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Design of Transmission Line Tower- A Review

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Abstract- Transmission line towers are one of the most important structural components in power transmission infrastructure, ensuring safe and uninterrupted transfer of electrical energy from generating stations to substations and load centers. The rapid growth in electricity demand, industrial development, and expansion of urban and rural electrification has significantly increased the requirement for economical, safe, and optimized transmission tower systems. Transmission towers contribute nearly 28% to 42% of the total cost of overhead transmission line projects, making structural optimization and material efficiency critical for sustainable power transmission development. The design of transmission line towers is governed by several factors such as tower configuration, bracing pattern, base width, height, wind zone, conductor arrangement, and foundation soil condition. Wind load remains the most governing and critical loading condition, while seismic load, ice load, temperature variation, and conductor load also influence the design. In recent years, advanced software tools such as STAAD.Pro, ETABS, and finite element modeling techniques have improved the accuracy and efficiency of transmission tower analysis. Moreover, modern research trends focus on alternative tower geometries such as triangular towers, guyed towers, tubular steel sections, and dynamic wind analysis considering tower-line coupling effects. This review paper critically examines the previous literature related to transmission line tower analysis, design, optimization, bracing system influence, section selection, dynamic wind response, and modern metaheuristic optimization techniques. The review highlights the importance of economical tower design and identifies research gaps related to nonlinear analysis, dynamic coupling effects, reliability-based design, corrosion degradation, and sustainable design approaches. Finally, the paper presents future scope and research opportunities for improving transmission tower performance, cost-effectiveness, and safety under extreme environmental conditions.

Keywords: Transmission Line Tower, Lattice Tower, STAAD.Pro, Wind Load, IS 802, Bracing System, Tower Optimization, Tubular Section, Dynamic Analysis, Tower-Line Coupling, Metaheuristic Algorithm, Structural Stability.

I. INTRODUCTION

Electrical transmission line towers are tall steel structures used to support overhead conductors, earth wires, and insulator strings for high voltage power transmission. They act as lifeline structures in modern society, as failure of a transmission tower can lead to severe consequences including power interruption, economic losses, damage to surrounding infrastructure, and threats to public safety. Transmission towers are mainly categorized as suspension towers, tension towers, transposition towers, and terminal towers depending upon their location and function in the transmission line route. Their structural configuration varies with voltage level such as 66 kV, 110 kV, 132 kV, 220 kV, 400 kV, and 765 kV. In India, the design of overhead transmission towers is primarily governed by IS 802:1995 along with other related codes like IS 800:2007 and IS 875. The most commonly adopted transmission towers are four-legged self-supporting lattice steel towers made from steel angle sections. However, due to land scarcity and Right of Way (ROW) constraints, narrow-based towers, multi-circuit towers, and compact towers are increasingly preferred.

Furthermore, with the occurrence of extreme climatic events such as cyclones and strong windstorms, tower collapses have become more frequent, emphasizing the need for improved design methods and dynamic wind-resistant analysis. Transmission tower design involves both electrical and structural requirements. Electrical considerations include minimum ground clearance, phase-to-phase clearance, phase-to-tower clearance, insulator string length, and shielding angle. Structural considerations include tower geometry, stability against wind load, member strength, buckling resistance, slenderness limitations, and foundation stability. Traditional design methods involve manual computation of wind load, member force analysis, and section design checks. However, due to the complexity of 3D lattice geometry and multiple load combinations, structural software has become essential for accurate modeling and optimization. The use of advanced finite element techniques and optimization algorithms has further enhanced tower performance and reduced structural weight. This review paper aims to study existing literature on transmission line tower design and analysis and identify the key gaps for future research.

II. LITERATURE REVIEW

A detailed literature review was conducted on the analysis, design, optimization, and performance evaluation of transmission line towers under various load conditions. The review is presented chronologically and thematically.

Punse (2014), in the paper "Analysis and Design of Transmission Tower", analyzed the role of transmission towers in meeting India's growing electricity demands. The study emphasized that transmission line towers constitute nearly 28–42% of the total cost of transmission lines, making their optimization essential for cost-effective power distribution. The research highlighted that steel lattice towers are the most commonly used supports for Extra High Voltage (EHV) transmission lines, and factors such as clearances, insulator design, conductor configuration, tower weight estimation, and span optimization significantly affect design efficiency. The author proposed a design approach using Multi-Voltage Multi-Circuit narrow-based self-supporting lattice towers for 220 kV and 110 kV systems, aiming to maximize the utilization of limited Right of Way (ROW). The analysis and design, carried out using STAAD.Pro V8i, demonstrated that lightweight, optimized tower geometries can reduce costs while ensuring structural stability and reliable electricity supply.

Halkude and Ankad (2014), in their study "Analysis and Design of Transmission Line Tower 220 kV: A Parametric Study", conducted a parametric investigation to identify economical and efficient tower configurations for self-supporting 220 kV transmission towers. The research examined the influence of key design parameters, including width-to-height ratios, bracing systems, and the number of panels in the tower body. Using IS:802 (1995) guidelines and Excel-based wind load calculations, a total of eighty tower configurations were analyzed and compared in terms of slenderness effects, critical sections, forces, deflections, and structural weight. Results revealed that the choice of bracing system significantly affects tower economy, with X-bracing demonstrating up to 45% savings in steel area compared to K- and XBX-bracing systems. The study emphasized that optimizing base width and bracing arrangements plays a pivotal role in reducing overall material consumption while maintaining safety and serviceability. Thus, the authors highlighted X-bracing with optimized panel configurations as a cost-effective solution for Extra High Voltage (EHV) transmission towers in densely populated and land-restricted regions.

Reddy et al. (2016), in their study "A Study on Analysis of Transmission Line Tower and Design of Foundation", analyzed the structural behavior of a 132 kV double-circuit transmission tower designed for wind zone V. The authors modeled the tower using STAAD.Pro V8i as a three-dimensional structure with constant parameters such as height, bracing system, angle sections, base width, conductor, and ground wire specifications. The loads were calculated as per IS: 802 (1995), and the study focused on deflections, stresses, axial forces, slenderness effects, and critical sections of the tower members. Their findings highlighted that proper analysis and design of transmission towers not only ensure stability under wind loading but also optimize the weight of the structure, making it more economical. Additionally, the study demonstrated that advanced software tools facilitate accurate design and foundation analysis, ensuring structural reliability and safety in transmission line projects.

Mathur and Mathur (2016), in their paper "A Review on Electrical Transmission Tower Structure and Its Design", presented a comprehensive review of transmission tower structures and their design principles. The study emphasized the dual importance of structural and electrical requirements in the planning and construction of transmission towers. Key design aspects such as ground clearance, conductor spacing, and insulator string length were highlighted as critical factors in ensuring operational safety and reliability. The review also examined different types of transmission towers, their configuration, and material selection, noting that proper choice of tower type and materials plays a decisive role in achieving both safety and cost-effectiveness in power transmission projects. The authors concluded that systematic design considerations are essential for the long-term durability and efficiency of electrical transmission lines.

Jyothi and Mahesh (2017), in their paper "Design Transmission Tower and Its Foundation", presented a detailed study on the structural analysis and design of a transmission line tower along with its foundation system. The authors highlighted that transmission towers are critical lifeline structures responsible for the safe and continuous distribution of electrical power from generating sources to various load centers. The study mainly focused on the design of a transmission tower located in Wind Zone V, which represents severe wind conditions, and the tower was designed to carry a 132 kV DC transmission line. In this research, the authors modeled the transmission tower by adopting constant design parameters such as tower height, bracing system, steel angle sections, base width, span length, wind zone, conductor and ground wire specifications, and required electrical clearances. The loads acting on the structure were calculated as per the provisions of IS 802 (1995), which is the standard code for transmission line tower design in India. The study considered key loading components such as self-weight, wind load, conductor load, and other relevant forces governing transmission tower stability. The structural analysis and design of the transmission tower were carried out using STAAD.Pro V8i, where the tower was modeled as a complete three-dimensional space structure. After completing the analysis, the tower was evaluated in terms of important structural performance parameters such as deflections, stresses, axial member forces, slenderness ratio effects, critical member sections, and overall tower weight. Based on the analysis results, the tower members were designed accordingly to ensure stability and safety under extreme wind conditions.

Aravind Pandiyan A, John Peter S., and Kamala Kannan P. (2018), in their paper "Comparative Analysis and Design of Transmission Line Tower Using Steel Section with Tubular Section", presented a comparative study on the structural performance and economy of transmission line towers designed using conventional steel angle sections and tubular steel sections. The authors highlighted that transmission line towers contribute approximately 28% to 42% of the total transmission line project cost, and therefore reducing tower weight through efficient section selection is essential for achieving economic power transmission infrastructure. The study emphasized that conventional steel sections often lead to heavier and costlier structures, whereas tubular sections offer improved strength properties and serve as an effective alternative. In this research, the authors analyzed and designed a 220 kV double circuit transmission line tower using STAAD.Pro software, following the design provisions of IS 800:2007. The transmission tower was modeled under various loading conditions, with particular focus on wind loading, as it is one of the governing loads in tower design. The study mentioned that for optimizing member sections, repeated wind load computations are necessary, as every change in member size affects the analysis and design results. The tower considered in the study had an overall height of 30.3 m, and its structural configuration was adopted according to IS 5613 (Part 2/Sec 1):1995. The authors developed tower models using diagonal bracing systems and compared two major structural arrangements: one model using Indian Standard Angle (ISA) sections, and another using tubular steel sections. The design methodology also referred to relevant transmission tower loading codes such as IS 802, ensuring that tower design meets safety requirements under different loading combinations. The comparative analysis demonstrated that tubular steel sections can significantly reduce structural weight while maintaining adequate strength and stability. The authors concluded that tubular sections provide better structural efficiency due to higher strength-to-weight ratio and improved resistance to buckling compared to conventional angle sections. Their research strongly supports the adoption of tubular steel sections as a modern optimization strategy for transmission tower design, helping engineers achieve economical, lightweight, and reliable tower structures for high-voltage power transmission systems.

T. Abhiram Reddy, K. Murali, DSVSMRK. Chekravarty, and P. Anil Sagar (2018), in their paper "Analysis and Economical Design of Transmission Line Towers of Different Configurations Subjected to Wind Load", focused on optimizing transmission line tower structures by evaluating alternative tower configurations under wind loading conditions. The authors highlighted that transmission line towers contribute approximately 28% to 42% of the total transmission line project cost, making economical tower design an essential requirement for meeting the increasing demand for electrical energy. The primary objective of the study was to develop lightweight and cost-effective tower configurations by modifying both the geometry and structural behavior of conventional transmission towers. In this research, a 220 kV single circuit transmission line tower was considered, and three different tower configurations were modeled and compared. Initially, a rectangular base self-supporting suspension tower was designed, and then it was replaced with a triangular base self-supporting tower to study the potential reduction in material and cost. Further, the structural performance of the existing tower system was examined by developing a rectangular base guyed mast, which provides an alternative structural arrangement for improving economy. The tower geometry and loading calculations were carried out using Excel-based programs and AutoCAD, ensuring accurate configuration and load distribution. The complete three-dimensional analysis of all three tower types was performed using STAAD.Pro software, and the structural members were designed using ISA angle sections. The study emphasized that for optimization of tower members, repeated wind load calculations, structural analysis, and redesign iterations are required. Therefore, the authors performed three successive iterations to arrive at the most economical design solutions for the square/rectangular base self-supporting tower, triangular base self-supporting tower, and square base guyed mast. Finally, the comparative results demonstrated that changing tower geometry and configuration significantly influences the structural behavior, weight, and overall economy of transmission towers.

Balaji Patil et al. (2020), in their paper "Design and Analysis of Transmission Line Tower Using STAAD-PRO", presented a detailed study on the structural design and analysis of transmission line towers considering varying wind conditions. The authors emphasized that transmission towers must not only support heavy electrical conductors at a safe clearance height but also resist natural forces such as wind load, earthquake forces, and snow loads to ensure structural safety and serviceability. In this work, a 220 kV double circuit self-supporting transmission line tower with a square base configuration was selected for analysis. The study mainly focused on the estimation of an economical and feasible tower design under different wind speed zones by adopting hot rolled steel sections and comparing the performance of three different bracing systems. The structural analysis was carried out using STAAD-PRO software, and wind load calculations were performed according to the provisions of IS 802:1995. The tower was analyzed for wind loads corresponding to Zone-II, Zone-III, and Zone-IV, representing increasing wind intensity conditions. The comparison of bracing patterns and wind zones helped identify the optimal structural arrangement that provides maximum stability with minimum material consumption. The authors concluded that wind load is a governing factor in transmission tower design, and selecting appropriate bracing systems along with hot rolled sections significantly improves the overall efficiency and economy of the tower structure. Their research highlights the importance of software-based structural analysis for transmission line towers and supports the development of safe, reliable, and cost-effective tower designs under varying wind speed conditions.

Julius O. Onyeka and Ochonogor Hycent Ifechukwudeni (2020), in their paper "Towards Sustainability in Infrastructural Development: Structural Design of a 330kV Transmission Line Tower in Warri, Nigeria", investigated the structural design approach for improving the sustainability and reliability of power transmission infrastructure in Warri, located in the Niger Delta region of Nigeria. The authors highlighted that Warri faces major ecological challenges such as flooding and pollution, along with persistent power supply failure due to ineffective transmission systems and frequent tower collapses. The study emphasized that transmission towers contribute nearly 50% of the total cost of transmission line projects, making economical and stable tower design essential for large-scale infrastructural development. In this research, the authors aimed to develop a more cost-effective and structurally stable transmission tower by modifying the tower geometry with respect to its height. A 330 kV single circuit square-based self-supporting transmission line tower was designed, and preliminary member sizing was carried out manually using first principles by determining the radius of gyration for both compression and tension members. For ease of fabrication, weight reduction, and improved connection efficiency, the tower members were designed using equal angle steel sections, and bolted connections were adopted. The loading conditions considered in the study included the self-weight of the tower and wind load, which were calculated according to ANSI/TIA 222-G (2006) and ASCE Guide (2004). The complete structural modeling and analysis were performed using STAAD.Pro V8i, and member forces were evaluated through both manual calculations and software-based analysis for validation. The authors performed compression and tension resistance checks using the obtained member forces, ensuring adequacy of the selected sections. The final member selection and bolt provisions were designed in compliance with BS 5950-1:2000, which governs structural steel design practices.

Jadhav et al. (2022), titled "A Review on Analysis and Design of Transmission Tower", the authors emphasized that the planning and design of transmission towers require not only structural engineering knowledge but also practical application of design codes, safety standards, and judgment based on experience. The study highlighted that transmission towers are steel structures designed with a careful balance between economy and safety, where public safety and environmental protection are of prime importance. The authors pointed out that conventional methods of design and analysis are time-consuming; hence, modern computational tools such as STAAD.Pro V8i are adopted to perform efficient and accurate analysis. The review concluded that proper design and maintenance of transmission towers are essential to ensure long-term durability, reliability, and structural stability.

Alshambati and Ahmed (2022), in their paper "Static Analysis and Design of Transmission Line Towers", investigated the structural behavior of 110 kV transmission towers commonly used in Sudan. The study adopted the British Standards (CP3: Chapter V: Part 2, 1972) for manual design and utilized ETABS software for detailed static analysis. The research focused on the influence of leg slopes and tower head width on load transmission to foundations and overall tower weight. Results indicated that Sudan's natural conditions, characterized by relatively lower wind intensities and strong soil foundation, significantly reduced the stresses in tower legs and lower portions compared to similar designs in Britain or the USA. The authors concluded that the use of steel angles in tower design is not only structurally reliable but also more economical. Additionally, the study recommended improved understanding of tower load behavior through simulation tools, highlighting ETABS as an effective platform for analyzing and optimizing transmission tower structures under different load conditions.

Pranjal Dupare, Amey Sarage, Atharva Nilawar, Nilakshi Somkuwar, and Mangesh Bhorkar (2023), in their paper "Design of Transmission Tower for a Sub Station of 132 KV", presented a detailed study on the planning, structural design, and analysis of a 132 kV transmission tower used for substation power transmission purposes. The authors emphasized that the design of transmission towers requires not only conceptual understanding but also strong technical knowledge of structural engineering principles, recent design codes, and practical judgement to achieve an optimum balance between economy and safety. The study highlighted that transmission towers are critical steel lattice structures which must be designed carefully to ensure the safety of surrounding infrastructure and living beings. In this research, the authors focused on the traditional and modern approach of tower analysis by performing manual calculations using conventional design methods, followed by software-based modeling and analysis using STAAD.Pro V8i. The study discussed that traditional methods of analysis are time-consuming, whereas structural software can significantly reduce computational effort and improve design efficiency. The paper explained the key components and materials used in transmission towers, including ACSR conductors (Aluminium Conductor Steel Reinforced), earth wires, and lattice tower members, which play an important role in ensuring stability and electrical clearance requirements. The authors described that transmission towers generally range from 15 m to 55 m in height, and their design depends on factors such as ground clearance, insulator string length, conductor-to-tower clearance, and ground wire position relative to outer conductors. The tower members were mainly designed using ISA steel angle sections, and different bracing patterns such as K bracing, X bracing, and KX bracing were adopted to reduce the overall weight and improve structural performance. The research further stressed that transmission towers must withstand extreme natural events and must satisfy both structural strength criteria and electrical safety requirements, ensuring safe insulation and adequate clearance of conductors from the ground.

Zhu (2023), in the paper "The Structure Design Optimization of Transmission Line Pole Tower Body", investigated the importance of structural optimization in transmission line pole tower design to improve stability, safety, and cost efficiency in power transmission projects. The author highlighted that transmission line towers contribute more than 30% of the total construction cost of transmission line projects, and therefore optimizing tower structure plays a major role in reducing project expenditure while maintaining quality and reliability of power system operation. In this study, the author emphasized that with the continuous expansion of electric power infrastructure investment in China, there is an increasing demand for improving tower structural design methods to control costs and enhance construction and installation quality. The research was carried out based on fundamental understanding of transmission line pole tower design theory, and it considered practical requirements such as foundation selection criteria and common design practices followed in transmission line projects.

The author mainly focused on optimizing the operation platform of steel pole tower bodies, which is an important structural component for maintenance and functional performance. A verification analysis was performed to validate the proposed optimization scheme, ensuring that the improved design approach satisfies structural stability requirements. The study concluded that the optimized transmission tower structural design significantly enhances the stability and security of power grid construction and operation, while also supporting better cost control and improved construction performance. The author finally recommended that transmission tower optimization should be continuously adopted as a key strategy in transmission line engineering, as it strengthens the reliability of the overall power grid system and supports sustainable development of power infrastructure projects.

Khotkar et al. (2023), in their paper "Design and Analysis of Transmission Tower", presented a comparative structural investigation on the feasibility of using three-legged lattice transmission towers for power transmission applications. The authors stated that traditionally four-legged self-supporting lattice towers are most widely used for transmission line systems, whereas three-legged towers are generally limited to telecommunication, microwave, radio, and guyed tower structures. In this study, an attempt was made to evaluate whether a three-legged tower configuration can be effectively adopted for a 220 kV double circuit transmission line tower, with the objective of reducing steel consumption and improving economy. The research involved the analysis and design of two self-supporting 220 kV steel transmission towers, one with a three-legged model and the other with a four-legged model, while maintaining common parameters such as constant tower height, similar bracing system, and steel angle section members. The loading conditions were kept consistent, and wind forces were calculated as per IS 802 (1995). Structural analysis was performed to compare critical performance parameters including slenderness ratio effects, member forces, critical section behavior, and top deflections of both tower types. The comparative results showed that the three-legged tower model provided significant structural economy, resulting in a steel weight reduction of approximately 21.2% when compared to the conventional four-legged tower. In addition to structural performance, the authors also highlighted the practical durability issues associated with transmission towers, especially corrosion-related deterioration. The study discussed that tower legs are typically embedded in concrete, which generally provides protection, but cracks and defects in concrete allow water and salts to penetrate, causing corrosion and weakening of steel legs. The paper explained that corrosion leads to volume expansion of ferrous oxide, producing internal stresses in the concrete chimney and causing cracking, spalling, and further acceleration of corrosion. This type of deterioration is especially common in saline and coastal environments, where stub angle corrosion just above or within muffing is frequently observed, potentially leading to tower collapse under abnormal climatic conditions if not addressed in time.

Rechtman and Santos da Silva (2024), in their paper "Structural Analysis of Latticed Steel Transmission Towers Subjected to Nondeterministic Wind Loads", investigated the importance of considering dynamic wind effects in the structural analysis and design of lattice steel transmission towers. The authors highlighted that although lattice towers are widely used for supporting overhead power transmission lines, their dynamic structural behavior is often neglected in conventional design practices, which mainly rely on simplified static wind load assumptions. The study emphasized that many transmission tower failures occur even under wind speeds lower than the basic design wind speed, indicating that non-deterministic and dynamic wind actions may significantly contribute to tower collapse and structural instability. In this research, the authors proposed an advanced numerical methodology to accurately simulate the tower-line interaction system, including transmission towers, conductors, shield wires, and insulators, under stochastic wind loading conditions. The investigated transmission system consisted of a central suspension tower of 32.86 m height, supported by two end towers with a 450 m span length. A detailed finite element model (FEM) was developed to capture the coupled dynamic response of the tower-line system. The wind load was modeled as a random (non-deterministic) process based on its statistical characteristics, allowing a realistic representation of wind fluctuations and turbulence effects. The results of the study demonstrated a significant difference between static analysis and dynamic analysis outcomes, particularly in terms of displacement response and member force distribution in the transmission tower. The findings revealed that static methods may underestimate critical responses, which can lead to unsafe designs. Furthermore, the structural verification of a base leg member indicated the possibility of failure under higher wind velocities, confirming that dynamic wind effects have a major influence on tower stability and safety.

Ilyas and Tadkal (2024), in their paper "Analysis and Design of Electrical Transmission Towers with Various Sections and Bracing Configurations", examined the performance of a 400 kV, 50-meter suspension tower designed using STAAD.Pro. The study compared three steel section types (angle, tube, and channel) combined with bracing configurations (X, K, and D) under dead, live, and wind load conditions per IS codes. Results indicated that channel sections exhibited the least displacement but were the heaviest and least efficient in force distribution, while tube sections provided balanced performance but showed higher displacements in certain bracing patterns. Angle sections, when paired with X-bracing, proved to be the most effective, offering moderate displacement, minimal reaction and member forces, and the lowest structural weight. Manual connection and footing designs were also validated, ensuring safety and reliability. The study concluded that angle sections with X-bracing present the most economical and structurally efficient option for transmission towers, making them a preferred choice for large-scale grid applications.

Liu et al. (2024), in their paper "Dynamic Failure Mode Analysis for a Transmission Tower-Line System Induced by Strong Winds", investigated the dynamic collapse behavior of transmission tower-line coupled systems subjected to extreme wind conditions. The authors emphasized that conventional wind-resistant design of transmission towers is generally based on the quasi-static method, which has been widely criticized because it neglects the important tower-line coupling effect and the dynamic interaction between conductors and tower structures. The study highlighted that although several efforts have been made to enhance wind resistance, research focusing on failure mechanisms and collapse behavior of transmission towers under strong wind considering coupling dynamics remains limited. In this research, the authors developed a comprehensive numerical methodology to evaluate wind-induced failure modes by simulating the fluctuating wind field acting on transmission lines. The consistent discrete random flow generation method was applied to generate the wind field, ensuring realistic representation of turbulence characteristics and correlation effects. To capture structural nonlinearity and realistic collapse behavior, the study incorporated the compressive buckling characteristics of angle steel members and applied a plastic hinge model within frame elements to simulate mechanical nonlinear behavior. A detailed finite element model (FEM) was developed for a typical transmission tower-line system, consisting of a three-tower and four-line coupled configuration, which allowed evaluation of system-level response under extreme wind excitation.The results demonstrated that the primary trigger of tower collapse is the buckling failure of compressed main members, and the most vulnerable section of the tower was identified as the region beneath the lower cross-arm. The study revealed that under unfavorable wind direction, the transmission tower undergoes bidirectional bending and compression instability, leading to progressive collapse. Additionally, the authors compared their findings with traditional pushover analysis results and concluded that pushover collapse modes are insufficient to fully represent actual wind-induced collapse characteristics, mainly because pushover methods ignore the additional transverse wind forces generated due to tower-line coupling effects. The study further highlighted that the coupling action significantly modifies the dynamic response and failure mechanism compared to single-tower analysis.

Prof. P. O. Modani and Shrikant S. Warade (2024), in their paper "Analysis and Design of Transmission Tower using STAAD-Pro", presented a comprehensive study on the structural analysis and design methodology of electrical transmission towers using advanced structural software tools. The authors highlighted that transmission towers are essential components in power transmission systems, responsible for supporting overhead conductors and ensuring uninterrupted supply of electricity from generation plants to end users. The study provided an overview of transmission tower purpose, classification, and structural components such as tower legs, cross arms, insulators, and conductor attachment hardware, which collectively contribute to the stability and safety of the tower. In this research, the authors focused on the analysis and design of a 31-meter high, 220 kV double circuit self-supporting transmission line tower, considering key structural parameters such as tower geometry, configuration, unit loading, deflection behavior, and design performance. The analysis was carried out using STAAD.Pro software, which enabled the evaluation of internal forces, displacements, and member stresses under applied loading conditions. The study considered various environmental and operational loads including dead load (self-weight), wind load, ice load, and seismic forces, emphasizing that transmission towers must be capable of resisting these critical loads while maintaining structural integrity. The authors further discussed the stepwise design procedure in STAAD.Pro, starting from defining material properties, assigning loads, performing structural analysis, and finally generating design reports to verify the safety and stability of the tower structure. The study concluded that STAAD.Pro is an effective and reliable tool for the structural evaluation of transmission towers, allowing engineers to optimize tower design based on deflection limits and load combinations. Their work demonstrates the importance of software-based analysis in ensuring safe, economical, and code-compliant transmission tower design for modern power infrastructure projects.

Ogata et al. (2025), in their paper "Design of Transmission Line Towers by Metaheuristic Algorithms: A Comparative Study", investigated the application of advanced optimization techniques for the structural design of transmission line towers. The study evaluated four metaheuristic algorithms—Generalized Normal Distribution Optimization (GNDO), Differential Evolution (DE), Particle Swarm Optimization (PSO), and Quantum-behaved PSO (QPSO)—through more than 1080 independent optimizations of a 52 m high self-supporting tower with 1721 members. The results revealed that GNDO and QPSO significantly outperformed DE and PSO in terms of robustness, computational efficiency, and solution quality, particularly under critical wind load cases (0° EPS and 90° TS). The authors concluded that GNDO offers a competitive and efficient tool for real-world structural optimization, enabling cost savings while maintaining compliance with international design codes. Their work demonstrates how metaheuristic algorithms can enhance resource efficiency and reliability in modern transmission tower design.

Kim et al. (2025), in their paper "Simplified Design of Power Transmission Tower: Strategic Variable Analysis Study", proposed an innovative approach for minimizing the structural footprint and visual impact of power transmission towers through strategic geometric modification and member optimization. The authors highlighted that transmission tower construction is increasingly challenged by high costs associated with land acquisition and public resistance due to visual disturbance, which has created strong demand for low-profile and simplified tower designs. To overcome these challenges, the study investigated the effectiveness of reducing tower size by simplifying its structural configuration while maintaining adequate strength and stability. In this research, the authors focused primarily on reducing the inclination angle of the main posts, as it directly influences the tower's overall footprint and geometric spread. The study also evaluated the feasibility of removing structural components such as horizontal members and auxiliary members, aiming to streamline the tower framework without compromising safety. The findings indicated that although simplification is beneficial, a minimum of three horizontal members at the tower base is necessary to ensure structural integrity and stability. Furthermore, the study revealed that the inclusion of auxiliary members significantly enhances tower resistance against buckling failure, as these members reduce the effective buckling length of the main structural elements. A major contribution of the study was the comparison of different reinforcement strategies. The authors found that replacing conventional L-angle main posts with hollow circular steel pipes greatly improved elastic buckling strength and overall load-carrying capacity. This modification was especially effective when the inclination angle of the main posts was reduced to 4.5°, resulting in a substantial reduction in tower geometry. The optimized design achieved an impressive 74% reduction in tower footprint and a 21% reduction in wind-blocking area, demonstrating both structural and aerodynamic benefits.

III. RESEARCH GAP

After reviewing the above literature in detail, it is observed that several significant research gaps still exist in the field of transmission line tower design and analysis. Most of the Indian research works are primarily based on conventional static wind load calculations as per IS 802 (1995), whereas recent advanced studies such as Rechtman (2024) and Liu (2024) have proven that wind is highly random, turbulent, and dynamic in nature, and therefore static methods may underestimate the actual critical member forces and displacement response, indicating a major lack of comprehensive dynamic wind analysis in the Indian context. Furthermore, it is found that many researchers model only the tower body and apply conductor loads as simplified concentrated loads, while the realistic coupled behavior of conductors, insulators, and shield wires is not properly incorporated; hence the tower-line interaction effects such as conductor sag, insulator swing, galloping, and wind-induced vibration remain insufficiently studied. In addition, most reviewed works are based on linear static analysis and conventional member design checks, while actual transmission tower failures frequently occur due to nonlinear buckling instability and progressive collapse mechanisms, showing that research on geometric nonlinearity, material nonlinearity, plastic hinge formation, and collapse simulation under extreme wind is still limited. Another major gap identified is the lack of reliability-based design and probabilistic approach, because most tower designs are deterministic and consider fixed loads, whereas in reality wind speed variation, material strength uncertainty, and fabrication imperfections are probabilistic, and reliability-based design (RBD) and probability-based failure prediction methods are rarely adopted in tower research. Moreover, although seismic load is mentioned in many studies, detailed seismic dynamic analysis using response spectrum or time history methods is not commonly performed, resulting in a lack of comparative understanding between wind-dominated and earthquake-dominated design scenarios, particularly for Indian seismic zones. It is also evident that soil-structure interaction effects are widely neglected, as most tower models assume fixed supports and do not consider foundation flexibility, settlement, and soil behavior, creating a major research gap related to realistic tower foundation response. Additionally, corrosion degradation is a serious durability issue for transmission towers, especially in coastal and industrial regions, but only limited studies such as Khotkar (2023) have addressed corrosion, and detailed modeling of corrosion-induced thickness loss, bolt deterioration, and life cycle performance assessment is still missing.

CONCLUSION

This review paper presented a detailed analysis of previous literature related to the design and structural performance of transmission line towers. It is observed that transmission towers form a major portion of the overall cost of overhead transmission line projects, and therefore structural optimization is essential. Early research mainly focused on static wind analysis, bracing pattern optimization, and steel weight reduction using software tools like STAAD.Pro. Studies showed that X-bracing is one of the most economical bracing systems for lattice towers, and triangular towers can provide considerable material savings compared to conventional rectangular towers. Further research explored the use of tubular sections, which improve buckling resistance and reduce structural weight. Recent studies have shifted towards advanced modeling approaches such as dynamic wind load simulation, tower-line coupling interaction, and nonlinear progressive collapse analysis. Metaheuristic optimization algorithms have also proven effective in reducing tower weight while ensuring code compliance. Despite advancements, significant gaps remain in dynamic wind-resistant design, nonlinear collapse modeling, soil-structure interaction, corrosion degradation assessment, and sustainability-based optimization. Therefore, future research should focus on developing comprehensive design methodologies integrating probabilistic wind analysis, nonlinear modeling, and advanced optimization techniques to improve the safety, reliability, and economy of transmission line towers.

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