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On reliability characteristics and service time limits of 500 kV overhead lines

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Abstract. The results are given of statistical analysis of the values of the failure rate (failure frequency) and its structure for overhead lines (OHL) 500 kV of the European part of the country over a long time period. The age structure of the 500 kV OHL is presented, according to which about 40% of the OHL have developed a normative service time of more than 50 years. It is shown, that an increase in the duration of the OHL operation from about 30 to 60 years leads to a doubling of their accident rate. The maximum possible service time period of 500 kV OHL was estimated. For this purpose, instrumental surveys of the strength property of reinforced-concrete foundations and the degree of corrosive deterioration rate of 500 kV OHL steel transmission tower in three regions of the country were carried out: Vologda, Moscow and Volgograd regions. It is shown that the most critical element of 500 kV OHL affecting the service time limit is their transmission towers. Moreover, the degree of wear condition of the metal of the transmission towers depends on natural-climatic and man-made factors and decreases from the southern to the northern regions of the country. At the same time, the maximum possible service time limit of 500 OHL, put into operation in the middle of the last century, can be increased from 50 to 70-80 years. After that, the main structural elements of the 500 kV OHL should be completely replaced, which will be a large scientific and technical problem from the standpoint of reliability of the operating modes of the country's united power system.

1 Introduction

It is known [1] that the main amount of the ultra-high voltage overhead transmission lines (OHL) was built in the 60-70 years of the last century. Their design focused on 30 years of service time, including corrosive protection, the effects of variable loads, as well as material deterioration. It has been stated [2], that in case of a deterioration of the OHL there is an increase in the accidence wear rate at the level of 3-5% per year. At the same time, it is rightly emphasized [3], that "the end of the standard service time of the OHL means not the occurrence of its limit state, but the onset of its deterioration stage"…existing regulations for the operation and repair of the OHL, which are fair for the stages of running-in and normal operation, require actualization for the stage of OHL deterioration as well.

According to [4] the following normative service time of OHL elements is regulated: wires or supply leads, cables, ground wires, guy wires, overhead line hardware, insulators - 25 years; foundations and reinforced concrete transmission towers - 35 years (a number of documents of recent years refer to service time of at least 50 years); steel transmission towers - 50 years. If the standard service time of the lines is exceeded, the results of periodic technical inspection of their elements are the basis for the extension of the OHL service time [5].

In [6], the accidence of 500 kV OHL was investigated with a total length of about 8.5 thousand km of the vast region of the central European part of the country; it turned out that about 40% of the lines are over 50 years old. That is, they worked out not only the 30-year term planned in the middle of the last century, but also the normative 50-year service time according to [4].

Overhead lines with a voltage of 500 kV form the main backbone of the country's power systems. Therefore, it is of particular interest to assess, firstly, the accidence of 500 kV OHL that has developed a standard service time and, secondly, the limit service time of lines, that is, the period before their complete reconstruction or replacement.

2 500 kV OHL reliability characteristics

The main reasons of OHL accidents are natural-climatic impacts and human activity. The first of them includes ice-frost sediments, strong winds, natural fires, atmospherics overvoltage, etc. The second reason is the unauthorized impact on the OHL elements and their poor-quality operation: special vehicle hitting on the transmission towers, touching of wires with lifting mechanisms, untimely detection of defects, etc., including socio-economic crises. In particular, Table 1 shows as an example the structure of stable, i.e. irreparable by the action of automatic re-inclusion, failures of 500 kV OHL with a total length of about 8.5 thousand km of the central European part of the country for the period 2011-2018 (see [6]). It follows from Table 1 that socio-economic (items 1, 4) and natural impacts (items 2, 3, 5) have an approximately equal effect on the accident rate of OHL.

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A significant part of 500 kV OHL failures is a consequence of damage to wires, insulators, as well as disconnections due to thunderstorms. The transmission towers are fairly a reliable element of the lines (not a single case of transmission towers falling is recorded in Table 1). However, their destruction has the most severe consequences and leads to high costs associated with the restoration of OHL and the underutilization of electricity.

Table 1. Organizational reasons of OHL failures for the period of 2011-2018.

№	Failure cause	Failure number	
		pcs	%
1	Failure to comply with deadlines, failure to perform the required amount of maintenance or repair of equipment and devices, including:	34	12.8
1.1	Untimely identification and elimination defects (broken or untwisting wires and ground wires, the destruction of the set of insulators)	17	6.4
1.2	Other interruptions	17	6.4
2	Birds intervention	5	1.9
3	Exceeding the parameters of the impact of natural disasters regarding the conditions of the project	8	3.0
4	The intervention of unauthorized persons and organizations not involved in the technological process	91	34.2
5	The effects of recurring natural disasters, including:	121	45.5
5.1	Ice and rime coatings	17	6.4
5.2	Atmospheric overvoltage (thunder)	57	21.4
5.3	Natural fires	17	6.4
5.4	Other effects of adverse natural events (falling trees)	30	11.3
6	Undetected reasons	7	2.6
7	Total	266	100.0

Table 2. Reliability characteristics of overhead lines.

Period	ω<50, 1/(year 100 km)	ω≥50, 1/(year 100 km)	ω, 1/(year 100 km)
2011	0,14	0,24	0,18
2012	0,14	0,41	0,26
2013	0,29	0,3	0,29
2014	0,20	0,47	0,32
2015	0,06	0,24	0,13
2016	0,16	0,12	0,14
2017	0,12	0,21	0,16
2018	0,06	0,18	0,11
2011–2018	0,14	0,27	0,20

To assess the reliability of 500 kV OHL that have worked out the standard service time, the failures from Table 1 are divided by the years of the period under consideration and the age of the lines. See Table 2 for results, where $\omega_{<50}$ is the failure rate (failure frequency) of lines with a service time of up to 50 years; ω≥50 - also, but with a service time of 50 years or more; ω - also, but regardless of service time.

Apparently from table 2, the parameter of failure rate ω ≥ 50 practically in all range of years exceeds ω <50, (in some cases up to three times), and in general for the considered period - twice: 0.27 against 0,14 1/(year of 100 km). In the above time intervals, "different aged" of OHL were present. Therefore, weighted average service time was calculated for them according to the formula $\sum l_i t_i / \sum l_i$, where li is the total length of the OHL with a service life of t_i; i=1, …, 63. For the interval of t≥50 years, a weighted average age of 57 years was obtained, and for t < 50 years - 31 years. Thus, exceeding the OHL service time of 500 kV by about twice (from 31 to 57 years), also increases the failure frequency twice (about 4% per year); this dependency can be written as 2 (t-30)/30.

It should be noted that over the past five years, a record low accidence of 500 kV in the region has been recorded: from 0.1 1/(year 100 km) in 2019 to 0.16 1/(year 100 km) in 2017. This is many times less than in other years. For example, in 2012-2014 the failure frequency of OHL 500 kV was two to three times more (0.26-0.32 1/(year 100 km)), in abnormally hot 2010 with its strongest fires - 0.66 1/(year 100 km), finally, in 1998 (famous default) - 0.86 1/(year 100 km).

Thus, at this specific time interval, the accidence associated with the wear of the OHL elements has not yet affected the main structural elements of OHL (foundations and transmission towers) and its effect on the reliability of the latter is weak. The impact of exceeding the standard service time on the reliability of the OHL was somewhat exaggerated. Let us turn to the assessment of the technical condition of OHL based on the results of their periodic surveys (technical inspections).

[4] defines the terms of technical inspections of the OHL: at least once every five years. Statistics on the elimination of defects identified at the same time shows that the main emphasis is placed on quickly replaceable elements, such as wires, sets of insulators, linking hardware, etc., and are mainly limited:

- restoration of destroyed sets of insulators due to atmospherics overvoltage; often insulators are the object of "attention" of hunters who shoot them with hunting rifles;
- cleaning insulators from contaminants and deposits, primarily along highways where contaminants are significantly increased, especially in winter due to the use of anti-ice reagents;
- elimination of wire untwisting by installation of bands and spiral reinforcement;
- cutting down vegetation close to the line route;
- installation of bird protection devices to prevent nesting of feathered birds on crossbeams and tower structures.

All specified works are performed with OHL shutdown and are scheduled.

In relation to foundations and transmission towers, visual inspections are usually carried out for their damage, the presence of chips and cracks, angle deflections, vertical deviations, tightening of nuts, and metal corrosion depth. Transmission towers and foundations are difficult to replace. Therefore, their service time will determine the occurrence of the limit state of the OHL.

3 Limit service time of 500 kV OHL tower foundations

The author of this work carried out a selective survey of the structures of reinforced concrete foundations and steel transmission towers of the most often damaged 500 kV OHL over 50 years old in three climatic zones: Vologda, Moscow and Volgograd regions. The total number of metal transmission towers, taken into account, was 408 pcs.

Surveys of pad and chimney unified foundations and monolithic foundations, tangent suspension towers and anchor and angle tension towers were carried out with drilling to a freezing depth of 1.0-1.5 m. Visual inspection of the load-bearing constructions showed: for 50 years or more, approximately 97% of the foundations were preserved almost in their original form. Only partial damage was found to the upper part protruding from the ground (cracks and chips). The underground part of the foundations, as a rule, had a clear stable initial structure.

Concrete strength studies were carried out using a sclerometer - Schmidt hammer. They showed that the above-ground part of the foundations has concrete strength in the range of 245-330 kgf/cm2 at the standard of 196.5 kgf/cm^2 (GOST 26633-91), and the strength of the underground part - in the range of 390-460 kgf/cm^2.

A minor (less than 2%) part of the supports shows complete destruction of the above-ground part of the foundations. Most likely, this is not due to the aggressiveness of the external environment, but to poor-quality manufacture of the structure (at the manufacturing plant or at the site of the installation of the monolith) or interference from the outside, i.e. as a result of human activity (impact of equipment, etc.).

Foundation defects are eliminated during repair works using modern methods and materials with improved wear-resistant properties. On the basis of the above, a logical question arises: what forecast can be given for the ultimate service time of 500 kV OHL reinforced concrete foundations built in the middle of the last century?

A large number of specialized works are devoted to the durability of reinforced concrete structures, which go far beyond the scope of this article. We will use the estimates given in [7]: the estimated service time of reinforced concrete structures is $t_d=\gamma t_q$, where γ is the reliability factor for service time; t_q is the specified service time. For critical limit state (serious social, economic, or ecological consequences of physical destruction of the structure) coefficient γ = 2.5-3.3 depending on calculated conditions. Accepting the set service time, equal to standard (i.e. 35 years, see above), we will get a settlement deadline of service of OHL reinforced concrete foundations of 500 kV of 88-116 years. Thus, it can be cautiously assumed that the lines under consideration will serve at least another 25-30 years from the standpoint of the operable state of their foundations.

4 Limit service time of 500 kV OHL steel transmission tower foundations

According to [8], the reduction of the cross-section of the steel transmission towers due to corrosion shall not exceed 20% (0.8). Inspection of the above-mentioned 500 kV OHL revealed continuous full corrosion of steel structures; in exceptionally rare cases, pitting corrosion was found.

The main attention in the line survey was paid to the load-bearing elements - the main legs. The reason lies in the fact that the repair of the main leg corners of the towers without performing its dismantling is difficult, since a large number of corners of the transmission tower slat are connected to them. When replacing the main leg corners, it is required to disconnect the OHL, remove the wires, transmission tower, with subsequent assembly and installation of a new structure. The period of such work by a team of 12-15 people, depending on weather conditions, is 4-6 days with the involvement of a significant number of machines and mechanisms.

As a result of the survey of 500 kV OHL main leg corners, the following decreases in metal thickness were obtained due to corrosion wear: 2-3% in Vologda, 3-7% in Moscow and 4-12% in Volgograd regions. Corrosion is more to appear in the lower part of the transmission towers, up to a height of three meters. It is believed that this is due to a stronger blowing and drying of the upper part of the transmission tower.

The relatively slight corrosion wear of the OHL of the Vologda region seems to be associated with special requirements for their material. The 09G2S steel brand recommended for areas with low temperatures is used here. In the central and southern regions, the brand of carbon steel of "ordinary" quality St3 was used.

With the greatest corrosion wear detected of 12%, the actual cross-sectional area of the main leg corner of the anchor transmission tower was 2408 mm^2 with a nominal value of 2736 mm^2 (angle 12 × 120). Therefore, the value of the local attenuation index of its cross-section is equal to 2408/2736 = 0.88, which is greater than the normative value 0.8 (see above).

According to the proportion rule, it is not difficult to estimate how many years it will still take to exhaust the margin of local weakening of the cross-section for transmission towers, put into operation in the late 50s and early 60s of the last century: at the level of 40 years. Thus, the minimum limit service time of 500 kV OHL steel transmission towers can be about 100 years (twice the standard service time of 50 years), which approximately corresponds to the estimated limit service time of reinforced concrete foundations (88-116 years - see above).

5 Maximum service time of 500 kV OHL reinforced concrete transmission towers

As noted earlier, the standard service time of reinforced concrete transmission towers is 35 years. For 500 kV OHL, we are talking about centrifuged transmission tower bodies for tangent suspension towers. During periodic inspections, reinforced concrete transmission towers with longitudinal or transverse cracks, through holes, concrete chips until hardware is bare are detected. Struts with unacceptable longitudinal (transverse) deviation from OHL axis are also defined. If the above defects are detected, the reinforced concrete struts are changed by transmission towers, to new, tower in tower. Moreover, these works do not require new excavations, cutting of wires in places of replacement of the transmission tower, as well as replacement of wires and overhead line hardware. In total, less than 20% of such transmission towers are in the region under consideration, i.e. the remaining part is steel transmission towers.

An additional factor limiting the ultimate service time of reinforced concrete transmission towers is their deviation from the vertical axis. The comparative simplicity of their replacement stimulates this process. So, over the past five years, the rate of replacement of 500 kV OHL reinforced concrete transmission towers in the region has increased from 20-30 and reached 100-120 transmission towers per year and to date, their third part has been replaced. While maintaining this pace, all tangent suspension reinforced concrete transmission towers will be replaced within 10-15 years. Thus, their actual time limit is 60-80 years.

6 Limit service time of other 500 kV OHL elements

As noted above, the standard service time of rapidly replaceable line elements (wires, ground wires, sets of insulators, linking hardware) is 25 years. We will briefly address the cooperation between the service time of these elements, as well as the transmission towers and foundations of the latter.

The analysis of reporting documents of 500 kV OHL is more senior than 50 years of the considered region revealed that mass replacement of conductors wasn't made except for cases of replacement of ground wires by ground wires with the built-in optical cable for the organization of communication channels.

The state of ground wires is paid close attention to responsible crossings through railways, highways, large water barriers, etc. Every five years the defect identification of steel conductors shall be led to determine their suitability for further operation. Thus, the actual service time of wires and ground wires was more than twice the standard time. At the same time, at this time interval there are no preconditions for its (i.e. service time) limitation.

In the late 80-90s of the last century, in the region on the 500 kV OHL, a massive replacement of porcelain insulation with glass insulation was carried out (linking hardware was also changed). The reason was not due to the exhaustion of service time, but to the desire to reduce labor costs during operation. Thus, each porcelain insulator is examined manually during technical inspection and determination of voltage distribution on a set of insulators. Glass insulation most often crumbles, which allows you to visually determine a failed insulator. Damage to one or two insulators in the set of insulators usually indicates factory defect or thunderstorm exposure, and a larger number - when shooting sets by hunters.

Currently, the 500 kV OHL of the region is almost completely equipped with glass insulation. About 3,000 insulators (0.12% of the total) are replaced annually. At the same time, failures were not revealed due to the exhaustion of their standard service time.

On 26 transmission towers of various 500 kV OHL in the region under consideration, starting in 1983, polymeric insulation was used as an experiment. So far (more than 35 years have passed) there have been no cases of technological violations related to its operation.

Polymeric insulation costs are several times lower than glass insulation costs. However, the deterrent factor here is the difficulty of determining out-of-service polymeric insulators (visually, as for glass insulators, not determined). Light sensors are currently being developed to detect their defects. At the same time, the relative novelty of the polymer material for the 500 kV OHL does not allow us to confidently assess their ultimate service time.

According to the linking hardware of the 500 kV OHL of the region, there were no restrictions on the maximum service time.

Thus, the service time limit of 500 kV OHL rapidly replaceable elements (excluding polymeric insulation) in the first approximation can be adopted in the same way as for transmission towers and their foundations.

It should be noted that the author of this article has proactively examined a limited number of 500 kV OHL. However, the patterns identified at the same time indicate the need for a wider survey of 500 kV OHL in other regions, since these lines form the main backbone of the country's energy systems.

Conclusion

Currently, the energy systems of the country have a significant (up to 40%) 500 kV OHL, put into operation in the 60s and 70s of the last century, that is, worked more than 50 years.

Sample surveys of the main, hard-to-replace, bearing structures of these OHL (reinforced concrete foundations and steel transmission towers) showed that, taking into account the actual condition, they can serve according to cautious estimates for at least another 25-30 years, i.e., exceed about two (for transmission towers) - three (for foundations) times their standard service time. At the same time, corrosion wear of metal transmission towers significantly depends on natural-climatic and man-made conditions.

The frequency of 500 kV OHL failures, which have developed a standard service time of 50 years, increases by about 4% per year (doubling in 30 years). However, the role of accidence seems somewhat exaggerated. This growth is significantly lower than the periodic long-term fluctuations in OHL accidence due to natural-climatic and socio-economic phenomena.

At this time interval, there is no urgent need for immediate, massive, deep reconstruction or replacement of 500 kV OHLs, put into operation more than 50 years ago (at least in the central European part of the country). However, it should be borne in mind that in a quarter of a century, this problem will be on the agenda. In this case, it is necessary to take into account the large organizational, material, and financial inertia, as well as the mode restrictions when replacing a large number of 500 kV OHL supporting structures at a limited time interval.

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