

Condition assessment of conductors and ground wires of overhead lines using non-destructive testing based on magnetic flux measurements

V. Y. Volokhovskiy *; A.N. Vorontsov; V.V. Sukhorukov; V.V. Tsukanov
INTRON PLUS (Moscow)
V. A. Shkaptsov**
Elektrosetizolyatsiya (Moscow)
M.S. Artem'ev; V.V. Chernetsov
Lenenergo (St.Petersburg)

Abstract:

Since 2010 the diagnosis of bimetallic conductor cores and ground wires of overhead transmission lines 35-500 kV was performed using the magnetic flux detection method. For past two years the above mentioned surveys were realized at twenty three crossings of 35-110 kV over different types of water obstacles. Magnetic non-destructive testing enables the diagnosis of local faults such as wire breaks and loss of metallic area due to corrosion wear. The paper deals with magnetic testing technology for technical condition assessment of ground wires and steel cores of bimetallic conductors. Method of residual bearing capacity (strength) evaluation for inspected objects on the basis of diagnostic information is proposed. The strength safety factor is treated as an appropriate parameter that may be used to predict a residual life-time for the overhead transmission lines elements and to plan the repair work at the lines surveyed.

1.Introduction

Many overhead lines (OHL) of 35-750 kV were built in Russia in 1960-70s, hence the period of their exploitation comes to more than 40-50 years and exceeds the normative operation time. Prolongation of service life of these lines which means reliable and failure-free work is very important. One of the main activities carried out by network companies to improve the reliability and availability of OHL service and of network infrastructure is instrumental monitoring of technical state of conductors and ground wires (hereinafter "GW").

Weather exposure and operating loads have a great influence on the technical conditions of OHL conductors/GW on distances between them and intersected objects (lower voltage OHL, buildings, communication lines, etc.). These influences provoke such effects as significant residual deformations produced by wind and ice loads; local fatigue damages caused by intensive vibration or galloping of conductors; degradation of mechanical properties of conductor wires owing to long-term heating by high operating currents or short-circuit currents. Also the cross section of steel core in bimetallic conductors (ACSR type etc.) may get reduced due to frictional and/or corrosion wear.

Due to development of NDT overhead lines equipment, the network companies operation teams have begun more widely use such methods of technical diagnostics as ultrasonic or heat monitoring, magnetic flaw detection, etc. [1]. Laser scanning and air-photography of transmission lines allow to identify the sags that do not meet the requirements of regulations. Re-tensioning of conductors/GW is one of the most common and effective ways to eliminate unacceptable sags and bring them in accordance with the requirements of regulatory documents. The level of permissible mechanical loads for conductor re-tensioning is specified by its residual strength. The residual strength of conductors/GW for long operated OHL can be determined on the basis of non-destructive testing (NDT) results using appropriate tools and can be numerically estimated by mechanical model if the actual values of material properties are available.

*vvolokhovskiy@intron.ru **shkaptov@yandex.ru

KEYWORDS

bimetallic conductors, ground wires, magnetic non-destructive testing, overhead transmission lines, residual strength.



Fig. 1. Monitoring of an OHL 35 kV conductor using an air drone equipped by video recording device

Since 2010 on demand of Russian and foreign network companies inspection of more than 150 OHL conductors of 35-220 kV was executed using the magnetic flux testing method. In some cases the defects such as wire breaks and reduction of metal cross section of GW and conductor steel cores were detected. Several results of these studies are presented below. Also, the evaluated residual strength of inspected objects is provided. These results should be considered during the repair or restoration activities of examined OHLs.

2. Review of NDT technology applied on OHL

Visual monitoring of OHL conductors and GW may be used as long as the field instrumental survey. But a frictional wear, corrosion and damage of inner wires in GW or steel cores of bimetallic conductors (ACSR type, etc.) cannot be detected by visual examination. These defects reduce a cross section of GW/conductor cores which is the most important parameter determining their

residual strength. According to normative documents, there are three basic discard criteria for helical wound steel objects: critical value of metallic cross-section area loss (LMA), ultimate number of local faults (LF) – wire breaks at particular section – and the specific number of wire breaks at reference lay length.

Magnetic testing is frequently used in Russian and foreign electric grid companies for inspection of GW, OHL tower guys and bimetallic (steel-aluminum or steel-bronze) conductors [1-3]. Regardless of implemented method (varying or constant magnetic field) and the construction of magnetic flux detectors, the majority of devices has two channels for measuring two kinds of defects - loss of metallic area and local faults i.e. the wire breaks.

To get more introduction to magnetic NDT technology and to reveal such issues as principles of measurements and instrumentation, field testing practice, data processing and displaying, calibration procedure of device etc., one should apply to general paper [4].



Fig. 2. Video recording device FPV moving system



Fig.3. Picture taken by FPV device



a)



b)

Fig. 4. Inspection of conductors and GW at OHL 35 kV river crossing
a) magnetic flux detector installation;
b) sensor head being moved along the conductor by the powered truck.

As a rule, diagnostics using magnetic flux detectors is performed without descending conductor or GW on the ground, but the OHL voltage must be disabled. The magnetic detector can operate either when there is an operating or induced voltage on conductors. To make safer the installation or removing the diagnostic equipment on controlled object a disabling of OHL is needed. Before magnetic testing starts, a visual inspection of conductors/GW should be performed to show whether there are any obstacles preventing the movement of sensor magnetic head and whether there are any surface defects (outer wire breaks of GW, damaging or disassembling of conducting wire layers). This inspection can be performed by an air drone (Fig.1) or by a wheel-system moving along the lines (Fig.2) equipped with a video control and video data transmission to the monitor device, so-called, FirstPersonView (FPV) system.

Fig. 3 shows a picture of defected conductor outer layer measured by the FPV system.

Installation and removing of magnetic detector and FPV systems at suspended conductors/GW are performed using the auxiliary equipment (hoist, erection trolley etc.). If LMA and LF- charts are needed to be recorded a sensor head should be moved along the tested object (it has to be pulled using an attached nylon rope). If pulling is impossible or too complicated (for example, when monitoring the peculiar or river crossings etc.) a remote-controlled powered truck is used (Fig. 4).

3. Technical state criteria of OHL elements based on NDT data analysis

Current technical conditions of conductors and GW are classified in accordance with Federal Grid Company of United Energy System regulatory documents. The qualitative criteria for examined OHL elements at issue are presented below:

- «**Normal**» condition – LMA not more than 3.6%;
- «**Work**» condition – LMA from 3.6% to 11%;
- «**Degraded**» condition – LMA from 11% to 20%;
- «**Pre-fault**» condition – LMA more than 20%, also the wire breaks in GW or conductor cores.

The number of broken wires in particular conductor cross section should not exceed 20%.

According to these guidelines it is recommended to set the terms for the next inspection as follows: “**Normal**” and “**Work**” conditions – 6 years after the previous testing; the “**Degraded**” condition – 3 years after the previous testing. More accurate testing frequency claims for extensive information concerning the past experience on line operation, collected data of deterioration as long as discussing with line owners/operators and any other relevant sources.

4. Method of strength loss assessment of OHL elements based on the magnetic testing data

Evaluation of conductors/GW strength reduction is an important part of general problem related to specify their service condition. The magnetic testing data do not provide itself any knowledge about changing of bearing capacity of inspected objects. However, the LMA and LF diagnostic parameters may be used as input data for mechanical structural model assigned for strength analysis. So one can make the objective conclusions about the technical conditions of the inspected objects.

Traditional methods of strength calculation of the ACSR conductors as bimetallic structures are developed in details [6]. Conductor is considered as the system of independent steel core straight wires and aluminum layer wires. According to this assumption, all results are obtained in the “rod” approximation sense. The

corresponding strength requirements for conductors are formulated at the Electrical Installations Code « PUE » [5] and other documents in the Russian Federation.

To get more precise strength estimates, the GW and bimetallic conductors should be considered as stranded ropes, i.e. as mechanical systems consisting of different elastic helical elements which are deformed compatibly [7]. The GW mechanical state equations connect a tensile force T and a torque M with generalized normal strain e and torsion strain t :

$$\left. \begin{aligned} T &= C_{11}e + C_{12}t \\ M &= C_{12}e + C_{22}t \end{aligned} \right\} \quad (1)$$

where C_{11} , C_{12} и C_{22} are the effective stiffness coefficients of the GW considered as a heterogeneous structure.

Conductor steel cores and GW are mainly under axial deformation caused by the tension T . As a rule, the effects of twisting (untwisting) may be neglected. So the dominant mechanical parameter in the relations (1) is the axial stiffness C_{11} , which depends on the wires stiffnesses and the geometric parameters of the helical structure:

$$C_{11} = \sum_{j=1}^J m_j E_j A_j \cos^3 a_j \quad (2)$$

The summation in (2) is taken over layers of the wires; m_j is a number of wires in the layer j , $E_j A_j$ and a_j are the axial cross section stiffness and the lay angle of the wires of layer j respectively.

The deformation e is defined for a given tension T and is transformed to tensile $e_w^{(j)}$, bending $b^{(j)}$ and torsion $t^{(j)}$ strains of the wires of each j -layer in the coordinate systems of respective helical axes:

$$e_w^{(j)} = e \cos^2 a_j \quad b^{(j)} = -e \frac{\sin^2 a_j \cos^2 a_j}{r_j} \quad t^{(j)} = -e \frac{\sin^3 a_j \cos a_j}{r_j} \quad (3)$$

Here r_j is the lay radius of layer j .

Normal s and shear p stresses are calculated regarding the deformations (3). Combined stress state in the wire is reduced to equivalent stress, for example:

$$s_{eq} = (s^2 + 4p^2)^{1/2}$$

The loss of bearing capacity should naturally be interpreted as a reduction of its strength due to the accumulation of defects in comparison with initial (undefected) situation. The strength safety factor may be considered as a state parameter of helical object at the current operating time. When the value of safety factor becomes close to the minimum acceptable level, the appropriate measures should be taken to continue the safe operation of the OHL.

Strength assessment of GW based on the stranded rope model takes the following steps. Strength parameters are calculated for three objects: a new rope without defects, a rope with metallic loss and a rope with local defects (wire breaks). The corresponding LMA and LF-maps are generated using the diagnostic information. In each case the deformations e are defined and tensile, bending and torsion strains and stresses in the wires are evaluated. Then an equivalent stress s_{eq} in the most strained wire is determined and the stress safety factor is calculated by following expression [8]

$$n_w = \frac{s_u}{s_{eq}} \quad (4)$$

Here s_u is the ultimate tensile strength of the material of the wires.

The relative strength loss parameters R_{LMA} and R_{LF} associated with two kinds of defects may be set like that:

$$R_{LMA} = 1 - \frac{n_{LMA}}{n_0} \quad R_{LF} = 1 - \frac{n_{LF}}{n_0} \quad (5)$$

where n_{LMA} and n_{LF} are the safety factors of the rope with defects, n_0 is a safety factor of a rope without defects. Parameters R_{LMA} and R_{LF} are determined independently. The resulting strength loss R in any cross-section is estimated by superposition

$$R = R_{LMA} + R_{LF} \quad (6)$$

The actual residual strength parameter n of deteriorated GW is determined by expression

$$n = n_0 (1 - \max R) \quad (7)$$

where $\max R$ is the maximum strength loss at the inspected length.

The validation of approach to damaged ropes strength assessment based on magnetic testing data was executed on experimental and theoretical studies performed by various authors. Details see in [9].

Strength calculation for bimetallic conductors ACSR or of steel-bronze type is performed in the same way as for the GW. Stress state parameters are evaluated by the methods adopted for combined structures [10]. For long-term operated lines the conductor materials become eventually more ductile due to reological changes. On account of this effect the stiffness parameter C_{11} looks like

$$C_{11} = \sum_j m_j \frac{E_j A_j}{1 + E_j Z_j(\tau)} \cos^3 a_j \quad (8)$$

where $Z_j(\tau)$ is an empirical creep functions of time τ , different for steel core layers and aluminum/bronze layers [11].

The safety factor n of the OHL element must remain above the minimum level n_* throughout the operation lifetime, i.e. $n \geq n_*$. The Electrical Installations Code [5] sets a requirement that the tension in the conductor must not exceed the permissible value $[s]$, which depends on the type and model of the conductor and specific

operation conditions. For ACSR conductors under «average temperature» the ratio $[s]=0.3s_u$ is taken [5]. In mechanics of structures this rule should be written as $[s]=s_u/[n]$, where $[n]$ is the normative strength safety factor. Rated tensile load for the new conductor is assigned by criterion $n_0 \geq [n]=3.3$. In case of GW a normative index $[n]$ is treated as so-called «operational factor» [8].

It is proposed to use the strength factors n or R for assessment of the current operation state of deteriorated OHL helical elements. Fig. 5 demonstrates the conformity of diagnostic core parameter LMA with above mentioned criteria of the technical conditions for different ACSR conductors.

The allowable strength safety factor (margin of survivability) n_* of deteriorated conductor/GW corresponds to permissible rates of defects on the bound between “Degraded” condition and “Pre-fault” condition. For the ACSR conductors with the ratio of aluminum and steel cross sections $k_{AS}=7.7$ and with LMA of the core 20%, the conductor relative strength loss R is about 10%. Hence n_* can be taken as $n_* = [n](1-R)=3.3(1-0.10)=2.97$ or, with some risk, even 2.5.

As an example, the results of residual strength

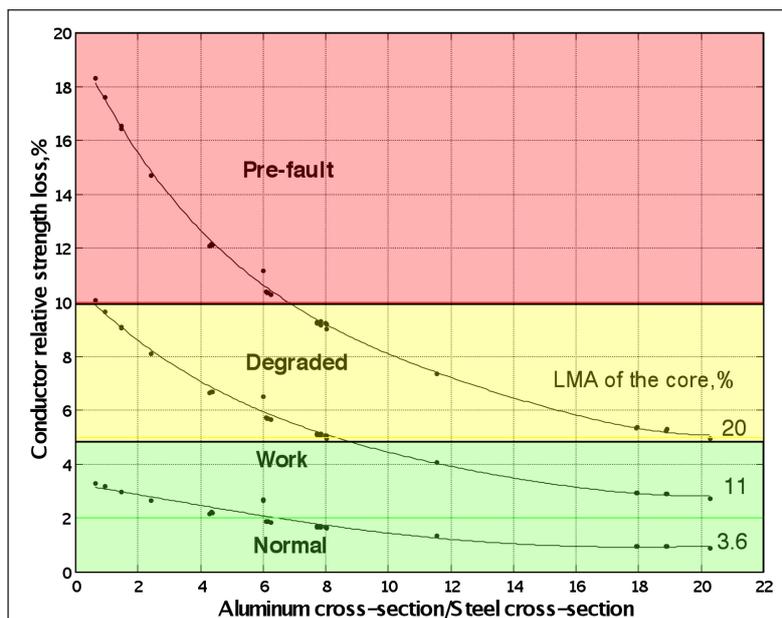


Fig. 5. Areas of steel-aluminum conductors operating states

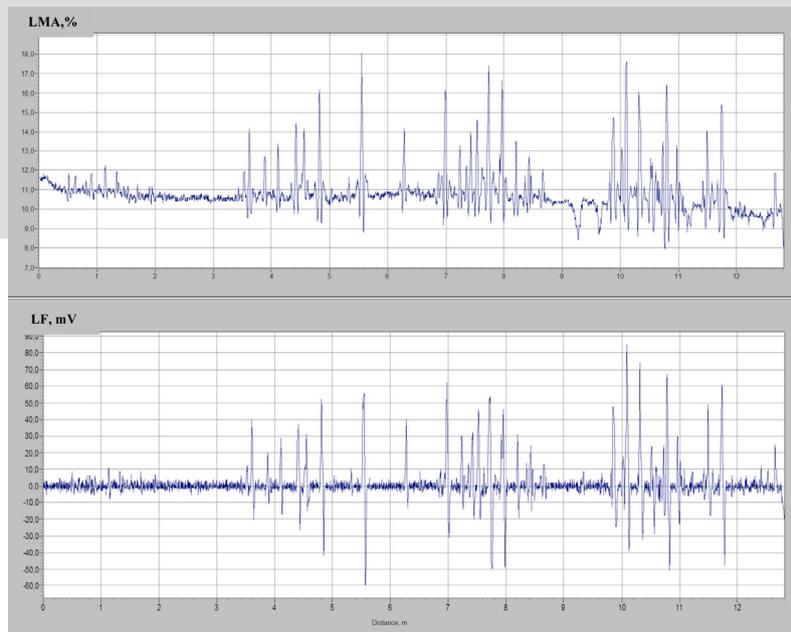


Fig. 6. LMA and LF-charts of the steel-bronze conductor BS185/43

assessment of the steel-bronze conductor BS185/43 will be presented here. This conductor is suspended on a 35 kV overhead line “Ladozhskaya-3” and was inspected on 25.12.2013. The LMA and LF- charts registered at the core are shown in Fig. 6.

Fig.7 presents the corresponding distribution of the strength factor calculated by the varying strength loss R along the conductor inspected length. The nominal tension is assumed to be 30 kN. Red circle marks the minimum value 3.57 at 10.1 meters that may be considered as an actual strength safety factor n of the conductor at inspected region. The dips at the graph correspond to local accumulation of wire breaks in a steel core. It should be noted that mechanical model takes into account an ability of broken wires to undertake the tension due to friction when moving away from break location. Distributed strength loss regarding to initial value $n_0=4.23$ is influenced mainly by corrosion damage and abrasive wear.

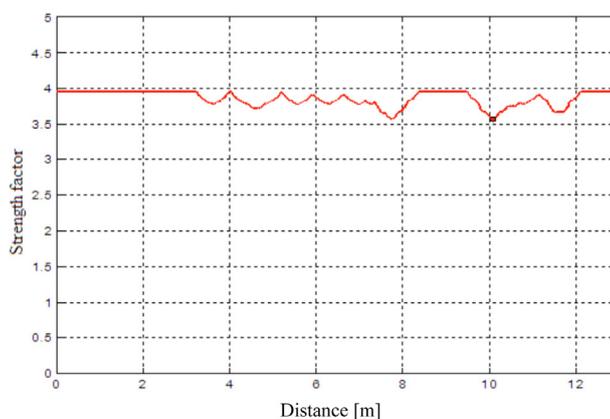


Fig. 7. Distribution of the strength factor along the inspected length of BS 185/43 conductor

Let now observe some problems and common features of residual strength estimation of the conductors and GW with defects:

- Theoretical estimation of bearing capacity should be carried out taking into account the changes of the strength characteristics of the structural materials during the long-term operation. Unfortunately, there is no reliable and systematic data concerning long-term strength of bimetallic conductors. The relevancy and reasonability of such research is of no doubt.
- Strength loss of bimetallic conductors is less than the core LMA value, because the load is partly undertaken by the conductive layers (aluminum or bronze).
- Refined rope model gives the nonuniform distribution of stresses in wires over cross-section due to their stretching, bending and twisting. This method ensures the greater strength loss than the ultimate-load approach based on rough rod approximation. For the same reason, the GW percentage strength loss is higher than the corresponding reduction of loaded metal cross-section.
- The strength safety factor decreases greatly especially for conductors with composite cores. The more complicated is a core, the more the strength of a new conductor differs from the strength of same conductor with defects (under comparable tensions).

5. Practice of technical state monitoring of OHL elements using the magnetic testing

Since 2011 the specialists of NDT-laboratory of INTRON PLUS company took part in inspection of 35-220 kV OHLs at the JSC “Lenenergo” and JSC IDGC «Center and Volga Region» Holding (Interregional distribution grid company). During this work magnetic testing of conductors and GW was carried out at transmission lines with long-time operation. Special attention was paid to the OHL river-crossings (the Neva, the Vuoksa,

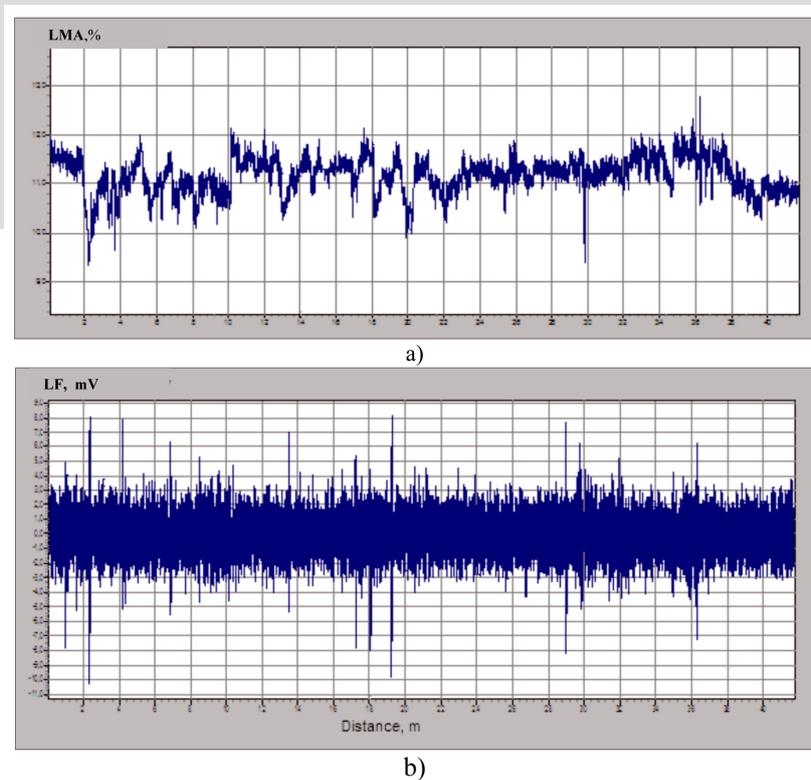


Fig. 8. LMA(a) and LF(b) charts of the lower-right phase conductor core at the span between supports N32 of OHL “Severnaya-10”

the Volga and the Oka rivers). Phase conductors were examined at 33 OHLs of 35-220 kV at 99 spans, GW – at 15 spans.

In a number of cases, the significant operational defects of the GW and cores of current-carrying conductors were detected. For example, at the 110 kV overhead line “Severnaya-10” at a crossing over the Vuoksa river a significant corrosion was detected along entire length of the GW ST 50, but no broken wires were registered. The maximum value of LMA was equal 14.6 %, and the relative strength loss $R=15.33\%$. The technical condition of the GW was qualified as “Degraded”, but it was suitable for further use. A significant corrosion wear of the cores was also found for the phase conductors ACSR120/19 along entire inspected length of this OHL. No broken wires at the cores were detected. The technical conditions of the conductors were declared as “Degraded”, but they were also suitable for further use. It was recommended to perform the next monitoring of

this overhead line in 2016. As an example, in Fig.8 the LMA and LF-charts of the lower-right phase conductor core are given. The maximum LMA value is 12.8% at a distance of 36.2 meters, and corresponding conductor relative strength loss is 6.41%.

Results of inspection of the conductors at overhead lines 35 kV «Ladozhskaya-3/4» which was carried out in December 2013 were more alarming. Steel-bronze conductors BS-185 (conductor diameter 19.6 mm, steel core diameter 8.4 mm) were installed at the crossings of these OHLs over the river Neva. Their operating time was more than 45 years. A significant LMA-value caused by cores’ corrosion, as well as the numerous broken cores’ wires were detected along entire inspected length. The technical conditions were qualified as «Pre-fault». The results of conductors testing (at the span between supports N42-43) and the calculated values of relative strength loss are presented in Table I.

N	OHL Name	Inspected object (phase conductor)	Maximum LMA of conductor core, %	Relative loss of conductor strength, %
1	OHL 35 kV «Ladozhskaya -3»	Lower	19.7	17.6
		Middle	18.1	16.1
		Upper	20.3	21.2
2	OHL 35 kV «Ladozhskaya -4»	Lower	28.4	24.4
		Middle	35.9	27.5
		Upper	36.3	27.7

Table1: Results of conductor testing of the OHL 35 kV «Ladozhskaya-3/4» span 42-43

Next inspection of the OHL «Ladozhskaya-3/4» conductors at the Neva river crossing has been planned by 2016 to clarify whether these conductors can stay further operation and to confirm the preliminary conclusions.

In September 2014 the specialists of «INTRON PLUS» NDT-laboratory took part in the pre-overhaul inspection of the Volga river crossing at the 110 kV OHL «Vichuga-Zavolzhsck» with GW of S-300 type with diameter 21.0 mm (Fig.9). Crossing scheme was the following: Dead-end – Suspension – Suspension - Dead-end. Results of this testing are presented in Table II.



Fig.9. Inspection of the OHL 110 kV «Vichuga - Zavolzhsck» conductors

The sampling percentage technical state diagrams of conductors and GW at overhead lines 35-110 kV obtained at JSC «Lenenergo» and JSC IDGC Holding «Center and Volga Region» in 2013-2015 by magnetic diagnostic method are shown in Fig.10.

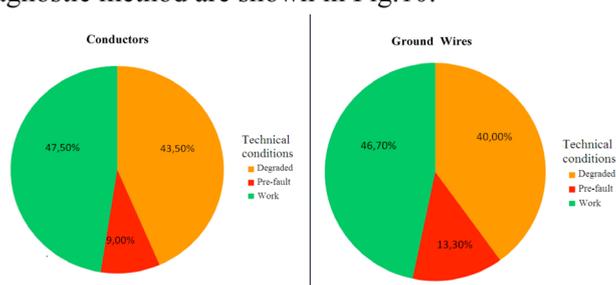


Fig. 10. Summary of testing results for OHLs 35-110 kV conductors and ground wires examined at JSC «Lenenergo» and JSC IDGC Holding «Center and Volga Region» in 2013-2015

In some cases, the magnetic testing results concerning the technical conditions of conductors/GW indicate a pre-alarm status of inspected objects. In other cases these results allow to prolong the period of safe operation thus saving significant financial costs for repair and replacement.

6. Conclusions

1.Magnetic flux detection is an effective method of non-destructive testing and diagnostics of technical

OHL Name	Inspected object (phase conductor/GW)	Maximum LMA of conductor core/GW,%	Relative strength loss of conductor/GW, %	Condition of conductor/ GW
OHL 110 kV «Vichuga - Zavolzhsck», span N116-117	Left phase	14.9	15.1	Degraded
	Middle phase	13.4	13.7	Degraded
	Right phase	16.2	16.3	Degraded
	Left GW	15.8	16.0	Degraded
	Right GW	12.8	13.1	Degraded
OHL 110 kV «Vichuga - Zavolzhsck», span N117-118	Left phase	13.6	13.9	Degraded
	Middle phase	14.7	14.9	Degraded
	Right phase	15.4	15.6	Degraded
	Left GW	14.9	17.7	Degraded
	Right GW	13.8	14.1	Degraded
OHL 110 kV «Vichuga - Zavolzhsck», span N118-119	Left phase	14.4	14.6	Degraded
	Middle phase	14.4	14.6	Degraded
	Right phase	14.7	14.9	Degraded
	Left GW	15.6	15.8	Degraded
	Right GW	14.5	14.7	Degraded

Table II : Results of conductors/GW testing at the OHL 110 kV «Vichuga - Zavolzhsck» Volga river crossing

conditions of bimetallic (steel-aluminum and steel-bronze) bare conductors and steel GW. It is more and more widely applied for inspection of overhead lines with 35-500 kV to estimate the technical conditions of line equipment.

2. The necessity of magnetic testing application for inspection the OHL equipment technical conditions should be reflected in normative documents, regulating the procedure and priority of control-diagnostic works at the lines.

3. The service-state parameter – residual strength safety factor evaluated on the basis of NDT data, gives an habitual engineering sense to diagnostic information. An empirical strength tendency can stimulate an additional motive for operating personnel to make a relevant decision which can reduce the multimillion-dollar costs for repair work or replacement of tested OHL conductors and GW.

4. Periodic inspection using magnetic flux technology makes it possible to estimate how fast the conductors and GW are wearing out as well as to develop on this basis a method for quantitative evaluation of their residual operation life.

7. References

[1] V.Volokhovskiy, A.Vorontsov, D.Sukhorukov, B.Mekhanoshin, V.Shkaptsov. «Assessment of OHL Availability and Residual

Life-Time by Using Non Destructive Instrumental Control for Conductors, Steel Wires and Guys». (CIGRE Session 2010, B2-309). Available: <http://www.cigre.org/gb/Events/session.asp>.

- [2] V.V.Sukhorukov, "Steel wire ropes NDT: new instruments", in Proc. 2001 Non-Destructive Testing in Engineering Conf., pp. 229-235.
- [3] V.S.Kotelnikov, V.V.Sukhorukov, A.A.Korotkii, Methodology guidelines for magnetic flaw detection of steel ropes. The fundamental principles. RD-03-348-00. M.: Russian State Technical Authority, 2000, p.18.
- [4] V.Sukhorukov, D.Slesarev, A.Vorontsov. Electromagnetic inspection and diagnostics of steel ropes: technology, effectiveness and problems. Materials Evaluation (ME), American Society of Nondestructive Testing. Vol. 72, N8, August 2014, pp.1019-1027.
- [5] Electrical Installations Code « PUE ». 7-th ed., St.Petersburg: Publishing house DEAN, 2008, p.704.
- [6] L.M. Kesselman, Fundamentals of Mechanics of Overhead Transmission Lines. M.: Energoatomizdat, 1992, p.354.
- [7] G.A.Costello, Theory of Wire Rope. Second ed., New York: Springer-Verlag, 1997, p.123.
- [8] K.Feyrer, Wire Ropes: Tension, Endurance, Reliability. Berlin, Germany: Springer-Verlag, 2007, p.326.
- [9] A.N.Vorontsov, V.Yu. Volokhovskiy. Mechanical Model for Strength and Life-Time Assessment of Tested Hoisting Ropes. Handbook. An Engineering Journal, LLC "Publishing house "SPECTR", N10(187),2012, pp.37-47.
- [10] L.P.Kollar, G.S.Springer. Mechanics of Composite Structures. Cambridge University Press, 2003, p.480.
- [11] V.Volokovskiy, Y.Chaiun. Strength analysis of ropes – OHL conductors subjected to creep. Steel Ropes, Kiev, Tekhnika Publ. Pt.8, 1971, pp.27-30.