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A 110 kV OVERHEAD TRANSMISSION LINE OF COMPACT TYPE :  
DESIGN, OPERATING EXPERIENCE, CONDUCTOR  
OSCILLATION CONTROL

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## ABSTRACT

The analysis is given of the design features of the first USSR commercial-and-test compact 110 kV line in comparison with conventional 110 kV lines. Described are the characteristics of conductors, insulators, structures. The subject for a more detailed study is aeolian conductor vibration. The results are given of the operating experience gained by the Smolensk-energo power utility.

**Keywords:** Compact line, Conductor, Polymer insulator, Structure, Vibration, Damper, Interphase spacer.

### 1. Introduction

The reducing of phase-to-phase spacing and increasing the number of subconductors per phase allow to decrease the specific inductive resistance of the line and, as a result, to increase its capability [1]. For example, with the delta arrangement of conductors of 282 mm<sup>2</sup> cross-section the reducing of phase-to-phase spacing from 2.13 m to 1.22 m will result in 1.11 times of line inductive resistance [2] and in 10% increase in line capability. The R&D conducted in the USSR for compaction of the lines of 110 kV to 1200 kV have shown that the use of the compact line designs would result in considerable growth of line capability limit and in reduction of electric power losses [1,3].

The reliability of compact line designs greatly depends on the accuracy of the measurement results for various types of conductor oscillation. Therefore, it was decided to conduct comprehensive studies of conductor vibration on a 110 kV compact line, using the measuring equipment given for this objective by the SEFAG AG.

Discussed are the problems of conductor swing and galloping.

### 2. DESIGN OF THE 110 KV COMPACT LINE AND COMPONENTS

#### 2.1 Conductor characteristics and arrangement.

A 110 kV overhead transmission line of compact type was commissioned in Smolensk-energo power utility in 1986. The 5.6 km long line was erected as a commercial-and-test line.

The main difference between this double-circuit line and the conventional lines of this voltage is the significant reduction of phase-to-phase spacings of each of two circuits to 1.5 - 1.7 m, which is secured by interphase insulating spacers installed in the spans.

The USSR standards existing at the present time [4], strictly limit the minimum permissible phase spacings (Table 1, line 1). The limits established by the USA standards [5] (Table 1, line 2) are much less strict, however they are applied only to fixed conductors. The analysis of the line operation [1] has shown that phase-to-phase spacing fixed with interphase spacers could be reduced 1.5 - 1.8 times, i.e. it would be 0.7 - 1.2 m for a 110 kV line, depending on the rated p.u. overvoltages.

The ACSR 185/29 conductor (one per phase) and one earth-wire of C-50 type with protection angle 30° are used for the described 110 kV line. The designed current density is 0.85 A/mm<sup>2</sup> for the fifth year of operation.

The ACSR 185/29 conductor was tested for endurance capability in the mechanical laboratory of VNIIE. The field conditions were simulated as closely to reality as possible. The conductor was fixed in a suspension clamp with the output angle 5°. The conductor tension during the fatigue test was maintained constant: EDS = 30% and  $\sigma = 85$  N/mm<sup>2</sup>. The alternating

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Table 1

	Type of conductor attachment at the structure	National standard	Horizontal separation between conductors, m with the sags, m					
			1.8	2.6	3.5	4.6	5	8
1	Suspension insulators	USSR rules [4]	2.8	3.0	3.1	3.3	3.5	3.75
2	Rigid attachment	NESC [5]	1.1	1.2	1.3	1.4	-	-

bending stresses were applied. The tests continued up to the failure of 3 wires in the outer conductor layer.

The result of the laboratory tests is a Wöhler curve (Fig.1, curve 2). Shown in the same Figure for comparison are the safe border line, max, (curve 1), and the safe border line (curve 5) recommended by CIGRE SC 22 [6].

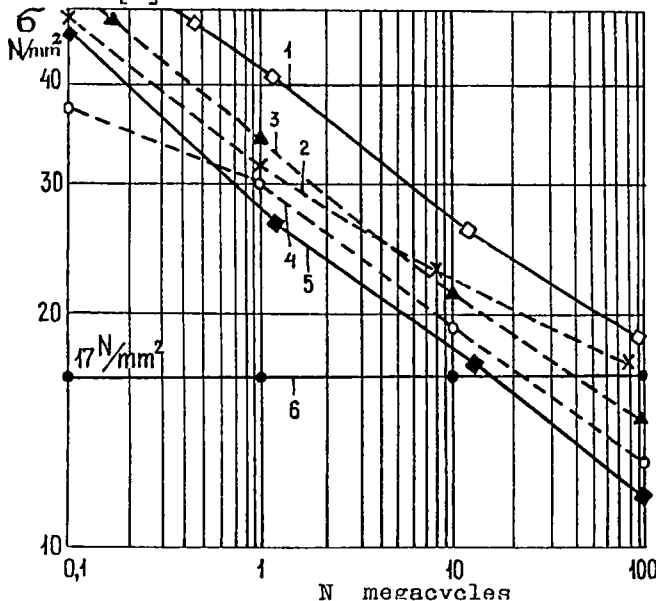


Fig. 1. Wöhler curves for ACSR conductors (1) safe borderline, max [6]; (2) ACSR 185/29, EDS=85 N/mm<sup>2</sup>; (3) ACSR 327/53, EDS=70 N/mm<sup>2</sup>; (4) ACSR 327/53, EDS=110 N/mm<sup>2</sup>; (5) safe borderline CIGRE; (6) safe borderline VNIIE.

The endurance characteristics of ACSR 185/29 conductor tested under the tensile stress  $\sigma = 85 \text{ N/mm}^2$  well agree with the results obtained under  $\sigma = 70 \text{ N/mm}^2$  and  $\sigma = 110 \text{ N/mm}^2$  [7].

## 2.2 Polymere insulators and interphase spacers.

The line insulation, including suspension and tension strings and interphase spacers, is made of polymere materials. One circuit (left) is constructed using 159 insulators of PDS 70B-110 type and 148 polymere interphase spacers of RIP-110 type (Fig.2, a) with PTFE coverings. The other circuit (right) is equipped with 179 polymere insulators of LK 70/110-3 type and 148 interphase spacers of RMI 110-K type (Fig.2, b) with silicon rubber coverings.

The tensile breaking strength of RIP-110 and RMI-110K spacers is 20 kN and 44 kN

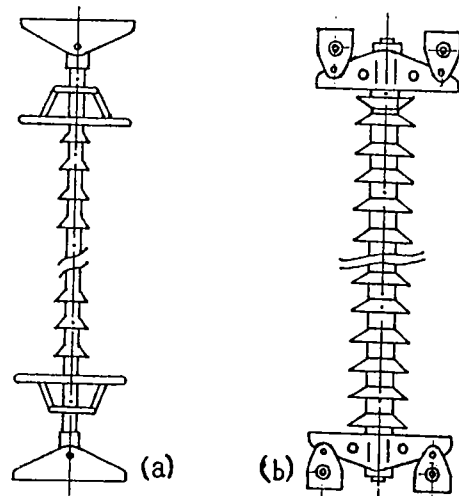


Fig. 2. Interphase insulating spacers a) RIP-110; b) RMI-110K

correspondingly. The leak-proofness of the protective covering of all spacers was tested by the application of tensile load of 20 kN under the voltage of 190 kV during 1 minute. All types of insulators and spacers, used for the compact line, were tested for the resistance to tracking and erosion under 126 kV during 182 hours without any significant damage. Critical voltages for visible corona on the spacers was not lower than 140 kV.

## 2.3 Suspension and angle structures

Specially designed double-circuit structures - PB 110-4K - with concrete poles SK-4 (Fig.3, a) are used as suspension towers. Two special crossarms at one level are used instead of 6 crossarms at three levels in conventional structure designs. Due to the increased crossarm height (5 m higher than for conventional designs) it became possible to use longer spans: 346 m instead of 278 m. Besides, the suspension height appeared to be enough to safely cross all engineering structures situated on the line route, which would be impossible with standard concrete structures. Conventional steel towers of U110-2 type are used as angle structures, with two special crossarms instead of six standard ones (Fig.3, b). This solution is not optimal, and in future for compact lines special angle and dead-end structures should be designed, aiming at significantly reduced structure mass.

## 3. CONTROL OF CONDUCTOR OSCILLATION

### 3.1 Aeolian vibration

Climatic conditions of the considered line

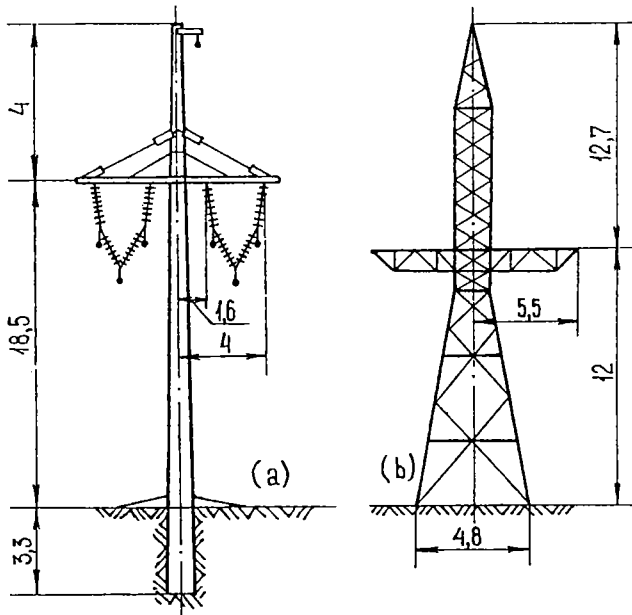


Fig. 3. Suspension concrete (a) and angle (b) structures of the compact 110 kV line, dimensions in metres

route (Smolensk area) are characterized by moderate ice and wind loads: wind velocity up to 25 m/s (wind pressure up to 400 N/m<sup>2</sup>), ice thickness on conductors up to 10 mm. Under such climatic conditions the USSR Rules [4] permit ACSR conductor operation with EDS=30%UTS. This approach differs greatly from the practice adopted in West Europe and North America, where the criteria on EDS=18-20% is applied, which corresponds to EDS=60-70 N/mm<sup>2</sup>. It is known that high level of conductor tension increases the risk of fatigue failures.

The objective of the measurements of conductor vibration on the compact line was to evaluate an influence of the mounting hardware and interphase spacers on the level of oscillation. Field measurements of vibration were performed using the measuring and processing equipment, given for this purpose by the SEFAG AG (Switzerland). Vibration recorder VR-100 and the programs for personal computer enable to read and process measurement results in laboratory, whereas microcomputer PSION ORGANISER-II and microprinter P-40 are used for readout and control of the measurement data in the field, which improves the efficiency of measuring procedure.

Three stages of measurements were performed with a total duration of 4 months. Field tests were carried out on a line section crossing an open terrain near the 330/110 kV Roslavl substation. Vibration measurements were made on both 110 kV line circuits in the spans №3 (275 m, between structures №3 and 4) and №5 (400 m, between structures №5 and 6).

Two groups of interphase insulating spacers were mounted in the span №3, dividing it into the subspans of 90, 110 and 75 m. The span №5 is divided into four subspans (110, 130, 100 and 60 m) by three groups of insulating spacers.

To obtain more accurate data on the susceptibility of the compact line conductors to

vibration, the Stockbridge dampers were removed from the phase A of the right circuit on the line section between the structures №2 and №6. The measurements made on this phase in the span №3 without vibration dampers during all field test stages were assumed as reference data.

Figure 4 shows the relationships between N, the number of cycles accumulated per year, and the alternating stresses  $\sigma$ . An undulating terrain is typical for the Roslavl area, so even without vibration dampers the level of accumulated stresses (curve 3) is much lower than the stresses which can cause fatigue damages (curves 1 and 2).

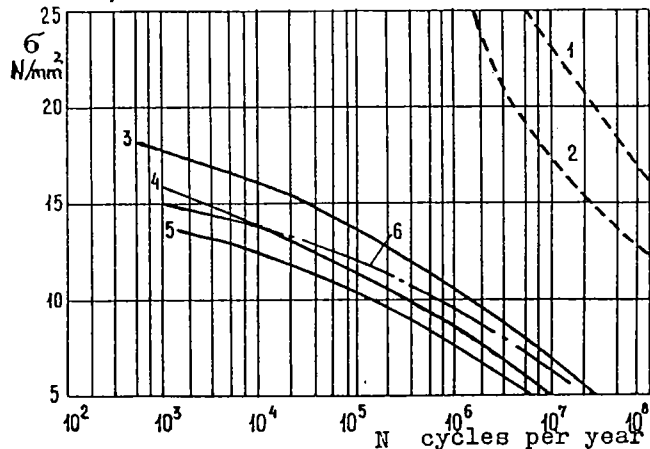


Fig. 4. Accumulated stress curves for ACSR 185/29

(1) - Wöhler curve, experiment; (2) - Wöhler curve (SEFAG method); (3) - no dampers; (4) - two dampers; (5) - double suspension; (6) interphase spacer clamp (400 m span).

The fragments of Wöhler curves shown in Fig. 4 were drawn basing on the laboratory tests of ACSR 185/29 conductor (curve 1) and using the SEFAG computer program (curve 2), the results being in good agreement.

Application of the standard Stockbridge dampers of GVN-4-22 type (two dampers per span) provides considerable reduction of the accumulated cycling stresses (Fig. 4, curve 4).

Basing on the measurement results the lower conductors of both circuits show the lowest vibration level. This can be explained by the fact, that V-suspension of the lower conductors on tangent towers is performed using separate attachment of conductor to each of two insulators. Conductor fixing in two clamps in combination with vibration dampers and interphase spacers in the span has resulted in a low level of vibration and cycling stresses (Fig. 4, curve 5).

Vibration measurements at the suspension clamp in the longest 400 m span, equipped with Stockbridges, did not reveal any significant difference in the mode and level of vibration comparing with 275 m span. The results of measurements at the clamp of interphase spacer have shown that conductor vibration between two groups of spacers in the longest 400 m span (subspan length 130 m) is notably higher than at the point of conductor suspension at the structure (Fig. 4, curves 6 and 4).

Table 2

Number of the curve in Fig.4	Span length, m	Point of circuit	VIBREC instal- lation phase	instal- clamp	Number of vibration dampers	Expected conductor life time, years
3	275 (90+110+75)	right	A	susp.	no	95
4		right	C	susp.	2	384
5		right	B	double- susp.	2	485
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-	400	left	C	susp.	2	304
6	(110+130+100+60)	left	B	interphase spacer	2	168

When constructing OH lines of similar designs in the areas with the high risk of severe vibration, application of armour rods should be considered at the points of spacer attachment.

In the course of processing of the field test measurement results the estimation of the conductor life expectancy was performed (Table 2) basing on the technique described in [6], founded on the Miner's hypothesis about the linear fatigue accumulation.

### 3.2 Conductor swing

The designer of a compact line should consider the relative conductor displacement under the action of wind gusts. Using the technique of swing amplitude evaluation, described in [2], it can be shown that under the maximum wind velocity of 25 m/s and EDS=30%, the maximum displacement  $Y$  of adjacent horizontal conductors towards each other does not exceed 0.55 m. With the span lengths above 120 m there is a trend to lower amplitudes of conductor swing (Fig.5, curve 1). Therefore, for a compact line with phase spacing of 1.5 - 1.7 m there is no risk of flashover of the air gaps between asynchronously swinging conductors.

### 3.3 Conductor galloping

Conductor galloping is one of the most serious causes of possible compact line tripouts. The most dangerous type of galloping is a one-loop mode. Estimation of this mode amplitudes based on the technique of galloping ellipses, adopted in the USSR [9], indicates that dangerous approaching of adjacent phases is possible with the span lengths above 130 m (Fig.5, curve 2). The method adopted in the USA [2] results in 2.5 - 3.5 times higher values of peak-to-peak galloping amplitude (Fig.5, curve 3), that is to prevent line tripouts the subspan length should not exceed 60 - 70 metres.

For the described compact line the design conductor spacing along the span is secured by interphase insulating spacers, installed in groups (3 spacers in each group with 1 m interval). The distance between spacer groups is from 45 to 130 m depending on the span length. This practically eliminate the risk of conductor clashing under galloping.

Among other galloping control measures which can be recommended for compact lines

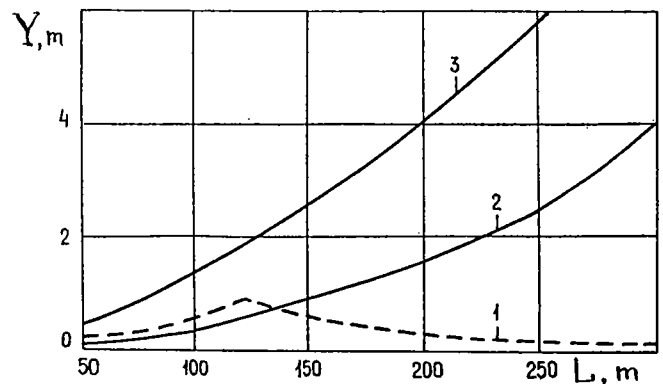


Fig.5. Low-frequency dynamic behaviour of ACSR 185/29 conductor

(1) - swing amplitude (peak-to-peak), wind speed 25 m/s; (2) - one-loop galloping amplitude (peak-to-peak) [9]; (3) - one-loop galloping amplitude (peak-to-peak) [2].

are air flow spoilers [10] and T-2 conductors.

## 4. OPERATING EXPERIENCE

Since the beginning of the line operation the damages of 12 interphase spacers of RIP - 110 type and of 5 insulators of PDS 70B - 110 type were revealed. In 8 cases the damage to spacers was of mechanical nature, which indicates their insufficient strength. In four cases the failure occurred due to spacer flashover. One of the two insulators used in tension assemblies failed due to the breakage of the fiberglass core near the end terminal, another - due to bad compression of the end terminal. Three failures of tension insulators were caused by arc flashover.

Laboratory tests have shown that coverings of the failed insulators had a bad bond with the core, and the core itself had insufficient electrical strength. The most probable cause of the spacer failures is the cracks in the core, which were not detected by the manufacturer.

There were no cases of failures of LK 70/110-3 insulators and RMI 110-K spacers during the operation.

Among the shortcomings of the compact lines is a more complicated maintenance, associated with the necessity of periodical inspection of a large number of insulating

Table 3

Parameter	Conventional design	Compact design
Height of insulators suspension on suspension structures, m	13.5	18.5
Maximum sag, m	5.5	8.6
Average span length, m	278	346
Number of suspension structures per 1 km	4	3.21
Volume of concrete (structures), m <sup>3</sup> /km	10.08	8.09
Mass of crossarm metal on suspension structures, tons/km	1.804	1.021
Mass of metal of angle and dead-end structures, tons/km	2.02	1.84
Cost of structures, roubles/km	1697	1266
Cost of insulators and interphase spacers, roubles/km	530	4500

constructions, the use of cars with the sky-lift, requiring easy access to the line which partly crosses an agricultural area.

#### 5. ECONOMIC PARAMETERS OF CONSTRUCTION AND OPERATION

Table 3 gives the comparison of technical and economic parameters for conventional and compact designs of a 110 kV line [8]. The analysis of these data indicates that the cost of structures and foundations and construction costs for a compact 110 kV line are about 25% less, than for a conventional line. At the same time the amount of insulating components for a compact line is 1.8 - 1.9 times higher, and their cost is almost 9 times more than for a conventional line.

#### 6. CONCLUSIONS

1. Experience of design, construction and operation of a compact 110 kV line in Smolenskenergo power utility confirms the feasibility of compact lines of 110 kV and above in the areas, where the reduction of right-of-ways must be combined with increasing line capability.

2. Application of polymere insulation (insulators, interphase spacers, crossarms) is the most efficient solution for compact lines.

3. Conductors of a compact line equipped with Stockbridge dampers and interphase insulating spacers are reliably protected against aeolian vibration, conductor swing and galloping. Compact line designs for the areas with higher wind velocities need more attention to the control of conductor fatigue failures at the points of spacer attachment.

4. The costs of materials and construction (excluding polymere insulators and insulating spacers) for a compact line are 20 - 30% lower than for a comparable conventional line. When designing new compact lines of 110 kV and above, it would be advisable to develop special designs of structures, phase conductors and insulating suspensions, which would result in improved technical and economic characteristics.

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#### RÉSUMÉ

On y expose des résultats des analyses des particularités constructives de la première ligne compacte de 110 kV construite en URSS à titre expérimental et industriel en les comparant à celles des lignes aériennes de conception traditionnelle. On y donne également des paramètres de certains éléments de la ligne tels que conducteurs, isolateurs, supports. On y passe en revue détaillée la vibration éolienne des conducteurs. Aussi y présente-t-on l'expérience d'exploitation de cette ligne installée dans le système régional énergétique de "Smolenskenergo".