Advances in Reliability, Safety and Security, Part 2 – Kołowrocki, Magryta-Mut (eds.)
© 2024 Polish Safety and Reliability Association, Gdynia, ISBN 978-83-68136-14-2 (printed), ISBN 978-83-68136-01-2 (electronic)

Advances in Reliability, Safety and Security

ESREL 2024
Monograph Book Series

A Review Of Overhead Power Line Component Degradation Models

Tom Ivar Pedersen, Maren Istad

Department of Energy Systems, SINTEF Energy Research, Trondheim, Norway, {tom.ivar.pedersen,maren.istad}@sintef.no

Abstract

This paper presents a literature review of degradation models for overhead power line (OHL) components. These models are important for informing decisions on when, where, and how to best renew parts of OHLs. The OHL components are grouped into the categories: conductors (the components that carry the electric energy), support structures (components that ensure the conductors are lifted overhead), and interfaces (the components that connect the conductors to the support structure). As found in the literature review, the available condition information, degradation processes, and failure modes varies between the three component categories. Thus, the suitability of the available approaches for degradation modeling, e.g., data-driven or physics-based, vary between the different categories. Another observation from the literature review is that degradation models have, over time, been expanded to better account for the condition information, attributes, and environmental loads on the individual components.

Keywords: degradation models, lifetime models, overhead power lines, critical infrastructure, power distribution system, literature review

1. Introduction

This review is performed as part of a research project on risk-based renewal of overhead power lines (OHLs) named Rifok. The Rifok project will develop a framework for assessing the condition and predicting the probability of failure of OHLs with the aim of helping distribution system operators (DSOs) make better decisions on when, where, and how to renew parts of their OHLs.

A necessary basis for developing this framework is models suitable for predicting how the individual components that comprise the OHLs age, degrade, and fail. As OHLs have several characteristics that separate them from the industrial systems usually treated in the reliability literature, we have conducted a literature review of degradation and lifetime models applied to OHL components. To the best of our knowledge, such a review is not available in the extant literature. This review focuses on components typically used on OHLs in distribution systems with voltage levels between 11 and 132 kV. However, as much of the existing research has been targeted at transmission lines operated at higher voltage levels, and because often new technology and methods are introduced to transmission lines before being applied at distribution lines with lower voltage levels, papers focusing on transmission have been included in the review when found relevant.

This review should interest anybody wanting to model the reliability of OHLs in the distribution grid. However, as OHL shares many of the same characteristics as other types of critical infrastructure, i.e., a large number of geographically dispersed components exposed to environmental loads and long lifetimes, this work may also be of interest to academics and practitioners in other fields, such as road, rail, and telecommunication.

The rest of this paper is organized as follows. The next section gives some background information on overhead power lines (OHLs) and the different approaches for degradation modeling. Section 3 presents the results of the literature review. The paper ends with some concluding remarks in Section 4.

2. Background

The electric energy system comprises power generation, transmission, and distribution systems. The generation systems produce the power needed to meet end-user demands. Transmission systems transport large amounts of electric power over long distances, while the distribution system delivers electricity to the individual end-user. A reliable supply of electric energy is of critical importance for modern society to function, and this dependence is increasing as more functions are electrified in efforts to reduce greenhouse gas emissions (Alvarez-Alvarado et al., 2022).

As distribution grids are natural monopolies, distribution system operators (DSOs) are usually tightly regulated by governmental bodies to incentivize the DSOs to achieve an acceptable balance between costs and the reliability of energy supply (Brown, 2002). E.g., by imposing a unit cost for expected energy not supplied during outages (Li, 2014) or defining design standards for OHLs (Wareing, 2005). While the components used in OHLs in different parts of the world are much the same, it is important to keep in mind that the design, operation, and maintenance policies used by the different DSOs are affected by the regulatory regimes imposed on them.

According to (Brown, 2002), distribution systems account for up to 90% of all customer reliability problems. In Norway, distribution system OHLs account for more than half of the energy not supplied (Statnett, 2019). Therefore, effective maintenance policies for OHLs are critical for ensuring an acceptable level of reliability of energy supply.

The electricity distribution grid comprises a huge number of geographically dispersed assets often organized in radial structures segregated into line segments by switches (Lu et al., 2022). Failure to one component will lead to an outage of the associated line segment (between switches) and downstream line segments until repair (Hilber et al., 2005). However, the resources that can be spent on analyzing the condition of the individual assets are limited due to the large number of assets.

The DSOs often inspect only a small percentage of their assets each year (Salman et al., 2020) and have traditionally often used subjective methods where assets are classified as either fit for service until the next inspection or in need of replacement based on the inspector's expertise (Bandara et al., 2021; Christodoulou et al., 2009; Datla and Pandey, 2006). Thus, the degradation rates of the components in the different parts of the grid are, to a large extent, unknown to the grid operators (Lovrenčič et al., 2022). As the distribution grids in many countries are reaching their design life (Wareing, 2005), it is increasingly important to be able to predict the remaining useful life (RUL) of OHL components in order to prioritize and plan for their timely renewal.

According to (Lei et al., 2018), three necessary steps before RUL predictions can be made are data acquisition, health indicator construction, and health stage division.

Data acquisition is about gathering data on the component's condition and the stresses it is exposed to. The potential for data acquisition on OHL components is improving with the ongoing developments in condition monitoring technology, e.g., wireless sensors (Fadel et al., 2015), drones and robots (e.g., for collection of RGB- and IR-images, and lidar-scanning) (Yang et al., 2020), and sensors for remote sensing of degraded components by measuring the voltages and currents at the lines terminals (Panahi et al., 2021). Another important aspect in this regard is software systems for organizing the acquired data, e.g., geographic information systems (GIS), which contain data on the geographical location and attributes of the individual components in the distribution grids (Zhou et al., 2016).

Health indicator (HI) construction is about relating the acquired data to the health of the components. HIs may be physical quantities, e.g., the measured corrosion depth of a steel structure, and may be defined using discrete states or a continuous scale. Physical HIs, such as corrosion depth, are advantageous to use when they directly relate to the component's ability to fulfill its required function, e.g., a steel structure's ability to withstand a specified load. When physical HIs are not available, or a complete understanding of the relation between the acquired data and the component's ability to fulfill its required function is lacking, synthetic HIs that fuse different data sources may be used.

Next is health stage division, which involves relating the HI to when a component is considered as-good-as-new, degraded, or failed (i.e., no longer able to fulfill its required function). OHL components are often considered to have reached their remaining useful life (RUL) when they reach a defined failure threshold and not when they physically collapse (Datla and Pandey, 2006). An example of a defined failure threshold used for OHL components is when the estimated residual strength of wood poles reaches two-thirds of their initial strength (Salman et al., 2020).

When these stages are completed, degradation models can be used to make RUL predictions. Approaches for degradation modeling are often divided into categories such as physics-based, data-driven, stochastic, knowledge-based, or hybrid approaches (Prakash et al., 2021). Physics-based models can give accurate RUL predictions when detailed knowledge of the degradation process is available but sometimes require computationally expensive finite element modeling. Data-driven models can be used when knowledge of the degradation process is lacking. However, data-driven models, such as artificial neural networks (ANNs), have drawbacks in that they need a lot of data for training, and lack of interpretability and transparency is an issue when the output is used to inform decisions that may have large consequences for safety or cost.

Stochastic models are often well suited because they can handle some unexplained randomness and thus do not require the same level of understanding of the system compared to a physics-based model. This approach also usually requires less data than data-driven models, but their application may require simplifying the actual degradation process to make the calculations tractable. Knowledge-based models are often based on IF-THEN rules collected from domain experts and can be used when both condition information and understanding of the degradation process are incomplete. A disadvantage of this approach is that considerable effort is often needed to elicit expert judgments and convert them into rules. Finally, hybrid models that combine elements from the different approaches are often useful when limited data and domain-specific knowledge of the degradation mechanism are available (Prakash et al., 2021).

See reviews by e.g., (Lei et al., 2018), (Prakash et al., 2021), and (Liao and Köttig, 2014) for additional information on the strengths and weaknesses of the different approaches.

3. The literature review

The following search string was used to search for papers that had the following words in the title, abstract, or keyword: *((transmission W/3 line) OR (overhead W/3 line)) AND (degradation OR deterioration OR wear OR decay OR fatigue OR corrosion) AND (predic* OR forcast* OR prognos*))*, where W/3 is a proximity operator indication that texts having the words before and after W/3 three positions apart, or less, are include in the search. As the state of wood poles is important for the reliability of distribution grids, a second search was performed focusing on this component: *((timber W/3 poles) OR (timber W/3 pylons) OR (wood W/3 poles) OR (wood W/3 pylons)) AND (predic* OR forcast* OR prognos* OR renew* OR maintain* OR replac*)*.

In total, 588 papers were found in the two searches. Based on reviews of the title, abstract, and complete text, 47 papers containing degradation models applied to OHL components were identified. Seven papers and reports were later added based on references in the identified papers. Papers focusing on extreme events such as hurricanes and forest fires have been excluded. Papers related to the identification and rating of probabilities of trees falling on lines were also excluded, as this is not in the scope of this review. The search was performed in the academic database Scopus in November 2023, and no papers were excluded based on publication year.

The remainder of this section presents the selected degradation models grouped in the following component types: *conductors*, i.e., the components that help transfer the electric energy; *support structures*, i.e., the components that ensure that the conductors are lifted overhead, e.g., wood poles, lattice steel towers, crossarms, and foundations; *interfaces*, i.e., components that help connect the conductors to the support structure, e.g., insulators and fittings. Examples of how the identified models have been used for informing maintenance decisions have been included to indicate the applicability of these models.

3.1. Conductors

The conductor is the most important part of an OHL as this component carries the electrical energy, and the conductors account for up to 40% of the investment costs for OHLs (de Mendonça and Caetano, 2021).

Wind-induced vibration of the conductors is of major concern regarding the reliability of OHLs. The three main types of vibration that damage conductors are aeolian vibration, galloping, and subspan oscillation (Kiessling et al., 2003). Of these, aeolian vibration is the most common cause of fatigue failure of conductors (CIGRE, 2007) and a phenomenon that has been the subject of many studies (de Mendonça and Caetano, 2021). Aeolian vibration is most likely to occur at long spans, with high support towers, and in flat areas with steady wind (CIGRE, 2007). This phenomenon is thus more relevant for transmission lines than lower-hanging distribution lines.

Aeolian vibrations lead to fretting fatigue of the wire strands in the conductor where they are arrested. This is normally most pronounced at the support clamps. Broken strands typically occur in the inner layers of the conductor. Degraded conductors due to aeolian vibrations are thus challenging to detect by visual inspections (Pouliot et al., 2016). The Poffenberger-Swart (PS) formula is often used to relate the amplitude of the conductor excitation 89 mm from the last point of contact (LPC) from the support clamp to bending stress. The rainflow method and Miner's rule can then be used to relate bending stress at different frequencies to residual lifetime based on Stress-Number (S-N) curves from experimental tests (de Mendonça and Caetano, 2021).

The PS formula rests on several idealized assumptions and simplifies the fretting fatigue process inside the conductor. However, as conduct-clamp systems have often been developed and tested using this framework, empirical coefficients that give acceptable results for most engineering applications are available (CIGRE, 2010). Nonetheless, one drawback of this approach is that expensive tests must be performed on each conduct-clamp configuration to estimate these empirical coefficients (Miranda et al., 2023).

Recently, several papers aiming to better represent the actual fretting fatigue processes in conductors have been presented. Examples are (Thomas et al., 2022), (Said et al., 2023), (Rocha et al., 2023), and (Gomes et al., 2023) using the Smith-Watson-Topper (SWT) parameter and detailed finite element (FE) models of the conductor-clamping system. However, (Thomas et al., 2022) express that due to the complexity of these models, it is unlikely that the industry will adopt them.

To predict the time to fatigue failure of a conductor, it is also necessary to predict the number and amplitude of excitations that that conductor is subjected to at the point where it is attached to the clamp. One way to do this is by installing sensors that measure the vibration of the conductor at 89 mm from the LPC (Kiessling et al., 2003), but conducting this type of measurement on a large scale is resource-demanding.

Efforts to predict where damaging aeolian vibrations may occur have mainly followed either the stylized Energy Balance Principle (EBP) or a more complex dynamic mechanical modeling of the system (Liu et al., 2022). Based on the EBP and field experience (CIGRE, 2005), give guidance on which ratios of conductor tension and span lengths are considered safe from aeolian vibrations for four different terrain categories and where measures such as dampers are advised.

(Liu et al., 2022) perform a numerical study using a computational fluid dynamics (CFD) model of the airflow around the conductor and a FE model of the conductor-clamp system and find that the EBP model overestimates the vibration amplitudes. Further, the time to fatigue failure is calculated at four wind speeds. However, (Liu et al., 2022) acknowledge that predicting the fatigue life for a conductor installed in the field requires an extension of the model to account for changing wind speeds and conductor tension due to differing temperatures over the seasons. According to (Cieren et al., 2020), the computational burden of CDF and FE models makes widespread use of them prohibitively expensive. On the other hand, as the simpler models based on the EBP are inadequate for predicting the occurrence of aeolian vibrations at low wind speed, they propose a computationally lighter model to fill this gap. However, the resulting predicted mean amplitude of the steady-state vibration is too small to explain the aging of conductors, and further development of this model is needed before it can be used to predict the cumulative damage to conductors in the field. Based on a study aiming to develop models for predicting conductor fatigue life, (Redford et al., 2019) state that due to uncertainties in several aspects, only relative predictions on which conductor-span configurations are expected to fail first are possible and not absolute RUL predictions. Relative predictions are nonetheless useful for guiding decisions on which spans to prioritize for replacement or mitigating measures such as dampers.

Another source of conductor fatigue is unbalanced wire tension that appears when the wind exerts uneven force on the two sides of the support. In (Takahashi et al., 2020), a field test is performed to investigate this phenomenon, and a physics-based model for estimating the unbalanced wire tension is developed.

(Di Pasquale et al., 2022) propose a health indicator (HI) for estimating the residual life of overhead conductors, where HI=100% is as-good-as-new (AGAN). The aging variables included in this HI are conductor weight, temperature, wind, snow, and ice. The stresses exerted on the conductor based on these five variables are calculated for each time increment using physics-based formulas collected from the IEC standards EN50341-1 and EN50341-2-13. Miner's rule is used to find the cumulative aging, and the conductor is considered to need "imminent replacement" when the HI is $\leq 30\%$. This model is not validated against experimental tests or field data.

(Havard et al., 1992) presents a degradation model for aluminum conductors with galvanized steel core. Based on tests of samples collected from the field, ductility loss of the wires in the steel core was found to be a good indicator for conductor RUL. An environmental corrosion index is proposed for adjusting the degradation rate depending on geographical location. Predicted degradation based on this model corresponded well with the results of test specimens collected at geographical locations with differing environmental corrosion indexes. In another study of corrosion, (Volokhovsky et al., 2010) measured cross-section loss due to corrosion of conductors and guy wires on an OHL located in Russia. Further, RUL predictions based on linear extrapolation of when the residual strength of these components reaches a minimum permissible safety factor are presented. In a study that uses a knowledge-based approach (Bhuiyan et al., 2011) present a model for predicting conductor deterioration depending on environmental factors such as ambient temperature, wind speed and direction, and pollution.

According to (Jiang et al., 2012), increasing power demand often results in OHLs being operated above the original design loads. This may lead to overheating of splice connectors, which often have higher electric resistivity than the conductors. (Jiang et al., 2012) use a physics-based approach where FE analysis and thermal cycling simulations are validated with experimental pull-out tests. A model for predicting the shear resistance capacity of splice connectors depending on the number of thermal cycles and peak cycling temperature is presented. Another paper that considers the aging of components based on increasing power demand is (Kalmár et al., 2022), which study how sensors, installed in association with the introduction of a dynamic line rating operation policy, may also be used to measure the permanent sag of the conductor caused by thermal cycles and ice loads. The conductors are considered to have reached their RUL when the conductor ground clearance reaches a defined safety margin above the legal minimum.

3.2. Support structures

For many DSOs, wood poles are one of the most common components; thus, the choice of maintenance strategy for this component may greatly affect the total maintenance costs (Li et al., 2005). In distribution grids, wood poles are often preferred over other materials, e.g., steel and concrete, due to low purchase and installation costs (Salman et al., 2020). However, as the material properties of wood are not as uniform as steel and concrete (Lu et al., 2022), there is uncertainty associated with the initial strength of the wood poles (Wang et al., 2008a). Poles are also subject to decay over time due to fungal attacks, and the failure of old wood poles during storms and hurricanes is a major contributor to outages in some locations (Lu et al., 2022). The rate of decay depends on the site-specific characteristics, i.e., humidity, rainfall, temperature, and soil properties, the wood species used, and preservative treatment, e.g., application of creosote, Chromate copper arsenate (CCA), or Copper chromium phosphate (CCP) (Wang et al., 2008b).

Decay of wood poles happens mainly on the ground level (Refsnaes et al., 2006), and loss of strength due to external decay at the ground level is the damage scenario with the most severe effect on the probability of wood pole failure due to wind load (Yu et al., 2016). Therefore, the degradation of the wood at the ground level is of great concern.

Based on an extensive study of the degradation of wood in ground contact, (Wang et al., 2008b) developed a set of decay rate models. A decay lag and a subsequent decay rate is expressed in decay dept in millimeters per year and depends on climate zone, wood type, and the preservative treatment used.

Several subsequent papers have used these empirical models for wood pole decay. E.g., (Wang et al., 2008a) presents a probabilistic procedure for the design of untreated wood poles in ground contact. Several papers have combined the degradation model from (Wang et al., 2008b) with scenarios for climate change to assess whether the rate of degradation and failure due to wind load can be expected to change in the future. In a study of Australian regions, the degradation rate and failure due to wind load were predicted to increase by 12 and 59 percent, respectively, in the period from 2015 to 2070 for the most affected region while improving slightly in another region (Ryan et al., 2016). Similar studies have been conducted for regions in Ireland (Hawchar et al., 2019) and the US (Salman et al., 2020).

In (Ryan et al., 2014), the model by (Wang et al., 2008b) is used to present a probabilistic model for pole failure that take maintenance into account, and they find that even minor changes to maintenance and design may have a large effect on the performance of the distribution system. (Salman et al., 2019) use renewal theory to find the renewal interval that minimizes long-run costs for treated and untreated wood poles under different climate change scenarios. In a later paper, (Salman et al., 2020) propose a stochastic approach where the pole decay is modeled as a homogeneous gamma process and find the inspection interval that minimizes the long-run maintenance cost.

Another paper that uses the degradation model by (Wang et al., 2008b) is (Lu et al., 2022), which presents a method for selecting the strategy for renewal and upgrading that minimizes investment and failure costs. (Lu et al., 2022) found through a case study, using a GIS system that contains information in the individual poles, that renewal and upgrading strategies targeted at the individual poles, as opposed to implementing the same measures for whole line segments, have considerably lower costs.

In (Li et al., 2005), a degradation model based on field measurements of the residual strength of 13,940 wood poles is presented. This model is extended by (Shafieezadeh et al., 2014), who developed an age-dependent failure model for wood poles considering wind load. Later, (Mohammadi Darestani and Shafieezadeh, 2019) builds on (Shafieezadeh et al., 2014) to develop a model for predicting the failure of wood poles that takes into account the pole’s circumference at ground level, height, age, number and diameter of conductors, and span length together with wind strength and direction. In a consecutive paper by (Mohammadi Darestani et al., 2021), this failure model is combined with a consequence model based on the grid topology to develop a risk-based pole replacement strategy to minimize expected power outages when a given number of poles are replaced in the defined period. The degradation model from (Shafieezadeh et al., 2014) is also applied by (Ma et al., 2021) for modeling the effect of adjacent spans on the probability of failure of OHLs under wind loads from different directions.

(Bajestani et al., 2015) and (Datla and Pandey, 2006) propose stochastic lifetime models for wood poles assuming Weibull-distributed failure times based on lifetime data from Canadian DSOs. Using lifetime data from Australian DSOs (Stillman, 1994) and (Stillman et al., 1995) use the three-parameter Weibull distribution, which includes a "warranty period"-parameter, γ, i.e., a period where the probability of failure is zero. In another study of wood pole lifetime data, (Christodoulou et al., 2009) compare three different probability distributions and find the Weibull distribution to be the best choice based on the Akaike information criterion. However, for these studies, differences in climatic and geographical conditions within the populations of wood poles were largely not accounted for.

Based on a study of about 40,000 creosote-treated wood poles, (Refsnaes et al., 2006) conclude that the decay rate depends heavily on climatic and soil properties. (Gustavsen and Rolfseng, 2005) suggest that the pole population should be divided into subsets with approximately the same conditions when estimating the parameters for the decay rate. This may avoid implementing an unnecessarily conservative age-replacement threshold for wood poles in locations with favorable conditions and an excess of failures in areas with unfavorable conditions.

(Onyewuchi et al., 2015) presents an example of how a GIS may be used to identifying wood poles with a high risk of failure based on pole attributes, e.g., age, species, treatment, and location, and environmental attributes, e.g., the return period of severe wind load, soil moisture, and rainfall. Based on a case study of 380,000 wood poles, the predicted number of failures was found to vary significantly depending on geographical location, indicating the potential benefits of diversified asset management policies based on data from individual poles.

Based on full-scale bending tests of new and used wood poles (Stewart and Goodman, 1990), model the strength of new wood poles as normally distributed and the bending strength, s, at time t as $s_t = s_0 \exp(-bt)$, where s_0 is initial strength and b is an empirical coefficient. These modeling choices are later used in (Gustavsen and Rolfseng, 2000), where a method for finding the expected number of wood pole failures and renewals for a distribution grid when the probabilistic nature of initial pole strength, wind load, and condition assessment based on field inspections are taken into account. This method was later expanded by (Gustavsen et al., 2002) and (Gustavsen and Rolfseng, 2005), where the optimal maintenance threshold for case studies based on data from Norwegian DSOs for condition-based maintenance policies with fixed inspection intervals are found. Both these papers conclude that a condition-based maintenance policy only pays off when the financial penalty incurred to Norwegian DSOs for non-delivered energy to end users is considered. This is in line with (Salman et al., 2020), which found a run-to-failure policy for wood poles favorable to a preventive maintenance policy when only the direct costs to the DSO, and no penalties for non-delivered energy, were included in the model.

Wooden crossarms have received less attention than wood poles in the literature, but (Ho et al., 2008) present a model for correlating the remaining bending strength of wooden crossarms based on the amount of surface decay in critical stress zones identified using an automated image processing technique. A health indicator and an end-of-life criterion are formulated based on experimental data and structural analysis of the crossarms.

(Rahman et al., 2016) argue for the importance of considering soil properties (e.g., clay content, pH value, and chemical composition) when modeling the degradation of wood poles below ground level. A numerical example based on lifetime data from a DSO located in an area with unfavorable soil types is used to demonstrate how an inground decay factor may be used to optimize the preventive maintenance interval based on soil properties. In another paper that considers the effect of soil properties, (Salamoni and Rohden, 2022) evaluate the effect of sulfates on the degradation of concrete foundations for OHLs. An empirical model from (Atkinson et al., 1985) and chemical analysis of the soil are used to make RUL predictions.

Some studies on the corrosion of lattice steel towers have been found in the literature study. (Korobov et al., 2019), present a data-driven formula for predicting the corrosion depth of steel. Empirical coefficients for calculating the degradation rate based on data collected from two Russian regions are presented. (Salazar and Mendoza, 2009), present a study where the loading of structural members of a lattice tower design is considered, and the allowable thickness loss due to corrosion is calculated based on wind load and a safety factor. Further, RUL predictions are made based on estimated correction rates for the zinc coating and bare steel. In (Der Van Wal and Voncken, 2008), measurements of degradation of zinc layer and bare steel are measures for steel lattice towers located in the Netherlands and the UK. The measured degradation rate at different locations is compared to the expected rate based on the climatic class in accordance with ISO 9223.

3.3. Interfaces

This subsection treats the components that help connect the conductors to the supports. Insulators have the important role of electrical insulation and mechanical fixation of the conductors to the supports and thus are vital for ensuring safe and reliable operation for OHLs. Insulators are made of materials such as glass, ceramics, or polymer composites with differing mechanical and electrical properties (Ghosh and Khastgir, 2018). The degradation and failure of insulators are affected by several factors, e.g., electrical, mechanical, chemical, and thermal stresses (Gjorgiev et al., 2023). The differences in design and interacting stress factors complicate RUL-predictions for insulators (Bezerra et al., 2018).

In (Ma et al., 2023), the variables years in operation, online monitoring of insulator crack length, annual relative humidity, average temperature, precipitation, sunshine hours, and “other information” are used to train an ANN for predicting the remaining useful life of insulator strings. When more than two-thirds of the insulators in an insulator string have a crack length exceeding 0.5 millimeters, the insulator string is considered failed, and renewal must be performed. Based on test data, the growth in crack length is divided into four stages: no crack, linear growth, stable phase, and exponential growth. An application of this model is presented, and the predicted RUL shows good accordance with actual RUL.

In (Valeriy and Iosif, 2022), leaked currents are measured on glass disk insulators with varying numbers or operating years. The primary degradation mechanism for these insulators is surface contamination, causing the insulator’s resistance to decrease. By assuming a constant contamination rate, the time when the resistance reaches the minimum allowed threshold is predicted by linear regression of the measured data. The authors acknowledge that the contamination rate will vary depending on environmental factors at the location of the insulator. However, this is not accounted for in this study.

(Ghosh and Khastgir, 2018) study the degradation of polydimethylsiloxane (PDMS) composite insulators. Working insulators with a service life of 1 to 9 years were collected from OHLs with similar climatic conditions and subjected to mechanical and electrical tests to evaluate their conditions. Accelerated thermal and UV aging tests were also conducted to better understand the contribution factors to the degradation of PDMS insulators. Based on these investigations, two health indicators are proposed. The first HI is the percentage of elongation at break (EB) for the silicon polymer housing material. An EB of 50% is set as the defined failure threshold, and the formula $f(t) = a\exp(-bt)$ with empirical coefficients a and b is used to predict the degradation at time t. The other HI is hydrophobicity, which is measured based on the contact angle of water droplets on the insulator surface. This HI has a defined failure threshold of 90°, and a similar exponential formula as for EB is used. The insulator is considered failed when one of the HIs reaches its defined failure threshold.

(Wańkowicz et al., 2006) investigate the degradation of long rod composite insulators due to mechanical load cycles caused by wind. Long rod insulators from three manufacturers are subjected to cyclic load tests until failure. S-N cures, which may be used to estimate the number of cycles at a given load to failure, are presented.

Fittings are components that perform the mechanical attachment, electrical connection, and protection of conductors and insulators (Kiessling et al., 2003). (Refsnaes, 1997) group fitting failures into two categories: sudden failure due to overloading, e.g., by a fallen tree, or failure caused by gradual degradation due to adhesive, abrasive, or corrosive wear.

Based on field inspections, (Refsnaes, 1997) asserts that the wear of support fittings is affected by several factors, e.g., wind-induced conductor swing, vertical load, climate, conductor support arrangement, and difference in hardness between the sliding surfaces. A later study by (Yi et al., 2021) focused on the wear and RUL prediction of the U-shaped fittings used to attach the insulator string to the crossarm. Based on numerical simulations and experiments at varying loads and swing angels the wear of the U-shaped fittings showed good accordance with Archard’s wear model: $V = \frac{K\,l\,W}{H}$, where V is the wear volume, l is sliding distance, W is vertical load, H is Vickers hardness of the softer of the two sliding surfaces, and K is an empirical coefficient often referred to as Archard’s coefficient. Further, (Yi et al., 2021) find the sliding distance by simulating how the wind induces motion to the insulator-conductor system and predict the wear rate based on this. These predictions are in good agreement with the wear rate from field data.

3.4. Several components

Some of the reviewed papers include degradation models from more than one of the three component groups. For instance, (Khalyasmaa et al., 2021) present a method for assessing the condition and residual life of reinforced concrete towers, conductors, and insulators. Models for predicting the failure probabilities based on expected wear rates that consider the effect of climatic conditions are also presented and tested on an OHL located in the Republic of Kazakhstan.

OHLs have several components subjected to corrosion. (Kenny et al., 2009) use principal component analysis and an ANN to predict the corrosion rate of low-carbon steel, aluminum, and copper used at an OHL located in Brazil. Ten environmental parameters were included in the model. At five measurement stations located along the OHL, test specimens representing the different components used in the OHL were placed for two years. These test specimens were used for training the model. (Kenny et al., 2009) use Pourbaix’s equation, $C = k\,t^n$, to predict the long-term corrosion, where C is the reduction in thickness per year, t is the time of exposure, and k and n are coefficients fitted based on the predicted corrosion rate in the first and second year of the test.

4. Concluding remarks

This literature review has identified several, quite different, approaches for modeling the degradation and remaining useful life (RUL) of overhead line power (OHL) components. The suitability of the different modeling approaches is affected by factors such as the material properties of the component in question, degradation mechanisms, environmental stress, availability of data and health indicators, and the intended use of the model’s output. For example, in the papers in this review stochastic approaches are often used to model the degradation of wood poles, as wood is a material with considerable randomness. On the other hand, degradation models related to corrosion of steel components, which have more uniform properties, are often deterministic.

With the technological development related to solutions for collecting, storing, and analyzing large amounts of data, there has been a trend toward developing more comprehensive degradation models for a more accurate representation of the actual degradation processes and local variations in environmental stresses for the individual components in a distribution grid. While this may contribute to more accurate predictions of the degradation and RUL of the individual components, these models are more demanding to implement and use. As distribution grids comprise a huge number of components, the tradeoff between potential benefits and cost of use is essential to consider when developing degradation models for OHL components.

Most of the papers covered in this review only consider the degradation of a single component. In future work, we plan to combine degradation models for the different component types in a framework to predict the aggregated probability of OHL failure.

Acknowledgements

This works has been funded by Rifok – Risk-based renewal planning of power lines, a project funded by the Research Council of Norway. Project number 332354.

References

Alvarez-Alvarado, M.S., Donaldson, D.L., Recalde, A.A., Noriega, H.H., Khan, Z.A., Velasquez, W., Rodriguez-Gallegos, C.D., 2022. Power System Reliability and Maintenance Evolution: A Critical Review and Future Perspectives. IEEE Access 10, 51922–51950. https://doi.org/10.1109/ACCESS.2022.3172697.

Atkinson, A., Goult, D.J., Hearne, J.A., 1985. An assessment of the long-term durability of concrete in radioactive waste repositories. MRS Online Proceedings Library (OPL) 50, 239.

Bajestani, M.A., Montgomery, N., Banjevic, D., Jardine, A.K.S., 2015. Maintenance resource planning for utility poles in a power distribution network, in: 2015 Annual Reliability and Maintainability Symposium (RAMS). Presented at the 2015 Annual Reliability and Maintainability Symposium (RAMS), pp. 1–6. https://doi.org/10.1109/RAMS.2015.7105167.

Bandara, S., Rajeev, P., Gad, E., Sriskantharajah, B., Flatley, I., 2021. Structural Health Assessment of Timber Utility Poles Using Stress Wave Propagation and Artificial Neural Network Techniques. Journal of Nondestructive Evaluation 40. https://doi.org/10.1007/s10921-021-00821-6.

Bezerra, R.C., Kowalski, E.L., Conceicao, F.W.S., Teixeira, J.M.T., Filho, O.G.S., 2018. Instrumental Inspection Methodology to Evaluate Corrosion in Transmission Line Glass Insulator Metallic Pins, in: 2018 IEEE International Conference on High Voltage Engineering and Application (ICHVE). Presented at the 2018 IEEE International Conference on High Voltage Engineering and Application (ICHVE), pp. 1–4. https://doi.org/10.1109/ICHVE.2018.8642079.

Bhuiyan, Md.M.I., Musilek, P., Heckenbergerova, J., 2011. An expert system for condition assessment of ACSR conductors, in: 2011 IEEE Electrical Power and Energy Conference. Presented at the 2011 IEEE Electrical Power and Energy Conference, pp. 380–385. https://doi.org/10.1109/EPEC.2011.6070230.

Brown, R.E., 2002. Electric Power Distribution Reliability. Marcel Dekker, New York.

Christodoulou, C.A., Ekonomou, L., Stefanou, K.A., Fotis, G.P., Karamousantas, D.Ch., Oikonomou, D.S., Harkiolakis, N., Chatzarakis, G.E., Stathopulos, I.A., 2009. Life Expectancy Evaluation of the Wood Poles Which Support the Hellenic Electrical Distribution Network. J. Perform. Constr. Facil. 23, 314–319. https://doi.org/10.1061/(ASCE)CF.1943-5509.0000042.

Cieren, E., Redford, J., Guéguin, M., Allix, O., Yang, C., Hafid, F., Ghidaglia, J.-M., 2020. On the validation and use of a simplified model of aeolian vibration of overhead lines for parametric studies. Presented at the Proceedings of the International Conference on Structural Dynamic , EURODYN, pp. 2011–2021.

CIGRE, 2010. Engineering guidelines relating to fatigue endurance capability of conductor/clamp systems (No. 429).

CIGRE, 2007. Fatigue Endurance Capability of Conductor/Clamp Systems - Update of Present Knowledge (No. 332).

CIGRE, 2005. Overhead conductor safe design tension with respect to Aeolian vibrations (No. 273).

Datla, S.V., Pandey, M.D., 2006. Estimation of life expectancy of wood poles in electrical distribution networks. Structural Safety 28, 304–319. https://doi.org/10.1016/j.strusafe.2005.08.006.

de Mendonça, R.F., Caetano, E., 2021. Using structural health monitoring to estimate the remaining lifetime due to fatigue at a conductor from an overhead high-voltage transmission line. Presented at the International Conference on Structural Health Monitoring of Intelligent Infrastructure: Transferring Research into Practice, SHMII, pp. 1233–1239.

Der Van Wal, A., Voncken, R.M.A.M., 2008. Extending the service life of aged overhead line towers. Presented at the 42nd International Conference on Large High Voltage Electric Systems 2008, CIGRE 2008.

Di Pasquale, A., Pagano, M., Petrarca, C., Volpe, F., 2022. Assessing a Health Index Algorithm for High Voltage Overhead Power Lines, in: 2022 AEIT International Annual Conference (AEIT). Presented at the 2022 AEIT International Annual Conference (AEIT), pp. 1–6. https://doi.org/10.23919/AEIT56783.2022.9951791.

Fadel, E., Gungor, V.C., Nassef, L., Akkari, N., Abbas Malik, M.G., Almasri, S., Akyildiz, I.F., 2015. A survey on wireless sensor networks for smart grid. Computer Communications 71, 22–33. https://doi.org/10.1016/j.comcom.2015.09.006.

Ghosh, D., Khastgir, D., 2018. Degradation and Stability of Polymeric High-Voltage Insulators and Prediction of Their Service Life through Environmental and Accelerated Aging Processes. ACS Omega 3, 11317–11330. https://doi.org/10.1021/acsomega.8b01560.

Gjorgiev, B., Das, L., Merkel, S., Rohrer, M., Auger, E., Sansavini, G., 2023. Simulation-driven deep learning for locating faulty insulators in a power line. Reliability Engineering & System Safety 231, 108989. https://doi.org/10.1016/j.ress.2022.108989.

Gomes, R.C., Araújo, J.A., Cardoso, R.A., Ferreira, J.L.A., Silva, C.R.M., 2023. Fatigue life prediction using critical distance on aluminum alloy wire containing indentation produced marks. Theoretical and Applied Fracture Mechanics 128, 104135. https://doi.org/10.1016/j.tafmec.2023.104135.

Gustavsen, B., Rolfseng, L., 2005. Asset management of wood pole utility structures. International Journal of Electrical Power & Energy Systems, Special Issue on Probabilistic Methods Applied to Power Systems 27, 641–646. https://doi.org/10.1016/j.ijepes.2005.08.005

Gustavsen, B., Rolfseng, L., 2000. Simulation of wood pole replacement rate and its application to life cycle economy studies. IEEE Transactions on Power Delivery 15, 300–306. https://doi.org/10.1109/61.847266.

Gustavsen, B., Rolfseng, L., Andresen, O., Christensen, H., Falch, B., Jankila, K.A., Myhr, T., Sandvik, H., Thomassen, H., 2002. Simulation of wood-pole replacement rate: application to distribution overhead lines. IEEE Transactions on Power Delivery 17, 1050–1056. https://doi.org/10.1109/TPWRD.2002.800879.

Havard, D.G., Bissada, M.K., Fajardo, C.G., Horrocks, D.J., Meale, J.R., Motlis, J.Y., Tabatabai, M., Yoshiki-Gravelsins, K.S., 1992. Aged ACSR conductors. II. Prediction of remaining life. IEEE Transactions on Power Delivery 7, 588–595. https://doi.org/10.1109/61.127053.

Hawchar, L., Stewart, M.G., Nolan, P., Sweeney, F., Ryan, P.C., 2019. Climate change risk for Irish timber power pole networks, in: 13th International Conference on Applications of Statistics and Probability in Civil Engineering (ICASP13). Seoul National University, pp. 1212–1219.

Hilber, P., Hällgren, B., Bertling, L., 2005. Optimizing the replacement of overhead lines in rural distribution systems with respect to reliability and customer value. Presented at the CIRED 2005 - 18th International Conference and Exhibition on Electricity Distribution, pp. 1–5. https://doi.org/10.1049/cp:20051306.

Ho, V.W.K., Pandey, M.D., Bedi, S., 2008. Effects of Surface Decay on Remaining Strength of Transmission-Line Wood Cross-arms. IEEE Transactions on Power Delivery 23, 419–424. https://doi.org/10.1109/TPWRD.2007.905558.

Jiang, H., Wang, J.-A.J., Ren, F., Lee, D., Chan, J., Sibilant, G., 2012. Integrity study of ACSR and ACSS two stage splice connectors at high operation temperatures. Presented at the ASME International Mechanical Engineering Congress and Exposition, Proceedings (IMECE), pp. 837–844. https://doi.org/10.1115/IMECE2012-86358.

Kalmár, D., Szabó, D., Göcsei, G., Németh, B., 2022. Extension of dynamic line rating models with the effect of conductor aging, in: 2022 8th International Youth Conference on Energy (IYCE). Presented at the 2022 8th International Youth Conference on Energy (IYCE), pp. 1–5. https://doi.org/10.1109/IYCE54153.2022.9857524.

Kenny, E.D., Paredes, R.S.C., de Lacerda, L.A., Sica, Y.C., de Souza, G.P., Lázaris, J., 2009. Artificial neural network corrosion modeling for metals in an equatorial climate. Corrosion Science 51, 2266–2278. https://doi.org/10.1016/j.corsci.2009.06.004.

Khalyasmaa, A.I., Uteuliyev, B.A., Tselebrovskii, Y.V., 2021. Methodology for Analysing the Technical State and Residual Life of Overhead Transmission Lines. IEEE Transactions on Power Delivery 36, 2730–2739. https://doi.org/10.1109/TPWRD.2020.3025929

Kiessling, F., Nefzger, P., Nolasco, J.F., Kaintzyk, U., 2003. Overhead power lines : planning, design, construction, Power systems. Springer, Berlin.

Korobov, Y.I., Muhambetov, S.B., Laskov, N.N., Shveikin, I.E., Chernykh, V.K., 2019. Financial losses of electric power industry, caused by corrosion wear designs lighting poles. IOP Conf. Ser.: Mater. Sci. Eng. 537, 062082. https://doi.org/10.1088/1757-899X/537/6/062082.

Lei, Y., Li, N., Guo, L., Li, N., Yan, T., Lin, J., 2018. Machinery health prognostics: A systematic review from data acquisition to RUL prediction. Mechanical Systems and Signal Processing 104, 799–834. https://doi.org/10.1016/j.ymssp.2017.11.016.

Li, W., 2014. Risk Assessment of Power Systems: Models, Methods, and Applications: Second Edition, Risk Assessment of Power Systems: Models, Methods, and Applications: Second Edition. https://doi.org/10.1002/9781118849972.

Li, Y., Yeddanapudi, S., McCalley, J.D., Chowdhury, A.A., Moorehead, M., 2005. Degradation-path model for wood pole asset management, in: Proceedings of the 37th Annual North American Power Symposium, 2005. Presented at the Proceedings of the 37th Annual North American Power Symposium, 2005., pp. 275–280. https://doi.org/10.1109/NAPS.2005.1560538.

Liao, L., Köttig, F., 2014. Review of hybrid prognostics approaches for remaining useful life prediction of engineered systems, and an application to battery life prediction. IEEE Transactions on Reliability 63, 191–207. https://doi.org/10.1109/TR.2014.2299152.

Liu, J., Yan, B., Mou, Z., Gao, Y., Niu, G., Li, X., 2022. Numerical study of aeolian vibration characteristics and fatigue life estimation of transmission conductors. PLOS ONE 17, e0263163. https://doi.org/10.1371/journal.pone.0263163.

Lovrenčič, A., Peter, Z., Lovrenčić, V., Rizzetto, A., 2022. Inspection of energized aged conductors using non-destructive, in-situ inspection technology, in: 2022 13th International Conference on Live Maintenance (ICOLIM). Presented at the 2022 13th International Conference on Live Maintenance (ICOLIM), pp. 1–5. https://doi.org/10.1109/ICOLIM56184.2022.9840710.

Lu, Q., Zhang, W., Hughes, W., Bagtzoglou, A.C., 2022. Bayesian Decision Network-Based Optimal Selection of Hardening Strategies for Power Distribution Systems. ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering 8. https://doi.org/10.1061/AJRUA6.0001253.

Ma, D., Peng, J., Zhang, B., Ding, H., Yang, S., Liu, Y., 2023. Risk Assessment of Tower Transmission Based on Insulator Online Monitoring. Presented at the 2023 5th Asia Energy and Electrical Engineering Symposium (AEEES), pp. 384–389. https://doi.org/10.1109/AEEES56888.2023.10114165.

Ma, X., Zhang, W., Bagtzoglou, A., Zhu, J., 2021. Local System Modeling Method for Resilience Assessment of Overhead Power Distribution System under Strong Winds. ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering 7, 04020053. https://doi.org/10.1061/AJRUA6.0001103.

Miranda, T., Badibanga, R., Veloso, L., Araújo, J.A., Ferreira, J., 2023. Effect of Suspension Clamp Types on the Dynamic Bending Stress of All Aluminium Alloy 1120 Overhead Conductors. IEEE Transactions on Power Delivery 38, 833–841. https://doi.org/10.1109/TPWRD.2022.3199680.

Mohammadi Darestani, Y., Sanny, K., Shafieezadeh, A., Fereshtehnejad, E., 2021. Life cycle resilience quantification and enhancement of power distribution systems: A risk-based approach. Structural Safety 90, 102075. https://doi.org/10.1016/j.strusafe.2021.102075.

Mohammadi Darestani, Y., Shafieezadeh, A., 2019. Multi-dimensional wind fragility functions for wood utility poles. Engineering Structures 183, 937–948. https://doi.org/10.1016/j.engstruct.2019.01.048.

Onyewuchi, U.P., Shafieezadeh, A., Begovic, M.M., DesRoches, R., 2015. A Probabilistic Framework for Prioritizing Wood Pole Inspections Given Pole Geospatial Data. IEEE Transactions on Smart Grid 6, 973–979. https://doi.org/10.1109/TSG.2015.2391183.

Panahi, H., Zamani, R., Sanaye-Pasand, M., Mehrjerdi, H., 2021. Advances in Transmission Network Fault Location in Modern Power Systems: Review, Outlook and Future Works. IEEE Access 9, 158599–158615. https://doi.org/10.1109/ACCESS.2021.3129838

Pouliot, N., Rousseau, G., Leblond, A., Montambault, S., 2016. Portable X-ray system for in situ detection of broken ACSR strands at suspension clamps: Field results and equipping the LineScout robot. Presented at the CIGRE Session 46.

Prakash, G., Yuan, X.-X., Hazra, B., Mizutani, D., 2021. Toward a Big Data-Based Approach: A Review on Degradation Models for Prognosis of Critical Infrastructure. Journal of Nondestructive Evaluation, Diagnostics and Prognostics of Engineering Systems 4. https://doi.org/10.1115/1.4048787.

Rahman, A., Chattopadhyay, G., Hossain, M.J., 2016. Maintenance Decisions for Inground Decay of Power-Supply Timber Poles. IEEE Transactions on Power Delivery 31, 1106–1111. https://doi.org/10.1109/TPWRD.2015.2424428.

Redford, J.A., Gueguin, M., Nguyen, M.C., Lieurade, H.-P., Yang, C., Hafid, F., Ghidaglia, J.-M., 2019. Calibration of a numerical prediction methodology for fretting-fatigue crack initiation in overhead power lines. International Journal of Fatigue 124, 400–410. https://doi.org/10.1016/j.ijfatigue.2019.03.009.

Refsnaes, S., 1997. Wear of conductor support fittings, in: 14th International Conference and Exhibition on Electricity Distribution. Part 1. Contributions (IEE Conf. Publ. No. 438). IET, p. 22/1-22/6 vol. 3.

Refsnaes, S., Rolfseng, L., Solvang, E., Heggset, J., 2006. Timing of Wood Pole Replacement Based on Lifetime Estimation, in: 2006 International Conference on Probabilistic Methods Applied to Power Systems. Presented at the 2006 International Conference on Probabilistic Methods Applied to Power Systems, pp. 1–8. https://doi.org/10.1109/PMAPS.2006.360286.

Rocha, P.H.C., Langlois, S., Lalonde, S., Araújo, J.A., Castro, F.C., 2023. Influence of 1350 and 6201 aluminum alloys on the fatigue life of overhead conductors – A finite element analysis. Tribology International 186, 108661. https://doi.org/10.1016/j.triboint.2023.108661.

Ryan, P.C., Stewart, M.G., Spencer, N., Li, Y., 2016. Probabilistic analysis of climate change impacts on timber power pole networks. International Journal of Electrical Power & Energy Systems 78, 513–523. https://doi.org/10.1016/j.ijepes.2015.11.061.

Ryan, P.C., Stewart, M.G., Spencer, N., Li, Y., 2014. Reliability assessment of power pole infrastructure incorporating deterioration and network maintenance. Reliability Engineering & System Safety 132, 261–273. https://doi.org/10.1016/j.ress.2014.07.019.

Said, J., Fouvry, S., Cailletaud, G., Basseville, S., Coulangeon, M., Brocard, J., Yang, C., Hafid, F., 2023. A global–local approach to predict the fretting-fatigue failure of clamped aluminum powerline conductors: From mono-contact crossed wires to full conductor vibrational tests. Engineering Failure Analysis 146, 107073. https://doi.org/10.1016/j.engfailanal.2023.107073.

Salamoni, N., Rohden, A.B., 2022. Durability analysis of concrete foundations exposed to external sulfate attacks in the south of Santa Catarina, Brazil. Journal of Building Pathology and Rehabilitation 7. https://doi.org/10.1007/s41024-022-00205-x.

Salazar, J.E., Mendoza, J.A., 2009. Life prediction of electrical power transmission towers. Presented at the 2008 Proceedings of the 9th Biennial Conference on Engineering Systems Design and Analysis, pp. 313–323.

Salman, A., Li, Y., Bastidas-Arteaga, E., 2019. Impact of climate change on optimal wood pole asset management, in: Life-Cycle Analysis and Assessment in Civil Engineering: Towards an Integrated Vision-Proceedings of the 6th International Symposium on Life-Cycle Civil Engineering, IALCCE. pp. 1727–1734.

Salman, A.M., Salarieh, B., Bastidas-Arteaga, E., Li, Y., 2020. Optimization of Condition-Based Maintenance of Wood Utility Pole Network Subjected to Hurricane Hazard and Climate Change. Frontiers in Built Environment 6.

Shafieezadeh, A., Onyewuchi, U.P., Begovic, M.M., DesRoches, R., 2014. Age-Dependent Fragility Models of Utility Wood Poles in Power Distribution Networks Against Extreme Wind Hazards. IEEE Transactions on Power Delivery 29, 131–139. https://doi.org/10.1109/TPWRD.2013.2281265.

Statnett, 2019. Annual statistics 2018 - Operational disturbances, faults and planned outages in the 1-22 kV grid [Norwegian title: Årsstatistikk 2018 - Driftsforstyrrelser, feil og planlagte utkoplinger i 1-22 kV-nettet].

Stewart, A.H., Goodman, J.R., 1990. Life cycle economics of wood pole utility structures. IEEE Transactions on Power Delivery 5, 1040–1046. https://doi.org/10.1109/61.53119.

Stillman, R.H., 1994. Probabilistic derivation of overstress for overhead distribution in-line structures. IEEE Transactions on Reliability 43, 366–374. https://doi.org/10.1109/24.326427.

Stillman, R.H., Mackisack, M.S., Sharp, B., Lee, C., 1995. Case studies in survival analysis of overhead line components. Presented at the Second International Conference on the Reliability of Transmission and Distribution Equipment, 1995., pp. 210–215. https://doi.org/10.1049/cp:19950244.

Takahashi, T., Kanda, M., Tokuyama, H., 2020. Development of method for estimating dynamic characteristics of unbalanced wire tension acting on overhead line equipment in natural wind. Journal of Wind Engineering and Industrial Aerodynamics 196, 104047. https://doi.org/10.1016/j.jweia.2019.104047.

Thomas, O.O., Chouinard, L., Langlois, S., 2022. Probabilistic Fatigue Fragility Curves for Overhead Transmission Line Conductor-Clamp Assemblies. Frontiers in Built Environment 8. https://doi.org/10.3389/fbuil.2022.833167.

Valeriy, I., Iosif, B., 2022. Predicting the service life of high-voltage insulators using actual leakage current values. Current Science 122, 455–460. https://doi.org/10.18520/cs/v122/i4/455-460.

Volokhovsky, V., Vorontsov, A., Sukhorukov, D., Mekhanoshin, B., Shkaptsov, V., 2010. Assessment of OHL availability and residual life-time by using non destructive instrumental control for conductors, steel wires and guys. Presented at the 43rd International Conference on Large High Voltage Electric Systems 2010, CIGRE 2010.

Wang, C., Leicester, R.H., Nguyen, M., 2008a. Probabilistic procedure for design of untreated timber poles in-ground under attack of decay fungi. Reliability Engineering & System Safety, Probabilistic Modelling of Structural Degradation 93, 476–481. https://doi.org/10.1016/j.ress.2006.12.007.

Wang, C., Leicester, R.H., Nguyen, M.N., 2008b. Manual 3-Decay in ground contact (No. PN07.1052). Forest & Wood Products Australia.

Wańkowicz, J., Bielecki, J., Struzewska, E., 2006. Damage limit of composite long rod insulators subjected to cyclic loads. Presented at the 41st International Conference on Large High Voltage Electric Systems 2006, CIGRE 2006.

Wareing, B., 2005. Wood Pole Overhead Lines, IET Power and Energy Series. The Institution of Engineering and Technology, London.

Yang, L., Fan, J., Liu, Y., Li, E., Peng, J., Liang, Z., 2020. A Review on State-of-the-Art Power Line Inspection Techniques. IEEE Transactions on Instrumentation and Measurement 69, 9350–9365. https://doi.org/10.1109/TIM.2020.3031194.

Yi, Y., Xiaochun, N., Jianping, Z., Zhitao, Y., Min, L., 2021. Wear and life prediction of the U-shaped connecter of transmission line system under strong wind load. Engineering Failure Analysis 125, 105404. https://doi.org/10.1016/j.engfailanal.2021.105404.

Yu, Y., Li, J., Yan, N., Dackermann, U., Samali, B., 2016. Load capacity prediction of in-service timber utility poles considering wind load. J Civil Struct Health Monit 6, 385–394. https://doi.org/10.1007/s13349-016-0156-9.

Zhou, K., Fu, C., Yang, S., 2016. Big data driven smart energy management: From big data to big insights. Renewable and Sustainable Energy Reviews 56, 215–225. https://doi.org/10.1016/j.rser.2015.11.050.