MAINTENANCE COST REDUCTION BY IMPROVED METHODS FOR CONDITION ASSESSMENT OF WOOD POLES

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ABSTRACT

This paper describes methods for condition assessment of wood poles in the electricity distribution network. It is shown that there is a need to improve currently used methods for condition assessment, because the methods applied today do not take into account all relevant parameters that influence the remaining strength of the poles. The paper suggests several new methods for condition assessment, and their advantages and disadvantages are discussed. Furthermore, the paper will present a case study where one of the methods is applied. The case study show how the methods can be used as basis for estimation of remaining lifetime of the poles. The use of the new methods improves the accuracy of the condition assessment, leading finally to cost savings and better estimates of the remaining lifetime.

INTRODUCTION

Condition assessment and lifetime estimation of power system components are important issues in planning of maintenance and replacement. Considering the large number of wood poles in the electricity distribution network, proper condition assessment and estimation of remaining lifetime of the poles is indispensable for optimizing maintenance and replacement, and for controlling risk.

Current methods for condition assessment determine if the pole must be replaced now/soon or not. Current practices in wood pole inspection are mostly based on simple methods that provide neither a differentiated assessment of the pole condition nor a good estimate of the remaining lifetime of the pole. Thus, standardized and formalized methods for inspection, condition assessment and lifetime estimation of wood poles are required by the distribution companies.

This paper presents several methods for condition assessment that allow for condition-based decision making. The paper and the methods presented in the following section are based on handbooks for condition monitoring of power system components [1]. These handbooks were developed in an ongoing research project by SINTEF Energy in close collaboration with the Norwegian electricity industry association (Energy Norway) and Norwegian electricity distribution companies. The handbooks describe methods for inspection and condition assessment of different power system components. Furthermore, the handbooks suggest a classification system with discrete states to describe the technical condition (health) of different components in a standardized way. The technical condition is classified by five discrete states, where "1" represents good technical condition and "5" the fault state (the item does not fulfil the required function) [1].

The remainder of this paper is organized as follows: The next section describes and discusses methods for condition assessment and the estimation of remaining lifetime. Examples where two of the methods are applied in a case study are presented afterwards. Conclusions are drawn in the last section.

METHODOLOGY

Condition assessment

A power line pole is subject to different loads (climatic loads due to wind and ice, the weight of the construction, tension from the conductors, etc.). These loads result in forces and bending moments, which again lead to stresses in the wood. When designing or assessing wood poles, the general criterion is that the stress (σ) in the pole is less or equal the bending strength (fibre strength: f) of the wood.

Neither the design load nor the design strength is a deterministic value, but both are random (stochastic) variables. When designing the line, the diameter (d_0) of the pole is chosen in such a way that for a given return period of a climatic load (design load, Q_d), the stress in the wood is less or equal an admitted maximum stress (f_md). The value for the admitted maximum stress is based on the characteristic bending strength (f_mk), which is the 5th percentile of the bending strength of pine poles (pinus sylvestris; this type of poles is most commonly used in Norway). The value of $f_\text{mk} = 40.3$ N/mm^2 was determined for pine poles by full-scale bending tests [2], [3], [4]. The admitted maximum stress for poles designed according to the new Norwegian standard for overhead transmission lines NEK 609 [5] (a standard using the same probabilistic principles as in [6] and [7]) is given by $f_\text{md} = f_\text{mk} / \gamma_\text{m} = 40.3$ N/mm^2 / 1.35 $\approx$ 30 N/mm^2, where γ_m is a coefficient that takes into account uncertainty due to variances in the wood structure and strength of the pole, dimension variations, different designs and different execution of surrounding components, etc.

When the line is designed according to the old Norwegian standard NEN 11.2.65 [8] (before 1997), the corresponding values are $f_{\mathrm{mk}} = 21\ \mathrm{N/mm}^2$ and $f_{\mathrm{md}} = 15.7\ \mathrm{N/mm}^2$.

During the life of the pole, the pole's strength (f_{m}) will decrease due to decay and ageing of the wood. At the same time, the stresses in the pole (σ_γ) may increase, because of decay pockets, woodpecker cavities, leaning poles and other damages (Figure 1). The basic criteria for assessing poles is that $\sigma_{\gamma t} \leq f_{\mathrm{mt}}$, where $\sigma_{\gamma t}$ and f_{mt} are the maximum stress in the pole and the strength of the wood (= admitted maximum stress), respectively, at the time of inspection t. Thus, the challenge for inspection is to find good estimates for $\sigma_{\gamma t}$ and f_{mt}. Note that both quantities are not constant, but change over the pole's length.

A criterion for condition assessment can be based on the ratio between the estimates for $\sigma_{\gamma t}$ and f_{mt}. A natural interpretation of this ratio is: "safety factor" (s):

$$s = f_{\mathrm{mt}} / \sigma_{\gamma t} \qquad (1)$$

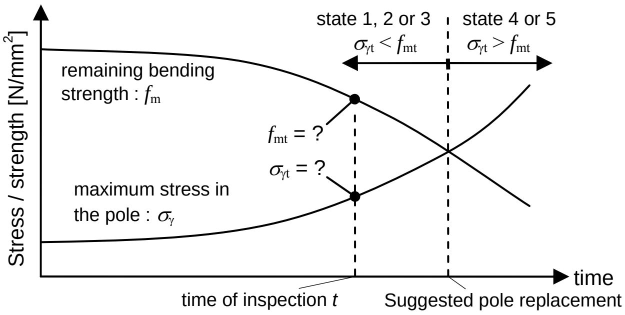

Figure 1 Changing of stress and bending strength

When $s > 1$, that is, when $\sigma_{\gamma t} < f_{\mathrm{mt}}$, the pole can probably resist the dimensioning loading, whereas when $s < 1$, that is, when $\sigma_{\gamma t} > f_{\mathrm{mt}}$, the pole will probably collapse when the dimensioning loading occurs, and consequently the pole must be replaced. The choice was made that $\sigma_{\gamma t} < f_{\mathrm{mt}}$ corresponds to state 1, 2 or 3, whereas $\sigma_{\gamma t} > f_{\mathrm{mt}}$ corresponds to either state 4 or 5 (Figure 1). Since exact estimates of the stresses $\sigma_{\gamma t}$ in the pole and the fibre strength f_{mt} are difficult to obtain, the estimates must be based on simplifications. In Table 1, four methods for condition assessment are presented which are based on different degrees of simplification for estimation of $\sigma_{\gamma t}$ and f_{mt}.

Method 1 requires that a good estimate of the stress $\sigma_{\gamma t}$ is established that is compared with the measured strength f_{mt}. Method 2a is based on the simplification that the strength is not measured, but the stress estimate $\sigma_{\gamma t}$ is compared with an absolute maximum admitted stress $\sigma_{\max}$. Method 2b uses a simplified method for estimating $\sigma_{\gamma t}$; however, f_{mt} is based on measurements. Method 3 is still more simplified, because the wood fibre strength is not measured. Both Methods 2b and 3 require that the pole is properly designed, i.e. that the pole has the correct diameter when the line is erected. Equations for estimation of stress ($\sigma_{\gamma t}$) and strength (f_{mt}) for the different methods are given in Table 1. In addition, advantages and disadvantages are summarized. Once the estimates for $\sigma_{\gamma t}$ and strength f_{mt} are established, the saftey factor s, which is basis for condition assessment, can be calculated. For further details, the interested reader is referred to [11] where the methods have already been presented. Criteria for condition assessment based on the safety factor s can also be found in [11], as well as more details about inspection methods.

Table 1 Methods for condition assessment.

		Method 1	Method 2a	Method 2b	Method 3
Description		Estimate for maximum stress in the pole ($\sigma_{\gamma t}$) is compared with an estimate of the bending strength (f_{mt})	Because strength estimate is not available, the estimate for the maximum stress ($\sigma_{\gamma t}$) is compared with an absolute maximum admitted stress $\sigma_{\max}$	Simplified stress estimated ($\sigma_{\gamma t}$) is compared with estimate for bending strength (f_{mt})	Because strength estimate is not available, simplified stress estimate ($\sigma_{\gamma t}$) is compared with maximum upper bound $\sigma_{\max}$
				Assumption that pole is properly designed	
Stress estimate $\sigma_{\gamma t}$		$\sigma_{\gamma t} = N/A_t + M/W_t$	$\sigma_{\gamma t} = N/A_t + M/W_t$	$\sigma_{\gamma t} = f_{\mathrm{md}} / w_t$	$\sigma_{\gamma t} = f_{\mathrm{md}} / w_t$
Strength estimate f_{mt}		$f_{\mathrm{mt}} = f_{\mathrm{mkt}} / \gamma_{\mathrm{m}}$	$f_{\mathrm{mt}} = \sigma_{\max}$	$f_{\mathrm{mt}} = f_{\mathrm{mkt}} / \gamma_{\mathrm{m}}$	$f_{\mathrm{mt}} = \sigma_{\max}$
Estimate properties	$\sigma_{\gamma t}$	☺ good stress estimate	☺ good stress estimate	😐 simplified stress estimate	😐 simplified stress estimate
	f_{mt}	☺ known (measured)	☹ unknown (not measured)	☺ known (measured)	☹ unknown (not measured)
Accuracy		☺ high	😐 medium	😐 medium	☹ low
Time consumption and complexity		☹ high	😐 medium	😐 medium	☺ low

A_t: cross section at time of inspection
f_a: average of strength measurements
f_{md}: admitted maximum stress for a new pole
$f_{\mathrm{md}} = f_{\mathrm{mk}} / \gamma_{\mathrm{m}}$
$f_{\mathrm{md}} = 30\ \mathrm{N/mm}^2$ (NEK 609)
$f_{\mathrm{md}} = 15.7\ \mathrm{N/mm}^2$ (NEN 11.2.65)
f_{mk}: characteristic bending strength
$f_{\mathrm{mk}} = 40.3\ \mathrm{N/mm}^2$ (NEK 609)
$f_{\mathrm{mk}} = 21\ \mathrm{N/mm}^2$ (NEN 11.2.65)

f_{mkt}: characteristic maximum strength [9]
(based on several strength measurements)
$f_{\mathrm{mkt}} = f_a - k \cdot f_{\mathrm{sd}}$
f_{sd}: standard deviation of strength measurements
k: critical value of t-distribution [10]
M: bending moment
N: vertical forces
w_t: relative remaining section modulus ($=W_t/W_0$)

W_0: section modulus at time of construction
W_t: section modulus at time of inspection
γ_{m}: coefficient that takes into account uncertainty
$\gamma_{\mathrm{m}} = 1.35 \approx 1 / 0.75$
$\sigma_{\max}$: upper bound for bending stress
$\sigma_{\max} = f_{\mathrm{mk}} = 40.3\ \mathrm{N/mm}^2$ (NEK 609)
$\sigma_{\max} = f_{\mathrm{mk}} = 21\ \mathrm{N/mm}^2$ (NEN 11.2.65)

Lifetime estimation

In the last years, SINTEF has collected information about deterioration of wood poles. In addition, SINTEF has carried out assessments of the condition of wood poles. Based on the knowledge and experience gained through these activities, an exponential function can be used as empirical model to predict the further degradation process and the useful lifetime of the poles. Thus, the safety factor can be expressed as

$$s(t;\theta) = s_0 + \frac{1}{\theta} e^{-t/\theta} \quad , t \geq 0 \tag{2}$$

where t is the age of the pole and $\theta < 0$ is an unknown parameter dependent on the surrounding conditions like climate, soil, design etc. Estimates for θ and s_0 can be calculated if the condition at $t = t_0 = 0$ is known or can be estimated, and if the value of $s(t)$ is known, because an inspection and condition assessment has been carried out at $t > t_0$.

CASE STUDY

The examples in the case study are from a Norwegian electricity distribution company. This utility had carried out inspections of several 37-year-old creosote treated wood poles in a 10 km long 132 kV overhead line by means of the sound and bore technique, which is a common practice among many utilities in Norway and other countries. A hammer was used to locate internal decay pockets by listening to the sounds and feeling the resistance of the hammer from the ground level zone and up to the top of the pole. When a cavity of decay was localized, a bore and a measuring tool were used to determine the remaining shell thickness. A simplification was then carried out by assuming that the wood pole is a tube with minimal detected shell thickness of the pole.

The measurement results were compared with the minimal permitted shell thickness. The bending strength of the wood (fiber strength, f_{mt}) was not measured.

According to this practice, five H-towers should be replaced. Because of the disadvantages of this simplified method (method 3), the distribution company wanted to carry out a more detailed assessment of the stresses and remaining lifetime of the poles. Since measurements of the pole strength have not been carried out, the best alternative for a better assessment of the pole is method 2a, as described in the following.

The stress ($\sigma_{\gamma t}$) and safety factor (s) according to method 2a were calculated. Figure 2 shows an example for leg 1 of tower no. 14 (= pole 14). The suggested pole replacement time is reached when s_{2a} is less or equal to 1, this corresponds to the point in time when $\sigma_{\gamma t} \geq f_{mt}$ (see Figure 1).

The curve "Stress with decay" in the diagram in Figure 2 shows that the maximum stress in pole 14 can be found approximately 2.1 m above the ground level, because decay pockets were detected at this location. Thus, the weakest point of the pole at time of inspection is 2.1 m above the ground level. Therefore, the condition assessment and the lifetime estimate for pole no. 14 is established for this point. The safety factor according to method 2a (s_{2a}) at time of inspection t is $s_{2a}(t) = 1.17$, which indicates that the pole's condition can be classified "state 2", but close to a transition to "state 3", which is still acceptable. The safety factor for the new pole was calculated as $s_0 = 1.37$.

Figure 3 shows the prediction of the further degradation when equation (2) in combination with method 2a is applied. The estimates for the suggested replacement time and the remaining lifetime of the pole are also illustrated in the figure. In an analogous manner, the lifetime of the other poles was estimated. The results are shown in Table 2.

The replacement of a pole will typically cost between 15 000 EUR and 50 000 EUR. In the following simple cost-benefit analysis, we assume that the replacement of each pole costs approximately 25 000 EUR. By assuming that the full remaining lifetime could be utilised by the company, an estimate of the savings (S) for the company

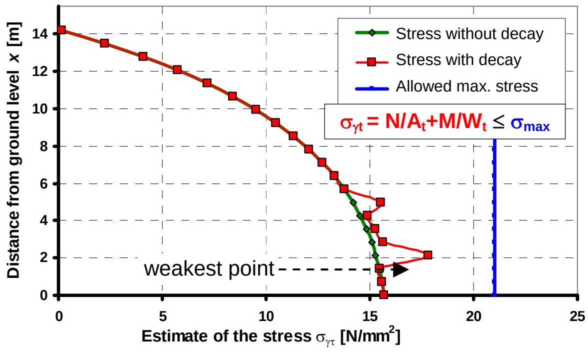

Figure 2 Estimated stress for pole no. 14

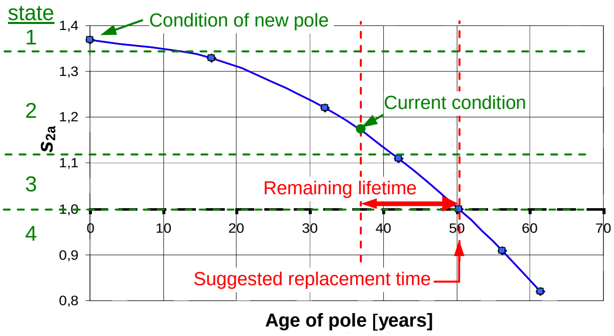

Figure 3 Prediction of further degradation, suggested replacement time and remaining lifetime (using method 2a) for pole no. 14.

Table 2 Results of lifetime analysis.

Pole no.		14	42	127	172	176
Age of pole [years]		37				
Method 3	Suggested replacement time	immediately				
	Remaining lifetime [years]	0	0	0	0	0
Method 2a	Suggested replacement time (age at replacement) [years]	50	53	48	127 1)	74
	Remaining lifetime [years]	13	16	11	90 1)	37
1) The diameter at ground level is 8 % larger than the designed pole diameter (pole oversized). Thus, the stress in the pole becomes 21 % less than expected, and the lifetime is extended.						

using method 2a instead of the traditional method 3 is given by the present values of the (n-1) annuities of the investment that can be postponed n years, which is

$$S = C \cdot \frac{1-(1+r)^{-(n-1)}}{1-(1+r)^{-m}} \qquad (3)$$

where C is the investment cost, r is the discount rate and m is the economic lifetime of the investment. In Norway, the authorities require that a rate of $r = 0.04$ is used for grid projects. A typical value for m is 40 years.

The results of this analysis are presented in Table 3. The savings for postponing the replacement are between 10 200 EUR and 30 600 EUR for each pole. Note that for pole no. 172, which was heavily oversized, the savings are higher than the replacement costs, because the lifetime analysis has shown that the pole probably have more than twice as long remaining lifetime than the economic lifetime. Thus, the company may save replacement several times by keeping the pole as it is (i.e. keeping it oversized) instead of replacing it with a weaker pole. This example shows also very clear that inspections methods based on the assumptions that poles are properly designed cannot utilize the potential when the components actually are stronger than intended. Note, that there is also the possibility that the situation is vice versa, that is, the pole is undersized. In this case, the advantage of method 2a is that this would be revealed, whereas method 3 might overestimate the strength. The latter might have the consequence that the pole is not replaced when the traditional method is used even though the pole must be replaced as the more advanced methods show.

Table 3 Potential benefit of method 2a.

Pole no.	14	42	127	172	176
Saving S [1000 EUR]	11.9	14	10.2	30.6	23.9

CONCLUSIONS

The paper has presented several methods for condition assessment of wood poles. The application in the case study showed that more accurate methods will improve the assessments. In addition, a better estimate of the remaining lifetime can be established by means of the improved assessment methods. Furthermore, by applying improved methods, the utilities have the possibility to reduce the maintenance and replacement costs, because the improved methods help to avoid that poles are replaced too early or too late.

Acknowledgments

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