

Again about reliability characteristics of electrical power grids elements

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Abstract. The reliability characteristics of the (auto)transformers and overhead transmission lines of the unified national electric grid are subjected to statistical analysis. It is shown that their scheduled outages for scheduled or unscheduled repairs, as well as maintenance, weaken the network layout much more than emergency repairs. At the same time, there was a noticeable deterioration in the (auto)transformers and overhead transmission line reliability indexes over the last 30 years, which requires the development and adoption of appropriate organizational and technical solutions.

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 indexes of electrical grids. The most important are: failure intensity (precisely – mean failure intensity or failure rate); mean restoration time; medium frequency μ and duration T_{rep} of scheduled repairs.

Reliability characteristics of (auto)transformers ((A)T) and overhead power transmission lines (OHL) were analyzed in many published papers [1–6]. On it may be concluded that their fault characteristics are roughly the same, despite different time periods of monitoring: from 1980s-era till the beginning of 2000s. It is to be supposed that the reason is that equipment failures are investigated thoroughly followed by development of organizational-technical measures of their prevention.

In its turn the information about reliability characteristics of scheduled repairs is less presented and it's often controversial. Published data about characteristics of (A)T scheduled outages and single-circuit and double-circuit OHL is shown in the Table 1; Metal OHL supports are taken as a basis, as the most

commonly used.

Table 1. Reliability characteristics of (auto)transformers.

Voltage, kV	μ , 1/year				T_{rep} , hrs		
	0,5	1,0	6,3	3,2	28	30	10,5
110	0,5	1,0	6,3	3,2	28	30	10,5
220	0,9	1,0	6,3	3,2	28	30	12,0
330	1,0	1,0	6,3	3,2	30	30	12,8
500	1,0	1,0	6,3	3,2	50	50	14,0
750	1,0	1,0	6,3	–	50	50	–
Source	[1]	[2]	[3]	[4]	[1]	[2]	[3]

Thus, frequency of (A)T scheduled repairs in [1] and [2] is defined as 1 1/year. It clearly says in [2], that it's periodicity of only current repairs. Therefore, medium and major repairs are left out of consideration. In [3] μ values are defined at a level of 6,3 1/year with reference to [4]. However, in [4] there was talk of scheduled commutations, i.e. total bringing into and withdrawal from operation count, from where frequency of scheduled repairs $\mu=6,3/2\approx 3,2$ 1/year. As one can see, inconsistent information about (A)T scheduled outages is presented in considered sources.

Table 2. Reliability characteristics of single-circuit overhead lines.

Voltage, kV	μ , 1/year					T_{rep} , hrs			
	2,9	2,1	15,0	7,2	2,7	14,9	14,5	4,2	15,2
110	2,9	2,1	15,0	7,2	2,7	14,9	14,5	4,2	15,2
220	5,0	2,8	13,2	7,4	2,9	25,4	17,0	5,9	12,4
330	5,7	3,0	12,0	5,2	2,4	20,1	21,0	7,9	14,3
500	12,8	3,1	10,0	5,0	1,5	16,6	18,0	12,0	16,7
750	10,0	0,17	–	–	–	9,6	–	–	–
Source	[1]	[2]	[3]	[4]	[5]	[1]	[2]	[3]	[5]

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Works [2, 5] should be recognized as works with the most significant statistical samples. A medium frequency of scheduled repairs of OHL 220-500 kV in [5] vary (table 2) from 1.5 to 2.9 1/year; but in [2] it's within the range 2,8–3,1 1/year. Later works refers to much greater values: 10,0–13,2 [3] and 5,0–12,8 [1] 1/year. A medium frequency of scheduled OHL commutations is presented in [4], which equals 10,0–14,8 1/year, i.e. sum of their switching on/off; it is clear, that frequency of OHL scheduled repairs from [4] will be twice as little, i.e 5,0–7,4 1/year. It can be assumed, that such significant spread in presented characteristics can't give an estimate of real reliability characteristics of overhead lines in terms of scheduled outages.

Table 3. Reliability characteristics of double-circuit overhead lines.

Voltage, kV	Downtime	μ , 1/year		T_{rep} , hrs	
		single circuit	3,8	3,2	14,8
110	single circuit	3,8	3,2	14,8	14,8
	double circuit	0,4	0,17	19,0	21,8
220	single circuit	3,3	3,36	17,4	11,9
	double circuit	0,5	0,08	24,0	24,2
330	single circuit	7,3	7,11	15,0	9,4
	double circuit	0,3	–	14,1	–
Source		[2]	[5]	[2]	[5]

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Only in works [2,5] there were undertaken a studies of scheduled outages of double-circuit OHL. But these works refer to period of late 1970s – beginning of the 1980s.

Thus, authors set themselves the task of throwing light on reliability characteristics of (A)T and OHL in main electrical grids from the perspective of real values of frequency and duration of scheduled repairs.

2 Reliability characteristics of (auto)transformers

Monthly reports of actual carried out repairs of (A)T and OHL for a period of 2014-2016 years of Federal

Grid Company (i.e. voltage of 220-750 kV) of most part of regions of the country were taken as source data. Statistical sample size for A(T) is shown in table 4.

Table 4. Statistical sample size for (auto)transformers.

Region	Amount of (auto)transformers-years in grids, kV			
	220	330	500	750
Central	615	63	111	32
North-West	213	291	6	16
Volga Region	477	–	84	–
Urals	471	–	96	–
Siberian	831	–	243	–
Southern	270	132	42	–
Total	2877	486	582	48

Classification of scheduled outages of grid elements was proposed in [6]. (A)T outages were considered by analogy with:

- for carrying out scheduled or unscheduled repairs or maintenance of (A)T (group 1);
- for carrying out scheduled or unscheduled repairs, maintenance or reconstruction of allied equipment (group 2);

Make notice that ‘unscheduled repair’ term was due to the fact that equipment is taken out from the service by an unscheduled dispatching form, but fundamentally it's scheduled outage. Whereby a common feature of scheduled outage is availability of certain period of time between making decision about outage and the moment of outage [6].

Number and duration of scheduled outages from table 4 is presented in table 5. As shown in table 5, scheduled outages connected with scheduled or unscheduled works on (A)T (group 1) constitute the major portion of outages (75-90%).

Table 5. Unscheduled (auto)transformers outages data.

Voltage, kV	Number of outages by groups, ea		Total duration of outages by groups, thous. hrs	
	1st group	2nd group	1st group	2nd group
220	5316	1389	902,8	124,3
330	1026	159	187,8	12,9
500	1164	276	231,4	30,4
750	108	33	31,4	0,8

There were calculated medium frequency and duration of scheduled repairs of (A)T according to table 5 data – see table 6.

Annually, (A)T 220-500 kV is scheduled taken out from the service more than twice (table 6). Thus, frequency of scheduled repairs (A)T from table 6 is close to values given in [4] about 50 years ago. But it should be noted, that actual medium durations and annual average durations of (A)T repairs turn out to be much greater than values published before. Thus, medium duration of a scheduled outage for (A)T 220 kV is 153 hours facing 30 hours shown in [1], for example. According to [1] failure rate of (A)T 220 kV

is 0,014 1/year with mean restoration time of 250 hrs. Hereof an annual average downtime of (A)T for emergency and restoration repair $0,014 \cdot 250 = 3,5$ hrs8,

i.e. is in 100 times lesser than 357 hrs, shown in table 6.

Table 6. Reliability characteristics of (auto)transformers.

Voltage, kV	μ , 1/year		Total by groups 1–2	T_{rep} , hrs		Total by groups 1–2	Annual average duration of repairs, hrs
	1st	2nd		1st	2nd		
220	1,85	0,48	2,33	170	90	153	357
330	2,11	0,33	2,44	183	81	169	412
500	2,00	0,47	2,47	199	110	182	450
750	2,25	0,69	2,94	291	25	229	673

3 Reliability characteristics of overhead lines

There were carried out a research of reliability characteristics of single circuit and double circuit overhead lines. Statistical sample size for OHL is shown in table 7 and 8.

Table 7. Statistical sample size for single circuit overhead lines.

Region	Number of OHL, thous. km-year/line-year in grids, kV			
	220	330	500	750
Central	49,4/1083	5,6/123	32,6/198	7,8/30
North-West	10,6/271	15,2/255	–	3/15
Volga Region	23,2/460	–	16,4/91	–
Urals	31,5/659	–	24,4/128	–
Siberian	55,0/1422	–	45,3/271	–
Southern	13,4/313	9,9/122	12,3/39	–
Total	183,1/4208	30,7/500	131,0/727	10,8/45

There were defied following fault groups for OHL (see [6]):

- for carrying out scheduled or unscheduled repairs or maintenance of OHL (group 1);
- for carrying out scheduled or unscheduled repairs, maintenance or reconstruction of allied equipment (group 2);
- for carrying out OHL reconstruction (group 3);

Table 9. Data of scheduled outages of single circuit transmission lines.

Voltage, kV	Number of outages by groups, ea				Total duration of outages by groups, thous. hrs			
	1st	2nd	3rd	4th	1st	2nd	3rd	4th
220	9344	1318	30	48	936,3	105,5	4,1	2,4
330	1405	123	11	3	215,0	12,5	1	0,8
500	2074	251	1	11	273,5	20,7	0,4	1,7
750	101	32	0	0	18,2	2,9	0	0

Unscheduled outages connected with works, carried out on OHL (group 1), are equal 75-80% of total number of outages. Medium frequency and duration of scheduled repairs of OHL were determined based on data from tables 7-10 – see tables 11-12.

From the table 11 following that each of OHL 220-750 kV is taken out from the service from 2,6 to 3,2

- for performing construction and installation and other works in fenced-off area of OHL on requests of outside organizations (group 4).

Table 8. Statistical sample size for double circuit transmission lines.

Region	Number of OHL, thous. km-year/line-year in grids, kV	
	220	330
Central	171	15
North-West	35	29
Volga Region	85	–
Urals	169	–
Siberian	157	–
Southern	35	6
Total	652	50

Number and duration of scheduled outages of OHL from tables 7,8 are shown in table 9,10 correspondingly.

Table 10. Data of scheduled outages of double circuit transmission lines.

Voltage, kV	Number of outages by groups, ea		Total duration of outages by groups, thous. hrs	
	Single circuit downtime	Double circuit downtime	Single circuit downtime	Double circuit downtime
220	3822	107	371,4	8,2
330	296	5	37,3	0,3

1/year. This is a bit more than it was in 1980s: 1,5–2,9 1/year – see [5]. However, average duration of scheduled repair of OHL 220-500 kV was grown from 12-17 (see [5]) to 98-159 hrs, approximately by an order of magnitude, during the same period. According to [3] nonrecoverable failure for OHL 500 kV is 0,3-0,4 1/year for 100 km for mean restoration time of

about 10 hrs. For average length of OHL 500 kV in Russia at a level of 200 km, its emergency and restoration downtime is $0,4(200/100) \cdot 10 \approx 8$ hrs. Whereby annual average duration of scheduled repair

of OHL 500 kV is (table 11) $3,2 \cdot 127 = 406$ hrs, that almost 50 times higher its annual average emergency and restoration downtime.

Table 11. Reliability characteristics for single circuit overhead lines.

Voltage, kV	μ , 1/year				Total by groups 1–2	T_{rep} , hrs				Total by groups 1–2
	1st	2nd	3rd	4th		1st	2nd	3rd	4th	
220	2,22	0,31	0,01	0,04	2,6	100	80	139	50	98
330	2,81	0,25	0,02	0,01	3,1	153	102	88	277	149
500	2,84	0,35	0	0,02	3,2	132	83	408	152	127
750	2,24	0,72	0	0	3,0	180	91	0	0	159

Table 12. Reliability characteristics for single circuit overhead lines

Voltage, kV	μ , 1/year		T_{rep} , hrs		Annual average duration of repairs (double circuit downtime), hrs
	Single circuit downtime	Double circuit downtime	Single circuit downtime	Double circuit downtime	
220	5,8	0,16	97,2	76,2	12,1
330	5,9	0,10	126	60,9	6,1

4 Analysis of scheduled repairs duration during a year

Additionally there were plotted distributions of scheduled repairs duration of (A)T and OHL by year of

period under review, i.e. proportions of the total number of repairs of given duration on time axis with accepted bin of 10 hrs. Obtained results are shown on fig. 1 and 2 as an example as applied to North-West region.

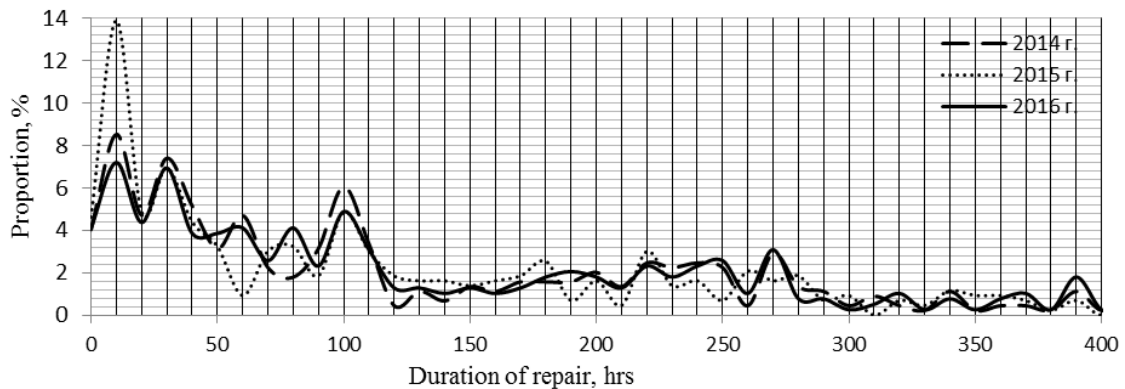


Fig. 1. Distributions of (A)T repairs by duration in North-West region.

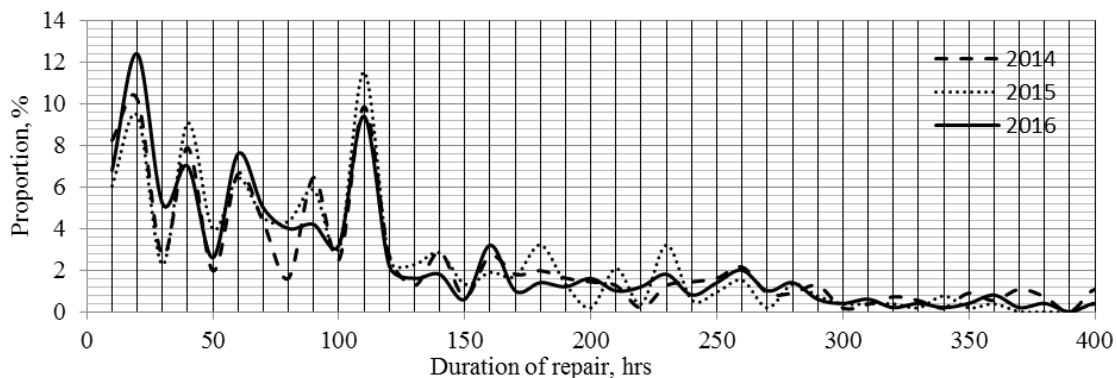


Fig. 2. Distributions of (A)T repairs by duration in North-West region.

Even visually on fig. 1 and 2 one can find similarity of distributions by year of period under review.

Additionally there was carried out correlation analysis for (A)T and OHL between regions of the country for a period of 2014-2016 yrs., where variables

were: proportion of total number of outages and proportion of total duration by month without classification by voltage, i.e. relative number and duration of repairs by month. Corresponding results for OHL are shown in table 13 as an example.

Table 13. Correlation analysis for OHL by regions.

Compared regions	Pearson coefficient for	
	Number of repairs	Duration of repairs
Urals – North-West	0,93	0,92
Urals – Southern	0,89	0,92
Urals – Central	0,89	0,76
Urals – Volga Region	0,95	0,93
Urals – Siberian	0,95	0,93
North-West – Southern	0,87	0,89
North-West – Central	0,94	0,78
North-West – Volga Region	0,89	0,88
North-West – Siberian	0,96	0,92
Southern – Central	0,86	0,72
Southern – Volga Region	0,93	0,88
Southern – Siberian	0,88	0,89
Central – Volga Region	0,93	0,68
Central – Siberian	0,93	0,84
Volga Region – Siberian	0,93	0,93

Minimum value of Pearson coefficient (R) is $R_{\min}=0,88$ for relative number of outages for comparison Southern and Siberian regions and $R_{\min}=0,68$ for relative duration of outages for comparison Central and Volga regions (table 4). It is commonly known that correlational relationship is high for $R \geq 0,7$ and very high for $R \geq 0,9$. Thus, it is to be supposed that for accepted maintenance and repair of OHLs system for a period under review a choice of a certain year of observation is not general contributing factor.

It is commonly assumed that in reliability evaluations scheduled repairs are carried out on 'summer' periods. With that a decreasing correction factor, that is approximately $K=0,5-0,6$, is introduced for calculation period. Therefore, scheduled outages from table 5 and 7 were classified by months. The result is shown on fig. 3 and 4.

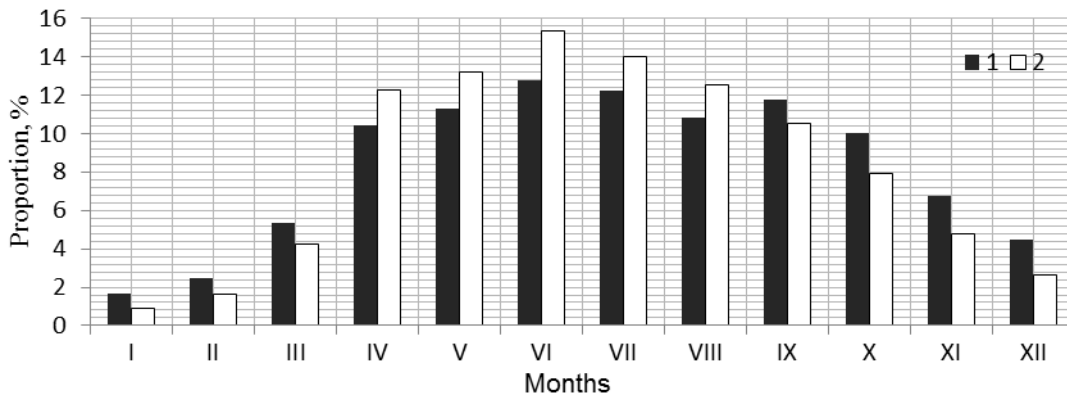


Fig. 3 Distributions of number and duration of repairs of (A)T by months: 1 - proportions of the total number of repairs; 2 – proportions of the total duration of repairs.

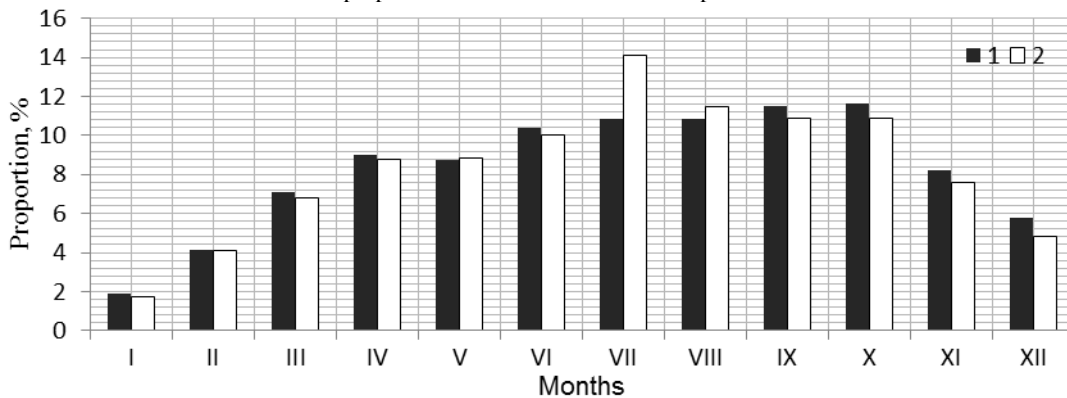


Fig. 4 Distributions of number and duration of repairs of OHL by months: 1 - proportions of the total number of repairs; 2 – proportions of the total duration of repairs.

Frequency and duration of scheduled repairs are constantly increasing from March till November; in the winter period a number of scheduled repairs is lower, than in summer period, however, they shouldn't be neglected. For example, 4-6% of annual number of repairs accrue to December, while the annual maximum is about 11-13% for both (A)T and OHL. From fig. 2 also following that histogram of total number of repairs is lower than histogram of total duration of repairs, but it's vice versa for the winter

period. The reason is obvious – it's necessary to carry out more labor and time consuming repairs in warm seasons.

The maximum value of proportion of total duration of scheduled repairs of (A)T accrues to June and equals about 16%, and to July for OHL (14%). Therefore, $100/16=6,3$ and $100/14=7,1$ are minimum necessary number of months to carry out scheduled repairs of (A)T and OHL by an analogy with maximum load utilization time in a power system.

Where $K=6,3/12=0,53$ for (A)T and $K=7,1/12=0,59$ for OHL, which is confirm the accepted technical practice, which is used for reliability evaluation of electric circuit schemes.

5 Analysis of medium frequency of scheduled repairs of OHL dependence on their length

Line length, km	to 100	100–200	200–300	Above 300
Frequency of repairs, 1/year	3,0	3,9	3,7	4,5

As we can see, some association between frequency of repairs and length appears at line lengths above 100 km. Thus, for OHL length above 300 km frequency of scheduled outages increases of 1.5 times more than

Line length, km	to 30	30–60	60–90	90–120	120–150	150–180
Frequency of repairs, 1/year	3,3	3,1	3,7	3,8	3,0	2,5

Therefore, it's confirmed once more that association between OHL length and frequency of its repairs in reliability evaluations of electric circuit schemes isn't general contributing factor and could be taken into account only for extremely long lines.

6 Conclusion

1. According to processed representative statistical data there were obtained reliability characteristics of (A)T and OHL in main electrical grids of power systems. It's found that from the perspective of medium frequency and duration of scheduled repairs they are way below than values obtained in the last century.

2. Average duration of scheduled repairs of (A)T increased of 5 times upon the average for last 30 years and annual duration of their scheduled downtimes – more than ten times. Applied in the last century normative approach to planning a periodicity of scheduled repairs of (A)T included their annual current repair and major repair once in 8-12 years. Technically, it could have been seemed more progressive than the modern approach, based on evaluation of current state of equipment, because it provided shorter periods of weakening of grid scheme during operation.

For the last 30 years average duration of scheduled repair of OHL 220-500 kV was grown from 12-17 to 98-159 hrs, i.e. almost in ten times. Upon that the main part of scheduled outages connects with repairs or maintenance of OHL itself, but not its reconstruction or other external reasons.

These facts require to be carefully thought.

3. It is found that annual duration of scheduled

It was shown in [6] that frequency of scheduled outages has small dependence on a length of lines. This was explained for a variety of causes. In particular, when it's necessary to performance greater quantity of work it's accepted to increase a number of personnel (teams), but not duration of outage.

According to processed statistical data (table 9) there was analyzed dependence medium frequency of scheduled repairs on their duration:

short lines.

As for rather short OHLs 330 kV, which are located only in European part of the country – there's no association between given characteristics at all:

downtimes of (A)T and OHL exceed their annual duration of emergency and restoration repairs more than ten times. Thus, reduction of duration of repair conditions of electric grid elements could be significant reserve of power systems reliability improvement.

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