About reliability characteristics of overhead electrical grids 6-10 kV elements

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Abstract. In the paper, failure outage statistics in 6–10 kV overhead electric grids of one of the largest electric grid companies in the European part of the country were analyzed to clarify the reliability characteristics of their elements. Failure intensity and mean restoration time for covered and uninsulated overhead lines, low-oil and vacuum circuit breaker cells, power transformers and secondary electrical grid elements were obtained. The obtained reliability characteristics of elements should be used in the tasks of technical justification and selection 6–10 kV overhead electrical grid preferred structure.

1 Problem description

Problem of power systems reliability performance existed before and continue to be relevant. One of its aspects is traditionally a research of reliability characteristics of electrical grids. At the same time, close attention is paid to the indicators characterizing their failure outages: failure intensity ω and mean restoration time T_r .

In the USSR there was centralized collection and processing of statistical data on the failure outages of power system elements. Its latest results are dated to the period 1977-1982 [1], which presents the reliability characteristics of elements of 6–10 kV overhead electric grid: overhead lines (OHL) with uninsulated wires, 6–10/0.4 kV power transformers, and low-oil circuit breaker cells.

In plenty of publications for OHL, an extremely wide range of failure intensity is given. So, in paper [1], $\omega=7.64$ 1/(year per 100 km), in [3] - 2–20 1/(year per 100 km), and in [2] - 25 1/(year per 100 km) and even more [4]. In addition, covered overhead lines, (i.e. with wires having a protective insulating outer sheath) apply more and more in the country's medium voltage grids. Compared with uninsulated wires they have certain advantages in terms of reliability, for example, in [5] it is noted that the covered OHL are protected from overlapping, have high mechanical strength, practically do not form icy-hoarfrost deposits and others. In [6] there was an assumption that the use of covered OHL will reduce the failure intensity of electrical lines by 2.4 times. The widespread use of covered overhead lines in distributing power systems dates back to beginning 2000-s and now this type of line occupies an increasingly significant share.

For power transformers, published failure intensity are also very different. For example, in [1] values of

0.008-0.016 1/year are indicated, and in [2] - 0.035 1/year. However, the studies presented were carried out almost 40 years ago.

For low-oil circuit breakers, the values of $\omega=0.009$ 1/year and $T_r=20$ h [1], obtained in the 80s of the last century, are similar to the reliability characteristics that are still given in various publications. For example, in [7] values $\omega=0.01$ 1/year is presented, including 0.003 1/year - fault type of short circuit and 0.007 - fault type of break circuit.

However, vacuum circuit breakers become more widely used over the last decade in comparison low-oil ones. For vacuum circuit breakers, the expert value $\omega=0.004$ 1/year is given in [8]. The same publication contains a reference that, according to leading world manufacturers, the mean operating time to failure of a modern vacuum circuit breaker is 2000 years, whence $\omega=0.0005$ 1/year.

Note that in the analysis of circuit breaker failure models consider not a only circuit breaker, but a connection failure, i.e. circuit breaker with all related equipment - disconnectors, measuring transformers, connecting buses, relay protection and automation devices, insulators and bushings [9].

Thus, the presented information on the reliability characteristic of the elements of 6–10 kV overhead electric grids is outdated or contradictory in a number of positions, and the reliability characteristic of elements of 6–10 kV grids, such as fuses, measuring transformers and etc. are almost not presented in the literature.

Therefore, the authors set themselves the task of analyzing failure outage statistics in 6–10 kV overhead electrical grids of one of the largest electric grid companies in the European part of the country and clarifying their reliability characteristic.

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2 Reliability characteristics of 6–10 kV covered and uninsulated overhead lines

Statistical sample for uninsulated OHL and covered OHL for 2015–2017 shown in table 1. As can be seen in the table 1 every year about 1000 km of covered OHL are put into operation and to date their share in the region has reached about one third of total length.

In the table 2 shows the total number of failure outages and their total duration for covered and uninsulated OHL from table 1. Based on the data in table 1 and 2, the values of failure intensity and mean restoration time are calculated - see table 3.

Table 1. The total length of the electrical grid in the region

Year	The total length of the electrical grid 6-10 kV, km		
	uninsulated OHL	covered OHL	Total
2015	20 033	8 067	28 100
2016	19 437	8 901	28 338
2017	18 708	10 177	28 885

Table 2. Overhead lines outage

Year	uninsulated OHL		covered OHL	
	Number of outages, ea	Duration of outages, hrs	Number of outages, ea	Duration of outages, hrs
2015	557	1038,4	25	86,5
2016	438	836,7	29	96,5
2017	345	862,5	31	189,5
Total	1340	2737,6	85	372,5

As can be seen from the table 3, the overhead line failure intensity was only 2.3 1/(year per 100 km). In the region, abnormal ice rains preceding the period under review caused numerous failure outages in electric grids of 6-10 kV and long-term restrictions on the power supply of consumers. Further, technical measures were organized, such as accelerated reconstruction of grids, widespread and uncompromising clearing of «no tree» zone OHL, replacing uninsulated OHL with covered OHL, which made it possible to achieve shown in table 3

characteristics.

It should be noted those 3-5 days each year, during which a quarter or more of all overhead line outage occur due to abnormal weather conditions (strong winds, ice rains, etc.).

Table 3. Reliability characteristics of overhead lines

Year	uninsulated OHL		covered OHL	
	ω , 1/(year per 100 km)	T_r , hrs	ω , 1/(year per 100 km)	T_r , hrs
2015	2,78	1,86	0,31	3,60
2016	2,25	1,91	0,33	3,33
2017	1,84	2,50	0,30	6,11
2015–2017	2,30	2,04	0,31	4,38

The failure intensity of covered OHL are approximately an order of magnitude more reliable (7.4 times) than uninsulated OHL: 0.31 compared with 2.3 1/(year 100 km) (table 3). A significant decrease in the failure intensity of covered OHL is partially offset by an increase in their mean restoration time. Obviously, the multiplied ωT_r is the expected average annual outage of line: $2.3 \cdot 2.04 = 4.7$ hours per 100 km for uninsulated OHL and $0.31 \cdot 4.38 = 1.36$ hours per 100 km for covered OHL, so we can conclude that the covered OHL have $4.7/1.36 \approx 3.5$ times more favorable characteristics.

Additionally, in the table 4 shows the organizational structure of the total failures of uninsulated OHL and covered OHL for the period 2015–2017 (classification of failures are taken from [10]). Data analysis table 4 shows that the failure structure of uninsulated OHL and covered OHL proved to be expected. So, the percentage of failures related with the intervention of unauthorized persons and organizations and adverse natural phenomena (tree contact), reaches in both cases 70–80%. In addition, the share of covered OHL failures associated with atmospheric overvoltages is several times higher than that for uninsulated OHL, as was mentioned earlier in [5].

Table 4. Overhead lines failure structure

Failure cause	uninsulated OHL		covered OHL	
	Number of outages, ea/%	ω , 1/(year per 100 km)	Number of outages, ea/%	ω , 1/(year per 100 km)
Bad-quality OHL maintenance	97/7,2	0,167	6/7,1	0,022
Intervention of unauthorized person or organization	192/14,3	0,330	20/23,5	0,074
Birds	69/5,2	0,119	–	–
Natural disasters including	888	1,526	54	0,199
– Ice-hoarfrost deposits;	10/0,8	0,017	–	–
– Wind speed load (wires overlapping);	103/7,7	0,177	–	–
– Atmospheric overvoltage (lightning);	27/2,0	0,046	7/8,2	0,026
– Tree contact	748/55,8	1,286	47/55,3	0,173
Installation defects	35/2,6	0,060	5/5,9	0,018
Unclassified cause	59/4,4	0,101	–	–
Total	1340/100	2,30	85/100	0,31

3 Reliability characteristics of 6–10 kV low-oil and vacuum circuit breaker cells

The failure outage statistics for the cells of low-oil and vacuum circuit breakers 6–10 kV at 611 substations 35–220/.../6–10 kV in the region for the period 2016–2018 were analyzed. The size of the statistical sample, see table 5.

As can be seen from the table 5, the share of low-oil circuit breakers is more than half of the installed equipment fleet, despite the fact that for many years they have not been used in new construction or reconstruction.

In the table 6 shows the total number of failure outage and their total duration for the circuit breaker cells from table 5. Based on the data in table 5 and 6, the values of the failure intensity and the mean restoration time of the circuit breakers are calculated - see table. 7.

Table 5. Number of circuit breaker cells 6–10 kV at substations

Year	Low-oil	Vacuum
2016	11 500	7063
2017	11 282	7281
2018	10 929	7634

Table 6. Circuit breaker cells outages

Year	Low-oil circuit breakers		Vacuum circuit breakers	
	Number of outages, ea	Duration of outages, hrs	Number of outages, ea	Duration of outages, hrs
2016	26	102,7	17	63,4
2017	15	35,4	3	15,7
2018	34	265,1	5	7,5
Total	75	403,2	25	86,6

Table 7 shows that the failure intensity and the mean restoration time of the vacuum circuit breaker cells are about two times less than the low-oil. One of the indirect cause for this is connected that the number of components and moving parts of a vacuum circuit breaker is half that of a low-oil one.

Table 7. Reliability characteristics of circuit breaker cells

Year	Low-oil		Vacuum	
	ω , 1/year	T_r , hrs	ω , 1/year	T_r , hrs
2016	0,0023	3,9	0,0024	3,7
2017	0,0013	2,4	0,0004	5,2
2018	0,0031	7,8	0,0007	1,5
2016–2018	0,0022	5,4	0,0011	3,5

Note that the operational logs that record failure outages usually indicate the time to restore the initial condition of the circuit, but not actual time for repair of the circuit breaker cell. The reason of it is that cells with withdrawable elements are mainly installed at

substation. Therefore, reserve withdrawable circuit breaker cell are used to quickly restore initial state of the circuit in case of a serious failure of circuit breaker.

Table 8 shows the failure structure of circuit breaker cells at substations. During the period under review, only two cases (2016 and 2018) of loss of airtightness of the vacuum circuit breaker arc chamber were recorded. The low-oil circuit breaker drive shaft failure share of about 20% of all failures. In general, the failure structure of low-oil circuit breaker cells in table 8 and in [8] are comparable. For vacuum circuit breaker cells, the main cause of failures was malfunctions of the control circuits, and for low-oil ones - insulation breakdown.

A comparison of the data from table 7 and the paper [1,7,8] shows that the obtained reliability characteristics of the circuit breaker cells become more optimistic. It can be assumed that this is because substation cells were analyzed. The operational specificity of substation's circuit breaker cells is the relatively insignificant (several times a year) number of switching and the presence of duty personnel at substation. Perhaps we should expect a deterioration in the reliability characteristics for circuit breaker cells in the auxiliary systems of 6 kV power plants, where technological conditions require much more frequent (once or twice a day [8]) switching.

Table 8. Circuit breaker cells failure structure

Failure cause	Constructional part failure, ea./%	
	Low-oil	Vacuum
Arc chamber	10/13,3	2/8,0
Drive shaft	17/22,7	0/0
Control circuits	19/25,4	13/52,0
Insulators and bushings	25/33,3	9/36,0
Bus bars	4/5,3	1/4,0
Total	75/100	25/100

For circuit breakers installed in prefabricated 6-10 kV distribution substation should be expected higher mean restoration time. Firstly, this failure takes extra time to detect it and personnel to arrive at the failure substation. Secondly, the design of the cells does not include withdrawable elements. However, a document, published more than 30 years ago, already described that in the scheme of medium voltage electrical grid, the construction of a 6-10 kV distribution substation should be used only in the present of feasibility studies [11].

Thus, vacuum circuit breaker cells 6–10 kV are approximately two times more reliable than outdated low-oil circuit breaker cells in terms of failure intensity and mean restoration time.

4 Reliability characteristics of 6–10 kV power transformer

The failure outage statistics on power transformers 6–10 kV in the distribution electrical grids of the region for 2015–2017 were processed. The size of the statistical sample, see table 9. Accepted designations in

table 9: capacity - total installed capacity of transformers).

Note that the installed capacity of transformers in city cable grids in this region is three times higher than that in the overhead electric grids of suburban areas, although the number of transformers in both cases is comparable. Moreover, in overhead electric grid installed capacity of transformers 6–10 kV three to four times exceed the maximum of their actual load, possibly due to the crisis that occurred in the country (the period of the 90s of the last century).

In the table 10 shows the total number of failure

Table 9. Number of 6-10 kV transformers substation and power transformers

Year	Cable electrical grids			Overhead electrical grids		
	Transformer substation, ea	Power transformers, ea	Total capacity, MVA	Transformer substation, ea	Power transformers, ea	Total capacity, MVA
2015	15379	28247	18621	19645	23037	5854
2016	15494	28415	18960	21424	24681	6479
2017	15623	28683	19350	22709	25174	6886

Table 10. Power transformers outages

Year	Cable electrical grids		Overhead electrical grids	
	Number of outages, ea	Duration of outages, hrs	Number of outages, ea	Duration of outages, hrs
2015	32	331,4	6	25,8
2016	29	473,1	8	39,2
2017	31	538,85	5	30,1
Total	92	1343,35	19	95,1

From the table 11 it follows that the failure intensity of power transformers in cable electrical grids is about four times higher than in overhead electrical grids. Apparently, this is due to two reasons associated with operation on urban areas: the obviously higher load of power transformers and their installation in enclosed spaces, which worsens cooling conditions.

Table 11. Reliability characteristics of 6–10 kV power transformers

Year	Cable electrical grids		Overhead electrical grids	
	ω , 1/year	T_r , hrs	ω , 1/year	T_r , hrs
2016	0,00113	10,4	0,00026	4,3
2017	0,00102	16,3	0,00032	4,9
2018	0,00102	17,4	0,00019	6,0
2016–2018	0,00106	14,6	0,00026	5,0

Comparing reliability characteristic from table 11 with previously published data, a significant improvement in the reliability of power transformers is

Table 13. Reliability characteristics of 6–10 kV secondary electrical grid elements

Electrical grid element	Number of outages, ea				The number of observed elements	ω , 1/year
	2015	2016	2017	2015–2017		
Current transformer	7	7	6	20	474711	$0,42 \cdot 10^{-4}$
Voltage transformer	1	1	2	4	158237	$0,25 \cdot 10^{-4}$
Fuse	13	11	5	29	474711	$0,61 \cdot 10^{-4}$
Disconnecter	6	2	1	9	158237	$0,57 \cdot 10^{-4}$

outage and their total duration for power transformers from the table 9.

Based on the data table 9 and 10, the values of failure intensity and mean restoration time of the considered power transformers are calculated - see table 11.

noticeable: the failure intensity decreased from 0.008 (see above) to 0.001 1/year (Table 11), which is a favorable factor.

The failure structure of power transformers 6–10 kV is given in table 12. As can be seen from it, the failure share of transformers associated with internal failures reaches approximately 70%, which must be taken into account during their operation.

Table 12. Power transformers 6–10 kV failure structure

Type of failure	Number of failures, ea/%
Internal equipment failure (short-circuit between phases or winding coil, breakdown in insulation, breakdown in tap-controller)	76/68,5%
External equipment failure (breakdown of bushings, short-circuit cable bus-bar)	29/26,1%
Breakdown in transformer tower or transformer tank, oil leak	6/5,4%

5 Reliability characteristics of 6–10 kV secondary electrical grid elements

In the table 13 shows the reliability characteristics of measuring transformers, fuses (on three phases) and disconnectors. Analysis of the data from the table 3, 7, 11 and 13 leads to the conclusion that the main part of the failures of 6–10 kV overhead electric grids consist of overhead line failures. Failures of other network elements can be neglected in reliability assessment

6 Conclusion

1. Based on the processing of representative statistical sample, the reliability characteristics of uninsulated and covered OHL in 6-10 kV electrical grids are obtained. It turned out, that the failure intensity of covered OHL has significantly more favorable reliability characteristics compared to uninsulated ones.

2. Vacuum circuit breaker cells 6–10 kV are more reliable than outdated low-oil ones: about two times from the terms of the failure intensity and mean restoration time. At the same time, the actual values of the reliability characteristic obtained at this time interval turned out to be more favorable compared to previously published ones.

3. The reliability characteristics of 6–10 kV power transformers turned out to be much more favorable than previously published values. However, it cannot be ruled out that the equipment fleet and its operating conditions have been updated over the past 40 years since the last reliability studies.

4. The failure intensity of secondary electrical grid elements (measuring transformers, disconnectors, fuses) is significantly lower than overhead lines, circuit breaker cells and power transformers described above. Therefore, in a first approximation, they can be neglected in reliability assessment.

5. The obtained reliability characteristics of the 6–10 kV overhead electric grid elements should be used in the tasks of technical justification and selection their preferred structure.

References

1. *Guidance on the application of reliability characteristics of power system elements and the operation of power units with steam turbine units* (SPO Soyuztekhnenergo Publ., 1985)
2. V. Pruss, V. Teslenko *Improving the reliability of rural electric grids* (Energoatomizdat, 1989)
3. L. Rybakov, Z. Ivanova, *Failure forecasting and planning of the reserve and spare elements, apparatus and equipment of 10 kV distribution grids*. Bulletin of the Chuvash University, **1**, 104 (2015)
4. L. Doletskaya, V. Kavchenkov, R. Solopov *Evaluation of the effectiveness of methods to improve the reliability of distribution electric grids*. NAUKOVEDENIE, **6**, 1 (2015)
5. *Advantages of self-supporting covered wires 6–35 kV. Ways to protect overhead lines from lightning surges*. Electrical engineering news. **3**, (2002). [Electronic resource]. URL: <http://www.news.elteh.ru/arh/2002/15/09.php>.
6. V. Gulkov. *10 (6) kV overhead lines with insulated wires*. PhD candidate's abstract. (1997)
7. Voropay N.I. *Reliability of power supply systems*. (Nauka, 2015).
8. A. Nazarychev. *Analysis of the main advantages*

of using vacuum circuit breakers. Energoekspert, **4-5**, 58, (2007)

9. P. Grudinsky, S. Mandrykin, M. Ulitsky *Technical operation of the main electrical equipment of power stations and substations*. (Energia, 1974)

10. Order of the Ministry of Energy of Russia dated 02.03.2010 No. 90 (as amended on 07.27.2017) “*On approval of the form of the act on the investigation of the causes of accidents in the electric power industry and the procedure for filling it out*.”

11. *Instructions for the design of urban and rural electric networks*. (Ministry of Energy of the USSR, 1984)