

# Strength assessment of deteriorated OHL conductors and earth wires based on non-destructive testing

Vasily Volokhovskiy, Vasily Sukhorukov, Victor Tzukanov

Intron Plus Ltd, Research Department, 11, b.1, Electrodnaya St., Moscow, 111524, Russia

[info@intron.ru](mailto:info@intron.ru)

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**Abstract.** Safety operation of overhead lines depends on many factors including strength of conductors and earth wires. Therefore worn-out or defective conductors or earth wires must be detected. Estimation of conductor technical conditions is based on comparison of revealed flaws with requirements of overhead line project and build documentation. It is well known that conductors are affected by corrosion, friction and fatigue wear. All this factors may cause loss of strength and even breakage of conductor. Steel core is the most important part of conductor when it comes to mechanical loads. That is why it is very important to know actual technical conditions of steel core of conductor. Worn or defective wires must be repaired or replaced. Principles of strength assessment of deteriorated of steel-aluminum conductors and steel earth wires based on magnetic non-destructive testing technique are presented. The retention of overhead line conductor and earth wire is one of the most reasonable ways to eliminate the unacceptable clearances. The allowable magnifying tension, regarding the reliable operation, is set relying upon the non-destructive testing of conductors or earth wires in actual state. The measured loss of metallic cross-section area due to abrasion, corrosion etc. and local wire breaks are treated as input data for mechanical model of objects under test. The residual strength estimates give the specialists network company further information that helps to make a valid decision on testing time-limit and policy. Some results of assessing the strength of overhead line conductors and earth wires according to the NDT data are demonstrated.

## Introduction

Instrumental monitoring of conductors and earth wires is a significant part of common surveying and maintenances aimed to improve the overhead lines (OHL) reliability and operational availability. Meteorological impacts and operational overloading have a great influence both on the technical state of conductors or earth wires and on their clearances to the ground and to the crossing objects (OHL of lowest voltage types, constructions and communications). This influence proves itself in such phenomena as creep stretching, growth of plastic strains due to excessive wind and ice loading; degradation of steel-aluminum conductors under the prolonged heating by high load currents or by short-circuits in emergency; loss of metallic cross-section area due to abrasion, corrosion etc.

Regarding existing statistics substantial part of technological disturbances in Russian network companies which operate 35 - 750 kV OHL is induced by the damages of conductors and earth wires. For a significant part (up to 65% of total) of existing overhead power lines 35, 110, 150 and 220 kV, i.e. high voltage (HV) by keep in view of their physical, moral aging and does not meet in full the requirements of existing rules and regulations [1] of a technical condition, a serious problem is the need to reduce OHL transmitting capacity. As a consequence, there is a real need to limit the current loads, reducing flows of energy and power that can safely be carried out in normal and post-

emergency operating conditions of networks. In organizational terms, this leads to the fact that those previously agreed between the network companies and the regional dispatch offices (RDO) mode parameters of overhead lines, in particular, the maximum allowable current loads require a revision and bring it into line with the current technical condition of the existing HV lines.

Engineering solutions aimed at restoring and enhancing the capacity of existing overhead lines, the extension service, reliability and operational availability of HV electrical networks are based on survey data from various types of technical condition of elements of the overhead line, including data on non-destructive testing of conductors and earth wires.

The Russian Federation network companies use the domestic device INTROS [2] for NDT technologies in combination with theoretical assessment of residual strength (bearing capacity) of tested steel-aluminum conductors (ACSR) and earth wires.

### **Magnetic non-destructive testing of earth wires and ACSR conductors**

Magnetic flaw detection is one of the successful NDT methods for diagnostics of conductors and earth wire of overhead lines, enabling to control extent degradation of the technical condition of inspected objects. There are two major parameters for estimation technical conditions of steel ropes (earth wire and steel core of conductor) - Loss of Metallic Area (LMA) and Local Faults (LF). LMA is relative amount of steel missing from a rope or core of conductor. LMA is usually caused by wear due to friction and corrosion. That is distributed along the length a rope or core of conductor fault defined in percents of the nominal value of metallic cross section area. LMA is quantitative value measured in %. Local Faults (LF) is discontinuity in core such as broken wires and pitting corrosion. LF is usually caused by metal fatigue and mechanical stress. The rules establish conductor discarded criteria based on the broken wire number limits (i.e. when quantity of broken wires in a core reaches discarded criteria the conductor must be repaired or replaced).

Instrumental NDT methods use the magnetic flux leakage (MFL) principle of operation when the conductor core or conductor itself under test made of ferrous steel. The principle bases on rope section magnetization up to magnetic saturation by permanent magnets producing a magnetic flux along the section. Any anomaly of the rope under test causes a change of the magnetic flux as like as change of the leakage flux around the rope. The changes are measured by magneto-sensitive sensors (e.g. Hall sensors) and/or by inductive coils. Principle of the MFL is shown on Fig. 1.

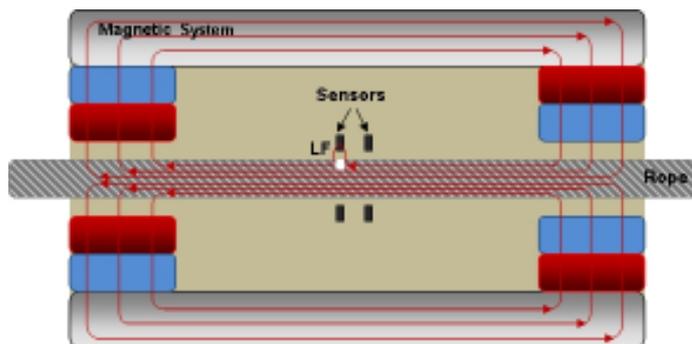


Fig. 1, MFL principle of operation.

Flaw detector INTROS was designed to check a steel rope but it can be used also for the inspection of ACSR conductor core. It consists of the portable Basic electronic Unit (BU) and the set of Magnetic Heads (MH) for various types of ropes/conductors (objects under test) and for the range of diameters. Basic unit (Fig. 4) collects and processes signals from magnetic head and store inspection data in its built memory. Basic unit connects to personal computer and unit allows downloading of inspection data to PC for further analysis and interpretation.

INTROS has wide range of magnetic heads for inspection of objects under test within 6...150 mm diameter range. The instrument simultaneously measures LMA value and detects LF as well as

many other parameters. INTROS inspects steel core when MH moves along a conductor or conductor moves through MH. The magnetic head MH20-40 is dedicated for inspection of conductors/rope with outer diameter from 20 mm to 40 mm (Fig. 5).



Fig. 2, Basic Unit.



Fig. 3, Magnetic Head MH20-40.

WINTROS is specially created software for application with all INTROS instruments for downloading measured data from internal memory to a computer and further evaluation of inspection data. WINTROS software window is shown on Fig. 4.

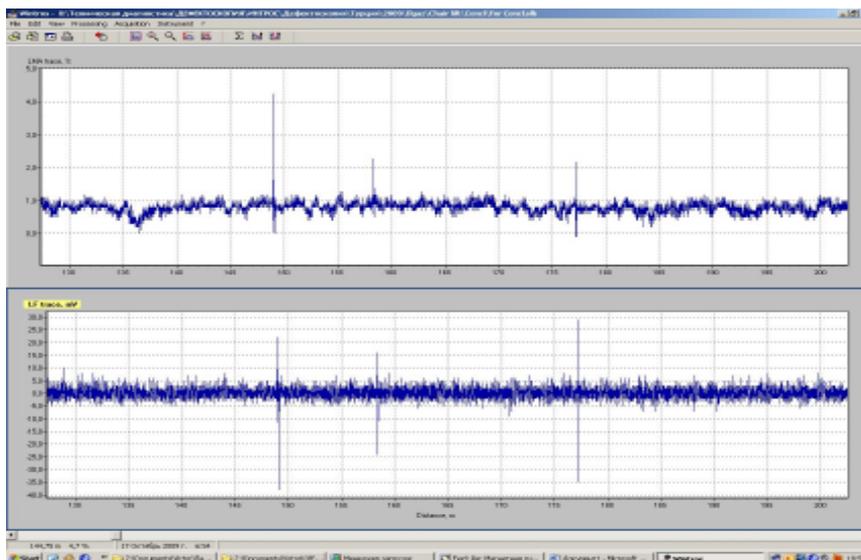


Fig. 4, Wintros software window with LMA (on top) and LF (underneath).

MH of INTROS must be calibrated properly before it will start to take readings. The sample of new brand object under test (conductor or earth wire) of the same type is required for calibration. After INTROS calibration and installation on the conductor for steel core inspection, it is necessary to make at least two records of core conditions by moving the instrument in recording mode along whole inspected length of the conductor. All inspection data shall be downloaded from BU to PC for analysis and determination of conductor steel core or earth wire technical conditions. After interpretation of the inspections results expert makes his conclusion of core conditions. Expert compares determined defects with discarding criteria for type conductors or earth wires under test.

When INTROS is installed on a rope or conductor, the object under test is located inside MH and the instrument can be moved in both directions. There are several possible ways of moving INTROS along the inspecting object. First and the simplest one is drawing of the instrument using ropes attached to MH using manpower. If MH of INTROS movement along the conductors or ropes by using manpower is not possible, self-propelled unit (the electric motorized, battery powered and remote controlled device, what can move independently along the conductor) can be used.

## Strength assessment of deteriorated OHL conductors and earth wires based on NDT data

The method for assessing the strength and life-time of steel ropes, which are used also as overhead earth wire, and the results of its practical application were published in papers [3-5]. This report focuses on the problem of assessing the strength of OHL ACSR conductors according to the NDT data.

The strength loss of deteriorated conductor is being estimated on information related to recorded (or visually noted) defects in steel core and/or aluminum lay. Distributed LMA and LF (wire breaks) are served as input parameters for the appropriate mechanical model of ACSR conductor. Strength assessment is performed on base of structural mechanics concepts [6]. Herein below are main notions used in strength calculation technique:

- The relative strength loss  $\chi$  is treated as changing of the safety factor of tested conductor in service against the initial healthy condition.
- The safety factor  $n$  is a ratio of the ultimate tensile strength of conductor and the maximum stress along its distance under real tension.
- Ultimate and real stresses are estimated by averaging the corresponding values in steel core wires and in aluminum lay wires regarding their volume fractions as it is ruled in two components structures mechanics.
- Stresses in wires are evaluated by mechanical model of wire ropes. The model accounts for helical arrangement of conductor components and strength deterioration due to defects in core and/or aluminum lay.

In the following expressions the upper indices (1), (2) note related correspondingly parameters of steel core and aluminum lay. The actual safety factor of new (healthy) conductor is defined as that:

$$n = \frac{\sigma_{ult}}{\max \sigma} \quad (1)$$

Here  $\sigma_{ult}$  is a certified tensile strength of conductor and  $\max \sigma$  is a maximum actual stress in conductor over its distance.

Tensile strength  $\sigma_{ult}$  is estimated as a ratio of conductor breaking load  $P_{ult}$  and its metallic sectional area  $A$ :

$$\sigma_{ult} = \frac{P_{ult}}{A} = \frac{\sigma^{(1)}(\varepsilon = 0.01)A^{(1)} + \sigma_{ult}^{(2)}A^{(2)}}{A^{(1)} + A^{(2)}} \quad (2)$$

Here  $\sigma^{(1)}(\varepsilon = 0.01)$  are stresses in steel wires at extension  $\varepsilon = 0.01$  (i.e. 1%) that corresponds to event when stresses in aluminum wires  $\sigma^{(2)}$  reach the tensile strength  $\sigma_{ult}^{(2)}$ .

Expression (2) demonstrates so called “mixture” rule used for estimation the averaged parameters of *composite structures*. The value of  $\sigma_{ult}$  is treated as an effective strength characteristic of complete conductor usually presented in its technical data sheet.

The actual averaged stresses in every section of tensed conductor are evaluated by a formula similar to (2):

$$\sigma = \frac{\sum_j \sigma_j^{(1)}A_j^{(1)} + \sum_j \sigma_j^{(2)}A_j^{(2)}}{A^{(1)} + A^{(2)}} \quad (3)$$

Here  $\sigma_j^{(1)}, \sigma_j^{(2)}$  are the uniaxial equivalent stresses in each  $j$ -th wire of steel and aluminum components. They are calculated by proper strength criterion using the mechanical model of conductor helical structure. Background of the model is well known theory Glushko-Malinovsky [7,8] developed for various kinds of wire ropes and loading conditions. Briefly, the constitutive equations of rope arrangement are derived from Kirchhoff thin bar relationships. They take into

account the geometric and stiffness parameters of rope components and make possible to estimate the combined stress state in each wire. Details of application of this theory for degraded ropes are described in papers [4,5].

The actual safety factor  $\tilde{n}$  of deteriorated conductor is estimated in the same way by relations (1) - (3) with reduced bearing sectional areas and changed ultimate stress  $\sigma_{ult}$ . We set two parameters to define the technical state of tested conductor: the relative residual strength  $\eta$  and corresponding relative strength loss  $\chi$ :

$$\eta = \frac{\tilde{n}}{n}, \quad \chi = 1 - \eta. \tag{4}$$

Note that strength loss  $\chi$  of complete conductor is always less than LMA detected in steel core because the aluminum lay still keeps on bearing some portion of tensile load.

### The results of assessing the strength of conductors and earth wires according to the inspection

According to Russian regulations “Standard operating instructions of 35-800 kV overhead transmission lines”, discarded criteria for conductor and earth wire are the following:

- LMA value greater than 20% are not allowed;
- a broken wire of steel core are not allowed.

Below are the criteria for assessing the technical condition of steel core ASRC conductor and earth wire on the base of NDT date:

- normal state - LMA no more than 3,6%;
- in-service state - LMA from 3,6% to 11%;
- deterioration state - LMA from 11% to 20%;
- pre-crash - LMA more than 20% and the presence of a wires breaks in the core.

In 2011-2012 by specialists of company “INTRON PLUS Ltd” in various regions of the Russian Federation have been inspected more than hundred OHL 35-220 kV, which service life is 30-40 years and more. The results of the diagnosis of inspected objects (ASCR conductors and earth wires) are presented on fig. 5.

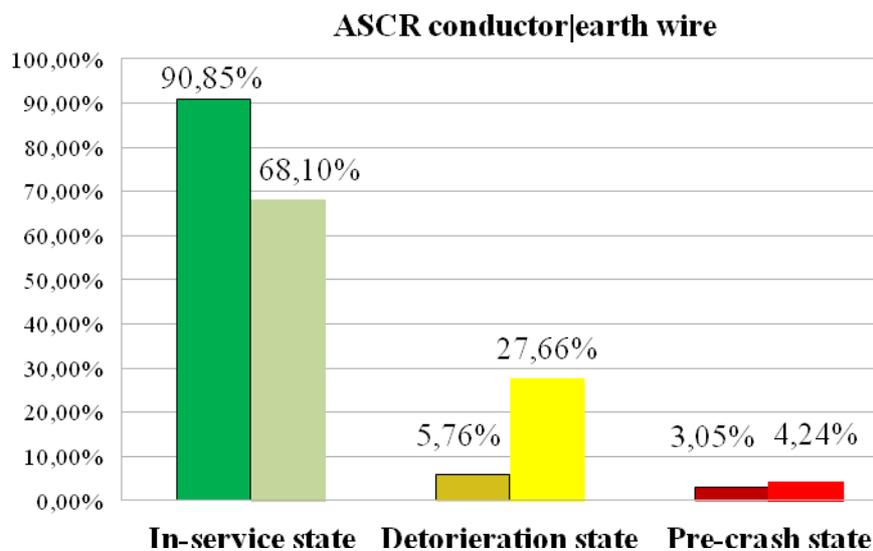


Fig. 5, The results of the diagnosis of inspected objects.

Network companies that exploit these overhead transmission lines took into account the results in planning of the maintenance and restoration works.

The non-destructive testing of conductor steel core of Hidroelectrica de Cahora Bassa overhead transmission line West was performed on September 2011. Type of inspected conductors is ACSR/GA ZAMBEZE 42/7 (nominal diameter – 31,8 mm; number of steel core wires - 7; diameter of steel wires - 2,32 mm). The conductors were inspected in eight spans between towers that were selected after aerial laser survey of this overhead line.



Fig. 6, Hidroelectrica de Cahora Bassa overhead transmission line West (Mozambique).

No critical damages as well as no defects reaching discarding criteria for steel core of conductors according to Russian regulations “Standard operating instructions of 35-800 kV overhead transmission lines” were found. The conductors are suitable for further exploitation. Brief information about testing results of conductor steel cores technical condition is given in table 1.

#### Results non-destructive testing of OHL Hidroelectrica de Cahora Bassa West

Table 1.

Conductor in span between towers #	Tension, kN	Max LMA of conductor steel core, %	Safety factor of conductor	Relative strength loss of conductor, %	Condition
729 - 728	22,85	5,1	5,155	1,30	In-service state
729 - 730	22,85	5,3	5,150	1,36	In-service state
1090 - 1089	23,23	5,4	5,066	1,38	In-service state
1090 - 1091	23,48	5,6	5,010	1,43	In-service state
1173 - 1172	23,74	4,6	4,968	1,17	In-service state
1173 - 1174	24,01	4,4	4,915	1,12	In-service state
1301 - 1300	29,96	3,6	3,947	0,92	In-service state
1301 - 1302	30,09	4,0	3,926	1,02	In-service state

The customer has incorporated the results of the implementation of activities aimed at ensuring the availability line.

Phase A conductor steel core between towers № 72 and № 71 of Sauda – Blåfalli 300 kV overhead transmission line Åkrafjord crossing (Norway, see fig. 7) was inspected on October 2011. Type of inspected conductor is 766-ALL/97-ST5E PARROT SP. Non-destructive inspection was performed by using INTROS with MH20-40. Starting point of inspection was located near tower №72. The cable car used for traveling of INTROS along the conductor. The INTROS recorded

inspection data while cable car was moving along phase conductor. All the obstacles such as aircraft warning markers were removed from inspected segment of conductor. Length of the inspected part is 822m.



Fig. 7, Sauda – Blåfalli 300 kV overhead transmission line Åkrafjord crossing

Maximum LMA value for Phase A conductor steel core is 5.2%. That is almost four times lower than 20% LMA stated as the discarded criteria limit. No broken wires were found in steel core of the inspected segment of conductor.

The detected LMA in steel core was accepted for estimation the residual strength of conductor. We did not know the actual tension so the tensile load was set as 0.3 of certified breaking load. The results are shown at two diagrams (see fig. 8-9). The first one (fig. 8) demonstrates the distribution of safety parameter  $\tilde{n}$  along the tested conductor distance. The minimal value 2.79 (marked by circle) may be treated as an actual safety factor of this conductor (see fig. 8). Figure 9 shows changing of absolute safety factor  $\tilde{n}$  and corresponding relative residual strength parameter  $\eta$  (in percents) during conventional service period (from setup to test date). The new healthy conductor has the safety factor  $n = 2,86$ . The relative strength loss  $\chi$  to test date is around of 2.4% .

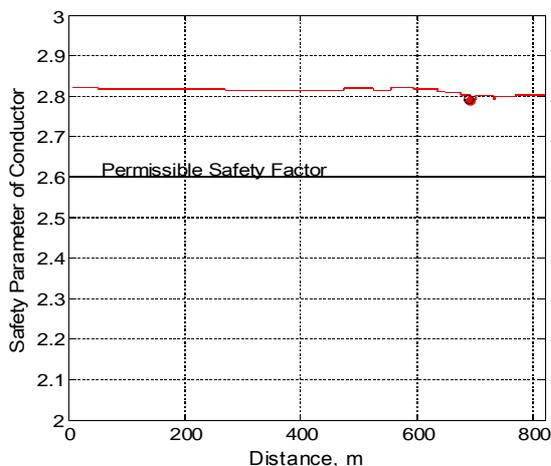


Fig. 8, Distribution of safety parameter along the length of conductor.

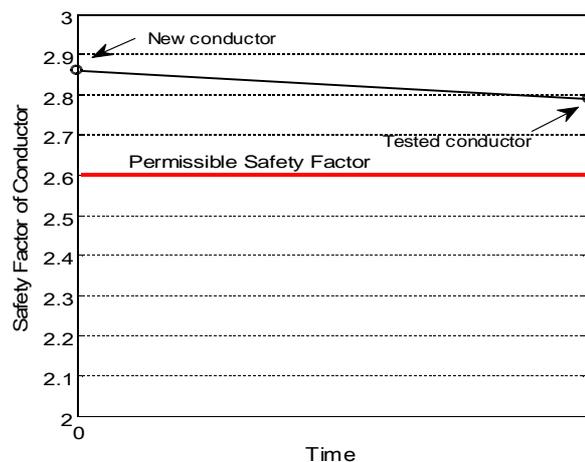


Fig. 9, Changing of conductor safety factor with operating period,

Normative rules usually order an allowable degradation level to a core of conductor. According to Russian rules and regulations this parameter for different cores is equal up to 20% LMA or to

comparable number of broken wires. For Akraffjorden conductor 766-AL1/97ST5E PARROT SP the corresponding allowable strength loss is near 9%. Permissible conductor safety factor of 2.6 relates just to this value in Fig.8 and Fig.9. Regarding the European standards this parameter may have another but nearby quantity. If conductor is being tested periodically the strength degradation history makes possible to suggest the time of next testing and to predict the residual life-time of conductor under investigation. The examples are presented in paper [5].

The results of phase A conductor diagnostic of Sauda – Blåfalli 300 kV overhead transmission line Åkraffjord crossing (Norway) are the following:

- Phase A conductors steel core is in normal technical conditions and suitable for further service.
- It is suggested to repeat non-destructive inspection of phase A conductor steel core after 5 years. Second inspection is desirable to understand development of steel core degradation also it is desirable to inspect full length of conductor steel core.

## Conclusion

1. Strength assessment model with input magnetic NDT data makes possible to estimate accurately the strength state of deteriorated ropes. It may be used for wide range of conductors and earth wires constructions and service conditions.

2. The proposed approach increases the reliability of rope inspection because the successive test dates are dependent upon the condition of the ACSR conductors and earth wires.

3. The NDT-mechanical-discard approach is adapted for object under test subjected to specific working conditions. In practical use the residual strength estimates give the specialists network company further information that helps to make a valid decision on testing and maintenance policy.

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