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Highlights

- ❖ The study reviews lightning protection approaches for wind turbines and towers.
- ❖ It analyzes soil properties, electrode placement, and turbine connections.
- ❖ Research gaps and recommendations for improved protection systems are identified.

Graphical Abstract



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Lightning Protection of WT Grounding Systems: A Comprehensive Review of Time-Frequency Effects and Modeling Techniques

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ABSTRACT

This study reviews approaches and models for wind turbines (WT) and tower grounding systems and their protection against lightning, based on a core set of approximately sixty (~60) grounding-focused scientific articles. This article also deals with various aspects such as the dependence of electrical properties of soil on frequency, the effect of ionization, heterogeneity and classification of soil and the optimal position of electrodes as well as the connection arrangements of WTs in a field. This review also deals with the effects of direct and indirect lightning on turbines, voltage distribution between turbines and the behavior of the earth system at different frequencies. At the end, the points in the reviewed articles are in the form of diagrams for a better understanding of the various topics discussed and a comprehensive view. This work shows the limitations and study gaps of previous works with recommendations for the evolution of lightning protection systems for WTs and tall electrical structures.

1. Introduction

WTs have become increasingly popular as the need for cleaner energy has grown and our environmental footprint shrinks. Modern turbines are tall structures often installed in lightning-prone sites, where the injected fast-front currents can produce significant ground potential rise (GPR) and transient over-voltages if the grounding system is not sufficiently effective [1,2]. Such conditions may lead to insulation stress, equipment malfunction, and safety hazards. Although IEC 61400-24 provides guidance for lightning protection of wind turbines [3], practical design challenges remain, particularly in high-resistivity and non-uniform soils. A key difficulty is that the soil electrical parameters and the resulting grounding impedance are often frequency-dependent in the lightning-relevant bandwidth; neglecting these effects can noticeably bias the computed transient response and impulse performance [4-7]. In parallel, the increasing scale of wind farms introduces coupling and transfer effects: interconnected turbine grounding systems, underground/overhead interconnections, and the collection network can influence how lightning surges distribute and how over-voltages propagate across the farm [8-11]. To address these issues, recent studies have employed a spectrum of modeling approaches ranging from circuit-based EMTP representations to wideband/full-wave electromagnetic methods (e.g., MoM/PEEC/FDTD/BEM) and hybrid techniques with frequency-to-time conversion [7,9,12-14]. In addition, optimization-oriented designs and parameter-tuning strategies have been reported for grounding improvements [15,16], while broader optimization and data-driven design trends in wind-power systems suggest further opportunities that remain underexplored for lightning/grounding-specific design workflows [17].

Unlike earlier reviews that focus on a narrow subset of topics (e.g., only soil ionization or only simplified grounding models), this paper presents a comprehensive review based on a core set of approximately sixty (~60) grounding-focused studies on WT grounding and lightning protection. We cover: frequency-domain and time-domain viewpoints, frequency-dependent soil behavior (including layered/heterogeneous cases), electrode placement and interconnection strategies, and wind-farm-scale interactions (including coupling between turbines and collection-network effects). By synthesizing the state of the art and highlighting limitations and study gaps, this review provides a coherent basis for improving lightning protection design and for identifying promising directions for future research.

In the renewable-energy context, turbine lightning damage has critical implications for operational performance and economics. Such reliability issues can lower wind farm availability and shorten component lifetimes while driving up operations and maintenance (O&M) expenses and ultimately the leveled cost of energy (LCOE). For example, industry analyses show lightning strikes account for 20% of operational losses and 60% of blade failures [18], costing operators over \$100 million annually [18]. In lightning-prone regions, these events can cause a majority of turbine downtime (up to 80%) [18], leading to expensive repairs and lost energy production, factors that directly translate into higher LCOE if unmitigated [19].

2. Problem definition and scope

Lightning-driven stress on WT grounding systems is a coupled *structure-ground-network* problem: fast-front currents excite a broad bandwidth, soil parameters can be frequency dependent, and wind-farm interconnections can redistribute both injected current and resulting overvoltages. The technical problem addressed in this review is to clarify which modeling assumptions and method families are appropriate for specific engineering questions (e.g., local GPR, transferred/induced overvoltages, insulation coordination, and mitigation ranking) while keeping the modeled bandwidth consistent with the targeted failure mode.

Scope. This paper reviews and synthesizes the set of studies covered in this manuscript (approximately 60), focusing on WT and wind-farm grounding and lightning-transient modeling. Emphasis is placed on (i) soil representation (uniform vs. multilayer/heterogeneous; frequency dependence; and ionization where considered), (ii) coupling/propagation paths (interconnection and collection-network effects), (iii) validation practice (measurement-linked vs. cross-check), and (iv) practical mitigation measures (bonding, SPDs, and topology). The review is qualitative by design and does not introduce new numeric performance metrics.

Paper organization. Section 3 organizes the reviewed literature by method family and application context. Section 4 then formalizes the classification framework and presents the method-comparison matrix (Table 3). Section 5 provides the comparative synthesis across methods and findings (including Table 2), followed by extracted challenges/gaps (Section 6) and a prioritized research roadmap (Section 7). Section 8 summarizes limitations of this review, and Section 9 concludes the paper.

Acronyms. For readability, Table 1 lists the acronyms used throughout this paper.

Table 1. Acronyms used in this paper.

Acronym	Definition
WT	Wind turbine
WF	Wind farm
GPR	Ground potential rise
SPD	Surge protection device
LPS	Lightning protection system
EMTP	Electromagnetic Transients Program
EMTP-RV	EMTP-RV (electromagnetic transient simulation software)
ATP	Alternative Transients Program
ATP-EMTP	Alternative Transients Program-EMTP family
PSCAD/EMTDC	Power Systems Computer Aided Design/Electromagnetic Transients including DC
FEM	Finite element method
FDTD	Finite-difference time-domain
BEM	Boundary element method
HEM	Hybrid electromagnetic model
MOM	Method of Moments
PEEC	Partial element equivalent circuit
TLM	Transmission line model
QS	Quasi-static
VF	Vector fitting
FFT	Fast Fourier Transform
IFFT	Inverse Fast Fourier Transform
RLC	Resistor-Inductor-Capacitor
NEC	Numerical Electromagnetics Code (e.g., NEC-4)
GB-IBEM	Galerkin-Bubnov indirect boundary element method
ROM	Reduced-order modeling
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
MATLAB	MATLAB (numerical computing environment)
COMSOL	COMSOL Multiphysics (multiphysics FEM software)
CDEGS	Current Distribution, Electromagnetic Fields, Grounding and Soil Structure analysis (software suite)
SPICE	Simulation Program with Integrated Circuit Emphasis
MVDL	Medium Voltage Distribution Line

3. Literature organization

This section organizes the reviewed WT lightning/grounding literature in a *method-family* structure (measurement-driven evidence, circuit-based EMT studies, and wideband/full-wave electromagnetic approaches, including farm/network-level models). The intent is to present the literature in a navigable order before introducing a formal set of comparative criteria in Section 4 and then extracting cross-study indicators and design implications in Section 5.

3.1. Literature Review by Method Family

3.1.1. Empirical and measurement-driven studies (field/lab evidence)

As it can be seen from some of the works, such as [20], laboratory experiment is used to examine lightning protection while analytical techniques are used in other works such as [21].

Reference [20] analyzes overvoltage in a scaled wind turbine (WT) under simulated lightning. An impulse voltage was applied to study the effect of varying ground resistances on induced voltage. Results show that lower ground resistance reduces induced voltage in the WT.

In [21], two grounding systems were compared: independent and connected to adjacent turbines. Connected systems show lower ground potential rise. Flexible graphite electrodes outperform galvanized steel at high frequencies due to current dispersion at electrode ends.

Several studies rely on measured data and process it using numerical tools (e.g., MATLAB) [15,22] or an advanced processing module (APM) [23].

The study in [22] has the following objectives: to develop simple formula for calculating the grounding resistance of WTs siting in two-layer soil conditions by using field measurements, regression model and MATLAB model. Various practical grounding configurations are considered in further case studies, and the accuracy of the given model is verified with real-world datasets.

In Reference [23], an experimental analysis of the time and frequency response of WT grounding systems is given. It involved obtaining measurements on the grounding system that is specifically in the foundation of the turbine before and after installation of the complete WT that is, the tower, nacelle as well as the blades. From this point of view, the impact of the ground impedance on the evaluated frequency dependence is shown, and APM simulations in steady-state conditions with two layer models of the soil are presented. Originally there was a cut down of static resistance by about 1ohm from full turbine assembly with reference to foundation only but which was considered insignificantly small and partly ascribed to variations in the type of soil; seasonal changes included.

In [15], the authors have discussed analysis and design of grounding system of wind farms located in the Taif region of Saudi Arabia. Sunde's apparent resistance model is then used to formulate an optimization problem of minimizing the error in the objective function which is solved by a genetic algorithm with the MATLAB optimization toolbox. Finally, considering data collected at each site, optimized ground parameters for a multi-layer approach are determined.

3.1.2. Circuit-based EMT modeling (time-domain) and practical equivalents

Several studies use electromagnetic-transient simulation tools such as Electromagnetic Transients Program (EMTP) and pre-built component models to represent major WT structures (e.g., tower and blades) in lightning-protection studies [8,24-29].

However, these approaches may rely on simplified or outdated component representations and may be less suitable when detailed high-frequency effects must be resolved. Some studies attempt to improve accuracy by combining specialized field solvers with general-purpose EMT tools (e.g., coupling COMSOL Multiphysics with EMTP) [30]. In [16], some general use soft wares like MATLAB and ORIGIN PRO3. 1 is incorporated, and in [31], PSCAD/EMTDC and CYMGRD software are employed; however, such models have some imperfections in-built.

The software packages mentioned in the reviewed studies serve complementary roles. EMTP-type programs (e.g., EMTP-RV and ATP-EMTP) are typically used for network-level electromagnetic-transient simulations in the time domain, where cables, surge protection devices, and collection-network elements can be represented via circuit equivalents. Multiphysics FEM platforms (e.g., COMSOL) are often used when geometry-resolved field distributions or coupling effects must be modeled explicitly. Grounding-focused suites (e.g., CDEGS) are commonly used to represent electrode/soil structures and to compute quantities such as grounding impedance and GPR under specified soil models and electrode configurations.

Reference [24] proposes a theoretical method to study electrostatic charging of wind turbine rotor blades during storms and its impact on lightning protection and overvoltage management. This charging may introduce new electrical issues in medium and low voltage systems and should be considered in lightning protection design.

In [25], a detailed model of wind turbine components affected by lightning, including tower, blades, coaxial cables, and control system, using the EMTP-RV software was developed. A frequency-dependent grounding model was examined. The study highlights the role of protective measures, such as low-impedance wires, conductive blades, and surge protection devices (SPDs), in mitigating overvoltage from indirect lightning strikes.

In Reference [26], authors proposed a lightning protection system (LPS) and tested it for WTs which are in accordance with IEC 61400-24 norms and used step and touch voltage range put forward in IEEE 80-2000. This model is designed using ATP-EMTP incorporated with lightning ionization of soil and the influence of steel tower for I_c and I_i lightning current waveforms and different soil resistances.

Using the EMTP-RV simulation model, Reference [27] analyzes the nonlinear ionization characteristic of soil and frequency dependence in high-frequency models of WTs, such as transformers, grounding systems, and underground cables. A reduction of lightning induced transient over voltages by 50% has been achieved through the proposed approach thus increasing reliability.

In [28], lightning-induced overvoltages were analyzed using EMTP-RV for two grounding methods: common and separate systems. Common grounding systems show higher overvoltages in direct and adjacent turbine impacts. Thus, shared grounding with connectors is recommended for wind farms.

In [8], the effect of various grounding system configurations (linear, circular, triangular, quadrilateral) on voltage distribution in transient modeling of wind turbine components was evaluated with the help of EMTP-RV. Interconnected systems exhibit lower overvoltage than separate systems. Transient voltage distribution depends on the grounding system type.

In [29] based on ATP-EMTP electromagnetic transient program, models of lightning current, tower, collector line, insulator, and arrester were developed to simulate lightning strikes on collector line towers. The impact of tower location and ground resistance on line overvoltage was studied. Results indicate these as key factors.

Reference [30] offers a comprehensive method for designing wind turbine grounding systems in high soil resistance areas, such as Taif, Saudi Arabia, excluding soil ionization effects. After site selection and soil resistance measurement, the initial grounding system per IEC 61400-24 was defined and enhanced with vertical electrodes. Transient analysis revealed that break points in vertical electrodes and the central axis significantly affect potential distribution. COMSOL Multiphysics and ATP/EMTP were used to perform the simulation and modeling.

Article [16] suggests a strategy to shield electrical networks from lightning by optimizing a proportionality factor (K) for lightning current distribution. Techniques like burying charcoal and adding ground electrodes reduced grounding resistance. Grounding system configuration should vary by soil type to optimize the proportionality factor. The software used in this study is MATLAB and ORIGIN PRO3.1.

Reference [31] introduces a numerical method to assess the transient behavior of a wind turbine under lightning strikes, accounting for the high-frequency nature of lightning currents in grounding system modeling. Wind turbine modeling is done using MATLAB and CYMGRD software. The significant potential difference in the proposed model versus the pure resistance model stems from neglecting capacitance and inductance effects.

3.1.3. Wideband and full-wave electromagnetic methods (distributed coupling)

To this end, various computational methods such as Finite Difference Time Domain (FDTD), Finite Element Method (FEM), Boundary Element Method (BEM), Hybrid Electromagnetic Model (HEM), Method of Moments (MOM), Partial Element Equivalent Circuit (PEEC), Transmission Line Model (TLM), etc. are used in the executive non-specialized software for non-comprehensive and imprecise models of lightning protection which have been shown in the reviewed articles. Subsequent to extraction, these models are usually post-processed by a solver in order to arrive for instance at results in the time or frequency domain.

These are papers which incorporates methods include [4,5,7,10-14,32-57].

Of the reviewed papers, FEM is applied in paper [33], BEM in papers [13,32], PEEC in papers [12,40], TLM in papers [38,39,45], FDTD in papers [41-44], TLM/FDTD in paper [46], HEM in papers [4,5,10,11,47-49], Circuit Method (CM) in papers [34-37], and MOM in addition, papers [50,52] deal with both the use of CM and MOM simultaneously.

These methods include some that are fully in the time domain, some fully in the frequency domain while others partially in both domains. Within the time domain, we do not need particular transformation and calculations are faster, yet modeling of specific frequency phenomena such as frequency-dependent soil electrical parameters is problematic. Since there are a large number of time intervals in lightning frequency, frequency domain modeling is typically better, however the results are again converted to time domain for clarity. This conversion is done via the inverse Fourier transforms and as such increases computational demands. To minimize this complexity, fitting techniques (e.g., Vector Fitting) have been used [58].

Papers 27 and 28 combine Vector Fitting (VF) with PEEC, papers [4,10,48,49] use VF with HEM. Papers [7,14,51] utilize VF with MOM and paper [59] uses rational function fitting and Current Distribution, Electromagnetic Fields, Grounding and Soil Structure Analysis (CDEGS) software. Such techniques enable analysis to be performed in real time in the time domain as well as in the frequency domain and makes the computational algorithms faster and precise.

Reference [32] focuses on modeling transient current distribution in WT under direct lightning strikes and evaluating low-impedance grounding systems for effective lightning protection using the Galerkin-Bubnov formulation of the Galerkin-Bubnov Indirect Boundary Element Method (GB-IBEM) and the transient response is obtained by performing Fast Inverse Fourier Transform (IFFT). Short vertical electrodes have no impact on transient impedance, while long ones do. Horizontal electrodes of similar size show comparable effectiveness.

In [33], a new mathematical model is introduced to calculate electric potential, electric field, and current density around the grounding system using FEM and MATLAB's Partial Differential Equation Toolbox. The total resistance of the grounding system with a ring electrode and auxiliary vertical rods is provided. The optimal grounding system position is achieved at a burial depth reported in the original study.

Reference [34] presents a model for lightning current dissipation in single and interconnected wind turbine grounding systems in which an ATP-EMTP circuit theory modeling applies. The grounding system evenly dissipates lightning current, reducing ground potential. Connecting grounding systems with wires is more beneficial than using similar horizontal electrodes.

The analysis of the transient behaviour of a WT grounding system using the soil condition and lightning characteristic with or without including the central vertical electrode is done in [35] with the help of the circuit theory in ATP-EMTP software. Further, a brief analysis of the reliability aspect of the system, the possibility of improvement, or risks for living organisms is discussed. The simulation results show that adding a central vertical grounding electrode enhances the WT's grounding system considerably even

though its contribution is negligible to the first cost. Moreover, it was observed that the step and touch voltages makes the area within a radius of 3 meters from the base of the tower as dangerous to both humans and equipment.

Reference [36] introduces a circuit modeling approach to determine transient responses to lightning strikes on wind turbines (WT). Blade, rotor, tower, and grounding system models are calculated separately and connected. The method's effectiveness is validated through simulations and laboratory measurements. It is also applied to a real 2 MW WT.

Reference [37] describes a new multi-element model to analyze grounding system behavior under magnetic fields from lightning and soil ionization. A novel circuit representation with RLC elements is introduced. The time-varying behavior of the grounding system and soil ionization effects are calculated to be directly usable in EMTP.

By using the TLM in [38], the transient behavior of isolated and interconnected wind turbine grounding systems under lightning discharge in uniform soil was modeled. In low-resistance soil, a single WT suffices, but in high-resistance soil, connecting grounding systems is desirable to reduce potential peaks and carry more current. A closed-loop grounding system outperforms a cascading system.

Reference [39] presents a model relying on the TLM approach to analyze transient behavior of grounding systems in uniform and non-uniform soil, considering soil ionization and frequency-dependent effects. Electromagnetic coupling and air-soil interface effects are included. Impulse impedance and time-domain voltage response are estimated. The impact of upper soil layer depth and impulse current is examined.

[40] analyzes the impact of four sheath grounding methods on voltage distribution during wind turbine lightning strikes using the electromagnetic coupling vector fitting PEEC simulation. Connecting the cable sheath to the grounding system improves voltage distribution. The most effective method is grounding the sheath at the WT tower ends. An SPD configuration reduces voltage and current.

A detailed transient modeling for lightning strike calculations with frequency dependence and different soil resistivity and soil ionization is described in reference [12]. The cited work proposes an advanced vector-fitted partial element equivalent circuit (PEEC) model implemented in TAES and SPICE for wind turbine systems. The study analyzes electromagnetic coupling and the influence of soil resistivity on current distribution.

Paper [41] presents the lightning current and associated electric field on sheath of an underground cable in wind farm on account of the lightning strike on the wind turbine tower with/without counterpoises, by applying 3-D FDTD method.

The FDTD method is applied in Reference [42] to analyze the WT foundation grounding system and the foundation size, lightning current front duration, and grounding system resistance are discussed according to the measured and simulated results.

Reference [43] presents a distributed parameter line model of a vertical conductor for circuit analysis by techniques using the computational results with time-domain FDTD and the EMTP software. The electromagnetic field advantages of using vertical conductor characteristics in circuit analysis programs are explained. The method's reliability is confirmed through small-scale tower model tests.

Reference [44] proposes an empirical expression for the effective length of counterweights connected to a 1.5 MW wind turbine foundation's ground electrode, based on wave propagation velocity and GPR peak time. Using FDTD, the impact of various counterweight configurations on impulse impedance was studied. Increasing counterweights reduces GPR gradient and impulse impedance but does not affect the grounding system's effective length.

Reference [45] investigates the transient response of wind turbine grounding systems to lightning currents. Electromagnetic modeling used antenna equation theory and TLM with soil ionization effects. TLM results were compared with FDTD and HEM simulations. Soil resistivity is a key design factor. Soil ionization minimally affects GPR but alters waveform shape.

Reference [46] analyzes the transient response of wind turbine grounding systems to high impulse currents using TLM-FDTD with ionization in homogeneous and heterogeneous soil. The effect of vertical electrodes on potential rise during lightning was studied. Vertical electrodes at the injection point are the most effective for mitigating transients, with soil ionization having no impact.

Reference [13] presents a numerical method using electromagnetic field theory with BEM and Galerkin FFT¹ to simulate lightning current distribution in a grounding network buried in horizontal multilayer soil. The model accounts for conduction, capacitive, inductive, and mutual coupling effects, validated against prior simulated and experimental results.

Reference [47] evaluates the impulse response of wind turbine grounding systems, considering frequency-dependent soil parameters and effects of first and subsequent lightning strikes. HEM modeling without soil ionization was used for various resistivities. Frequency dependence reduces GPR, impulse impedance, and impulse coefficient, particularly in high-resistivity soils and subsequent strikes.

Reference [48] analyzes isolated and interconnected wind turbine grounding systems under first and subsequent lightning strikes using HEM, VF technique, and ATP software. First return strokes perform better at low frequencies. Voltage is higher for first strikes and in high-resistivity soils.

Reference [4] examines how frequency-dependent soil parameters affect the lightning response of wind turbine grounding systems using HEM, VF, and ATP. Frequency dependence reduces GPR, lightning impedance, and impulse coefficient, notably in soils with resistivity above 300 Ωm and for short-duration currents.

Reference [5] analyzes low-frequency and impulse performance of isolated and interconnected wind turbine grounding systems using HEM without soil ionization. Interconnecting systems enhances impulse and low-frequency responses for currents with front times exceeding 1 ms, particularly in high-resistivity soils.

Reference [49] compares low-frequency and broadband modeling of distribution line tower grounding systems on overvoltages from indirect lightning using HEM and VF and EMTF. Simplified models underestimate voltage by up to 1.25 times, particularly for subsequent strikes and high-conductivity soils.

Reference [10] studies GPR in wind farm grounding systems with frequency-dependent soil parameters, excluding ionization. Effects of aerial parts, like blades and towers, on GPR were analyzed. For solving the problems, the HEM model, VF technique and power ATP-EMTP program designed for performing EMT analysis are used. Increasing interconnected systems reduces harmonic impedance at low frequencies, but effectiveness decreases at high frequencies. Omitting aerial parts does not affect GPR for first strikes but impacts subsequent strikes.

Reference [11] assesses the effect of connecting electrode length on GPR in a wind farm grounding system with five wind turbines. Frequency-domain simulations used the HEM model with frequency-dependent soil parameters. Results show that first-stroke peak GPR decreases in high-resistivity soil. With multiple strikes, electrode length does not affect peak GPR, but longer electrodes reduce low-frequency resistance.

Reference [50] investigates the transient behavior of wind turbine grounding systems using circuit theory and MOM, calculating resistive, inductive, and capacitive coupling. Results were compared with IEEE 142 standards. Transient responses for first and subsequent lightning strikes were computed in the frequency domain using inverse Fourier transform for various geometries.

Reference [51] proposes a Wide Band (WB) model of wind farm layout and grounding system frequency characteristics to evaluate transient overvoltages from direct lightning strikes to blades. The grounding system, modeled as a single 3-meter vertical rod, used thin-wire approximation and MOM. The admittance matrix was rationalized via state-space modeling for EMTF-RV. Results show lower overvoltage estimates than previous methods, especially in high-resistivity soils.

Reference [14] presents a technique for time-domain modeling of multi-port grounding systems using frequency-domain MOM, VF, and state-space equations for EMTF. Excluding soil ionization, this method accurately calculates lightning-induced overvoltages with reduced computation. Seasonal soil parameter variations indicate worse lightning impulses in dry soils, especially for subsequent strikes.

Reference [52] presents a numerical technique to evaluate transient overvoltages transferred between wind turbine grounding systems in a wind farm. Using circuit theory and MOM in the frequency domain, the transient response was calculated via inverse Fourier transform with double-exponential formulation.

Reference [53] examines wind turbine grounding impedance using a full-wave approach with NEC-4 code, thin-wire approximation, and MOM solution of the Pocklington integro-differential equation. Without varying soil parameters or ionization, low-frequency impedance depends on soil, but at high frequencies, adjacent impedances have minimal impact, and interconnected systems behave like single systems. Reference [54] evaluates wind turbine grounding system impedance per IEC TR61400-24 with interconnected systems, excluding frequency-dependent soil parameters or ionization. Spatial characteristics of first and subsequent return strokes, like GPR and step voltage, were simulated using MOM and MATLAB. Interconnecting systems reduces low-frequency impedance and peak GPR, but only nearby turbines improve late-time response in low-resistivity soils. Reference [55] studies factors affecting grounding performance in transient response to lightning current using an electromagnetic MOM model compared to a simple resistance model. At low frequencies, ground impedance approximates Low Frequency Resistance (RLF), but at high frequencies, it behaves inductively, exceeding RLF. Reference [56] examines the impact of grounding system structure and vertical electrode configuration on GPR and transient impedance during lightning impulses using MOM for blades, tower, and grounding system. Grounding rings and vertical electrodes reduce GPR and transient impedance but do not affect rise time and have minimal impact on early transient times. Reference [7] presents frequency-dependent broadband modeling of single- and multi-port grounding systems buried in homogeneous and two-layer soil without solving the impedance matrix equation. Using MOM, the impedance matrix was calculated from direct current (DC) to several MHz and processed to the time domain via VF. Simulations showed reflection coefficients and soil layer depth affect impulse impedance. Reference [57] investigates the lightning response of two coupled wind turbine grounding systems connected via a bare underground conductor. A frequency-dependent electromagnetic model (MOM) was combined with transmission line theory. Bare conductors yield greater GPR reduction. The influence of adjacent grounding systems decreases with frequency, particularly in high-resistivity soils.

Reference [9] analyzes distributed voltages in a wind turbine and medium voltage distribution line (MVDL) connected to a wind farm (WF) with four turbines in soils with 1000 and 5000 Ωm resistivity. Using X Grounding System Laboratory (XGSLab) and PEEC, GPR, MVDL phase conductor voltages, and blade tip voltages were computed. For the subsequent negative impulse (SNI), GPR exhibits oscillatory behavior due to multipath interference, unlike the first positive impulse (FPI).

The full-wave simulation of single and interconnected WT grounding systems is shown in Reference [60] for the verification of the proposed CDEGS coupled with MOM to analyse safe response for 50 Hz faults and lightning currents. Comparisons of these currents for single and two-turbine cases have shown invalidity of some of the design requirements set by the international standards.

Reference [61] computes the minimum electrode length for a two-layer soil model at three wind turbine sites, considering electrode dimensions, burial depth, and frequency. Using CDEGS's RESAP, FFTSES, and HIFREQ codes, simulations showed the proposed method reduces GPR by up to 64% and achieves grounding impedance below 10 Ω at low frequencies.

Reference [62] examines various ground electrode arrangements for wind turbine lightning protection in homogeneous soil with frequency-dependent and independent parameters using CDEGS. Frequency-dependent parameters reduce ground impedance by up to 85% at high frequencies. Horizontal electrode length should exceed IEC 61400-24 standards.

Reference [63] presents a method to evaluate lightning protection system effectiveness and select wind turbine grounding systems in wind farms. Full-wave simulations with CDEGS showed accurate soil classification is essential, with ring and horizontal electrode configurations offering optimal performance.

Reference [64] assesses GPR and impedance of wind turbine grounding systems across three Australian wind farm sites using four soil models in CDEGS, excluding concrete effects. Impedance is low in a three-layer horizontal soil model at low frequencies. Including rebar in grounding design reduces impedance, and frequency-dependent parameters yield lower impedance than frequency-independent ones.

Reference [6] examines frequency-dependent soil models' effects on grounding electrode performance during direct and indirect lightning strikes using CDEGS and MOM. In homogeneous and two-layer soil models, frequency-dependent parameters, particularly Messier's, reduce potential rise. Indirect lightning and frequency-dependent parameters have minimal impact on GPR.

Reference [59] models lightning strikes on transmission towers using vector matching techniques. With MOM and vector matching, a broadband circuit model of the tower and grounding system was developed. Results, validated with CDEGS and ATP-EMTP, confirmed the model's accuracy for scaled lightning waveforms.

Reference [65] studies the effect of lightning current waveform on impulsive characteristics of a horizontal grounding network with 0.6 m burial depth, 6 m length, 5 mm conductor radius, 14 Ω m conductor resistivity, and 240 relative permeability using CDEGS. Peak GPR, power frequency impedance, impulse impedance, and impulse factor for 50/26, 20/8, and 350/10 μ s waveforms depend on injection position and waveform shape.

Reference [66] presents a grounding design to enhance the lightning performance of a 500 kV transmission line by analyzing soil characteristics and comparing TFR and TFI of conventional and new configurations. Using CDEGS's RESAP, a two-layer soil model was identified. Low-frequency analysis was performed using CDEGS modules, while PSCAD/EMTDC was used for the high-frequency analysis. The new diamond-pattern design with four 60 m ground wires and one vertical rod reduced TFR compared to TFI.

Reference [67] examines impulse resistance of tower grounding systems using three-dimensional intersecting short conductors, reducing resistance with nonlinear soil ionization (i.e., local soil breakdown under high surge current) [68,69]. The optimized model with horizontal and vertical intersecting conductors offers the best impulse resistance reduction, especially in high-resistivity soils. CDEGS calculations differ by only 1.8% from laboratory results.

3.2. Recent directions and missing strands (2020–2025) mapped to this review

To directly address recent trends and to make the coverage explicit, Table 2 lists representative studies (primarily 2020–2025) aligned with the core themes of this review: (i) WT grounding transients (GPR/impulse impedance/over-voltages), (ii) wideband/full-wave electromagnetic modeling, (iii) frequency-dependent and multilayer soil behavior, (iv) wind-farm-scale coupling and collection-network effects, and (v) optimization-oriented approaches. These works complement the broader set of references discussed throughout Section 3.

3.3. High-Frequency Soil Behavior and Frequency-Dependent Parameters

Problem definition. Lightning currents excite a broad bandwidth, so soil electrical parameters (conductivity/resistivity and permittivity) and the resulting grounding impedance should not be assumed frequency-invariant in general. In this context, *frequency-dependent soil behavior* denotes dispersive soil response, which changes the wideband grounding impedance and therefore the transient GPR and overvoltage waveforms compared with constant-parameter assumptions [4,6,47,70].

Why it matters. Multiple WT-grounding studies report that adopting frequency-dependent soil parameters can materially change the predicted impulse impedance and GPR, particularly in higher-resistivity scenarios and for fast-front excitation [4,6,47,62]. Consequently, a model calibrated only at DC or power frequency may not provide a reliable picture of lightning-relevant performance [6,64].

Table 2. Representative recent literature (2020–2025) mapped to the main themes of this review.

Theme	Representative sources and how they relate
WT grounding transients (GPR, impulse impedance, over-voltages)	Field/measurement and transient-response evidence and assessment for WT grounding and lightning effects [1,2,8].
Wideband/full-wave EM modeling (MoM/PEEC/FDTD/BEM, hybrids)	Full-wave/wideband formulations and broadband-to-time equivalents for lightning studies in WT/wind-farm contexts [9,13,12,14,7].
Frequency-dependent soil parameters (incl. \ multilayer/heterogeneous)	Quantified impact of frequency-dependent soil modeling on grounding response and lightning performance (including layered soils) [4,5,6,7].
Wind-farm-scale modeling and coupling (incl. \ collection network)	Interconnected grounding, coupling length effects, and the role of the wind-farm network/links in transient voltage distribution [8,10,11,9].
Optimization and emerging data-driven design viewpoints	Optimization or parameter-tuning strategies for grounding improvement, and broader wind-system optimization trends that motivate future lightning/grounding workflows [15,16,17].

How studies model it. Typical workflows compute grounding impedance or admittance over frequency (using field or circuit formulations or tools such as CDEGS-type workflows), then map results to the time domain using inverse transforms or broadband rational fitting/state-space realizations [6,7,14,58,64]. Wideband fitting (e.g., vector fitting) is commonly used to build EMT-ready equivalents while retaining broadband behavior [7,14,37,58].

Limitations/pitfalls. A primary difficulty is soil-parameter identification over frequency (measurement burden and model-choice ambiguity), which can lead to non-unique calibrated dispersion models [6,64]. In addition, broadband-to-time workflows require attention to bandwidth selection, sampling, and fit diagnostics (stability/passivity/casuality considerations) to avoid artifacts in time-domain waveforms [7,14,58].

Practical implications. For engineering studies of WT lightning transients, frequency-dependent soil modeling should be treated as a key sensitivity axis, and EMT studies should prefer validated wideband grounding equivalents rather than purely resistive representations when fast-front behavior is under investigation [6,14,70]. This complements IEC 61400-24 guidance while clarifying that transient credibility depends on the modeled bandwidth and parameter calibration basis [3,6].

What to do next. More measurement-linked datasets and benchmark-style reporting are needed to calibrate soil dispersion models and to validate wideband grounding response under representative impulses [6,22,23].

3.4. Wind-Farm-Scale GPR Modeling and Grounding Interconnection

Problem definition. In wind farms, turbine grounding systems may be interconnected (via deliberate bonding conductors and/or through the collection system), so a lightning event at one turbine can redistribute GPR and transient voltages across multiple turbines. The modeling problem is to quantify how interconnected grounding networks share injected currents and how transferred potentials appear at neighboring turbines and nodes [8,10,11,38].

Why it matters. Interconnection can reduce local GPR at the struck turbine by providing additional current-return paths, but it can also increase the relevance of transferred voltages and multi-turbine coordination issues [9-11,57]. Therefore, conclusions drawn from isolated single-turbine models may not generalize to farm-scale configurations where topology and conductor type matter [8,9].

How studies model it. Farm-scale analyses have been performed using time-domain circuit/TLM approaches as well as frequency-domain/full-wave and hybrid methods, often supported by broadband equivalents to interface with EMT tools [9-11,38,39,52]. Parametric studies commonly vary interconnection topology and interconnecting conductor properties to evaluate GPR reduction and transferred voltage trends [11,57].

Limitations/pitfalls. Scaling to realistic farm footprints introduces computational and modeling burdens (multi-turbine geometry, long interconnects, and frequency range). Soil variability across the farm is often simplified, which can mask worst-case combinations of topology and local soil conditions [9,64]. Moreover, if interconnections are modeled without consistent wideband assumptions, predicted sharing and transfer may become tool- or parameterization-dependent [9,14].

Practical implications. Grounding design should be coordinated at the farm level: interconnection strategy, conductor type (e.g., bare vs. insulated), and bonding/shielding decisions can influence both local mitigation and transferred stresses [8,11,57]. These results motivate integrated studies that couple grounding interconnection with cable/sheath grounding and surge protection placement [9,40].

What to do next. Future work should emphasize validated multi-turbine benchmark cases and, where feasible, field/lab measurements that can confirm transferred-voltage and GPR-sharing predictions under representative impulses [9,23].

3.5. Electromagnetic Coupling Between Turbines and Collection Networks

Problem definition. Beyond direct conduction through interconnected grounding, lightning produces intense EM fields that can couple into nearby conductors. In wind farms, the collection network (MV cables, cable sheaths, bonding conductors) provides additional coupling paths, so induced and transferred transients can occur even at non-struck turbines [9,29,41].

Why it matters. EM coupling and network paths affect insulation coordination and surge-protection needs at farm scale, because induced/transferred overvoltages may stress equipment away from the strike location [9,49,51]. As a result, grounding and lightning protection should be analyzed as a coupled structure + ground + network problem rather than a purely local footing issue [9,12].

How studies model it. Approaches include full-wave or wideband system models (e.g., PEEC/MoM-type formulations) combined with broadband-to-time conversion, as well as multiconductor transmission-line modeling for the collection network integrated into EMT simulation [9,12,40,41,58]. Cable sheath grounding and bonding configurations are typically modeled explicitly because they strongly affect induced/transferred voltages [40,51].

Limitations/pitfalls. Coupling predictions depend on geometric detail (cable routing, spacing, sheath bonding, tower/WT representation) and on soil assumptions, while validation is often limited to simulation cross-checks due to measurement difficulty [41,49]. In addition, inconsistent grounding representations across tools (purely resistive vs. wideband) can bias induced-voltage conclusions [14,49].

Practical implications. Engineering mitigation measures include robust bonding of cable sheaths, appropriate SPD placement at key interfaces, and coordinated grounding/connection strategies that consider both conducted and EM-coupled transients [25,29,40]. These measures are most credible when assessed using models that include both the grounding network and the collection system under consistent wideband assumptions [9].

What to do next. Future studies should develop reproducible, integrated co-simulation workflows (grounding + collector network) and expand benchmark cases that quantify transferred/induced stresses under representative lightning excitations [9,51].

3.6. Multilayer Soil and Stratification Sensitivity

Problem definition. Real sites are frequently multilayered/stratified, and the lightning response of grounding electrodes depends on layer resistivity contrasts, layer thickness, and frequency dependence. The modeling problem is to capture how stratification modifies return-current distribution and wideband grounding impedance compared with homogeneous assumptions [6,7,13,22,61].

Why it matters. Layered soil can shift both impulse impedance and GPR predictions and can change the relative benefit of design choices (rod depth, ring/mesh layout, interconnection length) [6,13,61]. Therefore, conclusions from homogeneous-soil studies may be non-robust when applied to stratified sites [6,64].

How studies model it. Layered soils are modeled using multilayer-capable EM formulations (e.g., BEM/MoM with appropriate image/Green-function treatments) and/or commercial workflows that fit multilayer soil models from measurements (e.g., RESAP-type routines) [13,61,64,66]. Time-domain studies may incorporate multilayer effects via calibrated parameters and broadband equivalents [7,39].

Limitations/pitfalls. A major pitfall is insufficient site characterization: limited-depth resistivity measurements can yield non-unique layer fits, and spatial variability across the farm footprint is often ignored [22,23,64]. Sensitivity to layer assumptions should therefore be reported explicitly rather than presenting a single deterministic result [6].

Practical implications. For design studies, multilayer soil modeling (at least two-layer when justified by measurements) should be treated as a baseline rather than an optional refinement, particularly when lightning transient performance is the target [6,22,61]. This supports more credible grounding choices and can reduce mismatch between predicted and observed behavior [23].

What to do next. Future work should promote uncertainty-aware reporting (layer-fit ranges and sensitivity envelopes) and benchmark cases that link multilayer identification to transient validation metrics [6,23].

3.7. Lightning Attachment and Waveform Variability

Problem definition. Lightning attachment location (blade/tower pathways) and lightning current waveform variability (first vs. subsequent strokes, polarity, and front-time differences) influence how transient currents distribute through the WT structure and into the ground. The modeling problem is to capture how different representative waveforms and injection paths interact with wideband grounding impedance and farm/network coupling [3,9,11,47,48,65].

Why it matters. Different waveforms emphasize different physical mechanisms: fast-front currents increase the relevance of inductive/capacitive and coupling effects, while longer-duration components stress current-dissipation and low-frequency grounding performance. Several WT grounding studies explicitly compare first/subsequent representative currents and show that conclusions (e.g., the benefit of interconnection or the importance of frequency dependence) can depend on waveform characteristics [4,11,47,65].

How studies model it. Common practice is to evaluate a small set of representative lightning current waveforms (e.g., varying front-time and duration) and to compare responses for first and subsequent representative strokes, sometimes within farm-scale configurations [9,11,65]. Attachment and current-path assumptions are handled either by selecting the injection point(s) in circuit/EM models or by using scaled/lab configurations for validation of induced/overvoltage behavior [12,20,36].

Limitations/pitfalls. A common pitfall is drawing general conclusions from a single waveform or a single attachment assumption. Because waveform statistics are site- and storm-dependent, a limited waveform set may under-represent uncertainty unless treated as a sensitivity axis [3,65]. Moreover, if grounding is modeled as purely resistive, waveform-driven differences can be distorted for fast-front cases [14,31].

Practical implications. Engineering studies should test robustness against waveform variability by using a small, clearly documented set of representative waveforms and injection paths consistent with IEC 61400-24 practice [3,65]. This supports more defensible insulation coordination, SPD selection, and grounding/interconnection decisions under realistic uncertainty [8,25].

What to do next. More measurement-linked data on WT lightning currents and attachment-path effects would improve representativeness and help validate simulation assumptions [1,23].

3.8. Time-Domain Wave Propagation Mechanisms in Grounding and WT Structures

Problem definition. WT structures and grounding conductors are electrically long at lightning-relevant frequencies, so lightning response involves traveling-wave propagation, reflections, and distributed coupling rather than instantaneous lumped behavior. The modeling problem is to capture time-domain propagation along towers, cables, and grounding electrodes and its interaction with soil and interconnections [39,42-44,50].

Why it matters. Wave-propagation effects can shape the early-time GPR and overvoltage waveform and can create oscillatory behavior in some configurations. They also motivate the concept of an effective electrode utilization under fast impulses, where distributed geometry and propagation determine how quickly different portions of the grounding system participate [42,44]. Consequently, purely resistive (or overly lumped) grounding representations can mischaracterize waveform peaks and timing [14,31].

How studies model it. Time-domain approaches include TLM/FDTD and distributed-parameter representations integrated into EMT tools, while frequency-domain field solutions are also converted to time-domain via broadband fitting [14,39,42,43,58]. WT-specific transient models connect blade/tower representations to grounding and cables so that propagation and coupling are represented in system-level studies [12,36].

Limitations/pitfalls. High-fidelity propagation modeling can be computationally intensive and sensitive to discretization choices (time-step, segmentation and mesh), while parameter identification for distributed equivalents may be non-trivial [39,42]. Without clear bandwidth and fit-quality reporting, time-domain waveforms obtained from wideband conversion may include numerical artifacts [14,58].

Practical implications. Propagation-aware modeling supports more reliable conclusions about grounding configuration effectiveness for fast-front events and helps prioritize mitigation measures (bonding continuity, multi-point grounding, and coordinated network protection) [25,36,44]. In practice, this reinforces that EMT studies should incorporate validated wideband grounding models when waveform timing and peak values are design-critical [14].

What to do next. Future work should expand benchmark validation of propagation-sensitive cases (including multi-turbine layouts and collector-network interaction) and report reproducible best practices for wideband fitting and verification in WT lightning studies [9,14,58].

4. Classification framework

Because lightning is a broadband transient and because WT grounding involves coupled electromagnetic and soil phenomena, the modeling literature reviewed in this paper can be interpreted more consistently when grouped along a small set of criteria. We adopt the following framework to classify the approaches already discussed throughout this section, with the goal of clarifying what each method can (and cannot) capture, what it typically costs computationally, and how it is validated.

Domain (time/frequency/wideband). Time-domain models directly compute waveforms (e.g., GPR and over-voltages in the time axis) and are often implemented in EMT programs using equivalent circuits and transmission-line elements [25,28,36]. Frequency-domain models compute impedance or admittance and field quantities over frequency and then interpret the transient behavior via inverse transforms or broadband equivalents (commonly supported by rational fitting/state-space realizations) [4,5,14]. Wideband approaches explicitly target a consistent behavior from low frequency up to the MHz range by combining a broadband field/circuit formulation with a frequency-to-time workflow (e.g., vector fitting) [7,9,12].

Model assumptions (lumped vs. distributed; quasi-static vs. full-wave; linear vs. nonlinear). Lumped or circuit-oriented representations are efficient and practical for parametric design studies, but their fidelity depends on how grounding, cables, and towers are parameterized (and on whether frequency dependence is embedded) [25,36]. Distributed formulations capture propagation and coupling more explicitly: this includes time-domain grid-based solvers (e.g., FDTD/TLM) [39,42] and frequency-domain thin-wire/full-wave formulations (e.g., MoM/NEC-type models) [14,54]. In addition, some works incorporate nonlinear soil behavior (ionization), which is particularly relevant when studying extreme impulses and/or specific soil conditions; this adds modeling uncertainty and algorithmic complexity compared with linear soil models [26,37,39].

Soil representation. The soil model is a dominant source of variation in predicted impulse impedance and GPR. The reviewed studies span (i) uniform soil, (ii) multilayer soil, and (iii) heterogeneous soil, with further refinements such as frequency-dependent electrical parameters and ionization effects [4,6,7]. In practice, the chosen soil representation should match the question being answered: simplified uniform soils can support early-stage comparisons, whereas multilayer/frequency-dependent models are more appropriate for broadband transient predictions and for site-specific studies.

Computational complexity and typical bottlenecks. For clarity, we refer to qualitative complexity levels. Low complexity methods include circuit EMT studies where bottlenecks are mainly parameter identification and model tuning (especially for grounding wideband equivalents) [25,36]. Medium complexity methods include quasi-static FEM/BEM-type analyses and many frequency-domain impedance computations where meshing, integral evaluations, and frequency sweeps become limiting factors [13,33]. High complexity methods include full-wave or strongly distributed models (e.g., FDTD/TLM, large MoM/PEEC networks) where bottlenecks are memory/time-step constraints, large matrix solutions, and broadband sampling/fitting [9,12,42].

Expected accuracy and validation style. In this review, “accuracy” is interpreted in terms of agreement with one or more validation sources. Some studies are grounded in field or laboratory measurements [20,22,23], while many modeling papers rely on simulation cross-checks between different formulations or tools (e.g., circuit vs. field solver, or commercial vs. in-house implementations) [6,13]. Measurement-based validation typically provides the strongest evidence for model adequacy, whereas cross-checks are useful for establishing internal consistency and identifying sensitivity to assumptions.

Industrial applicability. Finally, the methods can be grouped by intended use: design-stage and compliance-oriented workflows often favor faster circuit or commercial grounding tools [3,6]; detailed R&D studies use full-wave/wideband solvers to investigate coupling, wave effects, and model limitations [9,54]; and site-specific characterization relies on measurements and calibrated soil models [22,23].

Table 3 provides a compact method comparison matrix using comparative indicators (domain, soil/coupling capability, validation style, qualitative computational cost, best-use, and main limitations). This complements the narrative by making cross-method tradeoffs explicit without introducing numeric performance metrics.

Table 3. Method comparison matrix with comparative indicators for WT grounding and lightning modeling (representative sources already cited in this manuscript). Domain: T = time-domain; F = frequency-domain; WB = wideband/hybrid. Cost is qualitative (no numeric metrics).

Method family (rep.\ sources)	Domain	Soil capability	Coupling capability	Validation type	Cost	Best-use	Main limitations
Empirical/measurement-driven [22,23]	T/F	Measured/inferred parameters; layering may be implicit	Limited control of coupling; site-specific configurations	Field/lab measurements	Low	Soil/grounding parameter identification; benchmark reference points	Site-specific; limited separation of mechanisms; instrumentation constraints
Circuit-based EMT (EMTP/ATP) [25,36]	T	Uniform/multilayer via parameters; freq-dep via equivalents; ionization optional	Network-level coupling modeled; structural EM coupling simplified	Case studies; cross-checks (sometimes measurement-linked)	Low--Med	System studies (collector network, SPDs, insulation coordination); comparative configurations	Accuracy depends on grounding equivalent and validity bandwidth; simplifications of geometry/coupling
Quasi-static FEM/BEM field solvers [33,13]	F/WB	Multilayer supported (tool/formulation dependent); typically linear	Mutual coupling among electrodes/s structures captured under QS assumptions	Benchmark/cross-tool comparison; literature validation	Med	Geometry/soil-profile sensitivity; design refinement under controlled assumptions	QS approximation limits propagation realism; sweep cost (meshing/frequency sampling)
Distributed time-domain EM (FDTD/TLM) [42,39]	T	Uniform/non-uniform; ionization/freq-dep study-dependent	High (propagation, reflections, spatial coupling)	Cross-checks; sometimes measurement comparison	High	Wave-propagation/front-time sensitivity; mechanism studies	High computational burden; discretization/dispersion sensitivity; large domains difficult
Thin-wire MoM/NEC-type + wideband fitting [54,14]	F/WB	Uniform/multilayer possible; typically linear; wideband impedance extraction	High (inductive/capacitive coupling among conductors)	Cross-checks; consistency across domains	Med--High	Coupling mechanism analysis; generation of EMT-ready multiport equivalents	Matrix size/conditioning; segmentation sensitivity; requires careful broadband sampling/fitting
Hybrid EM (HEM) + VF/state-space [4,5]	F/WB	Freq-dependent soil emphasized; layering possible; usually linear	Med--High (multi-port grounding and coupling trends)	Cross-check vs.\ simplified models; EMT integration studies	Med	Systematic soil-dispersion sensitivity; EMT-compatible equivalents	Fit/bandwidth diagnostics required; results depend on soil model choice/calibration basis
PEEC/integrated WT + network formulations [12,9]	WB	Uniform/layered possible; freq-dep study-dependent	High (multi-conductor + network coupling)	Cross-checks; case studies (validation often limited by measurability)	High	Integrated turbine--collector network transient stress allocation	High modeling/setup cost; geometry detail sensitivity; wideband conversion requirements
Commercial grounding packages (CDEGS/XGSLab-type) [6,60]	F/WB	Multilayer or heterogeneous fitting workflows; freq-dep modules available	Med (geometry coupling strong; network coupling depends on workflow/integration)	Benchmarking; engineering cross-checks	Med	Engineering practice/compliance workflows; complex geometry + soil interpretation	Tool/module assumptions must be understood; transient validity depends on selected modules and inputs
Optimization/parameter-tuning [15,16]	T/F	Depends on embedded solver; often uses fitted soil/electrode parameters	Typically low--med unless integrated with multiport/full-wave models	Case-study driven; sensitivity-based justification	Med	Design improvement and decision support (screening alternatives)	Quality limited by underlying model fidelity; can hide uncertainty if not reported

Transition: from organization to comparative synthesis. Using the above framework and the method matrix in Table 3, the next section synthesizes comparative indicators across studies (recurring qualitative findings, failure/overvoltage modes, and mitigation implications) without resorting to paper-by-paper narration or introducing new numeric performance metrics.

5. Comparative analysis

This section extracts and synthesizes *comparative indicators* across the reviewed literature using the classification axes defined in Section 4. The emphasis is on cross-study patterns (rather than paper-by-paper description), including soil modeling choices (dispersion/stratification), coupling and propagation paths at wind-farm scale, qualitative treatment of ionization, typical failure/overvoltage modes, and practical mitigation implications. Table 2 summarizes these recurring qualitative takeaways.

Comparative indicators across findings (cross-study takeaways). To complement the method comparison in Table 3, Table 4 summarizes recurring qualitative findings and design-relevant takeaways across the reviewed literature, grouped by themes (rather than paper-by-paper).

Synthesis (patterns across methods and findings).

5.1. Critical Comparative Analysis

The classification in Section 4 and the mapping in Table 3 make the reviewed literature easier to navigate; however, a high-quality review must also explain *why* different approaches produce different results and what this means for engineering design. In lightning-driven WT grounding studies, discrepancies across methods are not accidental—they typically arise from (i) the physics that is *included or excluded* (propagation, coupling, inductive/capacitive storage, soil dispersion and nonlinearity), and (ii) numerical choices (meshing/segmentation, bandwidth and sampling, fitting, and dispersion/stability).

Why methods differ: dominant physical and numerical drivers.

Lightning is inherently broadband; therefore, models that are equivalent at low frequency (e.g., matching DC or 50/60 Hz grounding resistance) can diverge in predicted impulse impedance, GPR peaks, and over-voltage waveforms once inductive and capacitive effects become influential [31,50,55]. Soil representation is another dominant driver: frequency-dependent soil parameters and multilayer/heterogeneous profiles change current diffusion/return paths and modify the wideband grounding impedance [4,6,7,13]. At the wind-farm scale, coupling through inter-turbine conductors and the collection network redistributes transient voltages; thus, isolated single-turbine modeling can miss transfer effects that arise only in interconnected layouts [8,9,11,52].

Table 4. Findings/takeaways matrix grouped by themes. Entries are qualitative patterns synthesized across the reviewed literature (no invented numeric metrics).

Theme	Recurring qualitative findings (patterns)	Design-relevant takeaway (what it implies)	Representative sources
Table 4 (continued). Continued on next page.			
Grounding configuration	Rings, counterpoises, and vertical electrodes can change early-time GPR and impulse behavior; interconnecting turbines can share injected current and alter transferred stresses; diminishing returns may appear for very long conductors under fast-front excitation (effective-length/propagation effects).	Prioritize low-inductance bonding and robust connections; evaluate topology (isolated vs. interconnected; loop vs. chain) under representative waveforms; treat geometry as a transient (not only DC) design variable.	[11,21,35,38,44,57]
Soil resistivity/stratification	Layering and frequency dependence can shift impulse impedance and waveform shape relative to homogeneous/constant-parameter assumptions; limited or shallow soil surveys can yield non-unique fits; seasonal variability can change transient severity.	Use at least a justified multilayer model when measurements indicate stratification; report sensitivity to plausible soil profiles; avoid generalizing from a single “average” resistivity when lightning transients are the target.	[6,7,13,22,23,61,64]
Ionization (qualitative)	Nonlinear soil ionization can reshape transient response in some high-current scenarios, but parameters and triggering conditions are difficult to verify for a given site; conclusions may be scenario-dependent without calibration.	Treat ionization as an explicit modeling assumption; use it for scenario envelopes unless supported by credible benchmarks; avoid presenting ionization-driven mitigation as universally valid.	[26,37,39,45,46]
Failure/overvoltage modes	Beyond local GPR and step/touch hazards, transferred and induced overvoltages can appear through interconnections and collector networks (cable sheaths, MV lines, LV/control circuits); propagation and reflections can contribute to oscillatory or timing-sensitive peaks.	Analyze lightning as a coupled structure + ground + network problem for wind farms; consider both struck and non-struck turbines; ensure model bandwidth matches the front-time sensitivity of the failure mode being assessed.	[8,9,12,29,41,49]
Mitigation measures	Bonding quality, cable sheath grounding choices, SPD placement, and interconnection conductor properties (e.g., bare vs. insulated) can materially influence transferred/induced stresses; wideband grounding equivalents improve EMT credibility for fast fronts.	Coordinate grounding, bonding, and SPDs at farm level; prefer validated wideband grounding equivalents when using EMT tools for lightning; align checks with IEC 61400-24 waveform practice.	[3,9,14,25,40,57]
Practical design implications (cross-cutting)	The dominant drivers of disagreement across studies are typically soil representation (layering/dispersion), coupling paths (farm/network), and bandwidth/propagation effects; validation is often limited by measurement availability and therefore relies on cross-checks.	Report applicability boundaries (bandwidth, soil model basis, topology) and perform sensitivity-based design decisions; where possible, anchor conclusions to measurement-linked datasets or benchmark cases.	[6,9,14,23]

On the numerical side, grid-based solvers (e.g., FDTD/TLM) can exhibit numerical dispersion if space/time resolution is not adequate, while frequency-domain workflows require adequate bandwidth sampling and robust broadband-to-time conversion (often via vector fitting/state-space realizations) [7,14,58].

Empirical and measurement-driven evidence: what it validates (and what it cannot)

Field and laboratory measurements provide the strongest grounding for model credibility because they expose real installation details (foundation rebar, soil variability, seasonal conditions, bonding, and measurement constraints) that are difficult to idealize. Measurement-based studies are therefore essential for calibrating soil parameters and validating impedance/response trends [20,22,23]. Their limitation is that measurements are often site-specific and do not directly separate individual mechanisms (e.g., soil dispersion vs. geometry vs. coupling), which means they are most powerful when used as reference points for model tuning and cross-validation rather than as stand-alone generalizations.

Circuit-based EMT (EMTP/ATP) approaches: fast system studies but sensitive to grounding parametrization

Circuit-based EMT models excel when the engineering question is network-oriented: surge propagation on collector lines, SPD placement, insulation coordination, and comparative evaluation of connection strategies. They are computationally efficient and integrate naturally with turbine electrical subsystems [25,28,29,36]. Their main vulnerability is the representation of grounding and soil over a wide band: if grounding is modeled only as a low-frequency resistance (or with insufficient frequency dependence), early-time peaks and waveform shapes can be mischaracterized because inductive/capacitive storage and distributed coupling are not explicitly represented [31,55]. Some EMT-based works address this by embedding frequency-dependent grounding models and/or incorporating soil ionization elements [25,26,37], but these additions introduce parameter-identification and validation demands that must be treated explicitly.

Quasi-static and hybrid EM frequency-domain methods: controlled geometry/soil modeling, but still assumption-driven

Quasi-static field solvers (e.g., FEM) and multilayer-capable formulations (e.g., BEM in multilayer soil) are valuable for understanding geometry-driven effects and soil-profile sensitivity under controlled assumptions [13,33]. Hybrid electromagnetic modeling (HEM) plus broadband workflows is especially effective for systematically studying frequency-dependent soil parameters and for producing EMT-ready equivalents through fitting [4,5,10,47]. The key limitation is that “quasi-static” and “hybrid” approaches still depend strongly on the chosen boundary conditions, the modeled frequency range, and how the frequency response is mapped into time domain. As a result, two studies can both be “frequency-domain” yet disagree if one uses simplified soil/return assumptions or a narrower bandwidth, or if the broadband conversion is insufficiently representative.

Full-wave and distributed time-domain solvers (FDTD/TLM): propagation realism at higher computational and modeling cost

Distributed time-domain solvers explicitly represent wave propagation, reflections, and spatial coupling, making them well-suited for studying lightning front-time sensitivity and geometric scale effects [39,42,44]. These benefits come with higher computational cost and practical numerical constraints: grid resolution and time-step selection influence accuracy (including numerical dispersion), and absorbing boundaries/soil interfaces must be treated carefully. Consequently, these methods are typically more appropriate for detailed R&D studies or for validating simplified equivalents rather than for routine design iteration.

Thin-wire MoM/NEC-type and wideband equivalents: strong coupling fidelity, but matrix/bandwidth constraints

Thin-wire full-wave formulations (MoM/NEC-type) naturally capture inductive/capacitive coupling among conductors and the frequency-dependent transition from resistive to inductive behavior that is often observed in grounding impedance [53-55]. When coupled with wideband fitting/state-space realizations, such models can provide multi-port equivalents suitable for EMT simulation while retaining broadband characteristics [7,14]. The bottlenecks are the cost and conditioning of large impedance/admittance matrices, the need for careful segmentation (which influences convergence), and the requirement for adequate broadband sampling. Engineering use is therefore strongest when these models are applied to generate validated equivalents or to study coupling mechanisms that circuit-only representations cannot resolve.

PEEC and integrated WT/collector-network modeling: multi-conductor coupling and system context

PEEC-based and related multi-conductor formulations provide a direct bridge between geometry-resolved electromagnetic modeling and circuit-level interpretation, which is particularly valuable when the WT structure, internal conductors, and external network interact strongly [9,12,40]. These approaches can reveal how coupling and topology distribute transient stress across components (tower/blades/cables and network links). Their limitations are similar to other wideband/full-wave approaches: computational cost, the need for careful broadband-to-time conversion, and sensitivity to geometric and soil modeling choices.

Commercial grounding packages and engineering workflows: practical breadth, but module-awareness is essential

Commercial tools (e.g., CDEGS/XGSLab-type workflows) are widely used in engineering practice because they support complex grounding geometries, multilayer soil interpretation, and standardized workflows for grounding assessment [6,9,60-64]. Their practical strength is rapid scenario evaluation and compatibility with compliance/design processes; however, users must remain aware of the underlying modeling assumptions (quasi-static vs. higher-frequency modules, soil fitting choices, and network coupling representations) and should cross-check results when the transient bandwidth or coupling regime pushes beyond the validated scope.

Cross-cutting issue: nonlinear soil ionization (when it matters, and why it is uncertain)

Nonlinear soil ionization models can alter predicted impulse behavior and waveform shapes under high-current conditions, and they appear in multiple modeling families (from EMT circuits to distributed solvers) [26,37,45,46]. Their main challenge is that ionization parameters and triggering conditions are difficult to verify for a specific site and installation; therefore, ionization-enhanced predictions should be treated as scenario-dependent unless supported by site-calibrated evidence or credible experimental benchmarks.

Another potential research direction is the *long-term conditioning* of soil by repeated lightning strikes. Experimental evidence indicates that lightning-induced heating and melting can form fulgurites and increase the resistivity of the affected material, which may raise the effective grounding/earthing impedance and compromise long-term performance [71]. Since grounding characteristics and soil properties can vary over time and with site conditions, future work should verify and quantify whether repeated strikes produce persistent changes that warrant periodic reassessment using established measurement procedures (e.g., IEEE Std 81.2-1991) [72]. Table 5 presents the mini-matrix of common modeling assumptions and their typical consequences and engineering risks.

Reviewer-facing synthesis (explicit, non-generic takeaways).

- Even when two studies match DC grounding resistance, their lightning transient predictions can diverge if one includes inductive/capacitive effects and the other uses a purely resistive grounding equivalent [31,55].
- Frequency-dependent soil modeling is not a “detail”: it is a primary driver of wideband grounding impedance and can change impulse-response trends compared with frequency-independent assumptions [4,6,7].
- Layered-soil formulations (e.g., multilayer-capable BEM/MoM workflows) can capture behaviors that homogeneous-soil simplifications inherently miss, especially when interpreting broadband responses [7,13].
- Wind-farm interconnection and collection-network paths are essential to the overvoltage story; isolated single-turbine models cannot represent transferred surges and coupling-driven redistribution [8,9,11].
- EMT tools are highly effective for system studies (SPDs, network surges, comparative grounding connection strategies), but they require validated wideband grounding equivalents to remain credible for fast-front lightning behavior [25,36].
- Full-wave/distributed methods (FDTD/TLM, MoM/PEEC families) become necessary when propagation and multi-conductor coupling determine stress allocation, rather than only steady-state or low-frequency grounding performance [9,12,14,42].
- Broadband-to-time conversion (often via vector fitting/state-space realization) is a powerful bridge from field solvers to EMT simulation, but its validity depends on the chosen bandwidth and fit quality [14,58].

Ionization models can strongly influence impulse-response predictions in some scenarios, but because site-specific parameter verification is difficult, conclusions should be framed as scenario-dependent unless validated [26,37,46].

Overall, the practical implication is that the “best” method depends on the engineering question: EMT-based models are often sufficient for rapid network-level mitigation studies and comparative grounding connection strategies, while wideband/full-wave or distributed solvers are justified when the dominant uncertainties are broadband soil behavior, wave propagation, and multi-conductor coupling (especially in wind-farm configurations and collector-network contexts).

5.2. Significance of Time-Domain versus Frequency-Domain Modeling in Lightning Effects on WTs and Tall Structures

The phenomenon of lightning can be represented as a transient current waveform whose relevant content spans a broad range of time scales and frequencies. Consequently, both time-domain and frequency-domain viewpoints are useful: time-domain simulations directly provide waveforms (e.g., GPR and overvoltages), while frequency-domain analyses help reveal how grounding impedance and soil electromagnetic behavior vary with frequency and how this variation maps into transient response. Two recurring factors in assessing grounding effectiveness under lightning are (i) the frequency dependence of soil electrical parameters over the lightning-relevant bandwidth, and (ii) potential nonlinear soil behavior (often discussed in terms of ionization) under severe impulsive conditions. The reviewed literature repeatedly indicates that neglecting frequency dependence can bias transient predictions in some scenarios, particularly for higher-resistivity soils and fast-front excitations [6,47,61,62]. By contrast, nonlinear effects are more scenario-dependent and are typically emphasized in studies focusing on high-current impulses and site-specific conditions [5,54]. Overall, incorporating frequency-dependent soil behavior is widely supported as a key step toward more credible transient grounding analysis, while nonlinear soil modeling should be treated with explicit assumptions and, where possible, validation.

Table 5. Mini-matrix of common modeling assumptions and their typical consequences and engineering risks (illustrative patterns observed across the reviewed method families).

Assumption	Typical consequence	Engineering risk
Grounding represented as a single low-frequency resistance (no L/C, no wideband behavior)	Early-time peaks and waveform shapes can be misestimated when inductive/capacitive effects dominate [55,31]	Non-conservative insulation coordination; underestimated step/touch or equipment stress
Frequency-independent soil parameters used for lightning-relevant bandwidth	Wideband impedance differs from reality; impulse impedance/GPR trends can shift [4,6]	Incorrect grounding sizing or mitigation priority for high-resistivity sites
Homogeneous soil assumed where multilayer/heterogeneity is present	Return-current distribution and attenuation differ from assumed behavior [13,7]	False confidence in design robustness across seasons/locations
Single-turbine model used for a wind-farm problem (neglect coupling and network paths)	Transfer and redistribution of transient voltages are not captured [8,9,52]	Misplaced SPDs/bonding; overlooked inter-turbine stress paths
Quasi-static approximation applied where propagation/reflection effects are relevant	Resonances and propagation-driven wave effects are suppressed or missed	Underestimation of cable/collector-line surge effects and timing-dependent peaks
Wideband fitting performed with insufficient frequency range or inadequate sampling	Time-domain response may not reflect the intended broadband behavior [58,14]	Non-robust conclusions from artifacts; incorrect mitigation ranking
Coarse spatial/temporal discretization in grid-based solvers	Numerical dispersion and stability constraints influence waveform fidelity	Design choices based on numerically distorted peaks/timings
Ionization included without site-calibrated evidence or credible benchmark comparison	Nonlinear mitigation effects may be over- or underestimated [26,46]	Overconfident risk reduction claims; unreliable worst-case assessment

5.3. Evaluation of Approaches, Methods, and Simulation Tools Across Reviewed Studies

This classification goes further than the writing methods of the articles; it also notes if the techniques concern time or frequency: what kinds of software are used (specific or general), and whether such software was used to solve models or to build them. In the development of software tools, however, a clear and marked evolution has occurred. First it started with the use of experimental approach, followed by the analytical and finally the use of scientific /number-based software or both. This change has facilitated modeling structuring and control of models in time and frequency domains much better. Because of the development in computer technologies, the application of lightning phenomena was earlier restricted to some experimental analytical or numerical ones, which in any case yielded approximate results, to say the least when performed by an ordinary software. Although there are large scale studies with respect to current through lightning on earthing networks, such studies were likely deficient due to classical software limitations leading to guesstimates and relatively imprecise results (2018 [14]). This has persisted up to the recent past, whereby increasing numbers of interventions have considered commercial software for analyses based on numerical solutions of Maxwell equations. Such technologies can provide detailed representations of lightning activity, including spatial/temporal characteristics and propagation-related effects. Nevertheless, commercial toolchains can be costly, which may limit their accessibility for some users. Examples include XGSLAB and CDEGS software.

5.4. Prevalence and Distribution of Analytical and Computational Approaches in the Literature

Figure 1 shows the distribution of modeling approaches in the reviewed core set; circuit-based EMT studies implemented in EMT-type tools appear most frequently. There are only a few articles with off-the-shelf models built into them. Fitting has been an effective approach in the papers for changing the obtained frequency models to time models and achieving convenience in solving the equivalent models. Next, the reason why these articles also employed the MOM technique for such application is that this technique gives good results and the problem being studied is of a high frequency nature. In the end, it also turned out that CDEGS software which is an elaborate system of components used for studying different sweat such as the Influence of Lightning Strikes on Tall Structures and Windmills has been used many times.

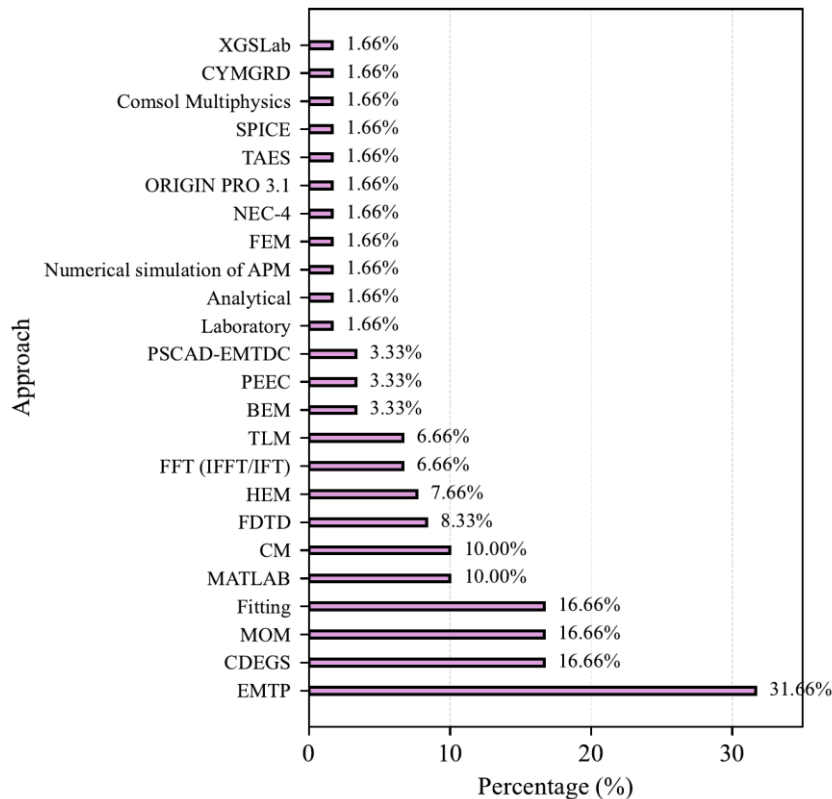


Figure 1. Distribution of modeling/analysis approaches reported in the reviewed lightning-WT grounding literature. The horizontal axis shows the share of reviewed studies (%) in which a given approach/tool is used (alone or within a hybrid workflow); the values annotated on the bars indicate the same percentage. The vertical axis lists the approach/tool categories used for classification.

Table 6 evaluates the extent of the multidimensional approach as well as using any one of the approaches as the only option in the literature reviewed, indicating the per cent of the approach used only and together with other approaches.

Note that the quantitative counts reported later (e.g., Figures 1–5 and Table 4) are computed from the core set of ~60 grounding-focused studies reviewed; additional contextual references added for completeness are not included in those counts.

For instance, looking at the fourth row in the table, BEM appears in two studies within the reviewed core set (~60 studies), and in both cases it is complemented by an FFT-based technique. Also, as it can be seen from the last row in the table, CDEGS software is used in ten studies within the reviewed core set; in eight of those, the software is used as a standalone tool. One study combines it with PSCAD/EMTDC, while another introduces CDEGS alongside EMTP and fitting techniques.

5.5. Critical Components of WT and Tall Structure Lightning Protection Systems for Modeling

A further question that may arise is: what finally is the part of lightning protection of a WT and tall structures that can be focused on the most?

This is also an important question, especially if we talk about modeling resources – be it modeling efforts devoted to a particular aspect, the modeling cycle in regards to parameters and hardware limitations, we are usually interested only in what called ‘the wicked component’. This way, we are in a position not to allow excessive modeling accuracy x which relates to some of the dimensions of the model, and, saves us so-called underfitting and overfitting modeling challenges and their effects. In this section, we cite and respond to concerns raised in papers that have been reviewed. A number of scientists emphasize that the most complicated process of modeling the components of a WT is the modeling of the earthing system. The following studies include these publications among years of publication: [34] 2016, [64] 2019, [52] 2018, [63] 2019, and [51] 2018. Further works advanced and stated that the only system that needs to be modeled is the Earth system: 2015 [50], 2019 [20], 2017 [47], 2019 [54], 2018 [35], 2017 [27], 2023 [9], 2016 [42], 2019 [4], 2021 [44], 2013 [45]. Within the core set of approximately sixty reviewed studies, five specifically cited the simulation of WT grounding-system components as an existing modeling gap. Seventeen of the articles, however, the authors maintained that it is not essential to model the other components of a WT apart from the grounding system, since the results obtained without modeling such components do not differ from those obtained when modeling all the components.

5.6. Extent of Modeling Efforts for WT Protection Systems and Transmission Line Towers

This section of the research is concerned with assessing the specific focus areas encompassed within the interpretative framework of the completed works. The current analysis will, afterwards, assess the extent to which the foundational system has been revisited independently, or where required, along with any of the individual components of each structure, all the structures, or in all the systems as a whole.

Table 6. The amount of use of approaches independently or in combination with other approaches in the reviewed core set of studies (~60), reported as counts.

Approach	The number of use of the approach	Use the approach in combination with	The number of use the approach independently
Laboratory	1	-	1
analytical	1	-	1
Numerical simulation of APM	1	-	1
BEM	2	FFT(IFFT/IFT)(2)	0
FEM	1	-	1
FDTD	5	EMTP(1),TLM(1)	3
NEC-4	1	MOM(1)	0
PEEC	2	Fitting(1),SPICE/TAES/Fitting(1)	0
ORIGIN PRO 3.1	1	MATLAB(1)	0
TAES	1	PEEC/SPICE/Fitting(1)	0
SPICE	1	PEEC/TAES/Fitting(1)	0
Cosmol Multiphysics	1	MATLAB/EMTP(1)	0
PSCAD-EMTDC	2	MATLAB/CYMGRD(1),CDEGS(1)	0
FFT(IFFT/IFT)	4	BEM(2),MOM/CM(2) ORIGIN PRO3.1(1), MOM(1),EMTP/Cosmol	0
MATLAB	6	Multiphysics(1),CYMGRD/PSCAD-EMTDC(1)	2
TLM	4	FDTD(1)	3
CM	6	MOM/IFT(2),EMTP(3)	1
HEM	7	EMTP/Fitting(4)	3
MOM	10	Fitting(1),\ EMTP/Fitting(2),\ MATLAB(1),\ NEC-4(1),\ CM/IFT(2) MATLAB/Cosmol Multiphysics(1),\ FDTD(1),\ HEM/Fitting(4),\ MOM/Fitting(2),\ CM(3),\ CDEGS(1)	3
EMTP	19	PEEC(1),\ PEEC/TAES/SPICE(1),\ MOM(1),\ EMTP/MOM(2),\ EMTP/HEM(4),\ EMTP/CDEGS(1)	7
Fitting	10	MATLAB/PSCAD-EMTDC(1)	0
CYMGRD	1	--	0
XGSLab	1	--	1
CDEGS	10	PSCAD-EMTDC(1),EMTP/Fitting(1)	8

Figure 2 shows the level of attention reserved for the reviewed papers in terms of the proportion of topics on one WT, a cluster of interconnected WTs, wind farms, towers, or high voltage structures. From that graph, it can be inferred that the majority of the reviewed papers were on the single WT while the rest covered inter-connected WTs or a wind farm which is also true in reality as WTs are manufactured in a wind farm. Not so much research was published regarding towers or other tall buildings designed to carry high loads of wind. However, it is also due to the fact that these are pretty much WT-like although having very different applications and shapes such studies would be applicable for WTs as well.

The subsequent diagrams illustrate the extent of detail, in terms of the ground system, that various constructions seen in the research articles were modelled both separately and together. Such constructions are, for example, erecting a single WT, several WTs in a cluster and a tower, as shown in Figure 3. Each of the categories is assigned a percentage. It is observable that throughout the three classes of structures that were reviewed, the focus and concern towards the problem of grounding system alone, considering other structures is out of question, is much higher than that involving the issue of grounding system integration with other structures.

Lastly, As shown in Figure 4, the discussion is rounded off with an overview to which the only question that arises, how many such articles were there that focused or at least included some research on the grounding grid by itself and how many articles studied articulation of it with other elements of structures grounding system in all the papers.

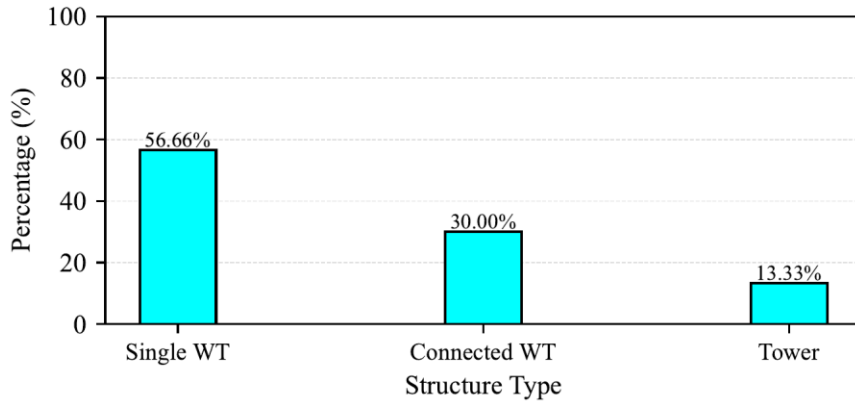


Figure 2. Share of reviewed studies (%) focusing on different analysis scopes: (i) a single wind turbine (Single WT), (ii) multiple interconnected turbines/wind-farm cluster (Connected WT), or (iii) tower-like structures. Percent values above bars indicate the fraction of the reviewed core set assigned to each scope.

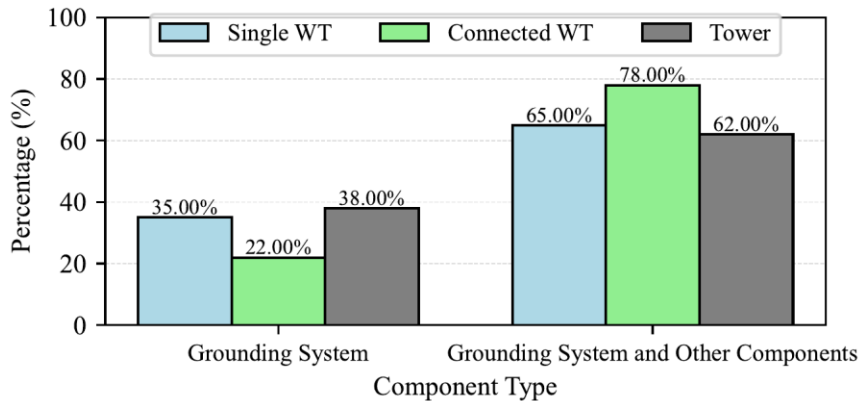


Figure 3. Within each study scope (legend: Single WT, Connected WT, Tower), this figure compares whether the modeled system includes (a) the grounding system alone or (b) the grounding system together with other components (e.g., tower, blades, or connected network elements). The vertical axis reports the share of studies (%) within each scope category; the two x-axis groups indicate the modeled component set.

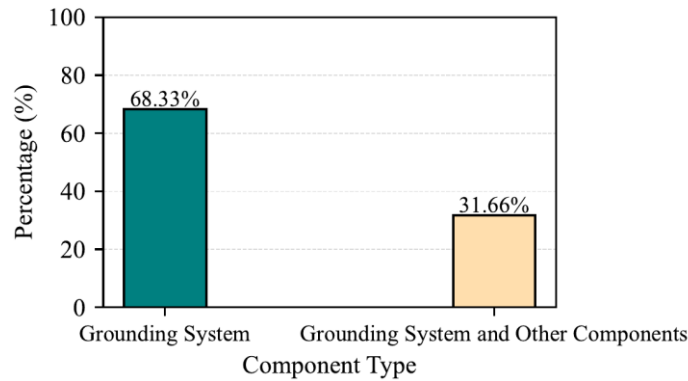


Figure 4. Overall proportion of reviewed studies (%) that model the grounding/earth system alone versus those that model the grounding/earth system jointly with other components. Percent values indicate the share computed over the full reviewed core set.

5.7. Key Insights and Observations from Reviewed Studies

Figure 5 focuses on aspects taken from review articles.

The far greater number of papers referencing frequency-dependent soil characteristics than soil ionization indicates the greater significance of this effect than that of ionization, and more potential for errors arising from its exclusion from numerical models. It is only a small number of papers that have tried to balance the intricacies of including both effects, and thus provide more realistic models. The next three columns show the percentage of articles that considered the soil to be uniform, non-uniform, or both uniform and non-uniform, which, as can be seen, a higher percentage of articles assumed the soil to be non-uniform because soil is inherently non-uniform. The next three columns also show the status of lightning studies in studies, where the first column shows the percentage of articles in which lightning with different parameters was used and studied, the second column shows the percentage of articles in which lightning with direct and indirect impacts was used and studied, and the third column shows the percentage of articles in which lightning with different parameters and also with direct and indirect impacts was used and studied. It can be inferred from these three columns that there is more focus on the discussion of different lightning with different parameters. The last three columns are dedicated to studies related to changes in soil resistance, transmission voltage in wind farms, and the effect of lightning at high, low, and medium frequencies.

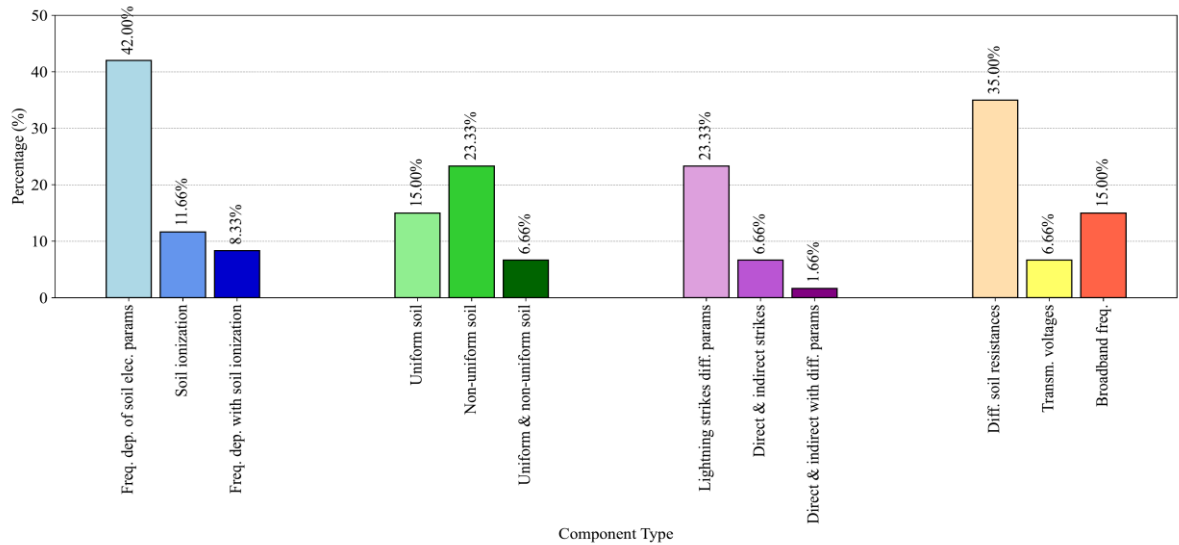


Figure 5. Coverage of selected modeling topics in the reviewed core set. Each bar reports the share of studies (%) that explicitly address the corresponding topic tag (e.g., frequency-dependent soil electrical parameters, soil ionization, soil heterogeneity, lightning-parameter variability, direct/indirect effects, and system-level operating factors as labeled on the x-axis). Multiple tags may apply to the same study; therefore, percentages across bars are not expected to sum to 100%. Abbreviations on the x-axis follow common usage (e.g., “Freq dep.” = frequency-dependent; “Diff.” = different; “Transm.” = transmission).

5.8. Relation to Standards and Practice

According to IEC 61400-24:2019 (see the 2018 revision discussion in [73]), wind turbine lightning protection and the associated earthing design are treated as an integrated system and aligned with general lightning protection principles (e.g., IEC 62305 series). In practice, each turbine is commonly equipped with a dedicated earthing arrangement (e.g., foundation electrode and/or a ring conductor) and the design objective is to achieve a low overall earthing impedance; guidance documents often describe target grounding resistance values on the order of $10\ \Omega$ as a practical benchmark [74]. The present findings are consistent with this direction: reducing earthing resistance and improving equipotential bonding among conductive components are associated with lower lightning surge-induced ground potential rise, supporting the emphasis on coordinated LPS/earthing design in the standard [73]. Moreover, personnel safety considerations require limiting hazardous potential gradients (step and touch voltages) during abnormal conditions, which is consistent with commonly cited safety guidance [75].

Practical design and operational implications:

- Provide each turbine with a low-impedance earthing network (e.g., ring conductor and/or deep rods as applicable) and verify that the resulting grounding resistance is kept low, typically on the order of $10\ \Omega$ as a practical benchmark [74].
- Ensure equipotential bonding among major metallic parts (e.g., tower, nacelle, and electrical equipment) to reduce dangerous voltage differences during lightning events [73].
- Evaluate step and touch voltage conditions under relevant worst-case scenarios and apply mitigation measures (e.g., surface layer/gravel, gradient control) if required by safety criteria [75].
- Use a robust lightning interception and conduction path (e.g., blade receptors and down-conductors) so that high lightning currents are safely conveyed to the grounding system [76].

Adopt operational safety procedures during thunderstorms (e.g., avoiding exposed maintenance activities and following site safety guidance) as emphasized in wind-turbine lightning protection practice [76].

6. Challenges and research gaps

A central objective of this review is not only to summarize modeling approaches, but also to extract the *dominant challenges* that repeatedly shape the lightning response of WT grounding systems and to identify the *research gaps* that limit predictive reliability and industrial transfer. Based on the reviewed studies, the gaps can be grouped into the following taxonomy (used to organize the discussion below):

- Soil and site representation gaps: multilayer/heterogeneous soils, frequency dependence of soil parameters, seasonal variability, and nonlinear effects (e.g., ionization) that are difficult to calibrate [6,7,13,64].
- Model-fidelity vs. practicality gaps: limitations of EMTP-type equivalents, quasi-static assumptions, and the difficulty of producing validated wideband equivalents for fast-front lightning studies [14,25,31,49].
- Source and excitation representation gaps: lightning waveform variability (front time, stroke type, subsequent vs. first strokes) and how it interacts with wideband grounding behavior [4,9,47,48,65].
- System-level interaction gaps: wind-farm coupling, inter-turbine interconnections, and collector-network paths that redistribute transient stresses beyond an isolated turbine [8,9,11,52,57].

Validation and benchmarking gaps: limited field/lab datasets, inconsistent reporting, and heavy reliance on simulation cross-checks rather than reproducible measurement benchmarks [20,22,23,42,67].

Seasonal changes in soil state, wet/dry cycles and freezing/freezing-thaw, can shift soil resistivity and therefore the effective grounding impedance seen by lightning currents, leading to season-dependent GPR and overvoltage predictions. IEEE guidance emphasizes that earth resistivity varies with both temperature and moisture and can increase rapidly in frozen conditions, motivating explicit seasonal envelopes rather than a single “average” soil model [77]. Accordingly, a key research gap is the integration of time-varying (or scenario-based) soil parameterizations and seasonal measurement campaigns into transient validation and sensitivity reporting for WT grounding studies.

6.1. Multilayer and heterogeneous soil modeling

- Challenge. Many WT grounding studies simplify soil as homogeneous, while site reality is often layered and spatially variable; this affects return-current distribution and the effective grounding impedance under lightning excitation.
- Evidence in reviewed studies. Multilayer or two-layer soil modeling appears explicitly in measurement-driven and numerical studies [6,7,13,22,23,61,64,66].
- What the literature often assumes. Idealized layer interfaces, limited parameter sets, and/or site-specific soil fits that are not always transferable across seasons or neighboring turbines [6,64].
- What is missing (gap). (i) systematic sensitivity studies across plausible layer profiles for a given site, (ii) common reporting of soil-identification workflow and uncertainty, and (iii) multi-turbine soil characterization (spatial correlation) at wind-farm scale.

Recommended direction. Establish a consistent workflow combining site measurements with calibrated multilayer models, and explicitly propagate soil-parameter uncertainty into GPR/overvoltage predictions (scenario envelopes rather than single curves) [22,23,64].

6.2. Frequency-dependent soil parameters and wideband grounding behavior

- Challenge. Lightning transients excite a wide frequency band; soil electrical parameters and grounding impedance can be frequency dependent, which changes impulse impedance, GPR peak, and waveform shape compared to frequency-independent assumptions.
- Evidence in reviewed studies. Frequency-dependent soil models and their impact on lightning response are emphasized in hybrid/wideband and CDEGS-based studies [4-7,47,62].
- What the literature often assumes. Frequency dependence is either neglected or implemented with a specific empirical model without clear guidance on selection/calibration for a given site [6].
- What is missing (gap). (i) unified comparison of different soil-dispersion models under identical geometry/waveforms, (ii) clear conditions under which frequency dependence is essential vs. secondary, and (iii) explicit coupling between frequency dependence and wind-farm interconnections.

Recommended direction. Report the modeled bandwidth, soil-dispersion model choice, and calibration basis explicitly; where EMT studies are performed, use validated wideband grounding equivalents rather than purely resistive representations [4,6,14].

6.3. Limitations of EMTP-type (circuit-based) models for lightning grounding studies

- Challenge. EMTP-type tools are highly practical for network studies, but their accuracy depends on the grounding equivalent and the inclusion of distributed coupling and wideband behavior.
- Evidence in reviewed studies. EMT-based WT lightning studies and hybrid workflows are widely used [8,25,28,36]. Multiple works explicitly motivate frequency-dependent and broadband equivalents to avoid overly simplified grounding representations [14,31,49,51].
- What the literature often assumes. Grounding represented by a small set of lumped parameters or low-frequency resistance, with limited discussion of validity bandwidth.
- What is missing (gap). (i) reproducible procedures to derive multi-port, wideband equivalents from field solvers/measurements, (ii) explicit error checks (time-domain waveform fidelity vs. a broadband reference), and (iii) clear guidance on when EMTP is sufficient vs. when full-wave is required.

Recommended direction. Use EMTP for system-level questions (collector network, SPD placement, insulation coordination) while embedding validated wideband grounding equivalents (e.g., via VF/state-space) where fast-front behavior matters [14,51].

6.4. Validation and benchmarking challenges (field/lab evidence vs. simulation cross-checks)

- Challenge. Validation is difficult because lightning transients depend on site soil, installation details (rebar, bonding), and measurement constraints; many papers therefore validate mainly via simulation cross-checks rather than repeatable measurement benchmarks.
- Evidence in reviewed studies. Measurement-based grounding characterization and scaled/lab validation exist but are limited relative to the breadth of modeling papers [20,22,23,42,43,67].
- What the literature often assumes. Idealized geometry/soil inputs and implicit calibration; validation is sometimes limited to agreement with another simulator rather than independent measurements.
- What is missing (gap). (i) shared benchmark cases (geometry + soil + excitation + measurement outputs), (ii) consistent reporting of measurement setup and uncertainty, and (iii) validation of wind-farm-scale coupling predictions.

Recommended direction. Promote benchmark-style reporting: provide geometry description sufficient for reproduction, soil identification method, excitation definition, and a validation metric/acceptance criterion for transient waveforms [23,42].

6.5. Lightning waveform variability and excitation uncertainty

- Challenge. Different lightning waveforms (front times, polarity, first vs. subsequent strokes) interact differently with grounding impedance and wind-farm coupling paths, and can change which component becomes most stressed.
- Evidence in reviewed studies. Multiple works explicitly compare first and subsequent strokes and/or study waveform dependence of impulsive characteristics [4,9,47,48,65].
- What the literature often assumes. A single representative waveform or a narrow set of strokes without systematically exploring waveform sensitivity together with soil-model uncertainty.
- What is missing (gap). (i) a standardized waveform set for comparing methods, and (ii) joint sensitivity studies: waveform \times soil model \times interconnection topology.

Recommended direction. Treat excitation as a sensitivity axis: evaluate design conclusions under a small, explicit set of representative waveforms (including first/subsequent strokes) rather than a single case [47,65].

6.6. Computational limits of full-wave and wideband methods

- Challenge. Full-wave and geometry-resolved wideband methods (FDTD, MoM/NEC-type, PEEC) provide high fidelity for coupling and propagation but face computational bottlenecks (meshing/time-step constraints, matrix size/conditioning, broadband sampling and fitting).
- Evidence in reviewed studies. Full-wave/distributed and PEEC-type studies are used to capture detailed coupling and distributed voltages [9,12,42,53,54].
- What the literature often assumes. Limited geometric detail or reduced domains to keep runtime manageable; wideband-to-time conversion performed without unified reporting of fit/bandwidth adequacy [7,14].
- What is missing (gap). (i) consistent accuracy-vs-cost reporting, (ii) scalable multi-turbine full-wave validation, and (iii) transparent criteria for broadband sampling and fit quality when creating EMT-ready equivalents.

Recommended direction. Use full-wave studies strategically to (a) identify dominant coupling/propagation mechanisms and (b) generate reduced-order/wideband equivalents for system-level EMT studies, with explicit bandwidth and fit-quality reporting [9,12,14].

6.7. Wind-farm coupling and collector-network effects (system-level gaps)

- Challenge. Wind farms introduce inter-turbine coupling, shared grounding paths, and collector-network surge propagation; isolated-turbine studies can miss transferred overvoltages and redistribution of GPR.
- Evidence in reviewed studies. Interconnected grounding and wind-farm studies address coupling length effects, transferred overvoltages, and network interaction [8-11,38,52,57].
- What the literature often assumes. Simplified representations of interconnections/cables or limited farm size; partial consideration of collector-network elements.
- What is missing (gap). (i) integrated modeling that jointly includes turbine grounding, inter-turbine links, and collector network under consistent wideband assumptions, and (ii) validated guidance for connection strategy and SPD/bonding placement at farm scale.

Recommended direction. Combine multi-port grounding equivalents with network EMT modeling for farm-level studies, and benchmark transferred-overvoltage predictions against measurements or cross-tool validation [9,52].

Table 7 reports the challenges and research gaps of the literature reviewed in this paper.

Table 7. Structured challenges and research gaps extracted from the reviewed literature, with recommended directions supported by representative cited studies.

Challenge	Why it matters	What literature assumes	What is missing	Recommended direction
Multilayer/heterogeneous soil	Changes current return paths and impulse response	Idealized layers; limited uncertainty reporting	Sensitivity + uncertainty propagation; spatial correlation across farm	Calibrated multilayer workflow + uncertainty envelopes [22,23,64]
Frequency-dependent soil parameters	Wideband impedance and waveform shapes shift vs. constant-parameter models	Single dispersion model choice; unclear calibration basis	Cross-model comparison under identical cases; explicit bandwidth reporting	Report bandwidth + calibration; embed wideband equivalents in EMT [4,6,14]
Seasonal/temperature-driven soil variability (moisture/freezing)	Soil resistivity (and hence wideband grounding impedance) can differ between wet/dry or frozen/unfrozen states, shifting predicted GPR/overvoltage levels across the year [77].	Time-invariant soil parameters; calibration from a single-season survey.	Limited seasonal field datasets for WT sites and limited use of time-varying soil parameterizations in transient models.	Report seasonal envelopes (wet/dry, frozen/unfrozen) and quantify sensitivity/uncertainty of key transient metrics under plausible seasonal soil states [77].
EMTP-type model limitations	System studies can be misleading if grounding is oversimplified	Lumped or resistive grounding without validity range	Reproducible wideband multi-port equivalent generation + verification	Use VF/state-space equivalents; define applicability boundaries [31,51,14]
Validation and benchmarking	Without independent validation, conclusions may be tool-dependent	Simulation cross-checks more common than measurements	Shared benchmark cases + consistent validation metrics	Benchmark-style reporting + measurement-linked validation [23,42]
Waveform variability	Different strokes/front-times can change the dominant stress mechanism	Single “representative” waveform cases	Joint sensitivity: waveform soil topology	Standard waveform set; report sensitivity of conclusions [47,65,9]
Full-wave computational limits	High-fidelity coupling/propagation is costly at farm scale	Reduced domains; limited cost/accuracy reporting	Scalable multi-turbine validation; transparent fit/bandwidth criteria	Use full-wave to derive validated reduced-order equivalents [12,9,7]
Wind-farm coupling/network effects	Transferred surges and redistribution cannot be captured by isolated models	Small farms or simplified interconnections	Integrated turbine + network modeling under consistent wideband assumptions	Multi-port equivalents + EMT network studies; validate transfers [52,57,9]

6.8. Prioritization of gaps (High/Medium/Low) and rationale

To guide future work, the extracted gaps are prioritized according to their expected impact on transient prediction accuracy and on practical wind-farm design decisions:

- High priority: (i) multilayer/heterogeneous soil representation, (ii) frequency-dependent soil parameters, (iii) wind-farm coupling and collector-network effects, and (iv) validation/benchmarking. These factors frequently dominate discrepancies in GPR/overvoltage predictions and directly influence design decisions [4,9,11,13,23].
- Medium priority: (i) EMTP-equivalent validity boundaries and reproducible wideband model extraction, and (ii) waveform-variability sensitivity when used to generalize conclusions. These are crucial for correct application of methods and for robust mitigation ranking, but they can be addressed once soil and coupling representations are under control [14,31,65].

Low priority (context-dependent): detailed nonlinear ionization modeling without site-calibrated evidence. Ionization can be important in specific scenarios, but parameter verification is often difficult; therefore, it should be treated as scenario-based unless supported by credible benchmarks [26,37,46].

6.9. Additional underexplored directions proposed by this review

Beyond the evidence-linked gaps above, the review suggests several design and modeling directions that appear underexplored and merit systematic study:

- Spatial variability of soil/grounding behavior across a wind-farm footprint and its impact on transient response.
- Non-standard grounding geometries and orientations (e.g., non-coplanar or inclined arrangements) and their effect on impulse behavior.
- Multi-ring or stacked ring configurations and the role of opposing/assisting magnetic coupling between rings.
- Inter-electrode spacing and angular placement strategies for horizontal/vertical electrodes under transient excitation.
- Multi-point observation/measurement perspectives during storms to relate local and transferred voltages.
- Comparative studies of alternative ring shapes (circular, rectangular, triangular, spiral, etc.) under the same soil/waveform assumptions.
- Systematic comparison of interconnection topologies (bridge, ring, partial mesh) across a range of soil conditions.
- Parallel interconnections: number of links vs. effective length and diminishing returns under high-resistivity soils.
- Transferred-voltage studies coupled to grounding configurations under different lightning conditions.
- Development of compact relations linking effective length, burial depth, number of conductors, and soil variability for design-stage screening.

These gaps motivate the practical engineering recommendations and the prioritized future-work roadmap summarized in the Conclusion.

7. Future research roadmap

To complement the challenges and research gaps identified, this section provides a forward-looking roadmap that is explicitly organized into three horizons. The intent is to translate the evidence synthesis of this review into concrete and reproducible next steps for (i) modeling fidelity and practicality, (ii) experimental validation and benchmarking, (iii) numerical acceleration and best practices, and (iv) industrial transfer and standardization alignment (e.g., IEC 61400-24) [3]. The roadmap also emphasizes wind-farm-scale coupling and seasonal/site variability (moisture/freezing) as cross-cutting issues that can amplify or mitigate lightning stresses [8,9,11,14].

7.1. Horizon 1 (1–2 years): consolidate reproducibility, best practices, and baseline validation

- (High) Reporting and reproducibility checklist for grounding-transient studies. Define a minimal reporting template for geometry, soil identification workflow, modeled bandwidth, waveform definition, and validation metric(s), to reduce ambiguity across studies and tools [6,23,42].
- (High) Wideband-ready grounding equivalents for EMT studies. When EMTP/ATP is used for lightning transients, prioritize validated wideband (multi-port where needed) grounding equivalents instead of purely resistive representations; document the frequency range and fitting adequacy of the broadband-to-time conversion (e.g., VF/state-space) [14,49,51,58].
- (High) Baseline field/lab benchmarking cases. Publish a small set of benchmark-style cases (site/geometry/waveform) with measurement-linked outputs (even if limited in scope) to enable cross-tool comparison and model calibration [20,22,23].
- (Medium) Sensitivity studies with multilayer and frequency-dependent soils. For representative WT grounding geometries, run controlled sensitivity sweeps that separate (i) multilayer soil profile effects and (ii) frequency-dependent soil parameter effects under consistent excitations [4,6,7,13].
- (Medium) Seasonal variability as an explicit axis. Where available, incorporate seasonal/site variability in soil parameters and evaluate the robustness of conclusions to that variability (scenario envelopes rather than single curves) [14,64].

(Low) Ionization modeling only with transparent assumptions. Use nonlinear ionization models as scenario studies unless parameters are supported by credible benchmarks; clearly state assumptions and intended applicability [26,37,46].

7.2. Horizon 2 (3–5 years): integrated wind-farm modeling, scalable validation, and acceleration workflows

- (High) Integrated wind-farm grounding + collector-network transient workflow. Develop and validate workflows that jointly include turbine grounding, inter-turbine links, and collector-network paths under consistent wideband assumptions, to capture transferred overvoltages and coupling-driven redistribution [8,9,52,57].
- (High) Scalable benchmark suite for coupling and multi-turbine behavior. Extend benchmark cases from single-turbine to small multi-turbine layouts with clear topology definitions (interconnection types/lengths) and comparable outputs (GPR, transferred voltage, key node waveforms) [9,11].
- (Medium) Reduced-order modeling (ROM) from full-wave to EMT. Use full-wave or wideband field/circuit formulations strategically to identify dominant mechanisms, then generate reduced-order, EMT-ready equivalents with explicit bandwidth and fit-quality reporting [7,9,12,14].
- (Medium) Numerical best practices and acceleration playbook. Document practical guidance for segmentation/meshing, time-step constraints, bandwidth sampling, and fit diagnostics; encourage sharing of scripts/workflows used for wideband fitting and verification [7,58].

(Medium) Waveform variability + soil uncertainty joint studies. Evaluate whether conclusions hold across a small, explicit waveform set (first/subsequent strokes and different front-times) jointly with soil-model uncertainty [4,47,48,65].

7.3. Horizon 3 (5+ years): industrial transfer, standardization-ready guidance, and robust design frameworks

- (High) Standardization-facing guidance derived from validated models. Translate validated findings on soil dispersion, multilayer effects, and wind-farm coupling into practitioner-oriented guidance aligned with IEC 61400-24 workflows (e.g., when wideband grounding equivalents are required vs. when simpler models are sufficient) [3].
- (High) Robust (uncertainty-aware) design envelopes for WT grounding under lightning. Move from single-scenario conclusions toward design envelopes that explicitly account for soil variability (including seasonal shifts) and waveform variability; this supports risk-informed engineering decisions without relying on a single “representative” case [64,65].
- (Medium) Wind-farm-scale mitigation co-design (grounding, bonding, SPDs, topology). Develop co-design studies that consider grounding/interconnection strategies together with surge protection and network layout, using validated multi-port equivalents and network-level EMT simulations [8,9,25].
- (Low) Data-driven acceleration for parametric design studies. Explore surrogate or data-driven models to accelerate parametric sweeps and optimization under uncertainty, while maintaining physics-based validation for lightning-relevant transients [17].

Table 8 provides the possible future trends.

Table 8. Future research roadmap horizons and concrete tasks suggested by the evidence synthesis in this review (no quantitative claims; tasks emphasize reproducibility, validation, acceleration, and wind-farm-scale realism).

Horizon	Topics	Concrete tasks	Expected impact
1--2y	Reproducibility, baseline validation, wideband EMT readiness, initial seasonal sensitivity	Reporting checklist; measurement-linked baseline benchmarks; wideband (VF/state-space) grounding equivalents with bandwidth/fit diagnostics; controlled sensitivity studies for multilayer and frequency-dependent soils; treat seasonal variability as an explicit axis Joint turbine-grounding + interconnection + collector-network modeling under consistent wideband assumptions;	More comparable studies; reduced tool-dependent conclusions; clearer applicability boundaries for EMT vs. wideband/full-wave approaches [23,14,6]
3--5y	Integrated wind-farm coupling + network effects; scalable validation; ROM and acceleration workflows	multi-turbine benchmark suite; reduced-order equivalents derived from full-wave/wideband references; best-practices playbook for meshing/sampling/fitting Standardization-facing guidance aligned with IEC 61400-24;	Validated farm-level predictions of transferred overvoltages and coupling; faster yet credible engineering workflows [9,57,7]
5y +	Industrial transfer and standardization; robust uncertainty-aware design; co-design mitigation	uncertainty-aware design envelopes (soil + waveform + topology); co-design of grounding/bonding/SPDs and farm topology; careful use of data-driven acceleration only with physics validation	Improved industrial adoption and consistency; designs that remain robust to site variability and excitation uncertainty; clearer guidance for practitioners [3,64,65]

8. Limitations of this review

This review synthesizes published studies that differ substantially in assumptions, tools, modeled bandwidth, and reporting detail; therefore, many comparisons are necessarily qualitative and bounded by what is explicitly documented (e.g., soil characterization basis, topology/coupling paths included, and validation style). In parts of the literature, validation remains constrained by measurement availability, so evidence is sometimes based on simulation cross-checks rather than independent field/lab benchmarks. Finally, the scope of this paper is electrical grounding and lightning-transient modeling for WTs and wind farms; it does not attempt to standardize economic comparisons across tools or to provide site-specific prescriptions beyond the comparative indicators and sensitivity-oriented guidance synthesized herein.

9. Conclusion

This paper reviewed and synthesized the literature on lightning-related transient behavior of wind-turbine (WT) grounding systems, with an emphasis on time–frequency effects, soil representation (including dispersion and stratification), and system-level coupling paths in wind farms. The review was organized by method families (Section 3), formalized using an explicit classification framework (Section 4), and distilled into two cross-study matrices: a method-comparison matrix (Table 3) and a findings/takeaways matrix (Table 2). The extracted challenges and gaps (Section 6) and the prioritized roadmap (Section 7) translate this synthesis into actionable directions for both research and practice.

Distilled technical insights (cross-study). Based on the comparative synthesis (Section 5) and Tables 3-4, the following technical insights emerge:

1. Grounding performance under lightning is inherently wideband. Models that agree at DC or power frequency can diverge in predicted impulse behavior once inductive/capacitive storage, coupling, and propagation become influential; therefore, the modeled bandwidth must match the targeted failure/overvoltage mode (Section 4, Table 3).
2. Soil representation is a dominant driver of disagreement. Stratification (multilayer/heterogeneous soil) and frequency-dependent parameters change return-current distribution and wideband grounding impedance, which can materially alter GPR and overvoltage waveforms relative to homogeneous/constant-parameter assumptions (Table 2; Section 6).
3. Interconnection is a double-edged design variable at wind-farm scale. Bonding/interconnection can reduce local GPR by sharing injected current, but it also introduces transferred/redistributed stresses that must be assessed at the farm/network level rather than only at an isolated turbine (Table 2).
4. Collector-network and cable-sheath paths are part of the lightning problem. Overvoltage and stress allocation depend on coupled *structure + ground + network* paths; thus, grounding design and surge-protection placement should be coordinated with cable/sheath bonding and the collection network representation (Section 3; Table 2).
5. Circuit-based EMT studies are powerful, but grounding parametrization is the credibility bottleneck. EMTP/ATP-style studies are well-suited for system studies (e.g., SPD placement and topology comparisons), but they require validated wideband grounding equivalents (multi-port when needed) to remain credible for fast-front lightning behavior (Table 3).
6. Full-wave/distributed solvers are justified when propagation and coupling dominate. FDTD/TLM and thin-wire/full-wave (MoM/PEEC-type) approaches become necessary when wave propagation, reflections, and multi-conductor coupling control peak timing and stress distribution (Table 3).
7. Broadband-to-time conversion quality is itself a technical risk. Frequency-to-time workflows (e.g., wideband fitting/state-space equivalents) provide an essential bridge to EMT simulation, but their reliability depends on bandwidth selection, sampling adequacy, and fit diagnostics; otherwise, time-domain artifacts may bias conclusions (Section 4; Table 3).
8. Nonlinear soil ionization is scenario-dependent and difficult to calibrate. Ionization models can reshape transient response in some high-current scenarios, but without site-calibrated evidence or strong benchmarks, ionization-driven conclusions should be framed as scenario envelopes rather than universal design rules (Section 6; Table 6).

Methodological gaps and their implications (why results differ). The gaps extracted in Section 6 have direct implications for both prediction credibility and engineering decision-making:

- Validation scarcity: limited field/lab benchmarks force many studies to rely on cross-tool consistency rather than independent measurements, which can mask shared assumptions and reduce confidence in absolute waveform fidelity (Section 6).
- Incomplete system context: isolated-turbine studies can under-represent transferred/induced stresses that arise through wind-farm interconnections and collector networks, leading to incomplete mitigation ranking (Section 6).
- Unstated applicability boundaries: conclusions may not transfer across soils, waveforms, or topologies unless the modeled bandwidth, soil calibration basis, and interconnection assumptions are explicitly reported.

Practical engineering recommendations (actionable). Without prescribing site-specific numeric thresholds (outside the scope of this review), the following qualitative recommendations are supported by the synthesized evidence:

- Treat soil modeling as a first-order design axis: when lightning transients are the target, prefer a justified multilayer soil model and evaluate sensitivity to plausible soil profiles and seasonal variability rather than relying on a single “average” resistivity (Section 6).
- Use wideband grounding equivalents in EMT studies: if EMTP/ATP is used for fast-front lightning waveforms, embed grounding models that represent the intended wideband behavior (multi-port where required) and document the modeled

frequency range and conversion/fit adequacy (Section 7).

- Analyze wind farms as coupled systems: evaluate both struck and non-struck turbines, including interconnection topology and collector-network paths, before finalizing bonding strategies and SPD placement (Table 8).
- Prefer topology comparisons under consistent assumptions: when comparing grounding layouts or interconnections, keep waveform sets, bandwidth, soil representation, and validation targets consistent to avoid method-driven ranking artifacts (Section 4).
- Report reproducibility essentials: provide geometry description, soil identification workflow, waveform definition, modeled bandwidth, and validation style to make results portable across tools and sites.

Prioritized future work aligned with the roadmap. The roadmap in Section 7 is summarized here as prioritized tasks:

- High priority (near term): publish benchmark-style measurement-linked cases and adopt a reproducibility checklist (geometry, soil identification, bandwidth, waveform definition, validation metrics) to reduce tool-dependent conclusions.
- High priority (near-to-mid term): develop validated integrated workflows that jointly model turbine grounding, inter-turbine links, and the collector network under consistent wideband assumptions to quantify transferred/induced stresses at farm scale.
- Medium priority: derive reduced-order, EMT-ready wideband equivalents from full-wave references with explicit bandwidth and fit-quality reporting to balance fidelity and practicality.
- Context-dependent priority: treat nonlinear ionization modeling as scenario-based unless supported by site-calibrated evidence or credible experimental benchmarks.

Novelty and positioning relative to narrower reviews. Many review-style discussions in this domain are organized around a single axis (e.g., a specific solver family, a specific soil effect, or a specific component-level lightning protection topic) and therefore do not provide a unified basis for cross-method comparison. In contrast, the novelty of this manuscript is the *integration* of: (i) an explicit classification framework that links modeling assumptions to applicability boundaries (Section 4), (ii) a method-comparison matrix (Table 3) and a findings/takeaways matrix (Table 2) that make trade-offs and recurring patterns explicit without introducing unsupported numeric metrics, and (iii) a structured, evidence-linked gap taxonomy with a prioritized roadmap (Sections 6 and 7). This structure is intended to help readers move from paper-by-paper descriptions to defensible method selection, sensitivity-aware interpretation, and reproducible future studies.

For completeness, the conclusions above should be interpreted together with the scope and comparison limits stated in Section 8.

Based on the above synthesis, this review provides the following explicit recommendations for key stakeholders:

- Turbine Developers: should incorporate enhanced lightning protection in turbine designs (e.g., improved blade receptors and grounding systems) to improve reliability. Strengthening lightning defenses is expected to help extend component lifetimes and reduce failure rates, which in turn can boost turbine availability and keep O&M costs in check.
- Wind Farm Operators: should utilize real-time lightning monitoring and conduct regular LPS inspections (e.g., in line with IEC 61400-24 recommendations [78]) so that any strike damage is detected and repaired promptly. This proactive maintenance approach can minimize lightning-induced downtime and prevent costly component replacements [78].
- Grid Planners: should include lightning-related outage scenarios in grid reliability and integration studies. By planning for potential turbine downtime (e.g., ensuring backup generation or energy storage during severe thunderstorms), planners can maintain grid stability and supply security even when lightning temporarily reduces wind farm output.

Policymakers: should support lightning resilience by enforcing standards and incentivizing protective measures. For example, requiring compliance with lightning protection standards and providing incentives or research support for improved turbine LPS technologies can help reduce lightning-related losses and ultimately lower the cost of wind energy.

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Declaration of competing interest

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