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Residual life assessment of overhead transmission lines 110 kV and above and determination of their reconstruction terms

Bauyrzhan Uteuliyev [1]*

[1]KEGOC JSC, Astana, Republic of Kazakhstan

Abstract. In this article is given a method for assessment the residual life of overhead transmission lines on reinforced concrete supports with centrifuged poles. Reinforced concrete poles of supports, wires and lightning protection cables are adopted as the main elements. The intensity of change in the actual state parameters of these elements is determined by the laws of random variables distribution that allow predicting the residual life and the timing of repairs and reconstruction of overhead transmission lines. The parameters of natural climatic conditions and other external factors are considered by including of coefficients into the formula for changing the actual state parameters.

1 Introduction

Practically, the reinforced concrete supports with centrifuged poles have a long service life of more than 40 years at all electric grid organizations who have an OHTL of 110 kV and higher.

With such an amount of outdated OHTL, electric grid organizations are trying to plan reconstruction considering their technical condition, but limited financial resources and network mode do not allow complete replacement of worn out components of OHTL. It should be noted that at first glance the deteriorated technical condition of the OHTL not always requires reconstruction, many defects can be eliminated by repair and OHTL can serve for several tens of years. In such cases, works on the OHTL reconstruction must be planned with consideration of the limiting state prediction, i.e. assessment of its residual life.

2 Life assessment of OHTL

The possibility of predicting the life assessment of objects is provided with simultaneous presence of the following conditions [8]:

1) the parameters determining the actual condition of the structure are known;

2) the criteria for the limiting state of the structure are known;

3) it is possible to periodically (or continuously) monitor the values of the technical state of the structure.

For the parameter of the actual state takes the characteristic of damage, defect or malfunction, changing during operation, whose numerical values exceed the threshold established by normative-technical documentation. The parameter of the actual state is monitored during the operation of the OHTL by diagnosing its elements.

For OHTL we take three levels of categories of technical condition [2]:

1) the first category is a workable state in which the change of the parameter of the actual state characterizes the breaking of the OHTL operational capability or a single failure case that slightly reduces reliability;

2) the second category is a critical state, in which frequent failures occur with high probability, which significantly reduce reliability;

3) the third category is the limiting state, in which the change of the parameter of the actual state leads to numerous failures, which restoration is costly.

The concept of the limiting state corresponding to the exhaustion of the resource allows for a different interpretation. In some cases, the reason for the termination of operation is the moral wear, in others - an excessive decrease in efficiency, which makes the further operation of the economic inexpedient, and thirdly - the reduction of safety indicators below the maximum permissible level. [1]. For OHTL with consideration of ongoing repairs and replacement of worn-out elements, it is advisable to adopt a state corresponding to the wear limit when the further operation of the OHTL is economically inexpedient.

As the actual state parameter of reinforced concrete centrifuged poles, we take the coefficient of concrete's state, derived by calculation and determined in the diagnosis of poles. For the actual state parameter of the wires and lightning protection cables, we take the fractional loss of strength, calculated from the results of diagnosing the conductor structure [3, 4].

For each category of the actual state parameter, determine the admit boundary values according to Table 1.

* Corresponding author: Uteuliyev@kegoc.kz

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Table 1. Characteristics of the actual state parameter of the OHTL

Catego-ry of states	Level of function-al ability	Reinforced con-crete supports (Coefficient of concrete's state)	Wires and lightning pro-tection cables (Fractional loss of strength, %)
First category	Workable state	$0 \le x_{\phi 1} \le 0{,}3$	$0 \le x_{\phi 1} \le 5$
Second category	Critical state	$0{,}3 \le x_{\phi 2} \le 0{,}6$	$5 \le x_{\phi 2} \le 10$
Third category	Limiting state	$x_{\phi 3} > 0{,}6$	$x_{\phi 3} > 10$

The experience of OHTL maintenance shows that in the process of their operation there is a diverse nature of the changing process of the actual state parameter in real conditions during the time that characterizes a workable or inoperative state.

During the operation in the survey of the OHTL is measure the value of the actual state parameter at a fixed moment of time. The results of the OHTL survey show that the change of the actual state parameter tends to increase during operation time. Naturally, the highest intensity of change of the actual state parameter is possessed by OHTL with a service life more than 30-35 year.

For the mathematical model of the change of the actual state parameter during operation, it is necessary to consider the natural and climatic conditions and other external factors. The impact of natural and climatic conditions and other external factors is considered by the introduction of the climatic coefficient k based on data [5, 7, 9, 10]. The value of this coefficient is determined by multiplying the coefficients from the following tables 2-6, depending on the region in question.

Table 2. Values of the coefficient for ice

Area on ice	Normative ice wall thickness, mm	Coefficient $k_г$
I	10	1
II	15	1,04
III	20	1,07
IV	25	1,1
V	30	1,15
VI	35	1,17
VII	40	1,19
Special	above 40	1,2

The coefficient of ice $k_г$ is corrected with multiplying by the coefficient k_i, considering the change in height over the earth's surface, and by a coefficient k_d that considering the change in the thickness of the ice wall, depending on the diameter of the wire [11].

Table 3. Values of the coefficient for wind

Area by wind	Normative wind speed at a height of 10 m above the ground, m/s	Coefficient $k_в$
I	25	1
II	29	1,04
III	32	1,07
IV	36	1,1
V	40	1,15
VI	45	1,17
VII	49	1,19
Special	above 49	1,2

The coefficient of wind $k_в$ is corrected with multiplying by the coefficient k_w that considering the height of the location of the gravity reduced center of the wires (cables) and the middle points of the structures zones of the OHTL towers above the ground [11].

Table 4. Values of the coefficient for absolute minimum air temperature

Climatic region	The average of the absolute annual minimum of air temperature, ° C	Coefficient k_m
Very cold	below -60	1,2
Cold with a very humid climate	from -60 to -45	1,19
Cold with a cold summer	from -60 to -45	1,15
Cold with a warm summer	from -60 to -45	1,1
Moderately cold	from -45 to -40	1,07
Moderate	from -40 to -25	1,03
Moderately warm	above -25	1

Table 5. Values of the coefficient of relative humidity

Average monthly relative air humidity, ° C	Coefficient $k_{ов}$
30	1
40	1,03
50	1,07
60	1,1
70	1,13
80	1,17
90	1,2

Table 6. Values of the coefficient of soil salinity

Types of soil	The content of water-soluble salts in soils, %	Coefficient k_n
Non-saline	up to 0,5 inclusive	1
Weakly saline	from 0,5 to 1,5 inclusive	1,1
Salted	over 1,5	1,2

2.1 The intensity of the change of the actual state parameter

To select the distribution law, a variation of the developments values [11, 17] was taken on the failure of reinforced concrete supports, wires and lightning protection cables. Empirical characteristics have shown that the failures distribution of reinforced concrete supports obeys the normal distribution law of random variables, and the wires and lightning protection cables – to the Weibull distribution.

In actual conditions, the change of the actual state parameter is difficult to observe continuously, and the control is performed periodically. At each moment of the next control, one of two solutions are possible: to continue operation or perform a repair. This decision is made based on an analysis of the intensity of the change of the actual state parameter.

The intensity of the change of the actual state parameter is determined by the formula

$$\mu = \frac{f(t)}{F(t)} \tag{1}$$

where $f(t)$ - the probability density of the change in the value of the actual state parameter in time t;

$F(t)$ - the probability of failure-free operation in time t.

In the normal distribution law, these two quantities are determined by the formulas

$$f(t) = \frac{1}{\sigma\sqrt{2\pi}} exp\left(-\frac{(t_i - T)^2}{2\sigma^2}\right) \tag{2}$$

$$F(t) = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{t} exp\left(-\frac{(t_i - T)^2}{2\sigma^2}\right) dt \tag{3}$$

where t_i - is the time of trouble-free operation (independent variable);

T - average predicted failure time (mathematical expectation), years;

σ - standard deviation.

In the Weibull distribution law, $f(t)$ and $F(t)$ are determined by formulas

$$f(t) = \frac{b}{T}\left(\frac{t_i}{T}\right)^{b-1} exp\left(-\frac{(t_i)^b}{T}\right) \tag{4}$$

$$F(t) = 1 - exp\left(-\frac{(t_i)^b}{T}\right) \tag{5}$$

where b - is the form parameter.

Given the permissible values of the actual state parameter, it is possible to determine with a high probability the transition time of state from one category to another. In this case, the stochastic process for OHTL with a service life of more than 30 years will look as follows [2]

$$X(t) = x_ф + k \cdot t_i \cdot \mu \tag{6}$$

where $x_ф$ - the average value of the actual state parameter recorded during the survey.

k - climatic coefficient, considering the features of changing of the actual state parameter in the region under consideration;

t_i - number of years under consideration, $t_i = 1, 2, 3\ldots$

μ - the intensity of the change of the actual state parameter.

2.2 Predicting residual resource of OHTL

When predicting the residual resource of OHTL structural components, with consideration of the change of the actual state parameter of its elements, the following calculations are made for plotting the graph:

1) determine the average value of the actual state parameter of the elements;

The average value of the actual state parameter of reinforced concrete supports is determined by the expression [16]

$$x_{ф.on} = \frac{\sum_{i=1} n_{oni} \cdot K_{ci}}{N_{on}} \tag{7}$$

where n_{oni} - the number of poles with the same coefficient of concrete's state;

K_{ci} - coefficients of concrete's state;

N_{on} - total number of surveyed poles.

Instead of the average value of the actual wire condition parameter (lightning protection cables), we take the maximum value of the section loss in the surveyed section

$$x_{ф.n.m} = max\,(p_{ci}) \tag{8}$$

where p_{ci} - the loss of the cross-section of wires (lightning protection cables).

2) determine the average operating time of the OHTL for failure [6, 11, 17];

3) determine the intensity of the change of the actual state parameter (for reinforced concrete supports according to the normal distribution law, for the conductor structure according to the Weibull distribution law);

4) determine the trajectory of the change of the actual state parameter;

5) determine the average value of the actual state parameter of the elements for subsequent stages, consider-

ing the residual wear, which is determined by the following formula

$$x_{ocmi} = x_{\phi 1} \cdot \frac{\sum n_0}{N} \cdot \frac{t_n - t_0}{t_0} \tag{9}$$

where $x_{\phi 1}$ - the actual initial mean value of the actual state parameter at the time of the survey, determined by formula (3);

n_0 - the number of defective items at the time of survey;

N - the total number of elements on the OHTL;

t_n - predicted time when the actual state parameter reaches the boundary value;

t_0 - time of the survey.

6) determine the distribution densities of each actual state parameter according to the normal distribution law;

7) determine the period of carrying out repairs or reconstruction at the highest peak of the distribution densities for each drift of the actual state parameter.

Figures 1 and 2 show the results of calculating the residual life of the OHTL 220 kV, examined at a service life of 41 years.

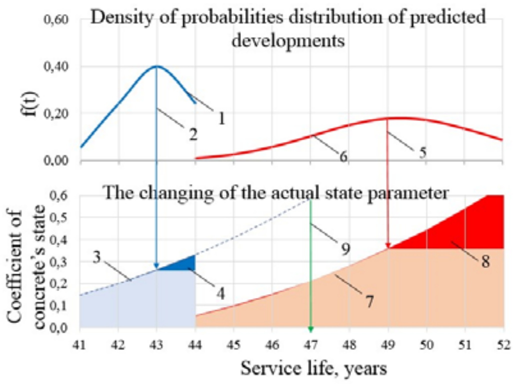

Fig. 1. Schedule of determination of residual life of reinforced concrete supports.

In Fig. 1 the following designations are accepted:

1 - density of probabilities distribution of predicted developments for repair;

2 - the projection of the distribution density peak on the trajectory of the drift of the actual state parameter, which determines the beginning of the repair;

3 - drift trajectory of the actual state parameter for repair;

4 - the period of repair;

5 - density of probabilities distribution of predicted developments for reconstruction;

6 - the projection of the distribution density peak on the trajectory of the drift of the actual state parameter, which determines the beginning of the reconstruction;

7 - drift trajectory of the actual state parameter for reconstruction;

8 - the period of reconstruction.

9 - the projection of the distribution density peak on the axis, which determines the guaranteed life of reinforced concrete supports.

By increasing the number of repairs, it is possible to extend the residual life of reinforced concrete supports.

If we compare the peaks of the distribution densities for each drift of the actual state parameter in Fig. 1, then it is possible to predict the average time for the onset of a OHTL failure. The predicted failure will occur in the region of decline in the distribution density, which is colored in a dark color on the graph. Accordingly, it is necessary to carry out the first repair to replace the supports with a coefficient of concrete's state of 0.6 during the service life of 43-44 years.

The predicted residual life of reinforced concrete supports is 52 years. Therefore, with a service life of 49 years corresponding to the peak of the probability distribution density, it is necessary to begin reconstruction of the OHTL 220 kV with the replacement of reinforced concrete supports.

According to [8], the guaranteed life of reinforced concrete supports was 47 years, which is marked by a green arrow in Fig. 1, i.e. the trajectory of the first predicted drift of the actual state parameter when it reaches the limit state is a guaranteed resource.

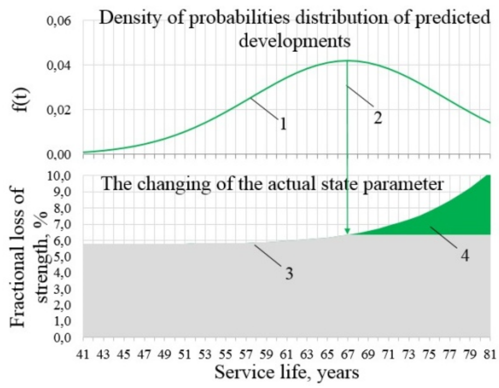

Fig. 2. Schedule of determination of residual life of the wire.

In Fig. 2 the following designations are accepted:

1 - density of probabilities distribution of predicted developments for replacement of a wire;

2 - the projection of the distribution density peak on the trajectory of the drift of the actual state parameter, which determines the beginning of the replacement of the wire;

3 - drift trajectory of the actual state parameter to replace the wire;

4 - the period of the replacement of the wire.

According to the calculated data, shown in Fig. 2, the residual life of the wire was 81 years. Therefore, with a service life of 67 years corresponding to the peak of the probability distribution density, it is necessary to begin replacement of the wire throughout the entire OHTL 220 kV.

Similarly, the calculation was made for a lightning protection cable, the residual life of which was 80 years, and with a service life of 66 years, it is required to begin the replacement of the lightning protection cable throughout the entire OHTL 220 kV.

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3 Conclusion

When predicting the residual resource and determining the reconstruction period of the OHTL, choose the worst-case version of the limiting state of the OHTL elements. The above calculations showed that the worst option for achieving the start of reconstruction are reinforced concrete supports. Therefore, the reconstruction of the OHTL 220 kV must begin with a service life of 49 years, subject to repairs with the replacement of reinforced concrete supports. The number of necessary repairs before reconstruction should be determined by the decision of the operating organization.

Thus, it is possible to determine the planned timeframes for the reconstruction of all surveyed OHTL, which will make it possible to draw up a perspective schedule for the OHTL reconstruction of electric grid organizations.

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