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Some considerations on the mechanical testing of aluminum-steel conductors and their cores

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1. Introduction

Mechanical testing of aluminum-steel conductors and their cores is essential in preventing excessive plastic straining or even early failure of high-voltage overhead power lines.

One of the basic experimental procedures consists of tensile testing the conductors and their cores to failure. A particular aspect of such tests is the fact that they are carried out on high length specimens, having in some cases over 10 m in length. Thus, the tensile testing machines for conductors are horizontal and differ significantly from the universal tensile testing machines.

Some of the conditions this type of machines have to meet are: distance between test-piece holders greater than 5 m, possibility of using special test-piece holders for mounting flexible pieces, possibility of operating as a creep testing machine, ensuring the horizontality of the conductor during testing, etc.

The tensile testing to failure of aluminum-steel conductors consists of several phases (loading-unloading cycles) and its aim is to plot the stress-strain ($\sigma - \varepsilon$) curve [1] to [5].

The conventional stress σ is given by the ratio of the applied load P and the total cross-sectional area S_t of the conductor: $\sigma = P / S_t$.

The strain ε is defined as ratio of the total elongation of the gauge length ΔL and its original dimension L_0, $\varepsilon = \Delta L / L_0$.

In contrast with usual tensile tests, strain ε is computed from elongations ΔL measured after certain periods of time, which can be either 30 or 60 min [1] to [5]. It can be deduced that the plotted stress-strain curve also includes the effect of creep at different loadings over short periods of time [6] to [7].

The authors point out the fact that in case of certain conductors, the stress-strain curves plotted based on strains measured after the time periods specified in the standards and the curves plotted based on strains measured at the beginning of each hold period respectively, differ significantly. This remark should be taken into account in standards regulating conductors' tensile testing, given that initial strains can be measured at different test phases.

The paper also contains some remarks regarding the testing of high rigidity conductor cores, where applying current standards limits testing conditions to the elastic region only.

In order to compare different conductors by their rigidity, the elastic compliance c is utilized, computed from the following equation:

$$\varepsilon = cP \,, \tag{1}$$

where

$$c = \frac{1}{ES_t} \,. \tag{2}$$

Elastic compliance can thus be defined as an elastic strain ε (mm/mm) produced by a force of 1 N (E is conductor's elastic modulus, S_t is conductor's total cross-sectional area).

According to BS EN 50182:2001, the elastic compliance of frequently utilized aluminum-steel conductors ranges from 6.93×10^{-7} to 0.153×10^{-7} mm/mm N.

2. Experimental setup

The experimental tests were carried out on a horizontal tensile machine MOT 2500kN/13m, designed and built at the "Politehnica" University of Timisoara [8] to [9] (Fig. 1).

Fig. 1 Horizontal tensile machine for conductor and cable testing MOT 2500kN/13m

The mechanically driven machine develops a force up to 2500 kN, and allows the testing of conductor and core samples up to 13 m in length.

Load measurement (Fig. 2) is carried out using interchangeable load cells (9) for different ranges, according to the conductor's rated tensile strength $(RTS)_C$. For strain measurement, inductive transducers are utilized, allowing the change of gauge length L_0 according to the tested conductor sample length.

The data acquisition system is comprised of an ESAM Traveller 1 (Measurement Group) amplifier (1) with ESAM software and a Compaq laptop (3).

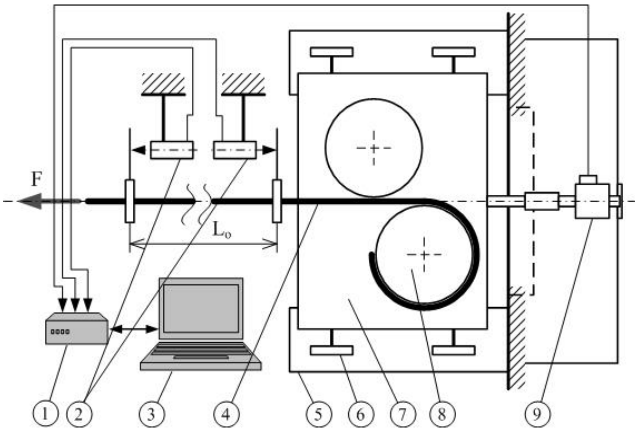

Fig. 2 Load and strain measurement system of MOT 2500kN/13m: *1* – amplifier, *2* – displacement gauge, *3* – laptop, *4* – conductor, *5* – cross-beam, *6* – guide roller, *7* – mobile carriage, *8* – mounting reel, *9* – load cell

3. Material and sample characteristics

The tensile tests were carried out on two aluminum-steel conductors, designated as 51-AL1/30-ST1A and 490-AL1/64-ST1A, having a length of 12.3 m (Fig. 3).

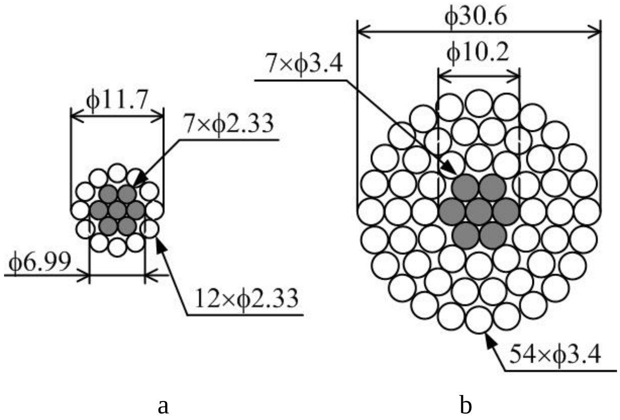

Fig. 3 Cross section of the two conductors (a) – 51-AL1/30-ST1A and (b) – 490-AL1/64-ST1A

The characteristics of the conductors according to BS EN 50182:2001 are presented in Table 1. The same table also contains the elastic compliances of the conductors and their cores, computed from the corresponding elastic modulus and cross-sectional areas.

After analyzing the rigidity based on the elastic compliances, it has been found that 490-AL1/64-ST1A has a 4.42 times higher rigidity than 51-AL1/30-ST1A.

Table 1

Mechanical characteristics of the tested conductors and cores according to BS EN 50182:2001

<table>
<tr><td>Conductor</td><td colspan="4">51-AL1/30-ST1A</td><td colspan="4">490-AL1/64-ST1A</td></tr>
<tr><td>Cross-sectional area, mm^2</td><td>Aluminum (S_{AL})
51.2</td><td colspan="2">Steel (S_{ST})
29.8</td><td>Total (S_t)
81</td><td>Aluminum (S_{AL})
490.3</td><td colspan="2">Steel (S_{ST})
63.6</td><td>Total (S_t)
553.9</td></tr>
<tr><td>No. of wires</td><td colspan="2">Aluminum
12</td><td colspan="2">Steel
7</td><td colspan="2">Aluminum
54</td><td colspan="2">Steel
7</td></tr>
<tr><td>Wire diameter, mm</td><td colspan="2">Aluminum (d_{AL})
2.33</td><td colspan="2">Steel (d_{ST})
2.33</td><td colspan="2">Aluminum (d_{AL})
3.40</td><td colspan="2">Steel (d_{ST})
3.40</td></tr>
<tr><td>Diameter, mm</td><td colspan="2">Core (D_{CO})
6.99</td><td colspan="2">Conductor (D_C)
11.7</td><td colspan="2">Core (D_{CO})
10.2</td><td colspan="2">Conductor (D_C)
30.6</td></tr>
<tr><td>RTS, kN</td><td colspan="2">Core
37.5</td><td colspan="2">Conductor
42.98</td><td colspan="2">Core
81.8</td><td colspan="2">Conductor
150.81</td></tr>
<tr><td>E, N/mm^2</td><td colspan="2">Core
2.1×10^5</td><td colspan="2">Conductor
1.07×10^5</td><td colspan="2">Core
2.1×10^5</td><td colspan="2">Conductor
0.7×10^5</td></tr>
<tr><td>Elastic compliance, mm/mm N</td><td colspan="2">Core (c_{CO})
1.6×10^{-7}</td><td colspan="2">Conductor (c_C)
1.15×10^{-7}</td><td colspan="2">Core (c_{CO})
0.748×10^{-7}</td><td colspan="2">Conductor (c_C)
0.26×10^{-7}</td></tr>
</table>

4. Experimental results

4.1. Conductor testing

The experimental tensile testing of the aluminum-steel conductors has been carried out according to the current European standards [1] to [4]. Thus the conductor has been initially loaded with $2\%|(RTS)_C$ in order to straighten it and to equalize strains in the component wires.

After this, the conductor was loaded with a force equal to $30\%|(RTS)_C$ and the load was maintained constant for 30 minutes, meanwhile the strains were measured after 0, 5, 10, 15 and 30 minutes.

This procedure was repeated for the other load levels, i.e. $50\%|(RTS)_C$, $70\%|(RTS)_C$ and $85\%|(RTS)_C$, and the strains were measured after 0, 5, 10, 15, 30, 45 and 60 minutes (Fig. 4).

After unloading the conductor from $85\%|(RTS)_C$, it is loaded again at a constant rate until failure (Fig. 4). The strains corresponding to previous loading levels are registered again.

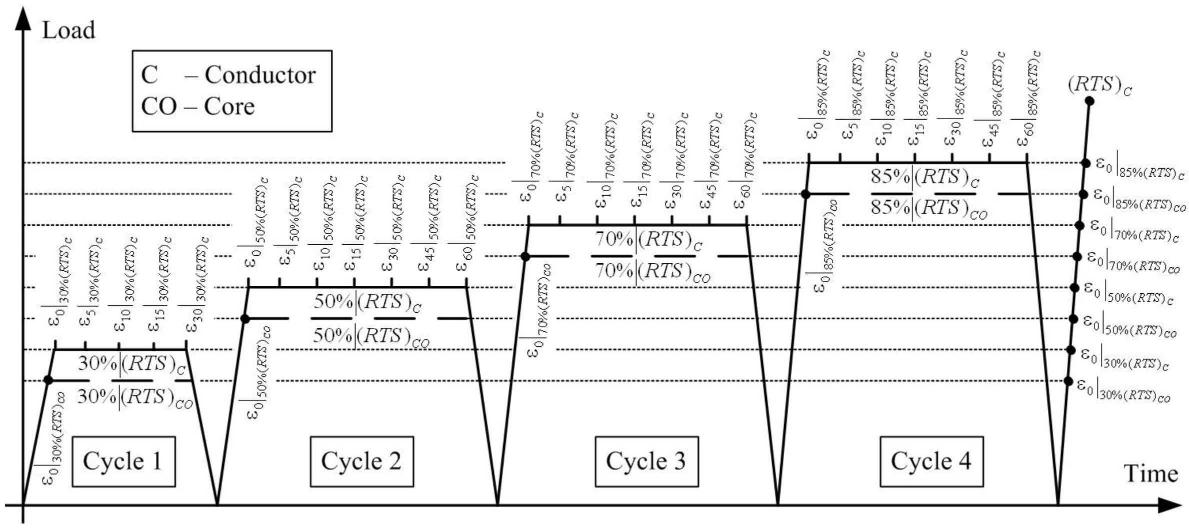

Fig. 4 Loading scheme for aluminum-steel conductors [1] to [4]

Table 2

Measured strains for conductor 51-AL1/30-ST1A

Load	*t*, min	5	10	15	30	45	60
30%|$(RTS)_C$ 12.89 kN	σ, MPa ε, %	163.98 0.11171	163.98 0.11244	163.98 0.11333	163.98 0.11382	- -	- -
50%|$(RTS)_C$ 21.49 kN	σ, MPa ε, %	273.30 0.24097	273.30 0.24122	273.30 0.24187	273.30 0.24260	273.30 0.24357	273.30 0.24496
70%|$(RTS)_C$ 30.09 kN	σ, MPa ε, %	382.62 0.41171	382.62 0.41203	382.62 0.41333	382.62 0.41528	382.62 0.41658	382.62 0.41951
85%|$(RTS)_C$ 36.53 kN	σ, MPa ε, %	464.61 0.51179	464.61 0.52114	464.61 0.52423	464.61 0.53171	464.61 0.53496	464.61 0.56732

The experimental results for conductor 51-AL1/30-ST1A are presented in Table 2.

In accordance with the current European standards, the stress-strain curves are plotted based on the conventional stresses σ, corresponding to loading levels 30%|$(RTS)_C$, 50%|$(RTS)_C$, 70%|$(RTS)_C$ and 85%|$(RTS)_C$, and the strains ε, corresponding to the above mentioned loading levels, measured after 30 and 60 min, respectively (Figs. 5 and 6).

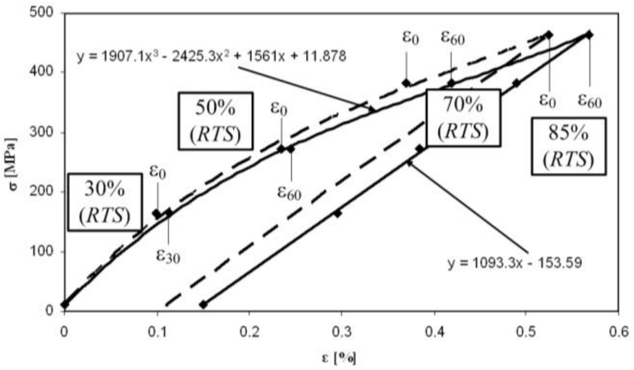

Fig. 5 Stress-strain curves for conductor 51-AL1/30-ST1A (continuous line – constant loading; dashed line – beginning of loading)

The continuous line in Fig. 5 represents the stress-strain curve of the conductor 51-AL1/30-ST1A based on the strains (ε) obtained at the end of the hold periods, after 30 or 60 min respectively. The dashed line in the same figure represents the stress-strain curve of the mentioned conductor, but plotted based on the initial strains, measured at the beginning of each hold period. The differences between the strains recorded at the beginning respectively the end of the hold periods with constant loading are the results of two phenomena: on one hand the rearrangement of the wires in the conductor starting from the moment of tensile load application while on the other hand the creep tendency over short periods of time. It can be seen that the last two levels of loading (70%|$(RTS)_C$ and 85%|$(RTS)_C$, which can be considered as overloads in creep testing) generate greater strain differences than the first two levels (30%|$(RTS)_C$ and 50%|$(RTS)_C$).

In case of conductor 490-AL1/64-ST1A no significant difference has been recorded between the stress-strain curves obtained for strains measured at the beginning of each hold period, respectively the ones obtained for strains measured after each hold period (Fig. 6).

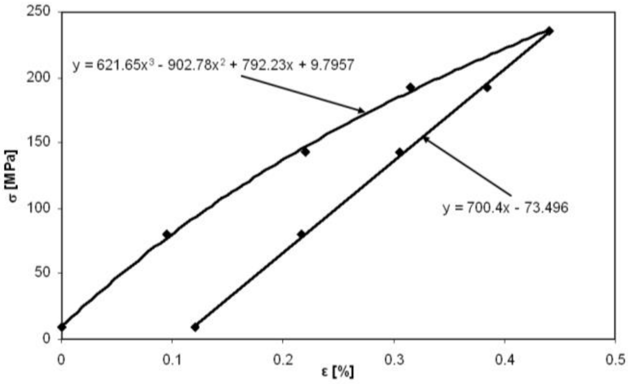

Fig. 6 Stress-strain curves for conductor 490-AL1/64-ST1A

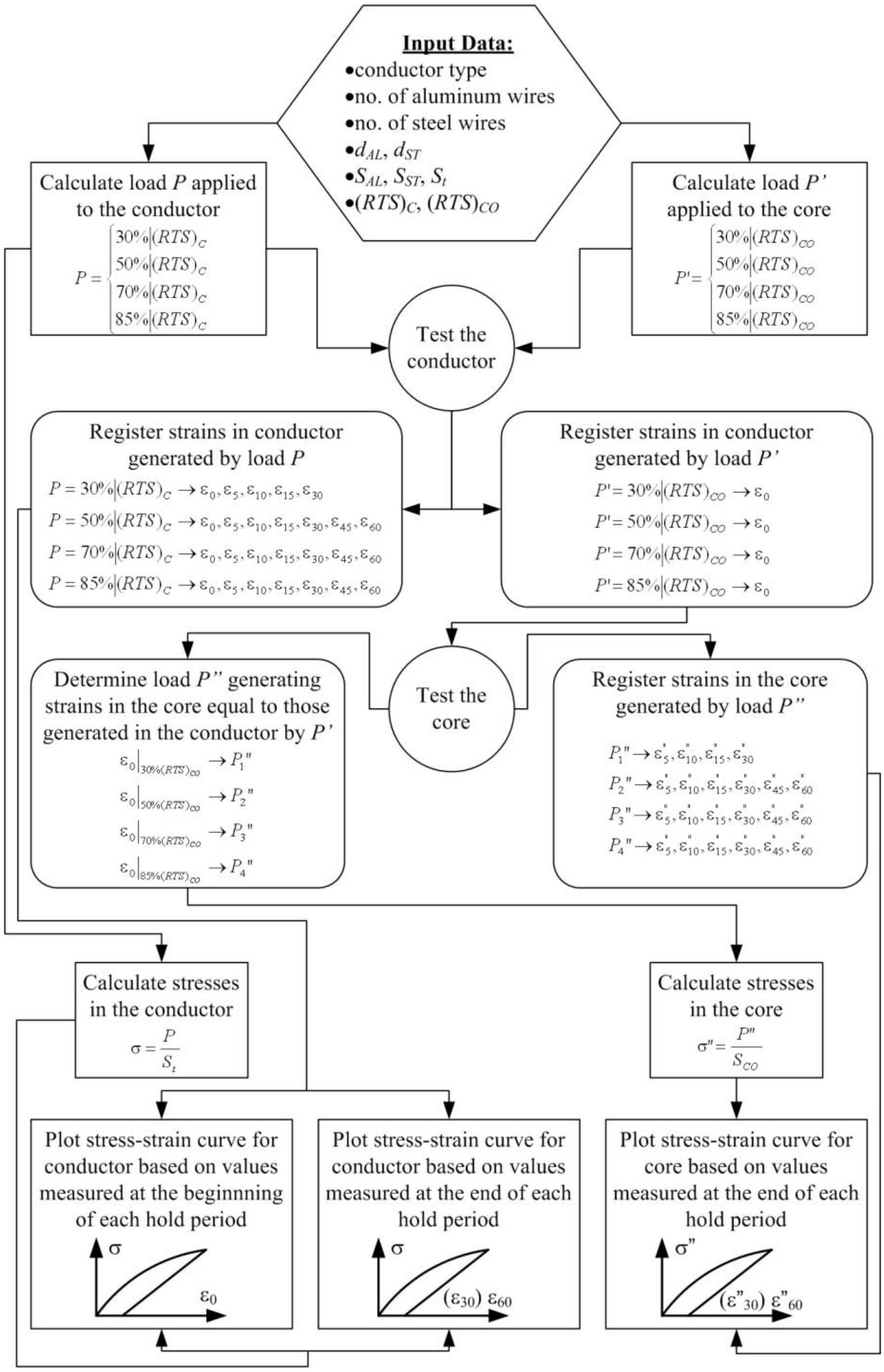

Fig. 7 Experimental procedure flowchart for plotting stress-strain curves of aluminum-steel conductors and their cores, according to the current European standards

Fig. 7 presents the experimental procedure flowchart, according to which the stress-strain curves in Figs 5 and 6 were obtained.

The tensile failure of conductor 490-AL1/64-ST1A is presented in Fig. 8. Necking of the aluminum wires can be observed in the failure region. Furthermore, failure of the core's steel wires occurred at a distance of 100 to 150 mm from the failure of the aluminum wires.

For comparison, Fig. 9 presents the loading scheme of aluminum-steel conductors in accordance with the standard ASG Rev. 1999 [5], [10] to [12]. It can be seen that after maintaining the constant load of $30\%|(RTS)_C$ for 30 minutes, the holding periods of the next two loading cycles ($50\%|(RTS)_C$ and $75\%|(RTS)_C$ respectively) are 60 min long.

Fig. 8 Tensile failure of conductor 490-AL1/64-ST1A corresponding to ultimate tensile strength of P_{max} = 158.75 kN

The 75%|$(RTS)_C$ load cycle is followed by tensile loading to failure [1] to [4]. The last load cycle, corresponding to 85%|$(RTS)_C$ represents one of the toughest testing phases for aluminum-steel conductors, during which many conductors fail. However, this standard does not contain this load cycle.

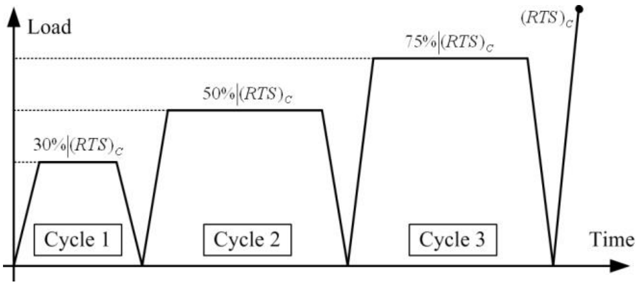

Fig. 9 Loading scheme for aluminum-steel conductors according to ASG Rev. 1999 [5], [10] to [11]

Furthermore, in case of some conductors the ultimate tensile strength is strongly influenced (i.e. lowered) by the 60 min long hold period at 85%|$(RTS)_C$. During this period high plastic strains appear in the conductor, influencing the conductor's behavior during the last loading to failure (Fig. 4).

4.2. Core testing

According to current European standards, tensile testing of steel cores first of all requires the measurement of strains ε_0 produced by load P' equal to 30%|$(RTS)_{CO}$, 50%|$(RTS)_{CO}$, 70%|$(RTS)_{CO}$ and 85%|$(RTS)_{CO}$ during the conductor tensile testing, as presented in Fig. 4.

According to the mentioned measurements, the core can now be loaded with P'', a load that, when reached, produces the strain ε_0 in the core (Fig. 7). For example P_1'' is the force which, applied to the core, produces a strain equal to the strain ε_0 measured on the conductor when loaded with $P' = 30\%|(RTS)_{CO}$.

During the 30, 60 min long hold periods with load P'', the strains ε_5'', ε_{10}'', ε_{15}'', ε_{30}'', ε_{45}'' and ε_{60}'' are registered (Fig. 7).

Based on the above mentioned strain values and on the stress σ'', computed as the ratio of load P'' and the core's cross-sectional area, the stress-strain curves are plotted for the conductors' cores (Figs. 10 and 11).

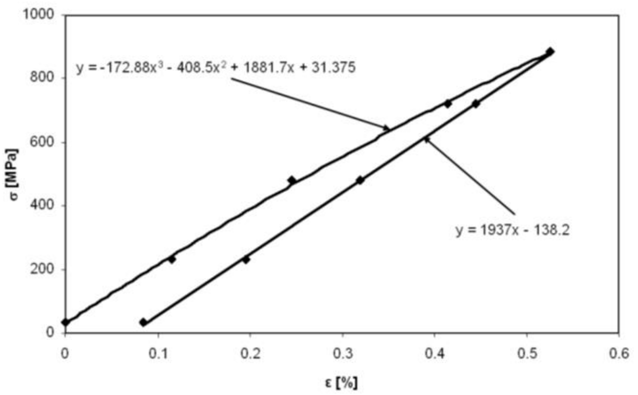

Fig. 10 Stress-strain curve for the core of conductor 51-AL1/30-ST1A

In case of conductor 490-AL1/64-ST1A, having rigidity 4.42 times higher than the other conductor, the stress-strain curve of the core is reduced to a straight line (Fig. 11). The applied load P'' being much smaller than the ultimate tensile strength of the core, the obtained stress-strain curve only depicts the core's behavior in the elastic region, not showing what happens at loads greater than the yield point.

This calls for the revision of testing standards concerning the cores of high rigidity aluminum-steel conductors.

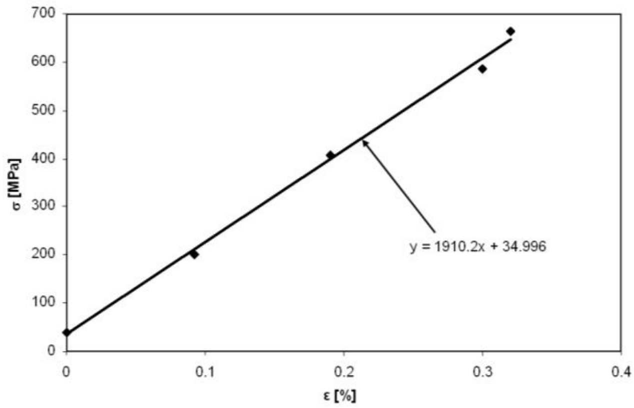

Fig. 11 Stress-strain curve for the core of conductor 490-AL1/64-ST1A

5. Conclusions

This paper presents the tensile testing procedure for aluminum-steel conductors and their cores, 12.3 m in length, according to the loading-unloading cycles specified in the current European standards [1] to [4], implemented on a horizontal tensile machine MOT 2500kN/13m, designed and built at the "Politehnica" University of Timisoara, Romania.

The experimental results in case of two conductors with different rigidity values (having a rigidity ratio of 4.42) are presented in the paper. The conductors' rigidity has been defined using the elastic compliance, defined as the strain ε (mm/mm) produced by a load of 1 N.

The experimental study has shown that in case of conductors characterized by high elastic compliance, the stress-strain curves plotted based on the strains measured at the beginning of each hold period and the ones plotted based on the strains measured after the holding periods of 30 or 60 min respectively, may differ significantly. Highlighting this remark is very important, since it shows the conductor's creep tendency when subjected to overloads over short periods of time. Even though the influence of creep on tensile testing of conductors is not dealt with in current standards, it is worth mentioning in experimental reports of conductor testing.

The present study has also shown that, given the interconnections specified in the current standards, the stress-strain curve for high rigidity conductor cores is limited to the elastic region.

Both findings can be the starting point for adapting current standards or completing them with new paragraphs regulating the influence of conductor creep tendency over short periods of time, as well for revising steel core testing procedures.

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ALIUMINIO IR PLIENO LAIDININKŲ IR JŲ ŠERDŽIŲ MECHANINIŲ BANDYMŲ SVARBA

R e z i u m ė

Kad būtų galima saugiai perduoti energiją aukštosios įtampos linijomis, aliuminio ir plieno laidininkų bei plieno šerdžių fizikinių mechaninių charakteristikų eksperimentinio patikrinimo rezultatus reikia lyginti su standartais. Pagrindinės aliuminio ir plieno laidininkų charakteristikos nustatomos tempiant laidininkus, iki jie nutrūks. Tokius tempimo bandymus reglamentuoja standartai CEI-IEC 1089, CEI-IEC 61089, SR-CEI 1089 ir BS EN 50182.

Dėl plataus stiprumo diapazono aliuminio ir plieno laidininkai reikalauja adaptuotų bandymo sąlygų ir eksperimentinių rezultatų analizės, siekiant užtikrinti, kad tempimo bandymų svarbiausios mechaninės charakteristikos būtų tinkamos visiems laidininkams ir šerdims. Todėl šiame darbe pasiūlyta visa laidininkų bandymo procedūra remiasi europiniais standartais ir pritaikyta dviem laidininkams, kurių stiprumo koeficientas 4.42. Eksperimentai buvo atliekami 13 m ilgio ir 2500 kN jėgos horizontaliosiomis tempimo staklėmis, suprojektuotomis ir sumontuotomis Timišuaros universiteto „Politecnika“ (Rumunija) laidininkų ir kabelių laboratorijoje. Tempimo bandymai pirmiausia parodė, kad įtempių ir deformacijų kreivės, gautos remiantis standartais, ir gautos deformacijas matuojant kiekvieno apkrovos periodo pradžioje, gali skirtis. Tai rodo laidininko valkšnumo padidėjimo per trumpą laiką, kai jis yra veikiamas perkrovų, tendenciją. Antra, buvo nustatyta, kad kai laidininko plieninė šerdis labai standi einamąjį standartinį bandymą riboja tik tamprumo zona.

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SOME CONSIDERATIONS ON THE MECHANICAL TESTING OF ALUMINUM-STEEL CONDUCTORS AND THEIR CORES

S u m m a r y

Safe electrical energy transport on high-voltage overhead lines requires the physical-mechanical characteristics of aluminum-steel conductors and steel cores to be experimentally determined and compared to standard values. The basic characteristics of aluminum-steel conductors can be obtained by tensile testing to failure. Such tensile tests are regulated by the standards: CEI-IEC 1089, CEI-IEC 61089, SR-CEI 1089 and BS EN 50182.

Because of a wide rigidity range, aluminum-steel conductors require adapted testing conditions and experimental data analysis, ensuring that by tensile testing the most important mechanical characteristics can be put into perspective, for the whole conductor and for its core.

Therefore, a complete conductor testing procedure has been developed in this paper, according to the European standards in effect and applied for two conductors with a rigidity ratio of 4.42.

The experimental tests were carried out on a horizontal tensile machine, designed and built in the Laboratory for Conductors and Cables of the "Politehnica" University of Timisoara, Romania, having a length of 13 m and developing a force up to 2500 kN.

The tensile tests have firstly shown that a (sometimes significant) difference can be observed between the stress-strain curves obtained according to the standards in effect and the ones based on the strains measured at the beginning of each hold period. This shows the creep tendency of conductors over a short period of time, when exposed to overloads. Secondly, it has been found that in case of high rigidity conductor steel cores, current standard testing is limited only to the elastic region.

Keywords: aluminum-steel conductor, conductor core, horizontal tensile testing machine, stress-strain curve, elastic compliance.

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