

Comparative Analysis and Structural Design of Transmission Line Towers under Wind Loading

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Abstract

Transmission line towers are critical structural components of electrical power transmission systems and are required to withstand various environmental and operational loads throughout their service life. Among these, wind loading is one of the most significant lateral loads influencing the structural stability, member forces, deformation, and overall safety of transmission towers. This study presents a comparative analysis and structural design of transmission line towers subjected to wind loading. The analysis considers the major design parameters, including tower geometry, material properties, wind speed, terrain conditions, exposure characteristics, and load combinations. Wind loads acting on the tower and conductors are evaluated according to relevant structural design provisions, and the resulting forces are used for the analysis and design of tower members. The structural response is assessed in terms of axial forces, stresses, displacement, reactions, and factor of safety.

A comparative evaluation is performed to identify the influence of different wind-loading conditions and structural configurations on the performance of transmission line towers. The study aims to determine the most suitable tower configuration by achieving an appropriate balance between structural strength, stability, safety, and material utilization. Numerical structural analysis can be carried out using engineering software such as STAAD.Pro or ANSYS to evaluate the behavior of the tower under critical loading conditions. The findings of the study provide useful insights into wind-resistant transmission tower design and can assist in developing safe, reliable, and economically efficient transmission line structures.

Keywords— Transmission Line Towers, Electrical Power, Wind Loading

1. INTRODUCTION

Transmission line towers are essential structural components of electrical power transmission networks, providing mechanical support to conductors, earth wires, insulators, and associated electrical equipment. These towers are generally designed as lightweight lattice structures fabricated from structural steel members and are required to maintain adequate strength and stability under different environmental and operational conditions. The structural performance of a transmission line tower is influenced by several types of loading, including self-weight, conductor and insulator loads, wind load, temperature effects, and, in some regions, seismic actions. Among these loads, wind loading is particularly important because it produces significant lateral forces on the tower body, conductors, and other exposed components. Improper estimation of wind loads can result in excessive member stresses,

large deformations, instability, or even structural failure. Therefore, accurate wind load assessment and appropriate structural design are essential for ensuring the safety, reliability, and serviceability of transmission line towers [1].

The design of transmission line towers involves determining the critical loading conditions and evaluating the response of individual structural members under these conditions. Wind pressure depends on parameters such as basic wind speed, terrain category, height above ground level, topography, exposure conditions, and aerodynamic characteristics of the tower and conductors. The resulting wind forces are transferred through the tower members to the foundation, generating axial forces, reactions, stresses, and displacements. Structural design standards provide guidelines for calculating these loads and determining the required strength of tower members. In India, standards such as IS 875 (Part 3) for wind loading and IS 802 for the use of structural steel in overhead transmission line towers provide important design provisions. Proper consideration of these standards enables engineers to develop structures capable of safely resisting the expected design loads while maintaining economical use of construction materials [2, 3].

The increasing demand for reliable electrical power transmission has resulted in the development of transmission networks across diverse geographical and climatic regions. Consequently, transmission towers may be exposed to substantially different wind conditions depending on their location and terrain. A tower design that performs adequately under one wind condition may experience significantly different structural responses under another. Therefore, comparative analysis of transmission line towers under different wind-loading conditions is useful for understanding the relationship between wind intensity, structural configuration, member forces, deformation, and material requirements. Such analysis can also help identify critical members and optimize the structural arrangement of the tower without compromising safety [4, 5].

In this study, a comparative analysis and structural design of transmission line towers under wind loading is presented. The study focuses on evaluating the structural response of the tower for selected wind-loading conditions and examining parameters such as axial member forces, stresses, displacement, support reactions, and factor of safety. Numerical structural analysis may be performed using software such as STAAD.Pro or ANSYS, while the calculated wind loads and structural responses are evaluated according to the applicable design standards. Different structural configurations or loading conditions can be compared to determine their effect on tower performance and material utilization. The results are intended to provide a systematic understanding of wind-induced structural behavior and support the development of transmission line towers that are safe, stable, reliable, and economically efficient [6].

2. WIND INFLUENCE ON TRANSMISSION LINE TOWERS

Transmission line towers: Transmission line towers are steel lattice structures, carrying overhead high voltage conductors for long distance power transmission with the required ground clearance and transmitting loads safely to the base. Their height is usually between

15 m to over 80 m and they are composed of four major components: tower body, cross arms, peak and leg-foundation system [7, 8].

Based on their functions, transmission towers are classed as suspension, tension (anchor), terminal (dead-end), transposition, river crossing and specific angle towers. The selection of tower depends on the transmission voltage, line alignment, terrain condition and loading requirements.

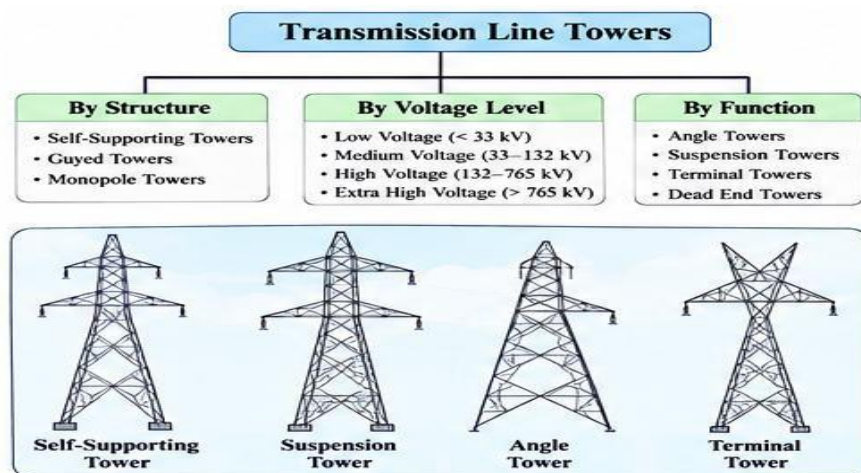


Figure 1: Classification of Transmission Line Towers

Wind Influence on Transmission Line Towers: Wind is one of the most important environmental loads acting on transmission line towers. Due to their large height, open lattice design and exposure to atmospheric conditions, transmission towers are subject to significant wind loads during their service life [9, 10]. Transmission towers are concurrently subjected to wind forces operating on the tower body and hung conductors, unlike normal building structures, resulting in complex structural behavior.

Wind pressure on a transmission tower is a function of various aspects including fundamental wind speed, terrain roughness, topography, height above ground level, structural geometry, shielding effects, and aerodynamic features. Since wind speed increases with height, the upper part of a tower is usually subjected to higher wind pressure than the lower part, which leads to large overturning moments and lateral displacements.

The main consequences of wind loading to transmission towers are

- Rise in axial forces of main members.
- Additional bending moments in structural members.
- Increased shear forces at joints and connections.
- Increased lateral displacement at the top of the tower.
- Increased foundation reactions and overturning moments.
- Possible buckling of a part in compression.
- Increased vibration from wind-induced oscillations.

3. LITERATURE REVIEW

American Society of Civil Engineers (2015) presented ASCE 10-15: Design of Latticed Steel Transmission Structures, which provides comprehensive guidelines for the structural design of latticed steel transmission structures. The standard addresses loading conditions, structural analysis, member design, connections, and strength requirements. It emphasizes the importance of considering environmental loads, particularly wind effects, in determining the critical forces acting on tower members. The provisions of ASCE 10-15 are useful for evaluating the structural adequacy and reliability of transmission line towers under different loading conditions.

American Society of Civil Engineers (2020) published Manual of Practice 74: Guidelines for Electrical Transmission Line Structural Loading, which provides detailed guidance for determining structural loads on electrical transmission line structures. The manual discusses wind loading on towers, conductors, ground wires, and associated components, along with load combinations and environmental considerations. It provides a systematic approach for establishing appropriate design loads and is particularly useful for evaluating wind-induced forces in transmission line structures.

Bentley Systems (2023) provided the STAAD.Pro CONNECT Edition Technical Reference Manual, which describes the theoretical and computational procedures used for structural analysis and design using STAAD.Pro. The software supports the modelling of complex steel structures and enables engineers to evaluate member forces, stresses, displacements, reactions, and design adequacy under different loading conditions. For transmission line tower analysis, STAAD.Pro can be effectively used to model lattice structures and investigate their response under wind and other critical loads.

Bureau of Indian Standards (1995) developed IS 802 (Part 1/Sec 1): Code of Practice for Use of Structural Steel in Overhead Transmission Line Towers. This standard provides specific requirements for the analysis and design of steel transmission line towers in India. It covers structural loading, design assumptions, member strength, slenderness requirements, and other important aspects of tower design. The standard serves as an important basis for ensuring adequate strength and stability of transmission towers subjected to environmental and operational loads.

Bureau of Indian Standards (2007) published IS 800: General Construction in Steel—Code of Practice, which establishes general principles and requirements for the design of steel structures. The standard provides provisions related to limit-state design, material strength, member capacities, buckling, connections, and serviceability. Its design principles are applicable to steel transmission tower components and can be used along with specific transmission tower standards to assess the safety and structural adequacy of tower members.

Bureau of Indian Standards (2015) presented IS 875 (Part 3): Design Loads (Other than Earthquake) for Buildings and Structures—Part 3: Wind Loads, which provides guidelines for evaluating wind pressure and wind forces on structures. The standard considers important parameters such as basic wind speed, design wind speed, terrain characteristics, height, topography, and structural characteristics. Its provisions are particularly important for

calculating the wind loads acting on transmission towers and their exposed components. The calculated wind forces can subsequently be incorporated into structural analysis to determine critical member forces and tower responses.

Bureau of Indian Standards (2016) specified IS 2062: Hot Rolled Medium and High Tensile Structural Steel—Specification, which defines the requirements for structural steel used in engineering and construction applications. The standard specifies material grades, mechanical properties, chemical composition, and other requirements necessary for structural applications. Selection of appropriate steel grade is important in transmission tower design because material strength directly influences the load-carrying capacity, weight, and reliability of tower members.

Bureau of Indian Standards (2019) provided SP 6 (1): Handbook for Structural Engineers, which serves as a practical reference for structural steel design and engineering calculations. It provides information related to structural sections, design properties, steel members, connections, and design practices. The handbook is useful for selecting suitable steel sections and understanding the structural characteristics required during the design and analysis of transmission line towers.

Chen and Lui (2018) presented the Handbook of Structural Engineering, which provides comprehensive theoretical and practical information related to structural analysis and design. The book covers structural mechanics, steel structures, loading, stability, material behavior, and design principles. The concepts discussed in this work provide a fundamental basis for understanding the behavior of structural systems under different loading conditions and can support the analytical evaluation of transmission line towers subjected to wind loading.

Cook (2016) presented The Designer's Guide to Wind Loading of Building Structures, which focuses on the principles and practical procedures associated with wind-load assessment. The work discusses wind characteristics, pressure distribution, aerodynamic effects, exposure conditions, and the calculation of wind forces on structures. Although primarily focused on building structures, the fundamental principles of wind engineering presented in the book are useful for understanding the effects of wind on exposed structural systems, including transmission line towers.

Research Gap

Research Area	Findings from Previous Studies	Research Gap	Present Study
Wind load analysis	Wind effects extensively studied	Limited comparison of all terrain categories	Comparative analysis of Terrain Categories I–IV
Finite element modeling	FEA widely adopted	Limited integrated evaluation of structural responses	Detailed 3D modeling using STAAD.Pro
Terrain effects	Individual terrain conditions investigated	Comprehensive terrain-based comparison lacking	Evaluation under all terrain categories as per IS

			875 (Part 3): 2015
STAAD.Pro applications	Used for structural analysis	Few comprehensive comparative studies	Analysis of forces, stresses, displacements, and reactions
Design standards	Various national and international codes adopted	Limited studies using updated IS 875 (Part 3): 2015 provisions	Code-compliant analysis based on IS 875 (Part 3): 2015 and IS 802
Design verification	Structural analysis emphasized	Limited verification of member adequacy	Design verification and comparison of member utilization

4. STRUCTURAL DESIGN OF TRANSMISSION LINE TOWERS

Structural Design of Transmission Line Towers focuses on designing a safe, stable, and economical steel lattice structure capable of supporting conductors, insulators, earth wires, and associated electrical components under various loading conditions. The design primarily considers dead load, wind load, conductor tension, broken-wire conditions, and other applicable environmental loads [11, 12]. The tower geometry, member sizes, material properties, connection details, and foundation reactions are selected based on the governing load combinations and relevant design standards such as IS 802, IS 875, and IS 800.

The structural design process generally involves tower configuration selection, calculation of design loads, load combination, structural modelling, analysis of member forces, and member capacity checks. Each tower member is evaluated for axial tension and compression, buckling, slenderness, and allowable or design strength. The overall structure is also checked for lateral displacement, stability, support reactions, and factor of safety. Software such as STAAD.Pro can be used to develop the three-dimensional tower model and perform structural analysis under different loading conditions [13, 14]. The final design aims to achieve adequate structural strength and serviceability with minimum practical material consumption, resulting in a safe, reliable, and cost-effective transmission line tower.

Methodology

A systematic research technique has been developed for the purpose of fulfilling the objectives of the present study. The methodology comprises theoretical studies, code provisions, finite element modeling, structural analysis and comparative studies to evaluate the effect of terrain categories on the wind-induced behavior of transmission line towers. The technique guarantees the study is consistent with recognized technical standards and gives dependable results for practical applications.

The research began with a literature survey of published articles in the domains of transmission line towers, wind engineering, structural analysis, and finite element modeling. The design framework and the methods for wind load computation and structural analysis

were established by referring to the relevant Indian standards like IS 875 (Part 3): 2015 and IS 802.

Then a representative steel lattice transmission line tower was chosen for detailed study. The geometry, member qualities and material parameters were determined according to normal transmission tower design techniques. The tower was then modeled in STAAD as a three dimensional finite element model. Advantage of employing beam components for representing the structural members. Appropriate support conditions, member connections and structural idealizations were integrated to approximate the real behavior of the tower.

Wind loads were computed for Terrain Categories 1, 2, 3 and 4 independently as per the methodology given in IS 875 (Part 3): 2015. Then the corresponding wind loads were applied to the STAAD.Pro model and other relevant loading conditions i.e. self-weight and conductor loads if appropriate. The structural analysis was performed considering the standard load combinations provided by the design code.

The finite element study results provided extensive information of axial forces, bending moments, shear forces, nodal displacements, stresses and support reactions for each of the terrain categories. These results were systematically compared to determine the effect of terrain roughness on the structural performance of the transmission tower.

Finally, the structural adequacy of the tower was checked as per the criteria of IS 802. The comparison results were used to determine the controlling terrain condition and to create engineering suggestions for the design of transmission towers under different wind situations. Figure.2 Shows the employed technique.

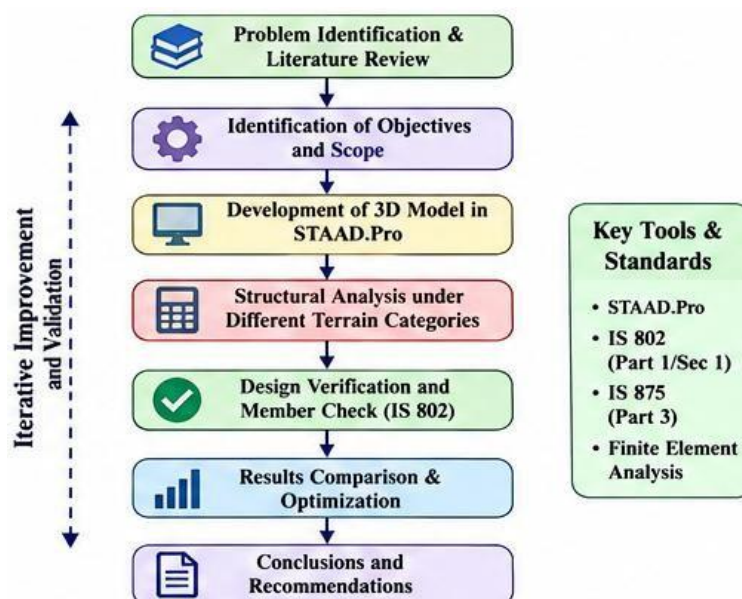


Figure 2: Methodology Flowchart

5. CONCLUSION

The present study focused on the comparative analysis and structural design of transmission line towers subjected to wind loading. Wind load represents one of the most critical

environmental loads acting on transmission line structures because of the large exposed surface area of tower members, conductors, and ground wires. The study established that accurate estimation of wind pressure and appropriate consideration of load combinations are essential for evaluating the structural safety and serviceability of transmission line towers. The relevant provisions of IS 875 (Part 3), IS 802, IS 800, and other applicable structural design guidelines provide a systematic basis for calculating wind loads and designing steel tower members.

The comparative analysis demonstrates that variations in wind-loading conditions can significantly influence axial forces, stresses, support reactions, and lateral displacement of tower members. As wind intensity increases, the structural demand on critical members also increases, making the identification of governing load cases essential for safe design. Numerical structural analysis using tools such as STAAD.Pro can effectively determine the behavior of individual members and the overall tower under different loading conditions. The assessment of member capacity, slenderness, stress utilization, displacement, and factor of safety helps in identifying potentially critical structural components.

Overall, the study highlights the importance of integrating accurate wind-load assessment with appropriate structural modelling and steel member design. A properly optimized transmission line tower should provide sufficient strength and stability while avoiding unnecessary material consumption and excessive structural weight. The findings can support the development of safe, reliable, and economical transmission line towers suitable for varying wind conditions. Future work may extend the study by considering different tower geometries, terrain categories, wind zones, conductor configurations, seismic effects, fabrication tolerances, and optimization techniques for achieving improved structural efficiency.

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