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# Reliability Assessment for Overhead Power Transmission Lines using Failure Rate Analysis

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**ABSTRACT**

The failure rate is one of parametric indices for the power system of evaluation. It is defined as the inability of the system to perform its designated function properly without interruption over a period of time. The speed at which failure distribution systems depends on many factors, some of which are the lack of maintenance, aging, unskilled nature of government policy and technical experts. This paper focuses on the development of a generalized analysis of default rates in assessing the reliability of overhead power transmission line. Energy equipment operation experience shows that the system overhead power transmission lines (OLs) are the least reliable component. Now, thousands of kilometers from LO in many countries through the 35 years of service boundary, hence the question about increasing the reliability OL moves to one of the first places on the agenda of electrical engineering. In addition, the LO components causing automatic cuts should be recorded separately. They include corrosion of parts of the tower, line equipment, cables and son; destruction of parts of insulators, etc. Great insulation length of transmission lines, combined with their high damageability, resulting in the need to consider the reliability of the OL in both the design phase and in the operation process

## INTRODUCTION

To compare reliability of various construction alternatives for an overhead line, and to assess reliability of lines in operation, reliability indicators are used. Reliability of overhead transmission lines can be quantitatively determined with a set of indicators including the following five indicator groups: failure-free operation, reparability, operating life, integral indicators, and economic indicators Collection and processing of operational statistics provides a main source of information about electric engineering equipment's reliability (Bollen, M., 1993; Heising, C., 1994). To address practical tasks, estimates of the following indicators are required: failure flow of OL components; mean time to recovery; periodicity of scheduled repair and operation works and their duration. Tables 1-3, contain values of the above-mentioned reliability indicators for some countries (Vesely W., 1997; Pecht, M., 1990). It should be noted that differentiation of reliability indicators by various attributes allows optimizing OL operation. Mathematical models are used to calculate and forecast reliability indicators.

### *Development Of Mathematical Model:*

The choice of a mathematical description method is dictated by the needs of practical tasks and by the capabilities of various mathematical models and methods. Literature (Brown, R., 2002; Wenyuan Li, 2005; Allan, R., 1999) considers a model allowing reliability assessment for the mechanical section of overhead lines. For this reliability indicators such as failure rate and failure-free operation probability are used. This model determines a line reliability by strength of wires and suspension towers, because these components determine a



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line's failure-free operation and time to recovery after destruction. Strength of other components should be properly coordinated with strength of the above-mentioned ones (Billinton, R., 2001; Arild, H. and T. Arne, 2006). An anchored segment is considered as a line model because anchor towers are regarded as actually indestructible (Ganiyu, A., 2014; Qing Yang, X., 2014; Jibril, Y. and K.R. Ekundayo, 2013). A line's failure-free operation probability is calculated by the following expression:

**Table 1:** OL failure flow indicator in some countries.

| Country | Voltage, kV | ω , 1/(100km*h) |
|---|---|---|
| Japan | 22-33 | 4.19-8.74 |
| | 67-77 | 2.09-4.32 |
| | 110-154 | 0.52-1.64 |
| | 220-275 | 0.3-0.98 |
| Germany | 30 | 3.0 |
| | 60 | 1.8 |
| | 110 | 1.6 |
| | 220 | 0.5-3.2 |
| | 380 | 2.1 |
| U.S. | 11-38 | 3.0 |
| | 69 | 0.2 |
| | 138 | 0.3 |
| | 220-240 | 0.227 |
| | 287-300 | 0.291 |
| | 345-360 | 0.536 |
| | 500 | 0.14 |
| Austria | 30 | 6.69 |
| | 60 | 2.53 |
| | 110 | 1.28 |
| | 220 | 0.53 |

**Table 2:** OL mean time to recovery (Tr) in some countries.

| Country | Voltage, kV | Tr, h |
|---|---|---|
| Europe | 750 | 18.2 |
| | 500 | 15.1 |
| | 330 | 13.6 |
| | 220 | 12.3 |
| Canada, U.S. | 500 | 0.902 |
| | 230 | 4.43 |
| | 138 | 8.95 |
| | 69 | 4.4 |
| | 33 | 8.0 |
| Japan | 220-275 | 0.27-2.48 |
| | 110-154 | 4.42-5.53 |
| | 66-77 | 2.92-5.81 |
| | 33 | 2.78-3.5 |

**Table 3:** Average periodicity and duration of scheduled OL outages.

| Voltage, kV | 35 | 110 | 220 | 330 | 500 |
|---|---|---|---|---|---|
| Average periodicity of scheduled outages per year | 1.25 | 2.30 | 2.31 | 2.43 | 1.48 |
| Average duration of scheduled outages, h | 17.9 | 14.3 | 16.8 | 17.6 | 19.0 |

$$P_{SL} = X_i \cdot P_V \cdot P_{VP} \cdot P_P \quad (1)$$

Where:

$Pv, Pvp, Pp$ : Failure-free operation probabilities of one line span in wind, glaze-wind, and glaze operation modes, respectively

$x_i$ Strength reduction coefficient of the component most frequently subjected to maximum permissible loads as shown in Table 4.

**Table 4:** Strength reduction coefficients (Vesely W., 1997).

| Component count | Strength reduction coefficient, % | | | | |
|---|---|---|---|---|---|
| | 5 | 10 | 15 | 20 | 30 |
| 1 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| 2 | 0.98 | 0.97 | 0.94 | 0.91 | 0.84 |
| 5 | 0.96 | 0.92 | 0.85 | 0.80 | 0.64 |
| 10 | 0.94 | 0.89 | 0.81 | 0.72 | 0.51 |
| 20 | 0.93 | 0.85 | 0.77 | 0.66 | 0.38 |
| 40 | 0.92 | 0.83 | 0.72 | 0.59 | 0.26 |
| 80 | 0.91 | 0.79 | 0.68 | 0.53 | 0.16 |

For practical calculations, this paper offers an algorithm for reliability assessment of the mechanical OL section as shown in Figure. 1. In the first stage of the reliability assessment, it is necessary to chart a distribution function of annual Table 1. OL failure flow indicator in some countries maximum loads of line components in glaze, wind, and glaze-wind modes. The type of distribution functions is determined from meteorological data about annual maximum loads in the line area. In the second stage, all the line's anchored segments are grouped by one-span parameters: wire grade, suspension tower type, span length. In the third stage, an anchored segment having the largest number of components (spans) is chosen out of every group. The second and third stages allow costs to be cut considerably because any anchored segments, reliability of which is not minimal in advance, are excluded from consideration. In the fourth stage, permissible wire loads in glaze, wind, and glaze-wind modes are calculated. Permissible wire load is calculated by the following expression:

$$\gamma_n = k_\partial \cdot \ \sigma_p \times \sqrt{24.\frac{K_\partial \cdot \ \sigma_p \cdot \delta_y + \alpha . E . \Delta t}{l^2 . K_M . E} + \frac{\gamma_y^2}{\sigma_y^2}} , \qquad (2)$$

Where:

$k_\partial = 0.7$ Coefficient determining maximum permissible wire strain

$\sigma_p$ - Strain in wire material causing its breakage, kgf/mm2

$\sigma_y$ -Strain in wire material within the elastic strain limits, kgf/mm2

$\alpha$ - wire thermal elongation factor, degree-1

$E$ - Modulus of elasticity, kgf/mm2

$\Delta t$ - Temperature change at wire transition from the elastic strain mode into the breaking force mode, Co

l- Span length, m; Km factor values were obtained by calculation based on data of tests: for aluminum and steel-aluminum wires, it is 0.42; for aluminum alloy wires, it is 0.6

$\gamma_y -$ Load causing wire strain equal to modulus of elasticity, kgf/m*mm2, determined by the expression (3);

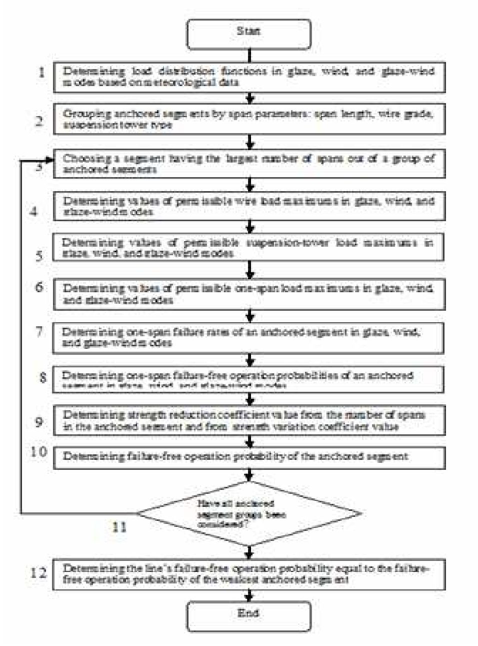


**Fig. 1:** Algorithm for reliability assessment of the mechanical OL section.

$$\gamma_y' = \frac{\sqrt{\left(\left(\sigma_y - \sigma_{ucx} + \frac{\gamma_{ucx}^2 . E . l^2}{24.\sigma_{ucx}^2}\right) + \alpha . E . \left(t_y - t_{ucx}\right)\right)\left(24.\sigma_{ucx}^2\right)}}{E . l^2} \, ., \qquad (3)$$

Where:

$\gamma_{ucx}$. $\gamma_{ucx}$. ,reference mode parameters determined by mechanical Calculation of wires. Wire slack for is determined by the formula:

$$f = \frac{\gamma'_y . L^2}{8.\sigma_y}, \quad (4)$$

If the obtained value of (f) is less than the permissible wire slack maximum value $f_n$, then $\gamma_y$ is taken as equal to $\gamma'_y$ . Otherwise,

$$\gamma_y = \frac{8.\sigma_y . f_H}{L^2} , \quad (5)$$

Permissible load maximums in glaze and wind modes are determined by the expressions:

$$\gamma_{PN} = \gamma_n - \gamma_1 \quad (6)$$

$$\gamma_{vn} = \sqrt{\gamma_n^2 - \gamma_1^2} \quad (7)$$

It is not possible to determine a precise value of the permissible load maximum in the glaze-wind mode ( $\gamma_{vpn}$ ), because vectors of the glaze and wind loads have different directions. However, it is obvious that ( $\gamma_1 vpn$) can assume values within those of $\gamma_{pn}$ and $(\gamma_{vn})$. It can be seen from expressions (5) and (7) that $\gamma_{vpn} < (\gamma_{vn})$. Therefore, we may assume that

$$\gamma_{vpn} = \gamma_{pn} , \quad (8)$$

In the fifth stage, maximum permissible values of wind pressure upon wires and towers in the glaze and glaze-wind regimes are determined. This is done with the formula:

$$W_n \quad \frac{K_3 . M_p - M_g}{C_{xnp} . \alpha . n . d . l . H_{np} + 0.5 . C_x . \beta . H_{cm} . S} , \quad (9)$$

Where:

$K_3$ - 1.2 strength reserve factor

$Mp$ - Calculated strength value, kgf*m

$Mg$ – Moment resulting from tower deformation due to moments of wind pressure upon the tower body and wires, kgf*m

$Cxnp$ - Wire aerodynamic coefficient

$\alpha$ – Coefficient considering non-uniform velocity pressure along the wire length

n- Number of wires

d- for non-glaze mode: wire diameter; for glaze mode – glaze ice coating size together with wire

l- span length, m

Hnp- average height of wire suspension determined from tower drawings

Cx-- tower body's head drag coefficient

$\beta$ – Coefficient considering wire's dynamic impact upon the tower

Hcm- height of the surface part of the tower body, m

S- Square of the body's side, m2

When calculating the permissible wind pressure upon a tower in the glaze mode, the glaze wall thickness may be taken as equal to a rated value for the given glaze area. The sixth stage includes determining permissible span load of the given anchored segment in glaze, wind, and glaze-wind modes. The permissible load is taken as equal to the least of the permissible loads upon wires and towers in a corresponding mode. When comparing loads in the glaze-wind mode, it is necessary to determine a permissible value of wide pressure upon wires at the rated thickness of the glaze wall. In the seventh stage, proceeding from distribution functions of annual load maximums, one-span failure rate is determined in glaze, wind, and glaze-wind modes as shown in Figure2 in the eighth stage, the formula

$$P_{ls} = e^{-\omega 1.N} \quad (10)$$

Where:

$\omega$ - One-span failure rate, 1/year

$N$ – Line service life, years

It used to determine failure-free operation probability of one line span in glaze, wind, and glaze-wind modes. In the ninth stage, based on the number of spans in the anchored segments (n) and the strength variation coefficient (v), the strength reduction coefficient (ℵ) is determined in (Table 4). When calculating the system strength reduction's dependence on the number of its components, it is recommended to proceed from the condition that a component may emerge in the system, strength of which is 10% less than the statistically average (under the probabilistic calculation method) or than the permissible minimum (under the semi-probabilistic calculation method).

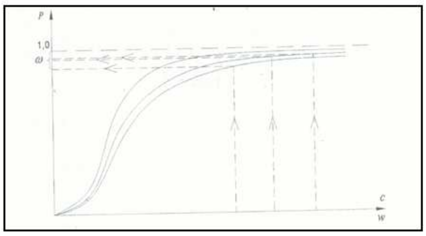

**Fig. 2:** Determining failure rate of one span in glaze, glaze-win, and wind

In the tenth stage, formula (1) is used to determine failure-free operation probability for the anchored segment under study. Stages 3-10 are repeated for all groups of anchored segments. In the twelfth stage, the line's failure-free operation probability is determined:

$$P_{SL} = min\{P_{isl}\} \quad (11)$$

The model considered above may be used to assess reliability of OLs of any voltage. However, when assessing reliability of 10 kV distribution networks, their low redundancy level should be taken into account, which determines the need for detailed consideration of the time needed to recover electric supply for consumers in reliability assessment models. Using the above-mentioned algorithm, failure-free operation probability was calculated for existing 330 kV OL. According to world experience in operating of electric plants and networks, overhaul of OLs on metal and reinforced-concrete towers should be carried out at least every 10 years. Therefore, the line's failure-free operation probability was calculated for this period of time. The result obtained, $P_{SL}$ = 0.53, shows a sufficiently high level of the line's reliability, that being confirmed by the absence of any failure during 30 years of its service. It should be noted that in recent years, due to massive expiration of OL standard operation life and because of related increased failure rates of the lines, the need has emerged for large volumes of repair and restoration works requiring huge material and labor inputs. This situation may be resolved by OL condition diagnostics allowing a shift to technical maintenance based on real needs.

## RESULTS AND DISCUSSION

Currently, new diagnostic methods and tools are used enabling equipment condition control without putting it out of operation. One of such diagnostic tools is thermal imaging control. Major benefits of thermal imaging control include high work safety, low operating costs, and inexpensive technical maintenance. Weaknesses of thermal imaging control include high cost of thermal imagers. However, in some cases one can find so many defects during one day that it would cover the cost. Using thermal imagers enabling high-precision temperature measurement at live OL components without approaching them provides a possibility to estimate conditions of wire contact connections quickly and absolutely safely based on their heat emission caused by load current. Mass objects of thermal control include insulators (especially porcelain) in HV line strings. While diagnostic methods for the electric OL section are developing swiftly, we should point out weak development of diagnostic methods for the mechanical OL section (reinforced-concrete towers, foundations, etc.).

However, ultrasonic and vibration-based diagnostics of reinforced-concrete OL structures have found its application recently allowing defects in concrete to be found in the early stage of their emergence. Hence, diagnostics allow saving huge funds due to timely detection of equipment defects as well as owing to the fact that any equipment, repair of which may be reasonably postponed for some later time, is excluded from the scope of repair. Studying the OL reliability problem, we should point out as a conclusion that OL reliability is a technical-and-economic category. Reliability level increase always entails growing costs. Hence, a question arises on what a reliability criterion should be used. In the design stage, when selecting an OL construction option, a minimum of reduced costs (or discounted costs, of the OL is constructed during a few years) should be the criterion. Hence, any increase of costs for higher reliability must be justified by decreasing damage for power consumers because of power supply breaks. Methodologically, it is reasonable to represent the damage as two constituents – because of downtime of an enterprise, its equipment and workforce with resulting underproduction, and a suddenness damage because of sudden outage (with possible equipment breakdowns, spoiled raw materials and finished goods, etc.). Hence, economic damage from every failure of an OL feeding i (i=1, 2,…I) enterprises can be determined by the expression:

$$y = \sum_{i=1}^{1} (\omega..Pi.y_o + \omega.Pi.y_{bh} \quad (12)$$

Where:

$\omega -$ failure flow parameter of the line under study, 1/year

$\tau$- mean time to OL recovery, hours

$Pi -$ power shortage at the j − th enterprise because of OL failure, kW
$y_o -$ specific main damage because of OL failure, dollar/kWh
$y_{bh} -$ specific suddenness damage because of OL failure, dollar/kWh

When increasing reliability level during OL operation, it is necessary to establish functional links between reliability indicators and indicators of the electric power supply system's cost-effectiveness. In general, a cost-effectiveness criterion consists of a ratio of a revenue gain to capital investments that caused the gain:

$$E = \frac{O - C}{K} \tag{13}$$

Where:
O – Annual production output in wholesale prices;
C – Cost of the annual production output;
k – Capital investments in the reliability-increase activity implementation.

Capital investments are considered to be effective if the actual indicator of total effectiveness is not lower than the standard value for the given enterprise type:
Ee ≥ Ese

***Conclusion:***

OL components not causing automatic outages should be recorded separately. They include corrosion of some tower parts, line hardware, cables and wires; destruction of insulating parts of insulators, etc. Great length of transmission lines, combined with their high damageability, results in the need of considering OL reliability both in the design stage and in the operation process. Increasing OL reliability is an urgent technical and economic issue. Therefore, this task should be addressed both in the design stage and in the operation process. In that, it is necessary to increase the extent of implementation of modern diagnostic tools substantially

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