EMF Exposure and Health Effects Near High-Voltage Power Lines

Study	*Findings*
Task Group on Environmental Health Criteria for Extremely Low-Frequency Fields	No significant health concerns are associated with ELF electric fields at the exposure levels typically experienced by the general population. The evidence regarding a connection between ELF magnetic fields and childhood leukemia is limited and lacks the strength to establish a causal relationship. It is estimated that merely 1% to 4% of children reside in households with average magnetic field exposures exceeding 0.3 μT. If ELF magnetic fields are linked to an increased risk of childhood leukemia, the implications for public health would be relatively modest, with an estimated 100 to 2400 cases annually across the globe, accounting for 0.2 to 4.95% of the total incidence for that year.
National Institute of Environmental Health Sciences (NIEHS) Report on Health Effects from Exposure to Power-Line Frequency Electric and Magnetic Fields	There is no evidence supporting a connection between EMF exposure and adult cancers, including leukemia, brain cancer, and breast cancer. Several studies indicated a potential connection between EMF field strength and a heightened risk of childhood leukemia; however, the correlation was weak.
Association between Exposure to Electromagnetic Fields from High Voltage Transmission Lines and Neurobehavioral Function in Children	The impact of electromagnetic fields from high-voltage transmission lines could play a crucial role in affecting neurobehavioral function in children. Students from regions with elevated power frequency EMF exposure exhibited diminished visual reaction time (VRT) and pattern recognition (PAT) scores, indicating possible neurobehavioral impacts.
Exposure to Electromagnetic Fields of High Voltage Overhead Power Lines and Female Infertility	Women residing within 500 meters of high-voltage power lines exhibited an increased risk of infertility (adjusted odds ratio 4.44, 95% CI 2.77 to 7.11) in comparison to those living beyond 1000 meters. The existing safety guidelines regarding exposure to electromagnetic fields may fall short of effectively safeguarding individuals from the potentially harmful effects of such fields.

- The operational environment affects transmission lines through humidity, temperature, and wind speed metrics.
- Voltage profile and load flow characteristics under steady-state and transient conditions

Using this foundation, the research method can represent physical transmission behavior, which helps us organize the placement of materials, including conductors and shielding wires.

Computational Simulations: Virtual Testing of Field Interactions

Our implementation relies on advanced computational methods to make the theory work in practice. These simulations show the magnetic field changes during brief and constant operations with less need for expensive field testing. Scientists use FEM and FDTD analytical approaches to determine field interactions.

Our system models electric field intensity and magnetic field strength throughout hybrid transmission corridor areas considering the above-mentioned simulation inputs.

- Examine how the corona discharge methods and charged particles move under different power settings.
- Review power loss and system stability patterns in different conductor choices.
- Check the effects of electromagnetic interference from transmission lines on adjacent infrastructure systems.

Simulation Conditions

- Electric field distribution is calculated at different electrical angle throughout the electrical cycle with 10-degree steps.
- To get accurate EMF, RI, and AN results, the Simulation model is extended beyond the RoW.
- RoW for the configuration is Optimized to be near 70 m for 765 kV EHVAC – 800 kV HVDC lines.
- Simulations are performed at centre of the span length since that condition provides the minimum ground clearance (Table 4).
- Two cases of simulation are performed:
    1. Case 1: Centre of tower structure. (Sag = 0 m)
    2. Case 2: Centre of span length. (Sag = Maximum DC = 8.84 m & Maximum AC = 13.42 m)

Optimization Techniques: Parametric and Sensitivity Analysis

The method uses modern optimization techniques, including these methods, to create the best hybrid transmission line design. Our design parameter tests show how each variable affects system results. For instance:

- The proper location of the shielding wire affects how the conductor surface gradient performs
- The way separated conductors affect the point where electrical discharges start
- We change the grounding level to reduce contact with the field environment.

This study finds which transmission elements mainly determine system performance and safety through sensitivity testing.

- Sensitivity analysis assesses the impact of changes in input variables on the target parameters, helping to understand how these parameters are influenced by variations in the inputs.
- A total of more than 500 design variations are considered for the simulation.
- 3 Major parameters are considered with minimum to maximum limit of dimensions to perform the sensitivity analysis:
    - DC Height = 18 m to 39 m, 1 m step.
    - DC - AC Clearance = 10 m
    - AC – AC Clearance = 5.09 – 24.68 m

Practical Implementation and Environmental Considerations

Simulations are performed utilizing MATLAB, the FEA-based software ANSYS Maxwell, and PSCAD-based FACE software to guarantee thorough analysis. The boundary conditions and excitations of the simulation models are first validated through test cases derived from existing literature to ensure accuracy. A hybrid transmission line offering a hybrid delta configuration which will be analysed, facilitating a comparative examination of more than one design option (Papadopoulos, A., Nikolaidis, A.,

Table 4: Comparison of Key Parameters between EHVAC and HVDC Transmission Systems

Sr. No.	*Parameter*	*EHVAC*	*HVDC*	*Remarks*
1	Voltage (kV)	765	±800	Delta Connection
2	Current (kA)	3.7	7	RMS Value
3	Power (MW)	2830	6400	Power Transfer Capacity
4	Sub conductor Diameter	31.80	40.59	(Value is in mm)
5	Sag	15 - 22	12 - 18	(Value is in Meter)
6	Splitting Distance	457.2	457.2	(Value is in mm)
7	Splitting number	6	6	NA
8	D Horizontal Distance	18 - 28	10 - 14	(Value is in Meter)
9	H Vertical Distance	35 - 42	35 - 42	(Value is in Meter)
10	DC to AC Phase Clearance	10		(Value is in Meter)
11	AC to AC Phase Clearance	7.09 - 26.68		(Value is in Meter)

& Stathopoulos, P., 2021). The version validation manner involves the simultaneous simulation of EHVAC and HVDC lines to assess essential parameters, together with the electric subject, magnetic discipline, audible noise, and radio interference. Upon a hit of the entirety of the validation procedure, the identical simulation setup is employed for the next evaluation, concentrating on the optimization of the layout configuration of the hybrid transmission line underneath numerous constraint situations.

This final method communicates how engineers should create transmission line systems that conform to environmental conditions.

- Regulatory compliance (IEEE, ICNIRP, WHO standards for EMF exposure)
- We selected locations for power lines that reduced host environments and would not disturb nature.
- Our method adds sustainable design solutions that protect against electromagnetic field radiation exposure.

Additionally, this research combines GIS platform capabilities for graphical field plotting and three-dimensional power corridor visuals to bring theory into real-life applications.

Integrating Theory, Experimentation, and Optimization

Combining electromagnetic field theory with optimization approaches helps us create a complete method to study and improve EHV/UHVAC-HVDC hybrid power lines. This complete plan enhances transmission quality, promotes green practices that align with energy transmission requirements, and protects people from EMF issues.

Results

Performance analysis of EHV/UHVAC-HVDC hybrid transmission lines gives rise to a considerable spread in electric field intensity and geographical implications. Finally, the electric field's distribution is examined in detail, and as lines are approached, the intensity of the electric field increases. The line graph of electric field variations graphically shows the Lateral distance changes in an electric field (Table 5).

The curves drawn represent the difference of electric field level values captured in the graph at any point along the transmission line, i.e., closer to the line has higher electric field strength. As such, electric fields could impact environmental and human safety, so providing these insights is essential to the design of suitable ROW policies and compliance with safety regulations and electromagnetic field (EMF) exposure limits.

Further results show that transposition is crucial for kI_2 as a function of distance and that there are very different results on the untransposed versus fully transposed configurations. The corresponding figure 3 details that the kI_2 data is provided completely, and the kI_2 increases with the

Table 5: EHV/UHVAC-HVDC Hybrid Transmission Line Methodology Data

Voltage level (kV)	*Insulation specification (Disc Insulators)*	*Live metal clearance (mm)*	*Cost savings per line (%)*	*Right of way reduction*
400	21	2400	7–9	Reduced
1200	97	Calculated	Calculated	Within Acceptable Limits

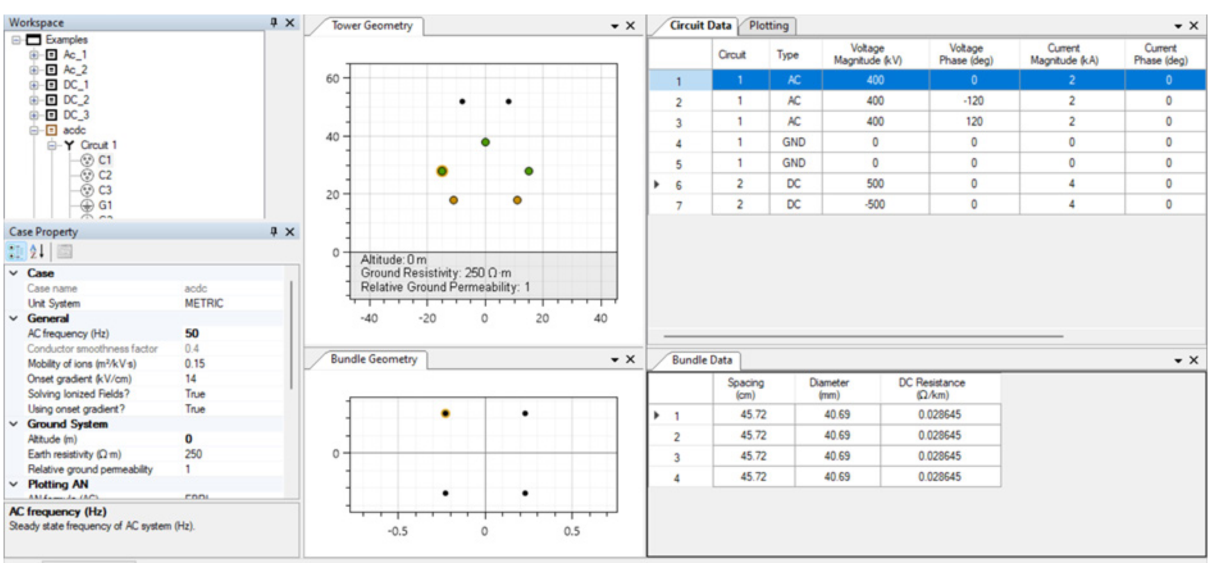

Figure 3: Simulation Interface Showing Tower Geometry, Circuit Data, and Bundle Configuration for AC and DC Systems

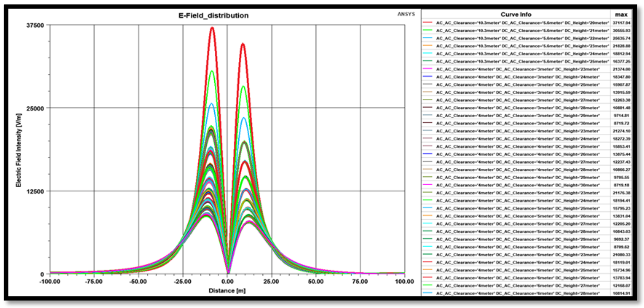

Figure 4: Electric field Distribution combining all three design variables

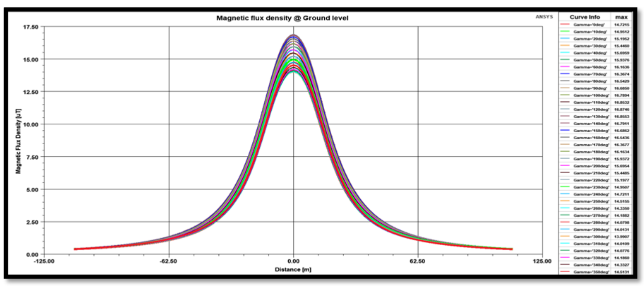

Figure 5: Magnetic Flux Density Distribution at Ground Level for Various Current Intensities

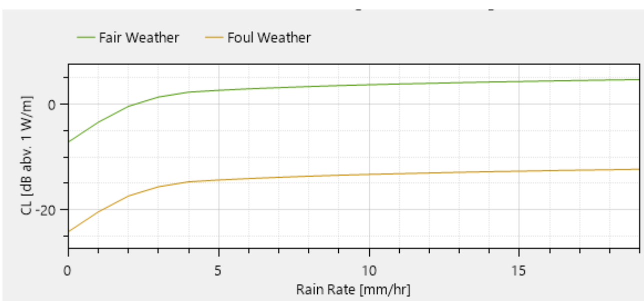

Figure 6: Corona Loss Cl (dB abv. 1 W/m]

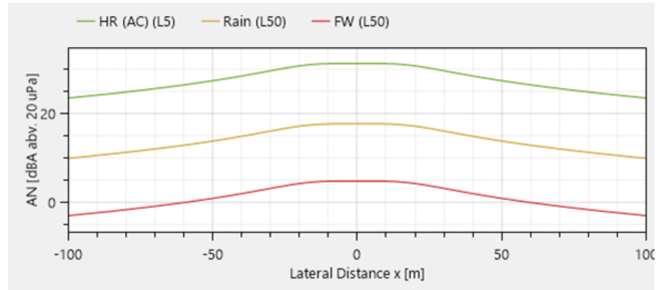

Figure 7: Audible Noise AN [dBA abv. 20 uPa]

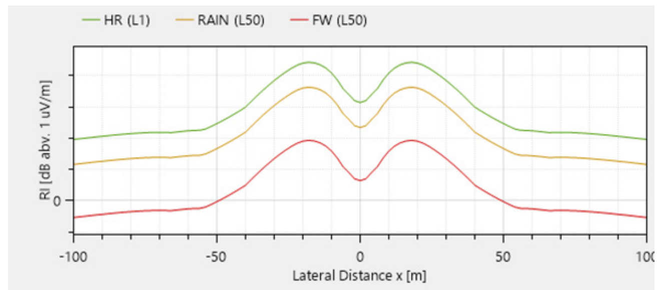

Figure 8: Radio interference RI [dB abv. 1 uV/m]

distance to the power line decrease, while the untransposed case reveals higher kI_2 compared to the same case upon transposition. This differential performance is important for designing a hybrid transmission system where the best line configuration is critical to minimize losses and maximize the overall system efficiency. The findings can also indicate that strategic transposition and EMF can reduce the EMF's adverse effects, which will significantly benefit power distribution planning (Figures 5-8).

Also, results involving the noise levels generated by the transmission lines represented beneficial results in accounting for the acoustic influence over the surroundings. The comparative analysis of sound pressure levels of sound pressure for a tower transmission is demonstrated by the sound pressure graph as a function of distance from the tower transmission for both minimum and maximum configuration of the transmission. Thus, the observed trend would suggest it is possible to disturb people living in rural or urban settings with sound pressure in the instant vicinities of the transmission lines as registered.

Appropriate placement of transmission lines and an understanding of the acoustic implications will be necessary for the community's response to areas exposed to noise pollution. So, their design must incorporate a proper acoustic study of EHV/UHVAC – HVDC systems for technical and public acceptance.

Discussion

A thorough understanding of land use controls, community concerns, and environmental protection is paramount. Efficient ROW management strategies can allow for integrating EHV/UHVAC-HVDC lines within the environment without disruption, thus significantly affecting their operational efficiency and acceptance by surrounding communities. Data visualization of right-of-way (ROW) arrangements and their interactions with surrounding land can elucidate potential problems, enhancing project planning and stakeholder engagement (John D McDonald). Additionally, the phenomenon of corona discharge is significant in determining the operational characteristics of extra-high voltage (EHV) and, ultra-high voltage alternating current (UHVAC) and high voltage direct current (HVDC) hybrid transmission lines. Corona discharge, mainly due to high electric fields, results in energy losses through electrical noise and radiation (Reed, L., Morgan, M. G., Vaishnav, P., &

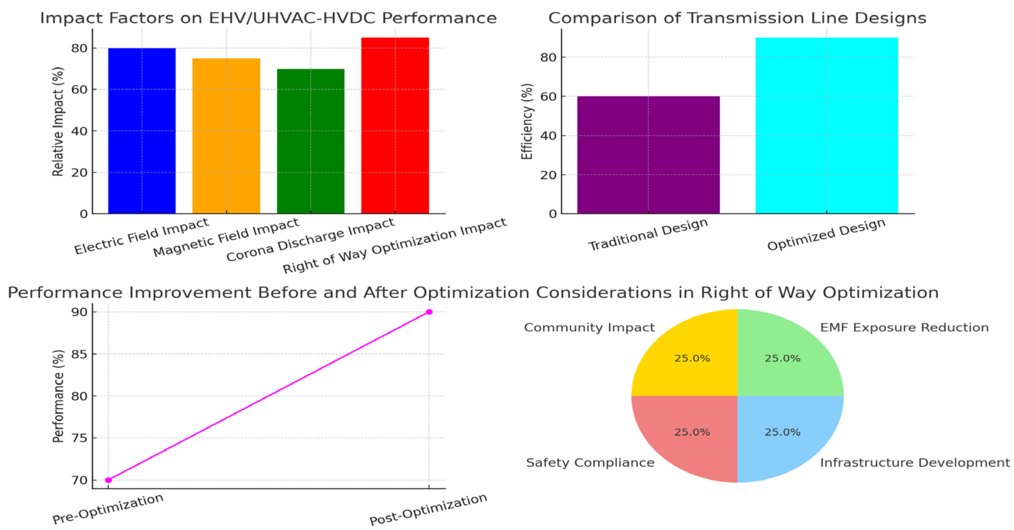

Figure 9: This chart illustrates various factors of transmission line performance. It includes bar charts depicting the effects of different factors on EHV/UHVAC-HVDC performance and comparison among conventional and optimized designs. A line chart suggests the overall performance development earlier than and after optimization, whilst a pie chart highlights the balanced considerations in Right of Way optimization strategies. Overall, the visualization emphasizes the importance of these factors and their impact on transmission efficiency and compliance.

Erian Armanios, D., 2019). The phenomenon can potentially affect the efficiency of energy transmission and pose safety issues around the transmission lines. It is, therefore, necessary to explore the factors involved in corona formation, such as line design, meteorological conditions, and physical properties of the surrounding environment. Engineers can design solutions to reduce associated losses and enhance overall transmission efficiency by utilizing design optimization techniques that consider corona effects figure 9 Using graphical means describing corona discharge distributions facilitates a comprehensive understanding of the phenomenon and is a valuable tool for engineering assessments and interactions with regulatory bodies (John D McDonald). This comprehensive analysis ultimately results in designing more efficient hybrid transmission systems that satisfy energy demands and comply with safety and environmental regulations.

Thus, the EHV/UHVAC HVDC hybrid transmission line is promising in terms of its performance; all of these performances can be improved by adequately considering the design's EMF, ROW, and corona effects. As found out, EMF levels must be carefully considered as stairs involving their public health ramifications and regulatory compliance. Optimal transposition steps provide notable infrastructure improvements; further modeling is warranted to incorporate the environmental and operational variables (Shrivastava, S., Srivastava, V. K., Khalid, S., Khan, I. A., & Nishad, D. K., 2024). The analysis also highlights how adaptive management strategies for ROW can alleviate the socio-environmental impacts of establishing transmission corridors to initiate greater acceptance of community and regulations. It turns out that these findings offer a pathway to more efficient and less responsible transmission solutions. Also, the intersection of technical performance and environmental stewardship complicates the development of EHV/UHVAC HVDC systems in this respect.

Summary of Key Findings

The infrastructure performance analysis of Extra High Voltage (EHV) and Ultra High Voltage (UHV) transmission lines shows interwork amid design optimization and environmental influence. Studies have shown that EHV/UHVAC-HVDC hybrid transmission systems are more efficient in terms of EMF, causing effects on the environment surrounding the systems. Among other relationships, it is important to understand the relationship between conductor configurations and EMF levels to be able to determine whether they present a hazard to the surrounding residential area and, if so, to then make changes to design parameters to reduce this risk (Shrivastava, S., Srivastava, V. K., Khalid, S., Khan, I. A., & Nishad, D. K., 2024). According to the findings, engineers can better shorten and possibly meet electrical safety standards by considering the electric field distribution, which offers engineers more flexibility in transmission line layout design. Therefore, energy transmission efficiency improves and becomes safer for populated regions of this kind of integration system when these factors are considered systematically. Moreover, the Right of Way (ROW) analysis stresses the importance of land use to transmission line placement. The study results show that the installation cost can be reduced while maintaining the optimal operational efficiency of ROW design by optimizing its width. It is shown that UHV systems require much narrower corridors than EHV counterparts. Improving project economic viability while decreasing the ecological footprint constitutes a win-win for any project. Work will be done by associating these disturbances with proactively controlled seating ROW and strategically placed shielding, which will allow for the optimization of ROW and have a mitigating effect on the disturbance to realize a sustainable energy transmission solution. ROW optimization is a crucial component in the equilibrium of infrastructure development with ecological and societal functions (). Findings related to corona effects also shed additional light on the issues related to transmission line design required for optimal line performance. Corona discharge may cause energy loss, increase electromagnetic interference, and reduce transmission efficiency and the environment. With that, engineers can analyze the electric field gradients and potential corona conditions depicted and anticipate and minimize this adverse effect. System reliability can be improved significantly from these impacts and the strategic

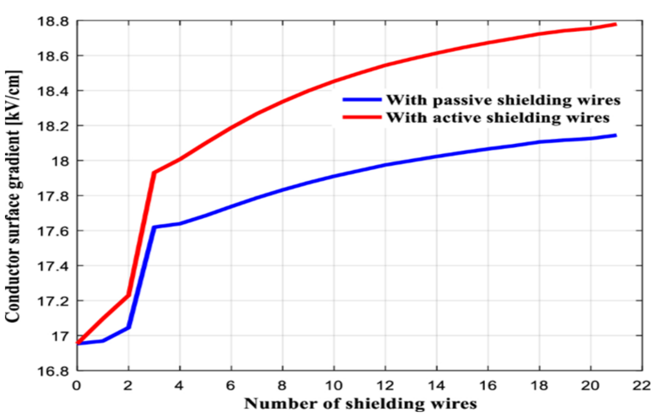

Figure 10: Effect of Shielding Wire Configuration on Conductor Surface Gradient

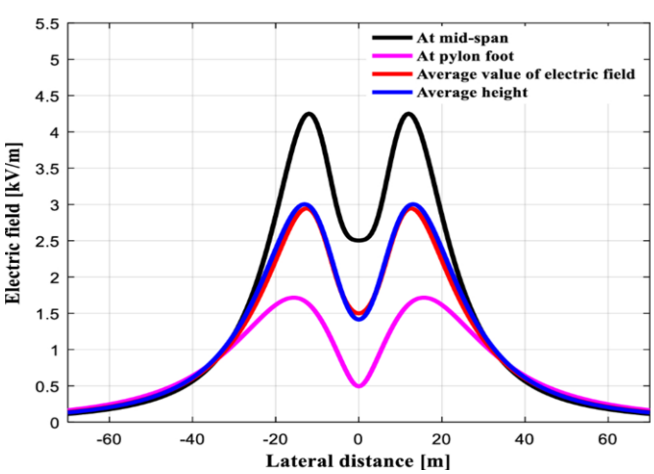

Figure 11: Lateral Distribution of Electric Field at Different Transmission Line Positions

installation of shielding wires, as shown in. These insights are critical to informing future design protocols for transmitting lines so that energy can be transferred effectively while keeping the lines resistant to the environment (Figure 10 and 11). Therefore, optimizing several design parameters that vary with corona considerations is crucial for designing advanced EHV/UHVAC-HVDC systems.

Suggestions for Stakeholders

Considering the optimal design of EHV/UHVAC-HVDC hybrid transmission lines, material science and technology development for improving the conductivity and insulation properties of conductors should be at the forefront of the stakeholders' interests. However, using high-temperature superconductors with new coating materials to reduce corona discharge and energy losses can increase power transmission systems' efficiency. Together with these technologies, transmission capacity is increasing, and it defends against issues of EMF exposure and similar. These advancements must be funded and promoted through collaborations among industries, academia, and research institutions. The schematic comparison of EHV and UHV transmission requirements can be used as a practical comparison of the material benefits of enhanced technologies for all system performance aspects to elucidate the subtleties of land and energy distribution efficiency.

Additionally, good stakeholder engagement in land use planning is essential for considering Right of Way (ROW) concerns in hybrid transmission line projects. The purpose of assessing the environmental and social impacts of proposed transmission corridors and engaging with local communities, regulatory agencies, and environmental advocates is to facilitate a pathway to sustainable development that can be achieved comprehensively. Obligatory communication strategies must be employed to resolve the public distrust in land use change and emissions. Furthermore, applying scientific research on EMF effects will contribute to the development of land management policies and minimize the negative perception by society. The visual presentation of sound pressure levels found in this study can underpin the importance of maintaining community standards and comfort levels in transit line proximity and that there should be balanced approaches in infrastructure development. Lastly, rigorous performance evaluation and monitoring of hybrid transmission line systems are needed to maintain reliability and sustainability. Stakeholders should use an adaptive management approach to incorporate real-time data monitoring and predictive modeling to determine the effect of either EMF, ROW or Corona on transmission efficiency. Periodic maintenance and assessment protocols will not only lengthen the lifespan of such assets but also increase the state of trust that stakeholders have in technology performance Table 6. Finally, although

Table 6: Key Recommendations for Enhancing Transmission Line Design and Environmental Management

Recommendation	*Details*
Optimize transmission line design	Implement design changes such as reducing the number of insulators and live metal clearance to achieve cost savings and reduce right-of-way requirements. For example, Uttar Pradesh Power Corporation Limited (UPPCL) reduced the number of insulators from 23 to 21 and live metal clearance from 3050 mm to 2600 mm, resulting in a 7–9% reduction in line cost and a 10–12 meter decrease in right of way requirements per line. [pmc.ncbi.nlm.nih.gov](https://pmc.ncbi.nlm.nih.gov/articles/PMC11541901/?utm_source=openai))
Assess environmental and visual impacts	Evaluate transmission lines' potential environmental and aesthetic impacts, mainly when constructed above ground. Stakeholders have identified potential disadvantages, including diminished economic or aesthetic values of the land if lines are built above ground. ([govinfo.gov](https://www.govinfo.gov/content/pkg/GAOREPORTS-GAO-08-347R/html/GAOREPORTS-GAO-08-347R.htm?utm_source=openai))
consider collocation with transportation rights of way	Explore the possibility of collocating transmission lines along existing transportation rights of way, such as highways or railroads, to reduce environmental and visual impacts. This approach may also simplify construction and maintenance processes. ([govinfo.gov](https://www.govinfo.gov/content/pkg/GAOREPORTS-GAO-08-347R/html/GAOREPORTS-GAO-08-347R.htm?utm_source=openai))
Implement quality control measures	Establish stringent quality control protocols for components like insulators to ensure the reliability and longevity of transmission lines. Operational challenges like tripping during adverse weather conditions have been linked to insulator quality issues. ([pmc.ncbi.nlm.nih.gov](https://pmc.ncbi.nlm.nih.gov/articles/PMC11541901/?utm_source=openai))
Develop strategies for mitigating Environmental Effects	Design transmission lines to minimize electromagnetic field (EMF) exposure and address potential health concerns. Additionally, the visual impact of transmission lines on the landscape should be considered, and measures should be implemented to reduce their visibility. ([govinfo.gov](https://www.govinfo.gov/content/pkg/GAOREPORTS-GAO-08-347R/html/GAOREPORTS-GAO-08-347R.htm?utm_source=openai))

potentially of concern based on electric field variation *versus* distance shown, the graph may illustrate EMF exposure concerns and, subsequently, the basis for improved operational strategies to minimize further risk. With an arduous analysis and teamwork efforts, stakeholders can delineate a durable transmission infrastructure designed for the present energy needs and for coming supply challenges.

Concluding Reflections on EHV/UHVAC-HVDC Hybrid Systems

EHV/UHVAC-HVDC hybrid systems present important opportunities and obstacles for present-day power transmission operations. Enhanced energy transmission designs have become essential because worldwide energy requirements continue to escalate rapidly. The dual technology capabilities of the hybrid configuration enable direct current and alternating current operation simultaneously to boost power distribution potential and reduce operational losses. Enhancing transmission line performance demands a detailed analysis of environmental hazards, including electric and magnetic fields (EMF). The scientific community continues to debate the influences of EMF on humans and wildlife, and special attention is required when creating and installing hybrid systems. Hybrid systems are an effective solution for handling modern energy infrastructure requirements because they preserve compliance with environmental standards (Wang, T., Li, F., & Yang, S., 2022). The relevant considerations derived from Right of Way (ROW) are vital in establishing EHV/UHVAC-HVDC hybrid systems. Essential management of ROW space ensures the resolution of conflicts between landowners and transmission line developers during the authorization and maintenance phases. These system configurations decrease the necessary land area to install them compared to conventional HVAC transmission lines, making them easier for communities to accept. Engineers who use developed design optimization tools can optimize ROW utilization to enhance technical performance while considering stakeholder needs. Strategic planning must incorporate public input during the initial stages of project development to address social and ecological impacts and sensitivities (John D McDonald).

Knowledge about ROW dynamics remains essential to achieve long-term success for transmission line projects that operate in the hybrid field. One must thoroughly understand corona discharge conditions in analyses of hybrid transmission lines (Zhang, X., Huang, X., & Yuan, Y., 2020). High-voltage systems show strong ionization effects in conductor-circulated air, creating power loss and noise with increased electromagnetic interference. Decreasing corona effects is a primary design consideration in the optimization process of EHV/UHVAC-HVDC systems since it affects operational reliability and efficiency (John D McDonald). Public well-being and electrical system effectiveness now benefit from recent advancements in engineering material applications designed to manage corona discharge

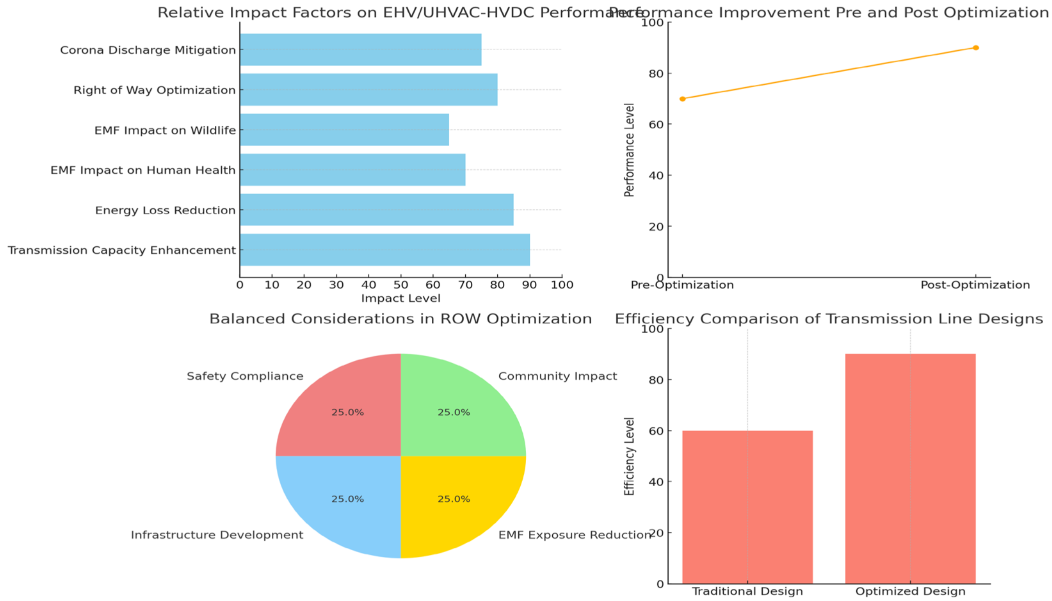

Table 12: *The charts describe different aspects of the performance of EHV/UHVAC-HVDC hybrid transmission lines. The bar chart shows that transmission capacity enhancement is the most important factor among all these. The line chart shows the performance improvement before and after optimization, wherein the performance notched up considerably afterwards. The pie chart is balanced, where Right of Way optimization takes equal considerations of community impact, safety compliance, infrastructure development, and EMF exposure reduction. Finally, the last bar chart compares the efficiency of traditional and optimized ones, in which the optimized design has higher efficiency.*

occurrences. Engineers implement innovative solutions to lower emissions and enhance durability with improved operational capacity of transmission lines while fulfilling safety requirements (John D McDonald) (Figure 12). A thorough investigation of corona discharge and its effects is vital to enhance hybrid transmission system effectiveness.

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