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Review Article

Research Trends in High Voltage Power Transmission

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Abstract *- High-voltage transmission is the most pivotal process in the electrical power industry. This critical aspect is enabling efficient and long-distance electricity transfer. It requires a robust infrastructure that can last for decades without causing impairment in human life. Research in this field continually evolves to address efficiency, reliability, and sustainability challenges. Due to global warming, the power transmission system has started to experience some challenges, which could presumably escalate more in the future. These challenges include renewable energy integration, extreme weather conditions, and growing electricity demand. In this paper, research efforts aimed at addressing these challenges are discussed. In particular, we focus on research in grid modernization, regenerative electric energy, grid resilience, policy and regulation, based on the transmission possibility. We conclude by drawing attention to specific areas that we believe need more research.*

Keywords *- High voltage, Power transmission, Regenerative electric energy, High Voltage Direct Current Transmission.*

1. Introduction

Electric power transmission forms the critical link in the electricity delivery value chain, enabling power transfer from centralized generation plants to load centers spread across large geographies. Robust transmission networks are vital for affordable and reliable electricity supply critical to economic growth and quality of life. However, power transmission infrastructure worldwide faces increasing challenges from aging assets, rising power demand, integration of renewable energy and vulnerabilities to extreme weather events arising from climate change.

Many transmission grids rely on equipment over 50 years old, approaching the end of service life. Growing electricity consumption driven by development, urbanization, industrialization and transport electrification necessitates large-scale grid expansion. Scaling up renewable energy also requires significant transmission investments to tap into remote clean resources and accommodate variable generation. Further, there are impacted grids [1].These challenges are testing the capabilities of transmission networks originally designed for fossil fuel-based centralized generation. Urgent grid models, substantial expansion, and adaptation areas are imperative for a reliable, affordable, clean electricity supply.

Governments and utilities must adopt proactive strategies focused on infrastructure upgrades, resilience enhancement and regulatory reforms. Leveraging emerging technologies like smart grid solutions, high-efficiency materials and advanced modeling tools can also help transform grids into intelligent, flexible and climate-ready networks.

This paper analyzes the key challenges faced in power transmission and highlights priority areas for research and investment to refurbish and upgrade electricity grids. Both institutional and technological interventions are required for transmission infrastructure to support future energy needs and sustainability objectives.

2. High Voltage Direct Current Transmission

High Voltage Direct Current (HVDC) transmission is an efficient long-distance bulk power delivery technology. HVDC lines utilize direct current for power transmission instead of HVDC, which requires converter stations at each end to change AC to DC and back to AC but offers advantages like lower losses and higher controllability over very long distances. Research and development of HVDC technology aims to improve aspects like capacity, efficiency, controllability and integration of renewable energy. According to Figure 1, In AC transmission, the direction of voltage and current continuously reverses, resulting in overheating of the lines and significant power loss. In contrast, current and voltage flow in one direction only in DC transmission. When high-voltage AC (HVAC) is converted to high-voltage DC (HVDC), there is a noticeable reduction in power loss, improving transmission efficiency. The HVDC transmission system combines AC and DC. The generated AC voltage is first converted to DC at the transmitting end. The DC is inverted back to AC for distribution at the receiving end. Conversion devices at both ends are needed for this process. However, HVDC transmission is economical only for long distances - overhead lines over 600km and underground cables over 50km.

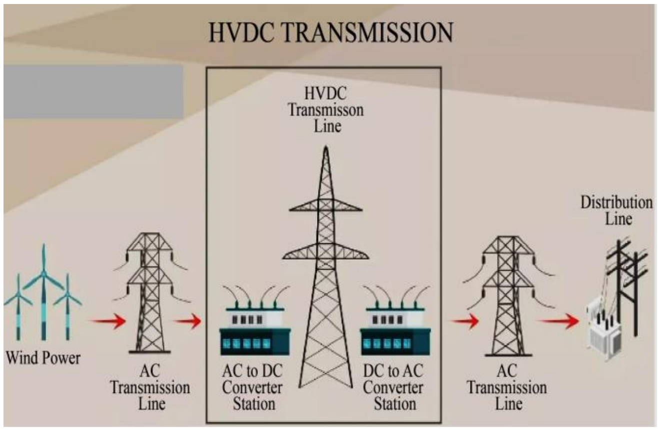

Fig. 1 HVDC transmission

2.1. HVDC Grids

Hajdasz [6] discussed increased research interest in offshore and onshore HVDC grids to effectively integrate renewable energy from distributed sources like offshore wind farms. HVDC grids can also enhance inter-regional power exchange capability and improve stability through rapid controllability of power flow. Key areas of study include protection systems, grid architecture, control systems and grid code development required for robust multi-terminal HVDC networks. Analysis models are being developed to simulate HVDC grid behavior under different contingency conditions. The feasibility of enabling renewable energy-based offshore HVDC grids in regions like the North Sea is being explored through projects by academic and industry groups.

2.2. Voltage Source Converters (VSCs)

Voltage Source Converter (VSC) technology uses self-commutated power electronics devices like IGBTs for AC/DC conversion. VSC offers benefits like independent active and reactive power control, compact converter stations and multi-terminal connectivity. The main research is on improving VSC-HVDC systems' capacity, efficiency, reliability and controllability.

Approaches like advanced pulse width modulation techniques, multi-level VSC topologies and switched capacitor banks are being investigated to reduce harmonic distortions and enhance the power handling capability of VSCs. Real-time simulation studies help evaluate the performance of proposed VSC control models under different operating conditions. Reliability is being improved through redundancies in the converter design and protection systems. Hybrid HVDC breakers that combine thyristor and IGBT capabilities are also being studied.

2.3. Line Commutated Converters (LCCs)

Line Commutated Converter (LCC) HVDC systems use thyristor valves for AC/DC conversion. LCCs are more economical than VSCs for bulk point-to-point long-distance HVDC links. Current research focuses on approaches to reduce losses, improve control capabilities and increase the power handling capacity of LCC-HVDC systems. Studies are being done on advanced firing and extinction angle control algorithms to minimize LCC converter losses.

Applications of multi-level LCC topologies using series-connected thyristor valves are being explored for higher voltage and power levels. Investigations are also being done on enabling LCC-HVDC to connect to weak AC grids, provide black start capability and have multi-terminal configurations. Hybrid LCC-VSC converters are also an emerging area of research.

Huzaifa et al. [34] did extensive research and development activities rapidly advancing HVDC transmission. The focus is improving efficiency, controllability and integration capabilities to address contemporary power transmission needs. Collaborative initiatives between academia, utilities and industry partners continue to foster HVDC technology innovations to build resilient and sustainable transmission infrastructure [34].

3. Superconducting Technologies

Superconducting technologies offer transformational capabilities for power transmission through properties like negligible electrical resistance and perfect diamagnetism. Research in applied superconductivity aims to harness these properties for next-generation transmission solutions. The focus areas are superconducting cables and fault current limiters.

3.1. Superconducting Cables

Research aims to make superconducting power cables more cost-effective and practical for high-voltage transmission. Superconducting cables can transmit large amounts of power with minimal losses. High-Temperature Superconducting (HTS) cables using rare-earth compounds like YBCO (yttrium barium copper oxide) are a promising alternative to conventional cables [2]. HTS cables have 200 times more ampacity than copper cables of the same size [3].

Ongoing research addresses the challenges in superconducting cable technology - high cost, insulation requirements and cooling needs. Approaches to improve superconducting layer thickness and homogeneity are being studied to enhance current carrying capacity [4]. Investigations are being done on cost-effective cryogenic insulation systems [4]. Hybrid HTS-copper cable designs are proposed to reduce cooling load [5]. Economic analysis studies help evaluate the feasibility of large-scale deployment [6]. Pilot projects by companies like Nexans and sponsored test installations demonstrate the reliable performance of HTS cable systems [7]. Further advancements in superconductor materials and cryogenic systems can potentially enable the adoption of HTS cables.

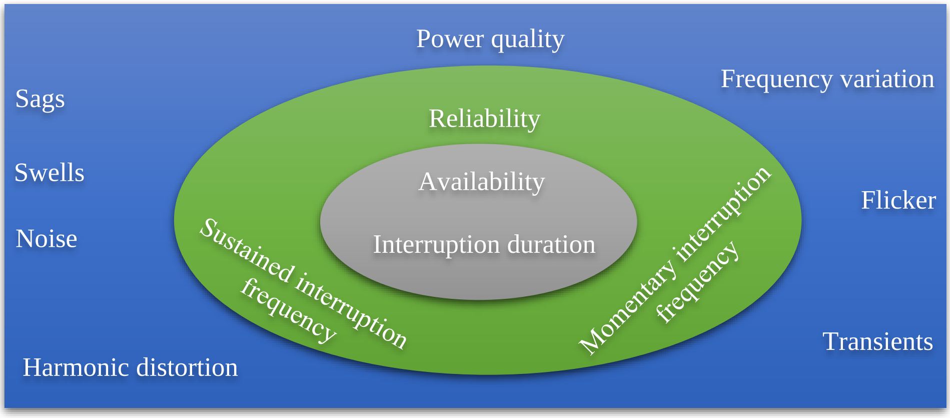

Fig. 2 Grid resilience and reliability

3.2. Fault Current Limiters

Developing superconducting fault current limiters to enhance grid stability. Abnormal overcurrents due to faults can severely damage transmission equipment. Superconducting fault current limiters (SFCL) utilize the transition from superconducting to resistive state to limit fault currents. SFCLs react within milliseconds, allowing uninterrupted power transmission [8].

Second-generation HTS films like YBCO deposited on metallic substrates are being explored for resistive-type SFCL devices. The focus is on improving quench homogeneity, recovery time and maximum limiting current ratings [9]. Optimized cryostat designs are being investigated for effective heat dissipation and interference reduction [9]. Control and protection systems are being developed for seamless SFCL integration into grid substations [10]. With successful field demonstrations and progress in commercialization [11], superconducting FCLs can become an integral component of resilient and self-healing smart grids. Cost reduction through standardized manufacturing and economies of scale can potentially drive widespread SFCL adoption. So, applied superconductivity holds great potential for building future efficient and reliable power transmission systems. Sustained research and development efforts are helping translate these advanced technologies from lab prototypes to practical grid solutions.

4. Grid Resilience and Reliability

A resilient and reliable power grid is crucial for an efficient electricity infrastructure. However, aging systems, extreme weather and human errors threaten grid stability. The research aims to enhance grid resilience and reliability through advanced monitoring, data analytics and innovative system design. Figure 2 shows that Electricity grids need to be resilient and reliable. A resilient grid is a reliable grid. Understanding grid resilience and reliability requires clearly defining both concepts and introducing relevant foundational ideas. It also necessitates precisely comparing grid resilience versus grid reliability.

4.1. Grid Monitoring and Control

Advanced sensors, monitoring systems and control algorithms to improve grid reliability and reduce downtime. Real-time monitoring of grid parameters like voltage, frequency and power flows coupled with intelligent control systems can rapidly detect and mitigate disturbances. Phasor Measurement Units (PMUs) use Global Positioning System (GPS) time-stamping to provide high-speed synchronized data on grid conditions [11]. Studies focus on optimal PMU placement for full observability and fast state estimation [12]. PMU data enables Wide-Area Monitoring Systems (WAMS) to track dynamic behavior over large regions and facilitate preventive and corrective control [13]. Machine learning algorithms are being developed to analyze PMU data and identify potential anomalies [14]. Automated control systems utilizing PMU feedback can take preemptive actions like generator adjustment to maintain stability after a fault [25]. Robust cybersecurity is critical for grid control systems. Blockchain, data encryption and system hardening techniques are being explored to secure monitoring infrastructure against cyber-attacks [26].

4.2. Grid Resilience Against Natural Disasters

Research on making power transmission infrastructure more resilient to extreme weather events, earthquakes, and other natural disasters. Extreme weather events like storms, floods and heatwaves are growing concerns for grid infrastructure. Studies aim to quantify climate impact on assets like overhead lines and transformers [13]. Hardening approaches include structural enhancements, insulated cables and vegetation management to reduce storm and ice damage [14].

Underground cable installation could improve resilience but requires extensive cost-benefit analysis [15]. Probabilistic risk models help evaluate system reliability under disaster scenarios [16]. Grid segmentation through distributed energy resources may mitigate widespread failures [17]. In earthquake-prone areas, seismic-resistant designs are critical. Innovations like self-centering towers, base isolation platforms and dampers improve structural performance during strong ground shaking [18]. The robustness of substation equipment against earthquakes is being enhanced through shake table testing and modifications [19]. Advanced grid analytics using stochastic models, predictive maintenance and condition monitoring can also help anticipate and prevent equipment failures [20].

Improving black start capability through microgrids and energy storage aids faster restoration after disasters [21]. So, the modernization of aging grid infrastructure coupled with smart resilience initiatives is imperative to withstand growing challenges. An integrated approach using advanced technologies, data analytics, climate preparedness and system hardening is required to build a reliable and robust grid.

5. Efficiency and Loss Reduction

Electricity infrastructure faces challenges of growing demand and aging components. Technical losses in transmission and distribution are estimated to be up to 20% in some countries [22]. Research targets materials, components and network architecture advancements to curtail these losses.

5.1. High-Efficiency Material

Conductor materials significantly impact transmission efficiency. Conventional aluminum conductors have limitations like low ampacity and thermal sag. Alternatives like Aluminum Conductor Composite Core (ACCC) replace the steel core with carbon fibers or alumina to reduce weight and improve conductivity [23]. ACCC conductors allow increased current flow and lower line losses.

Research also focuses on developing cost-effective high-temperature superconductors which can transmit large currents with negligible losses. Advances in second-generation rare-earth superconductors like Yttrium Barium Copper Oxide (YBCO) and magnesium diboride (MgB_2) are enabling practical applications [24]. Trials of YBCO tapes in power cables have demonstrated over 50% transmission loss reduction compared to copper [25]. Another active area is nano-engineered materials like graphene and carbon nanotubes to improve transmission components' electrical, thermal and mechanical properties [26]. These advanced materials can enable lighter, stronger and more efficient grid infrastructure. Developing materials with lower electrical losses for high-voltage equipment.

5.2. HVDC Circuit Breakers

Research into high voltage DC circuit breakers to reduce power losses during system maintenance. The absence of efficient DC circuit breakers is a major bottleneck in HVDC grid expansion. Current HVDC systems require complex shutdown procedures during faults, leading to power losses. Developing fast-acting HVDC breakers is a high research priority [27].Hybrid designs combining solid-state thyristors and electromechanical switches are being explored to achieve interruption times under 5ms [28]. Control systems and physical architectures are optimized through electromagnetic transient simulations [29]. Real-time testing platforms help evaluate the fault response of prototype DC breaker designs under various conditions [30]. Implementing high-speed HVDC breakers with current and voltage ratings over 10kA and 500kV can significantly improve system control, reliability and efficiency. This can facilitate robust HVDC grids to unlock renewable energy.

5.3. Network Optimization

Efficient network architecture and management are vital alongside component improvements. Topology optimization through grid reconfigurations and FACTS device placement is studied to optimize power flows and minimize losses [31]. Constraints from stability limits to voltage regulations are incorporated in grid planning models [32]. Condition monitoring, smart meters and data analytics further help detect wear in assets like transformers and lines for preventive maintenance [33]. Monitoring system data is combined with weather forecasts to assess real-time line ampacity and reroute power as needed [13]. Such dynamic grid management can curb inefficiencies and blackouts.A multi-dimensional approach is required to build smarter, optimized grids that minimize technical losses. Developing advanced materials, components and data-driven management strategies through continued research and field testing can significantly improve transmission efficiency.

6. Environmental Sustainability

Electricity transmission networks are critical infrastructures enabling long-distance power transfer from generation to load centers. However, high-voltage overhead transmission lines can have significant environmental and community impacts that must be addressed through rigorous assessment and mitigation strategies. This paper reviews research trends and developments to enhance the environmental sustainability of power transmission systems.

6.1. Environmental Impact Assessment

Evaluating the environmental impact of high voltage transmission lines and developing sustainable solutions. Robust methodologies are required to evaluate the diverse impacts of transmission projects. Studies employ geospatial analysis, multicriteria decision models, community surveys and life cycle analysis to assess factors like landscape alteration, biodiversity, electric fields, noise, land use and socioeconomic aspects [14]. The findings guide design and routing decisions to minimize ecological and community disturbances. Advanced 3D simulation tools also facilitate the assessment of visual amenity effects from transmission infrastructure [15]. Public acceptance can be improved through awareness campaigns and community engagement in planning processes [16]. Strong impact assessment and mitigation are vital for securing regulatory approval and social license for sustainable grid expansion.

6.2. Integration of Renewable Energy

Research into integrating renewable energy sources like offshore wind farms into high-voltage transmission networks. Strategic transmission planning is crucial for large-scale renewable energy integration into grids [17]. Geographic renewable generation potential assessments guide new infrastructure development, like long-distance HVDC connections to offshore wind farms [35]. Load flow simulations help evaluate grid reinforcements needed to accommodate renewables while maintaining stability and reliability [36]. Grid operations also require adjustments for variable renewable generation, including forecasting, demand response and energy storage solutions [37]. Advanced real-time monitoring and control systems help smoothly integrate renewables and overcome fluctuations. Environmental sustainability must be an integral focus in power transmission planning and operations. Continued research and policy efforts are imperative to develop green, resilient networks meeting future energy needs while safeguarding ecological and community interests.

7. Grid Modernization

Electricity transmission networks were traditionally passive systems with limited monitoring and control capabilities. Grid modernization aims to transform aging infrastructure into smart, resilient networks using advanced technologies and analytics [18-22]. Advanced monitoring, data analytics and automated control systems are modernizing traditional passive grids into intelligent, efficient networks [23-26]. However, cyber vulnerabilities must also be addressed. Further interdisciplinary research and field testing of smart grid technologies can support a flexible, resilient, sustainable power transmission infrastructure [38]. This paper discusses key focus areas of grid modernization research for high-voltage power transmission systems.

7.1. Smart Grid Technologies

Investigating how smart grid technologies can be incorporated into high voltage transmission networks for better control and optimization. Integrating information and communication technologies creates intelligent, self-healing transmission grids [27-32]. Phasor Measurement Units (PMUs) enable precise real-time monitoring of voltage, current and phase angle at critical substations [39]. These high-resolution synchronized measurements facilitate wide-area visualization, state estimation and control. To detect anomalies and prevent disturbances, machine learning algorithms are applied to PMU data. New power flow controlling devices like FACTS and HVDC lines incorporate smart communication and rapid control systems to redirect power and quickly respond to faults or bottlenecks. Distributed sensors on transmission lines monitor sag, temperature and other parameters. Combined with weather data, dynamic line ratings can be calculated to utilize full line capacity [13]. These smart grid technologies boost efficiency, flexibility and reliability.

7.2. Cybersecurity

Enhancing the cybersecurity of high voltage transmission systems to protect against cyber threats. With increased automation and connectivity, transmission grids are highly susceptible to cyberattacks. System hardening, encryption, access control policies and staff training enhance cybersecurity [40]. Blockchain mechanisms are also studied for secure key distribution and authentication. Anomaly detection systems analyze SCADA data to identify unusual network behavior from potential cyber intrusions [41]. Hardware redundancy, network segmentation and manual overrides prepare for malicious attacks. Robust cybersecurity is vital as grids adopt more smart technologies.

8. Materials and Insulation

The materials and insulation used in transmission lines, cables and substation equipment significantly impact electricity networks' efficiency, capacity and reliability. Research focuses on developing innovative materials to meet the evolving demands of power grids.

8.1. Advanced Insulation Materials

Developing materials with improved dielectric properties for high-voltage equipment. Polymeric insulators replace traditional porcelain and glass insulators for overhead lines and substation bushings. Engineering plastics like Silicone Rubber (SiR) and Ethylene Propylene Diene Monomer (EPDM) offer benefits like lightweight, hydrophobicity and resilience to vandalism [42]. Nano-engineered coatings using zinc oxide (ZnO) and titanium dioxide (TiO2) are applied to improve insulator surface hydrophobicity and pollution performance further [43]. Novel fiber-reinforced composites with epoxy, vinyl ester or polyurethane are also studied for better mechanical strength. For Gas-Insulated Switchgear (GIS), the research aims to identify eco-friendly gas mixtures to replace sulfur hexafluoride (SF6), which has high global warming potential. Investigated alternatives include fluoro nitrile and fluor ketone-based mixtures [44].

8.2. Nanotechnology

Exploring nanomaterials for insulation and conductor applications. Nanomaterials exhibit unique electrical, thermal and mechanical properties at the molecular level. Carbon Nanotubes (CNTs) and graphene have ultrahigh current densities, tensile strength and thermal conductivity, offering opportunities to improve transmission materials [45]. CNT composite conductors can carry higher loads than conventional aluminium conductors of the same weight. Nano-engineered coatings provide corrosion resistance. CNT added to fibre-reinforced polymers enhances insulator strength and lightning impulse withstand [45]. Nanodielectric materials like magnesium oxide (MgO) and aluminium oxide (Al2O3) nanoparticles dispersed in epoxy resins improve dielectric strength and partial discharge resistance for insulation [46]. Further research can translate these superior nano properties into next-generation power grid applications.

9. High Voltage Testing and Simulation

Rigorous testing and simulation capabilities are crucial to developing and validating the performance of high-voltage transmission technologies under realistic operating conditions. Investments in advanced high-voltage test labs and modeling tools support innovations in this field.

9.1. High Voltage Testing Facilities

Expanding and improving high voltage testing laboratories to validate equipment and technologies. Specialized high-voltage laboratories allow full-scale testing of components up to 1000 kV under controlled conditions. These include lightning impulse generators, power frequency test systems and climatic chambers for temperature, humidity and salt fog [47]. Recent initiatives have expanded testing capabilities for ultra-high voltages exceeding 1200 kV AC and 800 kV DC based on projected future transmission needs [48]. Testing evolving technologies like HVDC circuit breakers, nano-composite insulators, gas-insulated lines, etc., enables controlled environments to meet international standards before field deployment. Novel non-destructive testing methods are also emerging, including ultrasonic monitoring, frequency response analysis and partial discharge detection to assess asset condition [49]. These techniques help facilitate condition-based maintenance. Portable test equipment permits assessment of in-service apparatus.

9.2. Simulation and Modeling

Computer-aided design tools and electromagnetic transient simulation software model and optimize high-voltage grid performance. Detailed component modelling and 3D analyses provide insights into electric field distribution, insulation stresses, and reactances. The models incorporate complex multiphysics within composite insulators and gas systems, including electrical, thermal, mechanical, and chemical phenomena [50]. Real-time digital simulator hardware allows system-level closed-loop testing. Parametric analyses identify optimal designs. Modelling and simulation thereby enhance effectiveness and safety.

10. Interconnection of Grids

Interconnection of regional electricity grids through high voltage transmission lines allows effective sharing of power resources and enhanced reliability through mutual assistance. Research aims to expand interconnections to unlock these benefits while addressing associated technical and regulatory challenges.

10.1. International Grid Interconnections

Grid interconnections provide multiple advantages [21]. Power surplus regions can export to deficit areas, reducing the need for peaking plants. Diversity in demand profiles and generation mix between interconnected systems lowers the operating reserves required. Equipment failures or faults have a lower impact shared among multiple grids. Interconnections also enable the integration of large-scale renewables. Expanding transmission capacity between resource-rich and consuming regions is beneficial, as seen in Europe, China and India [51]. Overall cost savings, reduced outages and lower carbon emissions are achievable. Realizing interconnections requires overcoming technical barriers. Synchronization of different grids needs accuracy in control systems. Extra High Voltage (EHV) lines using HVDC are often necessary for long-distance connections. Stability analysis is complex for interdependent multi-area systems. Interconnections can suffer cascading failures if not designed with adequate protections and redundancies. Cybersecurity also needs coordination to secure interconnected operations. Effective policies and agreements between nations are crucial for progress on interconnections. Equitable sharing of costs and benefits, harmonized technical standards, fair electricity trade and dispute resolution frameworks need consensus. Coordinated planning, impact assessment and regulatory oversight are essential. Platforms for data exchange, grid monitoring and emergency response planning enable reliable cross-border grid integration. Capacity building and knowledge transfer further bolster technical cooperation.

11. Challenges Faced by Power Transmission

Electricity transmission networks face increasing stress from ageing infrastructure, rising demand, and integration of renewable generation. This tests the capabilities of grid infrastructure originally designed for centralized fossil fuel-based power systems. Urgent modernization is imperative to address emerging challenges.

11.1. Aging Assets

Power grids in many countries rely on equipment installed over 50 years ago, which is approaching the end of its useful life. Older transformers, lines, and substations increase failure rates and maintenance costs. Lack of asset visibility and monitoring makes targeted replacement difficult. Investments in grid digitization and non-destructive testing techniques can aid assessment and refurbishment.

11.2. Growing Electricity Demand

Global electricity consumption is projected to expand by over 50% by 2050, necessitating massive transmission expansion [47]. Urbanization and electric mobility will drive demand growth.

Building new high-capacity corridors requires substantial capital expenditure—novel technologies like compact HVDC lines and dynamic thermal rating offer potential solutions.

11.3. Renewable Energy Integration

Scaling up renewable energy hinges on transmission growth to connect generating sites and load centres. Wind and solar variability and uncertainty pose grid management challenges [46]. Improved forecasting, demand response, and energy storage can facilitate integration. Grid reinforcement with real-time control is vital for stability.

11.4. Extreme Weather Events

Climate change increases extreme weather events like storms, heatwaves and floods, damaging transmission infrastructure [41]. Hardening grid assets by using weather-resistant structures and underground cables where feasible will be critical. Smart grid technologies help quickly detect and recover from failures.

12. Efforts to Mitigate the Challenges

Electricity transmission networks face pressing challenges from aging assets, rising demand, renewable integration and climate threats. Targeted initiatives focused on grid modernization, expansion, and resilience are essential to address these issues.

12.1. Grid Modernization

Utility investments in digitalization and data analytics facilitate better asset monitoring and utilization. Dynamic line ratings, online condition assessment, and predictive maintenance enable optimized grid operations. Deploying smart technologies like PMUs, digital substations, and automated control systems transforms passive infrastructure into self-healing smart grids. Machine learning applied to system data also improves failure prediction and response [37].

12.2. Grid Expansion

Efficient planning models determine grid reinforcement needs in alignment with projected demand growth and generation additions. New high-capacity AC/DC transmission routes are identified along with dynamic line rating deployment on existing corridors [17]. Grid architecture enhancements through distributed energy resources and microgrids supplement central grid strengthening. Energy efficiency, demand response, and storage solutions also curb expansion needs.

12.3. Grid Resilience

Utilities are hardening assets using robust designs, weatherized components and redundancy. Underground cable burial, where feasible, prevents wind and lightning damage. Strategic spare inventory management reduces outage duration. Improved black start capability through microgrids, battery storage and islanding enables faster restoration after disasters. Grid segmentation and self-healing automation contain failures. Storm response is also enhanced through coordinated planning [17].

12.4. Policy and Regulation

Appropriate regulations, incentives, and cost recovery mechanisms are vital to facilitate utilities' requisite investments. Supportive policies also enable the demonstration and deployment of emerging technologies [17]. Federal grid resilience funding, renewable energy mandates and performance-based rate-making are key measures that directly or indirectly drive transmission system improvements.

13. Conclusion

Electricity transmission networks face critical challenges today, from ageing assets, rising power demand, large-scale renewable integration, and increasing impacts of climate change [10]. These issues threaten the reliability and adequacy of grid infrastructure fundamental to electricity access and security. Substantial efforts are required to modernize, expand and adapt transmission system capabilities in alignment with contemporary requirements.

Utility investments in grid digitalization, automation, and advanced analytics will enhance network asset monitoring, control, and utilization. Planning and deploying new high-capacity transmission corridors using technologies like compact HVDC must be accelerated to connect remote renewables and meet demand growth. Furthermore, significant grid strengthening is needed using robust designs, weatherized components and redundancy to improve resilience to extreme events. Policy and regulatory reforms must incentivize utilities to undertake necessary infrastructure upgrades and resilience programs. Supportive frameworks for demonstrating and deploying emerging grid technologies should also be instituted.In conclusion, a combination of urgent investments, technology innovation and institutional capacity building is imperative to transform ageing electricity grids into intelligent, efficient, climate-ready networks, enabling affordable, clean power for all. Collaboration between governments, regulators, utilities, manufacturers and academia can pave the way for a sustainable transmission system that meets the needs of the 21st century. Some areas requiring dedicated focus include high-efficiency conductors, grid-scale storage solutions, distributed energy resource integration, real-time stability management and climate vulnerability assessment. Holistic efforts encompassing engineering, economics and public policy will be key to establishing resilient transmission infrastructure to catalyze global energy transition.

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this paper.

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References

[1] Hun-Chul Seo et al., "Superconducting Fault Current Limiter Application for Reduction of the Transformer Inrush Current: A Decision Scheme of the Optimal Insertion Resistance," *IEEE Transactions on Applied Superconductivity*, vol. 20, no. 4, pp. 2255-2264, 2010. [CrossRef] [Google Scholar] [Publisher Link]

[2] Chang-Xin Zhao et al., “Multiscale Construction of Bifunctional Electrocatalysts for Long-Lifespan Rechargeable Zinc-Air Batteries,” *Advanced Functional Materials*, vol. 30, no. 36, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[3] Pavel N. Degtyarenko et al., “Investigation of an Opportunity of Using 2G HTS Tapes for High-Current Cables with a Current-Carrying Capacity More Than 10 kA,” *IEEE Transactions on Applied Superconductivity*, vol. 31, no. 5, pp. 1-4, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[4] V. Meerovich, and V. Sokolovsky, “9 - High-Temperature Superconducting Fault Current Limiters (FCLs) for Power Grid Applications,” *Superconductors in the Power Grid*, pp. 283-324, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[5] Henrique K. Miyamoto et al., “Novel Design of a Hybrid Superconducting Fault Current Limiter with Controlled Solid-State Device,” *Journal of Microwaves*, *Optoelectronics and Electromagnetic Applications*, vol. 20, no. 2, pp. 334-347, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[6] Sylwia Hajdasz et al., “Critical Current Degradation in HTS Tapes for Superconducting Fault Current Limiter under Repeated Overcurrent,” *Applied Sciences*, vol. 13, no. 7, pp. 1-19, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[7] Zezhao Wen, Hongye Zhang, and Markus Mueller, “High Temperature Superconducting Flux Pumps for Contactless Energization,” *Crystals*, vol. 12, no. 6, pp. 1-30, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[8] Hazelton Drew, “*Design, Test and Demonstration of Fault Current Limiting HTS Transformer*,” SuperPower Inc, Schenectady, NY, United States, Doe Final Report, pp. 1-154, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[9] Mathias Noe, and Michael Steurer, “High-Temperature Superconductor Fault Current Limiters: Concepts, Applications, and Development Status,” *Superconductor Science and Technology*, vol. 20, no. 3, 2007. [CrossRef] [Google Scholar] [Publisher Link]

[10] [63] Xiao Liu et al., “Seismic Resilience Evaluation and Retrofitting Strategy for Substation System,” *International Journal of Electrical Power & Energy Systems*, vol. 153, pp. 1-14, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[11] Matthew Bartos et al., "Impacts of Rising Air Temperatures on Electric Transmission Ampacity and Peak Electricity Load in the United States,” *Environmental Research Letters*, vol. 11, no. 11, pp. 1-13, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[12] Mubashir Husain Rehmani et al., “Software Defined Networks-Based Smart Grid Communication: A Comprehensive Survey,” *IEEE Communications Surveys & Tutorials*,” vol. 21, no. 3, pp. 2637-2670, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[13] Md. Kamruzzaman et al., “A Deep Reinforcement Learning-Based Multi-Agent Framework to Enhance Power System Resilience Using Shunt Resources,” *IEEE Transactions on Power Systems*, vol. 36, no. 6, pp. 5525-5536, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[14] Linge Sagar Gajanan, Mukesh Kirar, and More Raju, “Wide Area Monitoring and Protection in Cyber Physical Infrastructure,” 2023 *IEEE Renewable Energy and Sustainable E-Mobility Conference*, Bhopal, India, pp. 1-6, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[15] Dorothy A. Reed, Mark D. Powell, and Julie M. Westerman, “Energy Infrastructure Damage Analysis for Hurricane Rita,” *Natural Hazards Review*, vol. 11, no. 3, pp. 102-109, 2010. [CrossRef] [Google Scholar] [Publisher Link]

[16] Jean-Paul Watson et al., “*Conceptual Framework for Developing Resilience Metrics for the Electricity*, *Oil*, *and Gas Sectors in the United States*,” Sandia National Laboratories, Albuquerque, New Mexico, pp. 1-104, 2019. [Google Scholar] [Publisher Link]

[17] A. Kharrazi, V. Sreeram, and Y. Mishra, “Assessment Techniques of the Impact of Grid-Tied Rooftop Photovoltaic Generation on the Power Quality of Low Voltage Distribution Network - A Review,” *Renewable and Sustainable Energy Reviews*, vol. 120, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[18] Kaile Zhou, Chao Fu, and Shanlin Yang, "Big Data Driven Smart Energy Management: From Big Data to Big Insights,” *Renewable and Sustainable Energy Reviews*, vol. 56, pp. 215-225, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[19] Kaile Zhou, Shanlin Yang, and Zhen Shao, "Energy Internet: The Business Perspective,” *Applied Energy*, vol. 178, pp. 212-222, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[20] Mari Cruz Garcia, Miguel A. Sanz-Bobi, and Javier Del Pico, “SIMAP: Intelligent System for Predictive Maintenance: Application to the Health Condition Monitoring of a Windturbine Gearbox,” *Computers in Industry*, vol. 57, no. 6, pp. 552-568, 2006. [CrossRef] [Google Scholar] [Publisher Link]

[21] Ye Yan et al., “A Survey on Smart Grid Communication Infrastructures: Motivations, Requirements and Challenges,” *IEEE Communications Surveys & Tutorials*, vol. 15, no. 1, pp. 5-20, 2013. [CrossRef] [Google Scholar] [Publisher Link]

[22] Christian M. Franck, "HVDC Circuit Breakers: A Review Identifying Future Research Needs,” *IEEE Transactions on Power Delivery*, vol. 26, no. 2, pp. 998-1007, 2011. [CrossRef] [Google Scholar] [Publisher Link]

[23] Reza Hemmati, Rahmat-Allah Hooshmand, and Amin Khodabakhshian, “Comprehensive Review of Generation and Transmission Expansion Planning,” *IET Generation, Transmission & Distribution*, vol. 7, no. 9, pp. 955-964, 2013. [CrossRef] [Google Scholar] [Publisher Link]

[24] Rafael N.P. Colombo, *Biosensors in Point-of-Care: Molecular Analysis*, *Strategies and Perspectives to Health Care*, Advances in Bioelectrochemistry, Springer, Cham, vol. 3 pp. 169-198, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[25] Saqib Khalid et al., "Technical Assessment of Hybrid HVDC Circuit Breaker Components under M-HVDC Faults," *Energies*, vol. 14, no. 23, pp. 1-16, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[26] Annette Bussmann-Holder, and Hugo Keller, "High-Temperature Superconductors: Underlying Physics and Applications," *Journal of Natural Sciences B*, vol. 75, no. 1-2, pp. 3-14, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[27] Alexandre Rekeraho et al., "Cybersecurity Challenges in IoT-Based Smart Renewable Energy," *International Journal of Information Security*, vol. 23, pp. 101-117, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[28] Izuru Takewaki, Abbas Moustafa, and Kohei Fujita, *Improving the Earthquake Resilience of Buildings: The Worst Case Approach*, Springer, pp. 1-324, 2012. [Google Scholar] [Publisher Link]

[29] Ayodeji Olalekan Salau, Yalew Werkie Gebru, and Dessalegn Bitew, "Optimal Network Reconfiguration for Power Loss Minimization and Voltage Profile Enhancement in Distribution Systems," *Heliyon*, vol. 6, no. 6, pp. 1-8, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[30] Yuanshi Zhang et al., "Minimization of AC-DC Grid Transmission Loss and DC Voltage Deviation Using Adaptive Droop Control and Improved AC-DC Power Flow Algorithm," *IEEE Transactions on Power Systems*, vol. 36, no. 1, pp. 744-756, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[31] Zhanqing Yu et al., "The Design and Development of a Novel 10 kV/60 kA Hybrid DC Circuit Breaker Based on Mixed Solid-State Switches," *IEEE Transactions on Industrial Electronics*, vol. 70, no. 3, pp. 2440-2449, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[32] Stefano Bagli, Davide Geneletti, and Francesco Orsi, "Routeing of Power Lines through Least-Cost Path Analysis and Multicriteria Evaluation to Minimise Environmental Impacts," *Environmental Impact Assessment Review*, vol. 31, no. 3, pp. 234-239, 2011. [CrossRef] [Google Scholar] [Publisher Link]

[33] Syed Wajahat Ali et al., "Offshore Wind Farm-Grid Integration: A Review on Infrastructure, Challenges, and Grid Solutions," *IEEE Access*, vol. 9, pp. 102811-102827, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[34] Muhammad Huzaifa et al., "ILLIXR: Enabling End-to-End Extended Reality Research," *2021 IEEE International Symposium on Workload Characterization*, Storrs, CT, USA, pp. 24-38, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[35] Jon González-Ramos et al., "Upgrading the Power Grid Functionalities with Broadband Power Line Communications: Basis, Applications, Current Trends and Challenges," *Sensors*, vol. 22, no. 12, pp. 1-34, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[36] Matthew Cotton, and Patrick Devine-Wright, "Making Electricity Networks "Visible": Industry Actor Representations of "Publics" and Public Engagement in Infrastructure Planning," *Public Understanding of Science*, vol. 21, no. 1, pp. 17-35, 2012. [CrossRef] [Google Scholar] [Publisher Link]

[37] H. Yumura et al., "Update of YOKOHAMA HTS Cable Project," *IEEE Transactions on Applied Superconductivity*, vol. 23, no. 3, pp. 5402306-5402306, 2013. [CrossRef] [Google Scholar] [Publisher Link]

[38] Arturs Purvins et al., "Challenges and Options for a Large Wind Power Uptake by the European Electricity System," *Applied Energy*, vol. 88, no. 5, pp. 1461-1469, 2011. [CrossRef] [Google Scholar] [Publisher Link]

[39] Eklas Hossain et al., "Metrics and Enhancement Strategies for Grid Resilience and Reliability during Natural Disasters," *Applied Energy*, vol. 290, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[40] Raquel Santos Jorge, Troy R. Hawkins, and Edgar G. Hertwich, "Life-cycle Assessment of Electricity Transmission and Distribution—Part 1: Power Lines and Cables," *The International Journal of Life Cycle Assessment*, vol. 17, pp. 9-15, 2011. [CrossRef] [Google Scholar] [Publisher Link]

[41] USDoE, "Chapter IV: Ensuring Electricity System Reliability, Security, and Resilience," *Quadrennial Energy Review, Transforming the Nation's Electricity System*, 2014. Available: https://www.energy.gov/sites/prod/files/2017/01/f34/QER%20Transforming%20the%20Nations%20Electricity%20System%20Full%20Report.pdf

[42] Mahdi Jamei et al., "Anomaly Detection Using Optimally Placed µPMU Sensors in Distribution Grids," *IEEE Transactions on Power Systems*, vol. 33, no. 4, pp. 3611-3623, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[43] Amir Ameli et al., "A Learning-Based Framework for Detecting Cyber-Attacks Against Line Current Differential Relays," *IEEE Transactions on Power Delivery*, vol. 36, no. 4, pp. 2274-2286, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[44] Ioan Petri et al., "Blockchain for Energy Sharing and Trading in Distributed Prosumer Communities," *Computers in Industry*, vol. 123, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[45] S.M. Gubanski, "Modern Outdoor Insulation – Concerns and Challenges," *IEEE Electrical Insulation Magazine*, vol. 21, no. 6, pp. 5-11, 2005. [CrossRef] [Google Scholar] [Publisher Link]

[46] Mladen Kezunovic, Le Xie, and Santiago Grijalva, "The Role of Big Data in Improving Power System Operation and Protection," *2013 IREP Symposium Bulk Power System Dynamics and Control - IX Optimization, Security and Control of the Emerging Power Grid*, Rethymno, Greece, pp. 1-9, 2013. [CrossRef] [Google Scholar] [Publisher Link]

[47] Paul Denholm et al., "The Challenges of Achieving a 100% Renewable Electricity System in the United States," *Joule*, vol. 5, no. 6, pp. 1331-1352, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[48] International Energy Association, "*Global Energy Demand Rose by 2.3% in 2018*, *its Fastest Pace in the Last Decade*," International Energy Agency, 2019. [Google Scholar] [Publisher Link]

[49] USDoE, "*Climate Change and the US Energy Sector: Regional Vulnerabilities and Resilience Solutions*," United States Department of Energy, pp. 1-193, 2015. [Google Scholar] [Publisher Link]

[50] Zhengdong Wang et al., "Simultaneously Enhanced Dielectric Properties and through-Plane Thermal Conductivity of Epoxy Composites with Alumina and Boron Nitride Nanosheets," *Scientific Reports*, vol. 11, no. 1, pp. 1-11, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[51] S.G. Thakor et al., "Dielectric Spectroscopy and Structural Characterization of Nano-Filler-Loaded Epoxy Resin," *Journal of Advanced Dielectrics*, vol. 11, no. 2, pp. 1-12, 2021. [CrossRef] [Google Scholar] [Publisher Link]