METHOD AND ALGORITHM FOR QUANTITATIVE ANALYSIS OF AVERAGE MONTHLY VALUES OF THE OPERATIONAL RELIABILITY OF OVERHEAD POWER LINES

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Abstract

The relevance of ensuring the efficiency of equipment, devices and installations (object) of electric power systems increases every year and becomes the most important problem of maintaining energy security. The decrease in work efficiency is due to a number of factors, but, first, an increase in the relative number of objects, the service life of which exceeds the standard value. An illustration of the methodology for quantifying, comparing and ranking the monthly average values of indicators of the operational reliability of 110 kV overhead power transmission lines and above given in order to identify and restore the wear of the least reliable lines.

Keywords. Analysis, operational reliability, overhead power lines, automated system, classification, features, varieties

I. Introduction

At present, the service life of more than half of overhead power transmission lines (hereinafter - OHL) of electric power systems (hereinafter - EPS) exceeds the standard value, which leads to a decrease in their efficiency [1]. To limit the consequences of this change, risk oriented approaches are being developed for organizing their maintenance and repair (hereinafter - MRO) [2-4]. Their essence boils down to the theory of production assets management by ensuring a balance between operating costs and the risk of damage. It is known, that [5]:

– there is no methodology for calculating the technical condition index (hereinafter - TC). There is no monitoring of the TC overhead power lines, the methods used to assess the risk of damage are subjective;

– there are no operational recommendations to improve the efficiency of the overhead transmission lines.

TC OHL determines the reliability and safety of their work. Therefore, the possibility of assessing the indicators of operational reliability by analogy with the individual reliability of power units is relevant [6]. The apparent simplicity of this solution is deceptive, and, first of all, because there are no statistical data on continuous monitoring of the TC of overhead transmission lines, and according to statistical data on the failure within one month, it is impossible to assess the reliability indicators of specific overhead transmission lines due to their small number. When comparing and ranking indicators of operational reliability, the use of the mathematical apparatus for analyzing homogeneous statistical data is unacceptable, because the data are multidimensional and scarce [7].

We also shall remind that:

– the efficiency of functioning of EPS facilities today is understood as a joint accounting of efficiency, reliability of operation and safety of service;

– such an expanded concept of efficiency is due to the increase in the number of objects requiring operational inspection not only for efficiency, but also for reliability and safety;

– operational survey is understood as a quantitative assessment of work efficiency;

– if, for design purposes, a methodology for quantitative assessment of reliability indicators been developed and is widely used in practice to compare the design options of objects under design, then there is no methodology for calculating operational reliability indicators for solving operational problems. The science intensity, cumbersomeness and laboriousness of calculating operational reliability indicators requires a transition to automated systems for assessing, comparing and ranking, with monthly submission to the management of EPS facilities and electrical enterprises of guidelines for increasing the TC. The implementation of automated systems for analyzing TC of EPS facilities allows a large power grid enterprise to save tens of millions of rubles [5];

– unfortunately, there is no methodology for quantitative assessment of service safety indicators not only when solving operational problems, but also when designing EPS facilities [5];

– identity of the methodological approach to the assessment, comparison and ranking of EPS objects does not affect the discrepancy between the calculation algorithms due to the fundamental features of the functioning of these objects.

II. Initial data and indicators of operational reliability of OHL of EPS.

Initial data on OHL represented by constant and variable parts. The permanent part is compiled on the basis the passport data of the OHL and includes the name of the line, the name of the electro network enterprise (hereinafter - ENE), the nominal voltage, the year of commissioning, the material of the supports, the length of the line, the number of circuits. The variable part is compiled on the basis of operational logs and includes the following information about the change in the state of the OHL: name of the OHL, rated voltage, date (month, day, hour) of shutdown and activation, type of shutdown (emergency, by emergency or planned request). This information is entered into special tables of the database (we will designate them, respectively, as tables A and B) and are used in assessing the indicators of the operational reliability of the OHL EPS. These averaged indicators theoretically allow us to compare the operational reliability of a number of EPS and are necessary to control the nature of changes in the reliability of OHL in the calculated month in comparison with the reliability in the previous month. For illustrative purposes, table 1 shows the results of the assessment of indicators characterizing the initial data on the OHL of the EPS in one of the calculated months and their operational reliability.

Table 1. *Illustration of the initial data and estimates of the operational reliability indicators of OHL 110 kV and above EPS*

Parameters	Symbol	Unit of measure	Quantitative estimation	The formula of calculation
Initial data OHL				
Number OHL	$n_{t,l}$	unit	273	
Total length	$L_{t,l}$	кm	7918,5	$L_t=\Sigma L_i$
Number of automatic switching-off.	$n_{t,a}$	unit	58	
- the same, but with successful RUE	$n_{t,r}$	unit	50	
Number of switching-off under the emergency request	$n_{t,e,r,}$	unit	94	

Parameters	Symbol	Unit of measure	Quantitative estimation	The formula of calculation
Duration of emergency idle time	$T_{t,e}$	hour.	407	$T_{t,e}=T_e+T_{e.r.}$
Number AT OHL	$n_{t,l}^{AT}$	unit	164	
Total length AT	L_t^{AT}	км	4853	$L_t^{AT}=\Sigma L_i^{AT}$
Total service life AT	ΔT_t^{AT}	years	3718	$\Delta T_t^{AT}=\Sigma\Delta T_i^{AT}$
Parameters of operative reliability				
Specific number of automatic switching-off	$\lambda_{t,a}^*$	Sw-off /years	12,9	$\lambda_{t,a}^*=12\cdot 10^2 n_{t,a}/L_{t,l}$
Specific number of automatic switching-off with successful RUE	$\lambda_{t,r}^*$	Sw-off /years	7,6	$\lambda_{t,r}^*=12\cdot 10^2 n_{t,r}/L_{t,l}$
Specific number of switching-off under the emergency request	$\omega_{t,e.r.}^*$	Sw-off /years	14,2	$\omega_{t,e.r}^*=12\cdot 10^2 n_{t,e.r}/L_{t,l}$
Average duration of idle time under repair under the emergency request	$M^*(\tau_{e.r.})$	hour	4,3	$M^*(\tau_{e.r.})=\sum_{i=1}^{n_{e.r.з}}\tau_{e.r,i}/n_{t,e.r}$
Average duration of idle time in emergency repair	$M^*(\tau_{e.rp.})$	hour	3,3	$M^*(\tau_{e.rp.})=\sum_{i=1}^{n_{e.rp}}\tau_{e.rp,i}/n_{e.rp}$
Relative duration of idle time in emergency repair	$K_{e.r.}^*$	%	0,71	$K_{e.r.}^*=10^4 T_{e,r}/(T_m\cdot L_{e,r})$
Average length OHL	$M_t^*(L)$	км	29	$L_{t,av}=L_{t,l}/n_{t,l}$
Relative number AT OHL	$\delta n_{t,l}^{AT}$	%	60,1	$\delta n_{t,l}^{AT}=10^2 n_{t,l}^{AT}/n_{t,l}$
Relative length AT OHL	$\delta L_{t,l}^{AT}$	%	61,3	$\delta L_{t,l}^{AT}=10^2 L_{t,l}^{AT}/L_{t,l}$
Average service life AT OHL	$M_t^*(\Delta T^{AT})$	years	22,7	$M_t^*(\Delta T^{AT})=\Delta T_t^{AT}/n_{t,l}^{AT}$
Average length AT OHL	$M_t^*(L^{AT})$	км	23,6	$M_t^*(L^{AT})=L_t^{AT}/n_{t,l}^{AT}$

Note: Te<Te.r.; Tm - the duration of the calculated month, AT - symbolic designation of OHL, the service life of which exceeds the standard value

To compare these indicators with the reliability indicators given in reference books and literature on the reliability of EPS facilities, the monthly average estimates of the reliability indicators of OHL, multiplied by the number of months in a year (12) and reduced to a conventional line 100 km long.

As expected, the given monthly average values of operational reliability indicators may differ significantly from the average annual values due to the uneven distribution of the intensity of the impact of disturbing factors (for example, thunderstorm activity) throughout the year. Nevertheless, a significant excess of the reduced average monthly value of the estimate of the operational reliability indicator of the average annual value indicates insufficient protection of the OHL from the main influencing factor in the calculated month.

III. Initial data and indicators of operational reliability of OHL ENE EPS

The possibility of comparing the operational reliability of OHL ENE EPS is one of the most urgent tasks of the EPS and, first of all, because it allows you to optimize the total operating costs of the EPS. The methodology for assessing the operational reliability indicators of OHL ENE EPS is similar to the methodology for assessing the operational reliability indicators of OHL EPS as a whole. The essential difference is that information on passport data and changes in the technical condition of OHL must classify according to the "name of the ENE". Here, similar to the data in table A, tables AN are compiled, where N - is the conditional serial number of the ENE EPS, which are also practically unchanged, but unlike table A, they do not contain the column "name of the ENE". The automated generation of AN tables is not difficult.

IV. Initial data and indicators of operational reliability OHL ENE ESP.

The ability to compare the operational reliability of the OHL ENE ESP is one of the most pressing issues for EPS and, above all, because it allows you to optimize the total operating costs of the EPS. The methodology for assessing operational reliability indicators OHL ENE ESP is similar to the methodology for assessing operational reliability indicators OHL ESP as a whole. The essential difference is that information on the passport data and changes in the technical condition of the OHL classified according to the "ENE name" attribute. Here, similar to the data in Table A, tables AN compiled, where N is the conditional serial number ENE ESP, which are also practically unchanged, but unlike Table A, they do not contain the column "ENE name".

The automated generation of AN tables is not difficult. Of course, when classifying passport data according to ENE manually, the grouping process is laborious and cumbersome. But it is carried out only once. Formation of BN tables turns out to be much more difficult, since in table B, and of course, in the operational logs, there is no information about the name of the ENE, to which the OHL belongs, the state of which has changed. Searching for the passport data of a specific OHL among hundreds of considered OHL is tedious, and the risk of a wrong decision turns out to be unacceptably high. An automated search can, of course, solve this problem without error. But even in this case, the time spent turns out to be unacceptably large.

Offered:

– transform the adopted sequence of OHL placement (as a rule - by voltage class) into a sequence of OHL names in alphabetical order, indicating the name of the ENE of each OHL (analogue - telephone directory);

– define the OHL group, the first letter of the name of which coincides with the first letter of the name of the recognized OHL;

– among a relatively small number of OHL of this group (maximum - several tens of OHL), it is quite simple to identify the desired ENE, on the balance of which this OHL is located, manually.

Table 2. *Results of calculation of indicators of initial data and estimates of indicators of operational reliability*

Parameters	Unit of measure	ENE N							
		1	2	3	4	5	6	7	8
Initial data									
$n_{t,l}$	unit	49	22	28	7	29	34	69	18
$L_{t,l}$	км	1600	561	850	220	1026	604	1253	1802
$n_{t,a}$	unit	31	0	4	1	14	6	23	18
$n_{t,r}$	unit	25	0	3	1	7	3	9	3
$n_{t,e,r,}$	unit	20	2	7	0	15	13	23	14
$T_{t,e}$	hour	97,4	2,5	21,5	0	97,5	60	83,7	44,4
$n_{t,l}^{AT}$	unit	38	16	20	7	13	18	41	11
L_{t}^{AT}	км	1214	392	633	220	403	470	610	911
ΔT_{t}^{AT}	years	653	256	403	109	291	442	1340	224
Parameters of operative reliability									
$\lambda_{t,a}^{*}$	Sw-off /years	**23,3**	0	5,6	5,5	16,4	8,2	17,6	4,0
$\lambda_{t,r}^{*}$	Sw-off /years	**18,8**	0	4,5	5,5	8,2	6,0	8,6	2,0
$\omega_{t,e.r.}^{*}$	Sw-off /years	15	4,2	9,9	0	17,6	**25,8**	22	9,3

Parameters	Unit of measure	ENE N							
		1	2	3	4	5	6	7	8
$M^*(\tau_{e.r.})$	hour	4,9	1,5	3	0	**6,5**	4,6	3,6	3,8
$K^*_{e.r.}$	%	0,85	0,061	0,35	0	1,32	**1,38**	0,93	0,34
$M^*_t(L)$	км	327	25,8	30,4	31,4	**35,4**	17,8	12,2	100,1
$\delta n^{AT}_{t,l}$	%	77,6	72,7	71,4	**100**	44,8	52,9	59,4	61,1
$\delta L^{AT}_{t,l}$	%	45,9	69,1	74,5	**100**	39,3	77,8	48,7	50,6
$M^*_t(\Delta T^{AT})$	hour	17,2	16,0	20,2	15,6	22,4	24,6	**32,7**	20,4
$M^*_t(L^{AT})$	км	31,9	24,5	31,7	31,4	31	26,1	14,9	***82,8***

Table 2 shows the results of calculations of operational reliability indicators OHL ENE ESP. This data allows you to:

1. Compare and rank ENE. For example, according to the indicator, the ranking of ENE in order of increasing reliability is: ENE1, ENE7, ENE5, ENE6, ENE3, ENE4, ENE8 and ENE2. If we take into account that for EPS as a whole, the value is 12.9 sw-off / years (see Table 1), then we can conclude that the least reliable OHL are ENE1, ENE7 and ENE5.
2. Draws attention to the fact that the ranking results depend on the operational reliability indicator. For example, the OHL in ENE6 is the least reliable for the indicator and in ENE7 for the indicator. To overcome this ambiguity of the decision, it is necessary either to choose for comparison one of ten indicators of operational reliability or to calculate an integral indicator that takes into account the significance of each of the 10 indicators. The second method is more reliable, but it also requires solving a number of tasks, such as assessing the degree of relationship between indicators of operational reliability, overcoming the difference in their dimensions and scale, and preserving the physical essence [8].
3. Increasing the reliability of comparison and ranking of operational reliability indicators requires taking into account their random nature. As a first approximation, the ENE list classified into three groups. The indicators of the first group OHL ENE accidentally differ from the same indicator for OHL ESP as a whole, the second group is not accidentally less than the indicator for OHL ESP, and the third group is not accidentally higher than the indicator for OHL ESP.
4. An illustration of the solution to these problems requires special consideration.

III. Analysis of OHL ENE, the operational reliability of which is the lowest

Before carrying out this analysis, let us answer one non-standard question: how much can the operational reliability of the OHL ESP increase if the reliability of the OHL ENE1 increased at least to the level of the operational reliability of the OHL ESP in the calculated month? According to table 1, and according to table 2 for ENE1.

It is easy to see that approximate equality achieved by reducing the value by about half. At the same time, the specific number of automatic shutdowns OHL ESP will decrease by 102·15/85=17.6%. Such a dramatic change is certainly tempting.

The purpose of the analysis of OHL ENE1 is to recognize the types of signs for which the specific number of automatic shutdowns of OHL ENE1 most higher than the estimate for OHL ENE1. For illustrative purposes, table 3 shows the results of calculating the specific number of automatic trips when classifying OHL ENE1 by voltage class, service life, support material and OHL length. Analysis of these data shows:

– the dependence of the specific number of automatic shutdowns OHL on the voltage class, known from reference books, remains unchanged according to long-term data - with an increase in the nominal voltage, the specific number of automatic shutdowns OHL decreases;

– the dependence of the specific number of automatic OHL shutdowns on the service life is also clearly confirmed. It is somewhat overestimated in the initial period of operation and significantly increases when the service life is exceeded ΔT=53 years.
– at the initial stage, the classification of OHL according to the material of the supports [metal or mixed (metal, reinforced concrete or wood)] turned out to be inappropriate, since their significance is approximately the same;
– most often automatically shut off OHL, the length of which is in the range (31 ÷ 60) km.

Table 3. *Illustration of the significance of the varieties of features that characterize the operational reliability of OHL ENE1.*

The name		Parameters		
attribute	varieties	n_a, unit	$L_л$, км	λ^*, sw-off /years
ENE1		31	1600	23,3
Voltage class, кV	330	2	268	9,0
	220	5	284	21,1
	110	24	1048	27,5
Service life, years	≤ 17	6	228	31,6
	18-35	-	7,2	-
	36-52	4	654,8	7,5
	≥ 53	21	710	35,5
Material of support	Metal	10	513,3	23,4
	Mixed	21	1086,7	23,2
Length of a line, км	≤ 30	4	330,2	14,5
	30-60	20	613,3	39,2
	60-90	6	542,5	13,3
	≥ 90	1	114	10,5

Table 4. *Recognition of the most significant variety of signs for OHL ENE1 with L = 30-60 km*

The name		Parameters		
attribute	varieties	n_a, unit	$L_л$, км	λ^*, sw-off /years
ENE1, $L_л$=30-60 км		20	613,3	39,2
Voltage class, кV	330	-	-	
	220	2	78,7	30,4
	110	18	534,6	40,4
Service life, years	≤ 17	4	94,9	50,6
	18-35	-	-	-
	36-52	2	202	119
	≥ 53	14	316,4	53,1
Material of support	Metal	5	252,7	19,7
	Mixed	15	360,6	41,5

Table 5. *Results of the third stage of classification OHL ENE1*

The name		Parameters		
attribute	varieties	n_a, unit	$L_л$, км	λ^*, Sw-off /years
ENE1, L_l=30-60 км; $\Delta T_{сл}$>53 years		14	316,4	53,1
Voltage class, kV	220	-	-	-
	110	14	316,4	53,1
Material of support	Metal	5	173,3	34,6
	Mixed	9	143,1	75,5

To recognize the OHL features, with a length from 31 to 60 km, Table 4 shows the results of their classification according to the characteristics: stress class, service life and material of supports. The calculation results allow us to conclude:

– the significance of the varieties of the attribute "stress class" has changed little. Only the excess of the specific number of automatic shutdowns OHL 110 kV over OHL 220 kV became clearer;
– the dependence of the specific number of automatic OHL shutdowns on the service life has also remained unchanged;
– but the higher reliability of OHL on metal supports known from the operational experience was confirmed - the specific number of automatic shutdowns is almost two times less;
– the largest specific number of automatic shutdowns is observed at OHL, the service life of which is 1.5 times higher than the standard value. Since the length of these lines is 316.4 km, and the OHL number is 7, let us clarify the significance of these OHL by classifying them according to the remaining two features, stress class and support material. The calculation results are shown in Table 5.

Analysis of this data shows:
– the greatest significance of the varieties of signs established at the second stage of the classification - OHL with $\Delta T>53$ years is entirely related to OHL with $U_H=110$ kV.
– at the third stage, a significant excess of the operational reliability of OHL on metal supports compared to OHL on mixed supports manifests itself.

Let's summarize the results. Determined that:
– 110 kV OHL on mixed towers with a length of 30 to 60 km, the service life of which exceeds one and a half of the rated service life, are subject to increase in the reliability of operation on ENE1;
– it is easy to see that it is for these types of signs that an intuitive choice of OHL is made, subject to TC certification and overhaul;
– the recommended method allows to set the list of OHL to be restored in ENE automatically according to the statistical data of operation. It refers to risk-based approaches since it significantly reduces the risk of an erroneous decision;
– with all the apparent cumbersomeness and laboriousness, the apparent simplicity of the analysis of the operational reliability of OHL is deceptive, primarily because when comparing and ranking estimates of operational reliability indicators, their random nature was not taken into account, and thus the recommendations were not specified. The possibility of an accidental discrepancy is objective and indicates the inexpediency of classification, and the use of the recommended methods and algorithms requires an unconditional transition to automated systems for analyzing operational reliability

Conclusion

1. The developed methods and algorithms for assessing, comparing and ranking indicators of operational (average monthly) performance (economy, reliability and safety), practical testing of individual stages of their application according to statistical operating data indicate real possibilities for improving the management of production assets;
2. This result is due to a significant increase in the number of objects, the service life of which has exceeded the standard values;
3. For example OHL with voltage 110 kV and above:

– calculation formulas and quantitative estimates of monthly average values of operational reliability indicators characterizing their TC are given. These estimates can be compared with similar estimates calculated for the month preceding the calculated one;
– calculated and compared the monthly average values of OHL operational reliability indicators for ENE EPS. These estimates allowed for the first time to rank the operational TC OHL EPS, to identify enterprises with the least operational reliability;
– since this enterprise may include dozens of OHL, not all of which do not meet the requirements of operational reliability, an illustration of the OHL recognition method that requires immediate (prompt) recovery is given

The use of the developed algorithms in automated systems for assessing, comparing and ranking production assets eliminates the risk of erroneous decisions of an intuitive approach when organizing operation, maintenance and repair.

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