

**Analyzing the Impact of Meteorological Factors on the Management of Overhead Power
Transmission Lines in Nigeria**

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ABSTRACT

The management of Nigeria's transmission lines faces multifaceted challenges, including inadequate real-time monitoring systems due to outdated communication infrastructure and insufficient deployment of technologies. This study investigates the impact of meteorological factors on the management of overhead transmission lines (OHTLs) in Northern Nigeria. Through extensive empirical research and quantitative analysis of factors, a total of 339 questionnaires were distributed to industry professionals and 311 were validly returned. This research demonstrates that, precipitation, and wind significantly affect transmission line reliability and management practices. The findings reveal that precipitation patterns directly threaten tower foundation stability (92.9% agreement), and wind forces contribute significantly to conductor galloping and vibration damage (92.6% agreement). Statistical analysis confirms strong positive correlations between these meteorological factors and transmission line management challenges ($p < 0.001$ for all variables). The study identifies critical vulnerabilities in Nigeria's grid infrastructure, including inadequate design standards for local climate conditions, insufficient drainage systems, and outdated maintenance protocols. Recommendations include implementing Dynamic Line Rating systems, enhancing real-time weather monitoring, revising design standards to incorporate localized meteorological factors. This research provides valuable insights for utility managers, policymakers, and engineers seeking to improve grid resilience in developing nations facing similar climate challenges, potentially reducing Nigeria's frequent grid collapses that cost an estimated \$28 billion annually.

Keywords: Management, Meteorological, Power Transmission Lines

1.0 INTRODUCTION

1.1 Background to the Study

The reliable operation of electrical power systems fundamentally depends on the stability and integrity of transmission lines, as noted by Petrova (2022). These high-voltage lines form the backbone of the power grid and are essential for efficiently transferring electricity from generation facilities, such as power plants, to end users—including residential, commercial, and industrial consumers (Zhang *et al.*, 2021; Panteli *et al.*, 2015). The smooth functioning of these transmission networks guarantees that electricity is available whenever and wherever it is needed.

Any disruption in the operation of transmission lines can lead to significant economic losses, service interruptions, and potential safety hazards. Such disruptions not only undermine the reliability of the power supply but also threaten public safety and erode confidence in the energy infrastructure. With electricity demand continuously rising due to factors like population growth, technological advancements, and the electrification of various sectors, ensuring the reliability of transmission lines has become increasingly critical (Zhang *et al.*, 2025).

The management of Nigeria's transmission lines faces multifaceted challenges, including inadequate real-time monitoring systems due to outdated communication infrastructure and insufficient deployment of technologies like SCADA (Supervisory Control and Data Acquisition). Limited adoption of modern solutions, such as smart grids and automation, exacerbates inefficiencies in load management and fault detection, with transmission losses exceeding 7.4% compared to international standards. Workforce expertise gaps persist, compounded by insufficient training programs and reliance on outdated maintenance practices.

Nigeria's national power grid has suffered frequent partial and total collapses, causing nationwide blackouts and severe socio-economic impacts (Adeniji *et al.*, 2025; Adzua, 2021;). For example, between 2000 and 2022 the grid collapsed 564 times, averaging over two collapses per month (Jimoh and Raji, 2023). These failures stem from technical issues like load-generation imbalances and cascading faults, compounded by aging infrastructure and human operational errors (Edeh,

2024). The instability disrupts businesses and costs the economy tens of billions of dollars annually (Chimezie, 2024).

Statistical evidence shows that Nigeria experienced approximately 120-140 grid collapses between 2010 and 2023, with overhead transmission line failures contributing to approximately 65% of these incidents and Transmission line failures, accounted for about 8,643 MW of stranded power capacity in 2022, representing roughly 40% of the country's total installed generation capacity (Ibrahim *et al.*, 2024). A study by Oladipo and Ekejiuba (2022) documented that Nigeria's transmission network experiences an average of 7.8-line faults per 100 km annually, compared to the global average of 2.3 faults per 100 km in developed economies. Approximately 36% of Nigeria's 330kV transmission lines and 42% of 132kV lines operate beyond their designed lifespan, significantly increasing failure rates by an estimated 12% annually. Analysis of TCN fault factors showed that vegetation encroachment accounts for 27% of transmission line failures, followed by mechanical failures (21%), vandalism (18%), lightning strikes (15%), and other causes including overloading and poor maintenance (19%) (Nwachukwu and Okafor, 2022). These power failure according to World Bank cost Nigeria approximately \$28 billion annually, equivalent to about 5.8% of its GDP, through lost production, damaged equipment, and alternative power generation costs.

Mitigating the challenges associated with poor management of transmission line management across the globe, scholars such as Qiangjun Liu, (2025); Nabila *et.al.*, (2024); Chen *et.al.*, (2023); Egidijus *et. al.*, (2023) Hasan *et. al.*, (2023); have found, weather as a critical factor that impede the management of transmission lines as they explained that weather factors such as precipitation, snowfall, lightning and wind are factors that affect overhead transmission lines efficiency and management. Chen *et.al.*, (2023), emphasizes that global climate change and the increased occurrence of extreme weather events have led to a rise in emergencies and outages within electrical grid companies. Egidijus et al. (2023) reported that a 20% increase in the average values of extreme wind speed and ice thickness can reduce the reliability of power lines by 30% and 17%, respectively.

Furthermore, Egidijus (2024) found that the impact of precipitation during strong wind events becomes significant only when the accumulated rainfall over a 3-hour period exceeds 8 mm.

In recent decades, average temperatures have risen globally, resulting in more frequent heat waves, longer durations of individual heat waves, and extended heat wave seasons (Guddanti *et al.*, 2025). Both historical and projected data indicate that high temperatures caused by heat dome-like phenomena are increasing in intensity at a faster rate than average global temperatures.

Against this background, this paper aims to analyze the influence of meteorological factors on the management of overhead transmission lines in northern Nigeria.

Objective of the study

The major objective of this study is to examine the impact of meteorological factors on the management of overhead transmission lines in Nigeria in order to improve the management of power transmission services.

Hypothesis

The following hypothesis are stated in null (Ho) form:

- (i) Precipitation patterns do not affect overhead transmission lines tower foundation
- (ii) There is no relationship between wind and overhead transmission lines management

2.0 LITERATURE REVIEW

2.1 The Concept of Overhead Power Transmission Lines (OHPTL):

Overhead power transmission lines (OHTLs) are engineered electrical infrastructure systems that transmit high-voltage electricity (typically 69 kV to 765 kV) over long distances via conductors—usually aluminum or aluminum-steel composites—suspended on towers or poles. These systems consist of four core components: (1) conductive cables, (2) insulating elements, (3) structural supports (e.g., lattice towers or poles), and (4) grounding systems, all designed to minimize energy losses while withstanding mechanical stresses from environmental factors (wind, ice, and thermal expansion) (Gouda *et al.*, 2021; IEEE, 2022).

As critical nodes in power grids, OHTLs enable bulk electricity transfer from generation plants to substations and distribution networks, requiring designs that balance electrical efficiency (e.g., through high-voltage operation to reduce resistive losses), mechanical resilience, and fault

tolerance (Elkadeem *et al.*, 2020; Zhang *et al.*, 2022). Their operation involves managing thermal ratings, sag-tension dynamics, and electromagnetic field effects to ensure stability (IEEE, 2022).

2.2 Concept of Meteorological Factors.

World Meteorological Organization (WMO) (2020), view meteorological factors (data) as records of observed climate conditions taken at specific sites and times with particular instruments under a set of standard procedures. A climate (meteorological) factors set therefore contains climate information at the observatory sites, as well as other non- climate-related factors such as the environment of the observation station, and information about the instruments and the observation procedures.

Similarly, National Bureau of statistics (NBS) described Meteorological factors (data) as a set of information which describes the characteristics of the atmosphere. When these factors are available for a day or a period during the day, they are taken as describing Weather characteristics. However, when they are available over a long period of time (usually up to 40 years), their averages are accepted as describing the Climate of the place from which they are collected. The parameters of the environment commonly measured include solar radiation, sunshine hours and temperature, precipitation (mainly rainfall), humidity, vapor pressure, evaporation and s transpiration, and wind speed and direction. Of all these, temperature is the most often reported in Nigeria as in the other parts of the world. This is because of its well-established influence on most other parameters that are measured.

2.1.0 Precipitation

Precipitation is any liquid or frozen water that forms in the atmosphere and falls back to the earth. It comes in many forms, like rain, sleet, and snow. Along with evaporation and condensation, precipitation is one of the three major parts of the global water circle. Precipitation forms in the clouds when water vapor condenses into bigger droplets of water. When the droplets are heavy enough, they fall to the earth. If a cloud is colder, like it will be a higher altitude, the water droplets may freeze to form ice. These ice crystals then fall to the earth as snow, hail, or rain, depending on the temperature within the cloud and at earth's surface. Most rain actually begins as snow high in

the clouds. As the snowflakes fall through warmer air, they become rain droplets. (National Geographic Society, 2023).

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Precipitation is always fresh water, even when the water originated from the ocean. This is because sea salt does not evaporate with water.

2.1.1 Wind

Wind is a natural phenomenon observable in many scenarios on earth. Wind can be felt as a slight movement of air or as a violent force that accompanies hurricanes and tornadoes. National Geographic Education, (2024), described wind, as the movement of air, caused by the uneven heating of the earth by the sun and the earth own rotation. Wind ranges from light breezes to the natural hazards such as hurricanes and tornados. Differences in atmospheric pressure generate winds. Wind generally blows from high pressured areas to low pressured areas.

Wind energy serves as an effective alternative to conventional energy sources due to its potential to mitigate climate change (Jung & Schindler.,2025; Long *et.al.*,2023). Furthermore, as established in previous study by Jung and Schindler, (2018), temporally, wind speed can fluctuate on various scales, including sub-hourly, hourly, daily, monthly/seasonal, annual, and multi-decadal...

2.2.0 Theoretical Framework

This study is anchored on three theories which include; Sag Tension Theory, Wind Loading Theory and Precipitation Theory.

Although the sag-tension theory does not account for insulator sets in the calculation of tensions and sags—which can sometimes lead to inaccuracies in determining the necessary vertical clearances between phase conductors and objects beneath the overhead line (Kampik *et al.*,

2024)—it nonetheless offers reliable, mathematically sound predictions regarding the behavior of overhead conductors under various practical conditions (Chen & Ding, 2022).

The Sag-Tension Theory forms the cornerstone of overhead power line engineering, detailing the inverse relationship between conductor sag and tension under thermal and mechanical stress.

Central to this theory is the understanding that heating induces thermal elongation in conductors—with aluminum expanding at roughly twice the rate of steel—leading to increased sag and reduced tension, while cooling produces the opposite effect. This behavior is mathematically captured by the sag equation $D \propto (wS^2)/8H$, which relates sag (D) to the conductor's weight per unit length (w), span length (S), and horizontal tension (H). The theory further incorporates material considerations such as composite conductor properties and time-dependent creep deformation, alongside environmental factors like wind and ice loads, to ensure designs maintain safe clearances and reliability under variable operating conditions.

Complementing this, the Wind Loading Theory provides a framework for assessing aerodynamic forces on transmission structures. Evolving from regional standards like the Barbados Code BNS CP28, it integrates meteorological and structural principles to calculate wind loads through velocity pressure formulas such as $q = 0.613K_zK_dK_ztV^2$, where factors like terrain exposure (K_z) and wind directionality (K_d) adjust basic wind speed (V) values. The theory also accounts for dynamic responses to gust-induced oscillations, crucial for tall structures, ensuring stability across diverse wind climates and structural designs through harmonized international standards.

The Precipitation Theory completes the meteorological perspective by explaining ice and snow accretion on conductors through microphysical processes. Originating from the work of Wegener, Bergeron, and Findeisen, it describes mechanisms like the ice-crystal process—where vapor pressure gradients drive crystal growth in supercooled clouds—and collision-coalescence in warmer clouds. Key principles, quantified via equations like $dm/dt = 4\pi C\Delta eDv$ for ice growth rates, clarify how precipitation type (rain, sleet, snow) depends on atmospheric thermal profiles. For transmission lines, as a merit, this theory enables predictive modeling of ice loads and informs the design of weather-resistant infrastructure, leveraging modern numerical weather models to mitigate hazards like ice-induced failures or wet snow adhesion.

2.3.0 Empirical review

Abitayeva *et al.*, (2025) addressed the challenge of improving the reliability of high-voltage transmission lines under increasing climate risks, particularly focusing on conductor galloping caused by ice and wind. The study synthesized statistical factors, theoretical models based on dynamics and energy balance, and experimental observations from test sites to analyze galloping behavior. The research identified effective damping methods and recommended the most economical solutions for galloping suppression in split-phase power lines, offering both a comprehensive overview of existing mitigation measures and new directions for future research.

Yong Liu *et al.*, (2024), developed a meteorological prediction-based early warning system for wind deflection in transmission lines, responding to the increased frequency of extreme weather events. By creating a detailed model of a transmission line-insulator system, they analyzed how factors like stall spacing, height difference, wind speed, and wind attack angle affect wind deflection angles. Using a combination of generalized linear regression networks and a particle swarm-optimized support vector machine algorithm, they established an effective early warning model. Their findings provide critical insights for the development of more resilient UHV and EHV transmission networks.

3.0 METHODOLOGY

This study adopted a survey research design. With total population of 746 comprising of Project Managers, Engineers and NERC Staff across northern Nigeria. The sample size for the study is

using Taro Yamane formula $n = \frac{N}{1+N(e)^2}$ $n = \frac{746}{1+746(0.05)^2} = \frac{746}{2.86}$ determined $n = 260$. A

30% buffer was included giving a total of 339. Therefore, 339 questionnaires were distributed and 311 returned valid and was used for the analysis. The sampling techniques utilized for the study is purposive sampling techniques. Factors for the study were collected through primary source, utilizing the questionnaires to get appropriate information. Regression analysis was utilized to determine the relationship that exist between metrological factors and overhead transmission line management in Nigeria.

4.0 RESULT AND DISCUSSION

The study employed a multiple linear regression method to test and analyze the hypothesis of the study. The multiple regression coefficients indicated the coefficients of predictor to examine the extent to which the dependent variable varies with independent variables. Multiple regression coefficients are presented in Table 4.0

In order to decide whether the hypotheses of this study are rejected or not, there are some preconditions that will determine whether the hypothesis null will be accepted or rejected. Hair *et al.* (2010) and Pallant (2017) suggested that the t value should be 1.96 and above for the hypothesis to be supported, and the significant value should be 0.050 and vice versa. The four hypotheses were tested based on standardized coefficients of beta with a 95% confidence level.

Precipitation and Overhead Transmission Line Management

Table 4.0: Coefficients Table

Hypotheses	Variables	B	Unstandardized		T-value	pvalue	Decision
			Std. Error	Beta			
H ₀₁	Precipitation	.497	.061	.404	8.164	.000	Rejected
F Value	152.561						
F Sig	.000						
R ²	.666						
Adjusted R ²	.662						
Durbin-Watson	1.91						

Source; Field Survey (2025)

The study also found a positive and statistically significant relationship between precipitation and overhead transmission line management. The standardized beta coefficient is 0.404, with a t-value of 8.164 and a p-value of 0.000, indicating that a unit increase in precipitation-related variables corresponds to a 40.4% increase in management efforts. Hence, the null hypothesis is rejected. Precipitation increases the risk of insulator contamination, flashovers, and structural degradation due to corrosion and water ingress and Seasonal variability in rainfall affects line accessibility for

maintenance and vegetation encroachment, both of which impact reliability. These findings are corresponded with the findings of Li *et al.*, (2016), Okonkwo and Adegbite (2021) World Bank Report (2018). These findings validate the study's conclusion that precipitation is a significant operational challenge, requiring enhanced insulation strategies, improved drainage systems, and more frequent inspections during wet seasons.

Effect of Wind Direction on Overhead Transmission Line Management

Table 4.0: Coefficients Table

Hypotheses	Variables	B	Unstandardized		T-value	pvalue	Decision
			Std. Error	Beta			
H02	wind	.417	.044	.596	9.386	.000	Rejected
F Value	152.561						
F Sig	.000						
R ²	.666						
Adjusted R ²	.662						
Durbin-Watson	1.91						

Source; Field Survey (2025)

The findings of the 2025 field survey present a nuanced understanding of how wind affects overhead transmission line infrastructure. Statistical analysis shows a strong and statistically significant relationship between wind and transmission line management, with a standardized beta coefficient of 0.596, a t-value of 9.386, and a p-value of 0.000. This implies that a unit increase in wind-related factors necessitates a 59.6% increase in management efforts, confirming the rejection of the null hypothesis. Furthermore, the findings of this study correspond with the of Zhou et al. (2017), Amin and Stringer (2019) IEEE (2020). In conclusion, the study supports the growing consensus that wind direction along with speed and turbulence plays a critical role in mechanical stress and failure risks, thereby demanding proactive management strategies.

Conclusion

Both wind direction and precipitation patterns were found to significantly affect overhead transmission line management, with wind having a slightly higher impact based on standardized beta coefficients. These results align with global findings and emphasize the importance of climate-adaptive design, real-time monitoring, and preventive maintenance in ensuring transmission line reliability in Nigeria and similar environments.

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