ON THE INFLUENCE OF CONSTRUCTIVE AND FUNCTIONAL FACTORS CONCERNING MECHANICAL RESISTANCE ON STATIC AND VARIABLE STRESSES OF HIGH VOLTAGE CONDUCTORS

PhD thesis – Summary

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This PhD thesis comprises 7 chapters, 147 pages, 114 figures and diagrams, 29 tables, 95 bibliographic titles.

The theme of the thesis aligns with the new research directions on electricity transmission and distribution, addressing the concept of the durability of high voltage electrical conductors under variable load conditions generated by wind vibrations. Given the long operating lives of these airlines on the one hand and environmental conditions on the other, there are a number of elements underlying the phenomenon of fatigue.

The thesis summarizes the problems of degradation mechanisms and their effects on the 450/75 conductors of the overhead power lines (OPL) 220kV, under the exploitation conditions specific to the western area of Romania. The PhD thesis presents an interdisciplinary character by combining research using theoretical and experimental information of the following fields: mechanical and material resistance, vibrations, fluid mechanics, energetics, chemistry, reliability, terrestrial measurements, computer science and mathematics.

The main objectives of the thesis are:

- Systematization and correlation of the bibliographic material allowing a logical follow-up of the problem of the durability of the OPL conductors;
- Identification of the constructive factors and of the working environment that influence the durability of the conductors in the western area of Romania;
- Establishment of equipment and devices enabling the material base of the Materials Resistance Laboratory to be used for experimental studies on wires under conditions specific to overhead power lines;
- Conducting experimental tests on aluminum steel conductors, on the component wires and interpretation of results;
- Research on the variation of the mechanical properties of wires in conductors after long periods of operation;
- Identification of fatigue rupture initiation and propagation areas, as well as their particularities for conductors;
- Analyzing the state of stresses and strains in the conductor's contact areas by developing a numerical modeling methodology with finite elements;
- Experimental study on aerial conductors/ overhead power lines with regard to fatigue resistance.

Chapter 1 of the thesis reviews the current state of research on increasing safety in operation of overhead power lines (OPL) as well as on identification of critical areas and processes leading to their premature rupture. There are presented the types of mechanical stresses on conductors produced by static loads and types of oscillations generated by wind-induced vibrations. This highlights the complexity and difficulty of correlating the mechanical characteristics of the stresses on wires and of the behavior of the conductor as a whole.

Chapter 2 presents the main elements regarding the construction, geometry and the materials that make up the conductors (wires, strands, core, types of strands, special structures) with emphasis on some theoretical aspects of mechanical characteristics, wire application and conductor behavior in the OPL assembly. After the constructive elements are presented, the manufacturing technologies of aluminum and steel wires (wire drawing) are analyzed – the technological processes by which the steel and aluminum wires are twisted to form the conductors (the stranding process) identifying the influence of the technologies on the mechanical characteristics of the conductors.

Some relevant aspects referring to the geometrical peculiarities and to the stresses to which a conductor is subjected are reviewed in the following content. The analytical aspects of the angles of wire winding are analyzed on their contact resistance. Technological processes (mechanical, thermochemical, electrochemical) lead to flaws that manifest themselves through structural changes of the wire. Wiredrawing creates a series of changes in the crystalline network of punctual, linear or surface type, improves mechanical strength and hardness, but reduces ductility, tenacity and fatigue strength. During the process of helical layout of the layers, the wires are subjected to external forces having axial and normal direction on the cylinder that characterizes them. This process produces stresses in the mass of the material, and on the outside it creates tension-like zones in the form of lines, in the case of wire on the same layer, and punctuated when the case of interleaved.

The first part of **Chapter 3** represents a description of the type and characteristics of the conductors and the component wires subjected to the research and also of new and 42 years old used conductors on the Timişoara – Arad OPL system. The wires of the conductors of both states above mentioned are analyzed resulting in determination of the state of surfaces specifically characterized by the presence of chemical elements agglomerations and solid particles. This was done using energy dispersion X-ray spectroscopy. Changes in material properties of conductors wires used in energy transport (using differential thermal analysis) have been highlighted. There are a number of peculiarities of corrosion of conductors after long periods of exploitation as well as a number of environmental factors in the western part of our country. On this basis, a number of indices may be determined to predict the expected lifetime of the conductors. The above justifies the special attention required by the effect of aging on the lifetime of OPL conductors, personalized by the area they are crossing and future analysis to be done.

The second part of the chapter represents a study on the effect of the airflow over the conductor profile thus regarding the pressure variation exerted upon it by using the numerical and experimental simulation method. Based on some computational programs, a series of flow simulations were done, at different wind speeds thus used to identify the types and positions of the Karman vortices, their alternation and value of the dynamic pressure at various points of contact on the surface of the conductor. Experimentally, an airflow installation was put out over the 450/75 conductor profile, using a marker flow which forced a laminar flow at the inlet, with the formation of whirlpools at the outlet. The results were used for the pressure variation diagrams according to flow rate and, on this basis, an equation correlating the wind speed with the dynamic pressure applicable to numerical simulations of voltage states in wires conductor.

The final part of the chapter presents a method proposed to determine the bending stress amplitude for 450/75 ACSR conductors, using the Poffenberger-Swart equation and based on the actual sag from a 258m long aperture. The real sag measurements were done using an own method for determining the position of the conductors in certain openings on the OPL Timişoara – Arad route measurement. The measurements were done in three different atmospheric conditions.

This method uses geodetic measurement techniques and laser waves with a much higher accuracy than conventional methods. The method revealed very large variations of the sags over one year, which is reflected in variations in the contact stresses in the clamping zone areas. Determination of sags allowed the correct application of calculations and the determination of the voltage amplitude personalized by the vertical displacement of the conductor, under the conditions of changing operating parameters.

Chapter 4 presents theoretical elements regarding wire contact in the area of conductor clamps, elements of mechanics and contact physics in the elastic-plastic field and the application of Hertz's theory to rotating objects. At the same time the cylinder-to-cylinder contact is analyzed, with stress distribution and strains in the contact area being shown for different angles of inclination of the two cylinders.

The second part of the chapter contains a numerical analysis of the stress and deformation state that was done using the ABAQUS simulation program on numerical models that meet the mechanical and dimensional characteristics, using fine meshing. This numerical study of the conductor wires contact is a basis for calculating the appearance and development of imprints on the wire surfaces.

The theoretical results were validated experimentally using the methodologies presented in Chapter 5. With the help of the data obtained by the finite element analysis we could see the areas where the maximum stresses are, in the case of the contact between the wires, and the effect of the increase of the normal stress. Thus, it has been observed that the maximum value of the stress is found on the perimeter of the imprints at the contact surface boundary. Using the "XFEM" Expanded Finite Analysis Module and the Breakdown Criterion based on MaxPS, the crack initiation and propagation points were determined along the perimeter of the imprints. Diagrams of plastic deformations showing the three-dimensional variations of imprints created in the contact areas were drawn using the data obtained. The interrelation between the imprints surfaces and the penetration depth was analyzed.

This study is of particular importance because it provides a clearer understanding of deformation and stress states in wire contact areas, highlighting important parameters for the study of various contacts created by imprint angles. Accepting the linear variation of the normal stress, a nonlinear variation in the equivalent stress was obtained as well as the change in the ratio between the surface and the depth of the imprint. Modeling wire contact highlights that the emergence and development of the rupture mechanism cannot be understood without a punctual approach to the phenomena involved in the process. The interpretation of the imprint aspect provides information on the operating regime of the conductor and the creation of premises for the occurrence of local breaks.

Chapter 5 is entirely dedicated to the determination of the elastic and mechanical properties of the 450/75 conductor and of the component wires. The chapter contains several laboratory tests such as tension, imprinting, hardness determination, shear, alternating bending and torsion. All these were aimed at determining the modification of the mechanical characteristics of the conductor after 42 years of exploitation and the factors involved in the degradation process.

The chapter begins with a presentation of devices and equipment designed and adjusted for testing in conditions similar to those in operation. Most of the chapter includes an analysis of new and used power transmission wires. Working methodologies, materials used, graphical interpretations, calculations and interpretation of the gathered results are presented. The analysis also included a new interpretation of the characteristic curves (σ-ε) at the corresponding points for 30, 50, 70 and 85% of the rated breaking power of the 450/75 conductor.

This study allowed a comparative analysis of the new and aged conductors with the presentation of specific results and a description of the influence of shape and dimensions of the imprint on the durability of the wires. The relevance and effect of imprints existence at the surface of the wire is highlighted through specific tests regarding initiation and development of cracks. It has been pointed out that the cracks initiated on the edges of the imprints develop in a plane that traverses the imprint and has a 45° inclination from the wires axis. Based on the sustained results, a series of equations are proposed to quantify the dimensional characteristics of the imprint for new and aged wires, depending on their normal force and angle of inclination. These equations highlight the level of wire degradation after certain exploitation periods.

Chapter 6 shows a three-dimensional elastic-plastic model of the conductor-clamp assembly. Based on this model, a high fidelity numerical methodology has been developed to accurately analyze the stresses and strains occurring in conductors and clamp contact areas. The data of this newly created model and its results allows the development of test conditions that cannot be created in the laboratory in order to obtain eloquent results. In order to enrich the research effort to solve fatigue problems that are critical to the design and lifetime of conductors, this study helps to understand the complex contact and the mechanics of the conductive clamp assembly in order to develop a numerical approach to studying breaks caused by fatigue of conductors.

Another important contribution was to carry out experimental fatigue tests of the conductors in order to complete and validate the theoretical simulations. The fatigue test consisted in analyzing the behavior and life of the new 450/75 conductor which was subjected to variable demands. This was done by adapting the MOT 2500kN / 13m test machine to create a variable duty regime and complying with the requirements of the IEC 62568 fatigue test. The fatigue test was performed until the first wire was broken, without exceeding the conventional maximum number of 109 cycles. Following the results of this test, the fatigue curve was drawn in order to predict the life of the 450/75 conductor for different amplitudes of displacement.

In order to highlight the fatigue behavior of the conductor, a series of experimental tests were carried out on the aluminum wires based on cyclical stresses. Wire durability analysis was done on the basis of the fatigue tensile strength test using positive oscillating cycles, which are specific to the variable load conditions created by OPL exploitation. The gathered results from tests on new wires, imprinted wires as well as aged wires are presented by drawing the Wöhler fatigue curve. They are presented separately as well as overlapped for each wire type in order to highlight the influence of imprints and of the operating life on fatigue strength.

The particular characteristics of the initiation and development of fatigue cracks and of the initiation of broken wires during fatigue tests are detailed in the last part of Chapter 6. In general, three different areas are distinguished, each of them having a distinct character. In this case, an important feature of fatigue is the inhomogeneity of the distribution of strains in the material, in particular, to large numbers of cycles. There was a strong influence of imprints on fatigue resistance. Resistance to fatigue decreases by 37% for aged wires and up to 62% for imprinted wires compared to wires from an unused conductor. The final part presents the particular characteristics of the wires rupture areas for wires that have undergone fatigue tests.

Chapter 7 presents the general conclusions of the paper, the original contributions of the thesis, according to the proposed objectives, and the presentation of the way of capitalizing the obtained results in the studied field.

The main contributions relate to:

- drawing up a documentary synthesis on the current state of research;
- identifying unfavorable lifetime factors and contributing to the improvement of the conductor manufacturing process;
- assessment of the environmental factors specific to the OPL Iron Gates – Arad which directly influence the state of the conductors;
- elaboration of a study on the corrosion effects on conductor wires 450/75 after a period of 42 years of operation;
- analysis of the effect of wire degradation by application of X-ray spectroscopy and thermal analysis; - establishment of a marking system for the air flow over the conductor profile;
- elaborating the numerical model for determining the dynamic pressure applied by the wind;
- proposing the equation for the correlation of the wind speed with the dynamic pressure applied to the conductor;
- numerical analysis of the tri-axial state of stresses and strains at the contact between the wires of the conductor 450/75 with the highlighting of the crack initiation points;
- finite element modeling of the conductor-clamp assembly (450/75-CSA5) and stress and strain state analysis of static and fatigue stresses;
- elaboration of an experimental study regarding the influence of the ageing effect of 450/75 conductors on the basis of mechanical characteristics of tensile strengths, shearing, torsion, alternating bending;
- proposing equations to quantify the dimensional characteristics of the imprints according to the applied normal forces;
- analysis of influence of form and size of imprints on static and fatigue tensile strengths of 450/75conductors wires;
- the preparation of a set of measurements of OPL conductors under different environmental conditions and the determination of actual sags;
- experimental determination of fatigue resistance for conductor 450/75 and its compliance to EPRI norms;

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