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Risk of crack formation in power grid wooden poles and relationship with meteorological conditions: A Norwegian case study

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ABSTRACT: Predicting the occurrence of failures in power grids through specific outage risk predictors is a primary concern for utilities nowadays. Wooden poles represent core items to focus on in this process. Millions of them are used worldwide and they are all subject to the risk of crack formation. Analyzing the evolution of pole cracks is particularly relevant in reliability analyses of power grids for two main reasons. First: the cracks might highlight previously unconsidered or changing factors, such as unusual local weather conditions (e.g. overload of ice and/or wind). Second: as cracks provide an access for external threats (e.g. humidity, fungi, insects) to potentially non-treated internal parts of the poles, they might in turn accelerate the occurrence of further failures. Evaluating the role of crack formation is thus essential for estimating the risk of outages in power grids. As climatic variations are known to be among the most influencing factors in the initiation and propagation of cracks in wooden poles, we address this topic by suggesting a method combining open-access weather-data sources with information provided by new technologies, such as drones. We first highlight the influence of climatic factors on the reliability of wooden poles by reviewing studies describing the physical properties of wood. We then focus our research on a Norwegian case study and show how we can combine up to 60 years of meteorological information with the information provided by 17,352 geo-localized aerial pictures of cracked and non-cracked wooden utility poles. We finally discuss the way an indicator constructed on this combination can be used to predict the formation of cracks and optimize the allocation of decision-maker resources for inspection procedures.

1 INTRODUCTION

The modernization of the society has led to a global increase of power consumption over the last 50 years (Refsnæs, Rolfseng, Solvang, & Heggset, 2006; Shiu & Lam, 2004; Yoo & Kwak, 2010). As numerous businesses, public infrastructures and private households rely on the provision of power for their daily tasks, there is a need for companies in charge of the power supply to maximize their capacity and reliability in delivering power.

Predicting outage risks and avoiding downtime is crucial to ensure customer satisfaction. Moreover, anticipating unwanted events directly enables power utilities to significantly reduce losses and costs. Finally, it also enables them to optimize resource allocations for the inspection of their infrastructures after natural disasters (e.g. storms, flooding) or during scheduled maintenance procedures.

Ensuring this quality of service requires utilities to use reliable components, from the power source, through the transmission lines and to the consumption nodes. Wooden poles are widely used for the distribution part of the power grid (from regional substations to local substations and from local substations to end-users) (Eurelectric, 2010).

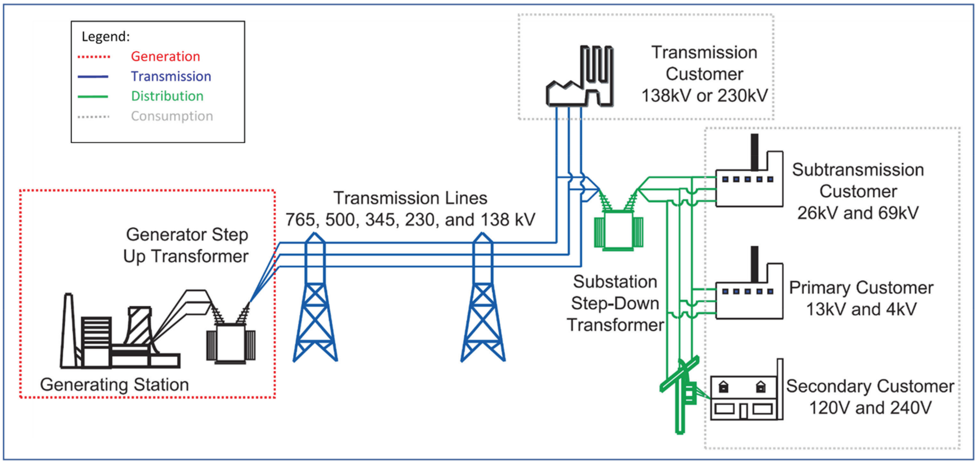

Figure 1. Outline of the transmission and distribution of power in a power grid, going from the production sites to the consumption nodes. Adapted from (U.S.-Canada Power System Outage Task Force, 2004).

Identifying the principal factors responsible for the apparition of cracks in wooden poles represents thus a main objective for predicting their failures. For this purpose, we suggest a method enabling to evaluate the effects of potential predictors. The contribution identifies the way forward for this research topic and presents preliminary findings, representing the basis for future research.

The rest of the paper is constructed as follows. Section 2 provides an overview on wooden poles characteristics and failures. Section 3 mentions various studies summarizing the main properties of wood on microscopic level. On this basis, it highlights the influence climatic variations can have on the physical structure of wooden poles. It furthermore shows how the variations can affect the reliability of the pole and thus of the transmission line. Section 4 describes the strategy applied to provide values of a crack-apparition likelihood using a Norwegian case study. It explains the choices made in the selection of the different datasets and the methods used to acquire them. Section 5 discusses the pros and the cons of the method used and shortly describes plans for future research. The last section finally concludes our work by summarizing and suggesting additional research possibilities.

2 WOODEN POLES CHARACTERISTICS AND FAILURES

Figure 1 shows schematically how power is delivered from a generating station, through transmission and distribution lines (respectively maintained by Transmission System Operators (TSO) and Distribution System Operators (DSO)), to different categories of end customers. Wooden utility poles used in the power grid exist in different shapes and configurations, depending on the physical requirements of the power lines, on the geographical conformation of their location, and on their position in the transmission or distribution line (see Figures 2–4 as illustrations).

Figure 2. First example of the shape of a wooden utility pole.

Despite the variety of the existing shapes and configurations, the number of elements basically composing an electrical pole is relatively limited. A wooden utility pole is generally composed of one or more wooden poles, one or more cross-arms and multiple insulators responsible for the junction between the electrical cables and the pole. Figure 5 schematizes this assembling.

Using wooden utility poles has multiple advantages in comparison to concrete or steel utility poles (Bolin & Smith, 2011; SEMCO, 1992; Stewart, 1996)

Figure 3. Second example of the shape of a wooden utility pole.

Figure 4. Third example of the shape of a wooden utility pole.

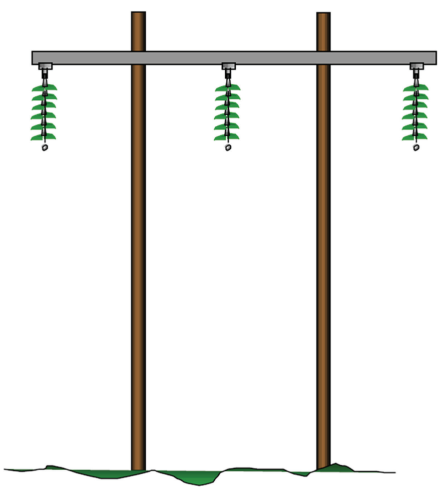

Figure 5. Basic components of a wooden utility pole: poles (brown), cross-arm (grey) and insulators (green) (Refsnæs, 2008).

– They are lighter and easier to transport on mountainous fields.
– They do not require earthing, which makes them interesting when lightning occur.
– They are easy to produce in wooded areas (e.g. Canada, Norway).
– They generally have a reduced environmental impact.
– They have interesting lifetimes, possibly going up to 75 years in favorable conditions.

Identifying the main threats for wooden utility poles enables to look for root causes of failures. This gives the possibility to estimate their effective remaining lifetime and optimize their replacement before any outage.

In their review on power line inspection procedures, Nguyen et al. (Nguyen, Jenssen, & Roverso, 2018) summarize some of the main common faults of power line components. They identify the apparition of cracks in the wooden poles as being one of the main failure to identify during visual inspection procedures. An additional review of the literature shows that there is need for inspection protocols enabling to recognize and assess cracks in timber structures in general (Dubois, Chazal, & Petit, 2002; Riahi, Moutou Pitti, Dubois, & Chateauneuf, 2016) and in wooden poles in particular (Morrell, 2012).

Identifying cracks is fundamental for two main reasons:

– First, as "stresses perpendicular to grain induce cracks which propagate longitudinally" (Coureau & Morel, 2005), we can consider multiple apparitions of significant cracks as being indicators of the presence of stress factors. This can for example suggest the existence of a localized area subject to harsher weather conditions (e.g. overload of ice and/or wind) (Wong & Miller, 2010) and prompt deepened analysis of the concerned region.
– Second, as cracks provide an access for external threats (e.g. fungi, insects, humidity) to potentially non-treated internal parts of the poles, their existence might accelerate the apparition of decay (Morrell, 2012; Refsnæs et al., 2006; SEMCO, 1992). This permanently alters the structural resistance of the pole and considerably increases its probability of failure.

3 WOOD PROPERTIES AND POTENTIAL INFLUENCE OF CLIMATIC VARIATIONS ON CRACK APPARITION

The theory of fracture mechanics has mainly been developed since the first half of the 20th century. Initiated by A.A. Griffith in 1920 (Griffith, 1921), it has then been popularized by G.R. Irwin in

1958 (Irwin, 1958) and is since being widely used to analyze the origins and consequences of crack apparition in physical objects. Focusing on the microscopic level, it enables to provide models describing the "mechanical behavior of cracked materials subjected to applied load" (Perez, 2017).

Multiple studies use this theory as a basis for the evaluation of crack growth in wooden structures (Barrett, Haigh, & Lovegrove, 1981; Coureau & Morel, 2005; Dubois et al., 2002; Riahi et al., 2016). A characterization of the structure is initially made on microscopic level to understand how wood behaves when it is subject to a modification of its external environment (load variation, climatic variation, etc.). Figure 6 shows the structure on microscopic level of a typical softwood. It highlights the anisotropic characteristic of wood and intuitively shows that cracks are more probable to occur parallel to the direction of growth of a three (longitudinal direction).

Wood being furthermore a viscoelastic material, its physical properties (e.g. modulus of elasticity, volume) are directly influenced by their environment. This is due to the hygroscopic behavior of wood (i.e. tendency to absorb humidity) and implies that physical properties of wood are highly sensitive to the meteorological properties of its surrounding (especially temperature and humidity) (Chaplain & Valentin, 2010; Hamdi, Moutou Pitti, & Saifouni, 2017; Lamy, 2016; Morrell, 2012; Refsnæs et al., 2006; Saifouni, 2014; Thybring, Lindegaard, & Morsing, 2009).

Because of the former functionalities of their cells during their living period and because of the variations in their environment during their growth, mechanical properties of timber-based structures can furthermore be locally modified. This includes structure modifications due to natural defects such as knots, rotten knots holes or cracks due to freezing lifeblood. Combined with the application of external loads (e.g. wind, ice on the wires in the case of wooden poles) and the modification of its internal structure due to temperature and humidity variations, there is a fertile ground for the apparition of cracks.

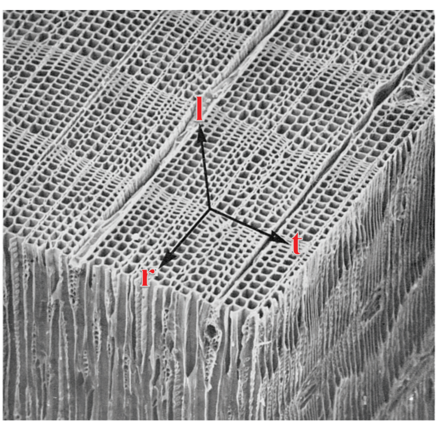

Figure 6. Typical softwood structure showing orientation of longitudinal (l), radial (r) and tangential (t) directions (Barrett et al., 1981).

4 DATA ACQUISITION AND PREDICTION METHODS

Utility companies in Norway use over 3.5 million wooden poles in their power grids to support over 25,400 km of electrical overhead lines (Eurelectric, 2010; Refsnæs et al., 2006). The Norwegian IT company eSmart Systems[1] is specialized in digital intelligence and uses artificial intelligence to support Statnett, Norway's TSO, as well as some of the main Norwegian DSOs (e.g., Lyse Elnett, Ringeriks-Kraft Nett, Troms Kraft Nett, Hafslund Nett). In particular, the algorithms used by eSmart Systems automatically identify specific objects and recognize pre-defined faults, such as cracks on wooden poles (see Figure 7 as an illustration). This enabled us to access a database of 17,352 geo-localized aerial pictures of wooden utility poles, from which 5383 are classified as cracked.

In most of the cases, two to three pictures of a unique utility pole were taken from different angles. This was done to ensure having accurate information for each of the observed poles without suffering from hidden information. We merged this information with the exact geographical coordinates of the electric poles, made available by the Norwegian Water Resources and Energy Directorate (NVE)[2]. We could thus analyze a dataset of 7653 geo-localized wooden utility poles, either classified as cracked or not.

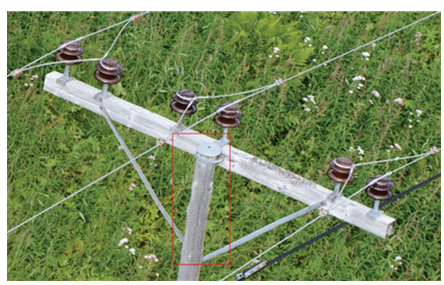

Figure 7. Wooden pole where a crack has been localized on the mast (see rectangle).

1. eSmart Systems: www.esmartsystems.com.
2. NVE: www.nve.no.

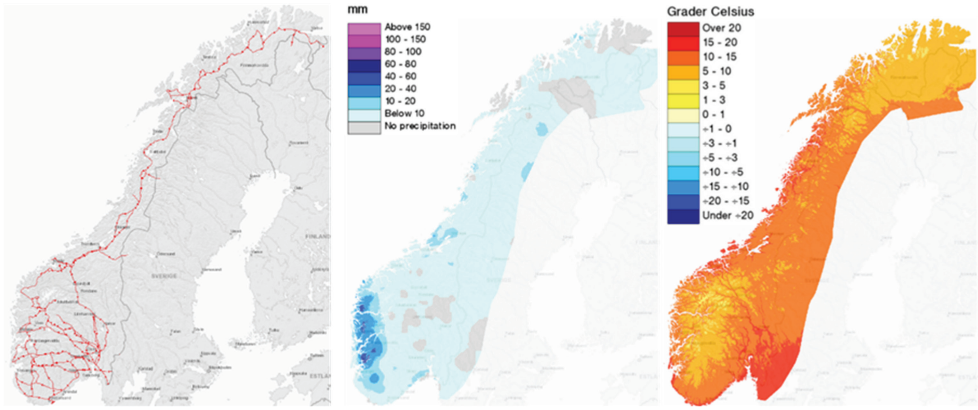

Figure 8. From left to right: main axes of the Norwegian electrical grid[6]; map of the precipitation in Norway on the 1st of August 2017[7]; map of the temperatures in Norway on the 1st of August 2017[7].

In parallel, seNorge[3] (created in collaboration between the NVE, the Norwegian Meteorological Institute[4] and the Norwegian Mapping Authority[5]) enables us to access daily observed (or interpolated) records of the climatic conditions in Norway. Especially, it enables us to access temperature and precipitation measures going as far back as 1957.

Figure 8 illustrates the type of information made available by NVE and seNorge. Using a scroll up/down feature of the websites, it is possible to move from a global and national overview up to a specific geo-localized point (in our case, the localization of the wooden utility poles).

Different approaches are considered in our work. The purpose is to create an indicator for the likelihood of crack apparition on wooden poles.

In order to benefit from the high granularity offered by the webservices used, we plan to use daily records of temperature and precipitation as potential predictors for a binary classification problem (labeling as cracked or not-cracked). Predictive features can be designed, that summarize at different granularities the daily weather data and extract relevant indicators that correlate with crack appearance. Considering an extreme reduction, we can for example summarize the intensity of the meteorological variation on a localized point into, e.g. a temperature coefficient and a precipitation coefficient. This would lead to a method using only two predictors when focusing on this classification problem.

Equation (1) provides an example of the type of coefficient c that can be used when focusing on a specific pole.

$$c = \sum_{i=2}^{n} \frac{|X_i - X_{i-1}|}{X_{max} - X_{min}} \tag{1}$$

Where n is the number of daily records since the installation of the wooden pole observed; i the enumeration index; X_i the value of the meteorological phenomenon observed on the specified location on day i (here in millimeters or in degrees Celsius); X_{i-1} the record of the same phenomenon on the same location on the previous day; X_{max} (resp. X_{min}) the maximum (resp. minimum) value of the observed phenomenon that has been recorded over the entire timestamp of observation on the specified location.

Alternatively, predictive features can be automatically learned from the raw temperature and precipitation time series using deep learning techniques. Such techniques, belonging to the class of artificial intelligence methods (and more especially, to the class of machine learning methods) are based on recursive analyses of data over time and/or over space, from which they identify and highlight step by step the most relevant characteristics.

High temperatures favor the proliferation of fungus, which weakens the structure of the wood. Furthermore, high humidity levels on extended periods might soften the wood and make it more sensitive to sudden external loads (e.g. wind or ice rain). Finally, the intrinsic properties of wood

3. seNorge: www.senorge.no.
4. Norwegian Meteorological Institute: www.met.no.
5. Norwegian Mapping Authority: www.kartverket.no.
6. https://temakart.nve.no/link/?link=nettanlegg.
7. http://www.senorge.no/index.html?p=senorgeny&st=weather.

lead it to easily accept slow variation of external loads and environmental conditions but make it particularly sensitive to sudden variations. These approaches will thus enable us to identify meteorological patterns favoring the apparition of cracks, as well as located regions where the likelihood of crack apparition will be higher.

An increase in the period of exposition to external factors leads to a rise of the probability of crack apparition. This implies that the age of the poles plays a big role in the suggested methods. However, part of this information might be missing. In such a case, we could consider a generic day of installation depending on the period of installation of the power line in the observed region.

5 DISCUSSION

The suggested methods enable to evaluate the role that temperature variations and precipitations have on the formation of cracks on wooden poles. These methods have the advantage to be flexible and easily integrated when accessing additional data sources, such as daily records of wind intensity and direction, humidity variations, clouds presence, etc. They are nevertheless highly dependent on two main facts:

- First, the initial classification of the poles as cracked or not. This is an important topic as the size of the cracks directly affects its detection by the algorithm used to classify the poles. There is thus a need for utility companies to define what should be considered as a problematic crack or not.
- Second, the information initially available on the poles themselves (e.g. age, maintenance tasks carried out). This information might be difficult to access because not necessarily well reported in the first phases of the grid installation.

Despite using relatively simple techniques and being highly dependent on initial parameters, the proposed methods represent a first approach in the analysis and handling of cracks in wooden poles. This information may in turn be useful for decision makers in the prioritization of additional inspection procedures and future maintenance tasks.

It is to mention that our paper only highlights preliminary results of an ongoing research, as the described methods have not yet been fully applied. Further work will thus focus on the extensive application and validation of these approaches and provide an in-depth analysis of the phenomenon of crack apparition on wooden poles by using additional real data from the Norwegian network.

6 CONCLUSION

Our paper highlighted the importance for utilities of early detection and analysis of cracks on wooden poles. We summarized how environmental conditions can directly affect the physical properties of wood and thus favor or limit the apparition of cracks on wooden poles. In order to better understand and predict their occurrence, we then suggested two approaches using pre-classified and geo-localized aerial pictures of cracked and non-cracked poles in combination with up to 60 years of meteorological measurements. Further, we saw that, despite being highly dependent on initial information, our approach might provide useful information for the generation of maintenance policies. This approach might finally be a good starting point for researchers wanting to combine fields of expertise such as structural study of wood on microscopic level and crack detection methods using image analysis.

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