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Electric field in a conductive medium – modelling and application

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Abstract. The paper presents some specific features of an electric field in a conductive medium, a theoretical base for numerical field modelling using the finite element method and its application in simulation of the processes in real electromagnetic systems. Application examples are presented, concerning simulations of the processes, taking part in contact resistance welding and insulation in the presence of conductive inclusions.

1. Introduction

A good and detailed knowledge of the processes, taking part in a given working system allows effective control and quality fulfilment of the requirements for the work process of this system. One of the most successful and modern methods of obtaining such knowledge is computer modelling of the processes in the studied system under different operating modes. In addition, the simulation of the device behaviour when changing the values of the design and operating parameters is an excellent opportunity for the possible optimization of existing devices and the synthesis of new, better ones.

The subject of consideration in this paper is the modelling of processes in systems operating on the basis of applying an electric field to given objects for the purpose of specific processing and impact on the structure of the parts of the object possessing conductive properties. As a result of this impact, currents flow in the conductive sections, the temperature state changes, changes occur in the properties of the materials and interaction forces arise, leading to qualitative changes in the microstructure of the treated objects.

The processing of various materials with the help of an electric field finds application in many fields [1-4]. Such type of treatment is applied to materials of both biological and non-biological origin. In some cases, these changes are necessary, desired and are the main purpose of the electric field treatment of the material, and in others some of these changes are a harmful side effect and should not exceed certain limits. The physicochemical changes in the state of materials treated with an electric field are the basis of many modern technologies. For example, the phenomenon of electroporation, which develops in this way, is widely used in the medicine, biology and food industry [5,6]. The processes taking part in creation of composite materials are also evolving in a similar way [7]. The principles used in high-tech technology of contact resistance welding lines are analogous [8]. The influence of the electric field acting on living nature often has harmful consequences. Also, a serious cause of aging and deterioration of



insulation quality is application of a high voltage electric field to insulation containing moisture inclusions [9].

The paper presents two examples of numerical modelling of processes in systems and devices in which the treatment of materials with an electric field is carried out: contact resistance welding systems and modelling of the processes in electrical isolation, in the presence of conductive inclusions. The computer simulations of the processes in the considered systems are based on determination and analysis of the electric field distribution and the resulting changes in the thermal and mechanical state of the system, taking into account accompanying changes in the properties of the materials. Numerical modelling of the electric and thermal fields is performed using the finite element method (FEM).

2. Electric field in a conductive medium– specific features, equations, modelling possibilities

2.1 Electric field in a conductive medium– specific features

The electric field application on objects containing regions with conductive properties leads to the changes that in a number of cases can be very significant. The presence of electric field in

areas containing conductive materials cause appearance of currents with density $\vec{J}$ whose magnitude and variation in time depend on the medium conductivity γ and on the value and

time variation of the electric field strength $\vec{E}$ of the applied electric field. The flow of electric currents is associated with Joule losses Q , which are a sources of heat. The heat sources appearance leads to changes in the thermal state of the treated object, i.e. the electric field causes appearance of coupled thermal field. The change in temperature T is a factor influencing properties of the treated material and at temperatures exceeding certain limit values, additional changes in the structure of substances occur. These changes are even more pronounced when the object under the influence of an electric field is not homogeneous, but consists of areas of different material properties. Then at the boundary of the regions with different conductivity, a very sharp deformation in the electric field distribution is observed and significant mechanical stresses are present, which also affect the changing of the object's structure.

2.2 Electric field in a conductive medium - governing equations and mathematical formulation of the problem

As it was described above, the problem of electric field in a conductive medium is associated with a complex of coupled electric and possible thermal processes, combined with changes of the structure and physicochemical properties of the considered region. In the most general case, the mathematical formulation of the studied problems is based on the consideration of a time-dependent electric field, impact of which on the conductive materials leads to the appearance of a transient thermal field.

The dependencies (1) and equations (2) describe the processes of propagation of a time-dependent electric field in a region with dielectric permittivity ε and conductivity γ .

$$\begin{aligned}\vec{D} &= \varepsilon \vec{E} \\ \vec{J} &= \gamma \vec{E}\end{aligned}\tag{1}$$

$$\begin{aligned}
\vec{\text{div}} \vec{D} &= \rho \\
\vec{\text{rot}} \vec{E} &= 0 \\
\vec{\text{div}} \vec{J} + \frac{\partial \rho}{\partial t} &= 0
\end{aligned} \tag{2}$$

Then taking into account that:

$$\vec{\text{rot}} \vec{E} = 0 \Rightarrow \vec{E} = -\text{grad} V \tag{3}$$

In the equation (3), V denotes the scalar electric potential. Then after simple mathematical transformations, the equation that describes the distribution of the time-dependent electric field is obtained as:

$$\text{div}(\gamma \text{grad} V + \frac{\partial}{\partial t}(\varepsilon \text{grad} V)) = 0 \tag{4}$$

In a case of time-harmonic electric field sinusoidally varying in time with frequency ω and when using complex quantities, imaginary unit j and ∇ operator, the equation takes the form:

$$\nabla \cdot \left(\left(\varepsilon - \frac{j\gamma}{\omega} \right) \nabla \dot{V} \right) = 0 \tag{5}$$

The following quantities are used in the description of the processes in the transient thermal field: T is temperature, k is thermal conductivity, ρ is density, C is heat capacity and Q is the heat source determined by the currents obtained in the electric field analysis.

Thus, the equation that describes the temperature field distribution in the studied area has the following form:

$$\rho C \frac{\partial T}{\partial t} + \nabla \cdot (-k \nabla T) = Q \tag{6}$$

2.3 Electric field in a conductive medium– modelling possibilities

The complex interactions and dependences between the interconnected coupled electric and thermal fields, propagating in a conductive medium, can be adequately modelled and analysed only if the changes in the structure and properties of the object during the process of treatment have been taken into account. A real possibility to fulfil these requirements is to model the fields distribution using FEM. It is important to consider separate consecutive time stages corresponding in time to the changes in the geometry, material properties of the object and the corresponding to the stage temperature.

The use of the finite element method for numerical modelling of the coupled electric and thermal fields is a suitable solution, since this method allows analysis of coupled field problems, as well as taking into account the nonlinear changes of the material properties. The presence of areas with complex geometry of the boundaries or change of the region's boundaries in the different stages of the analysis is not a problem, especially in 3D FEM modelling. In the examples presented below, the numerical modelling of the studied coupled electrical and thermal processes was carried out using COMSOL Multiphysics software package [10].

3. Examples

3.1 Modelling of the processes in a spot resistance welding system

The considered example presents the analysis of the coupled time-dependent electric and transient thermal field based on 3D field FEM modelling of the processes in a spot resistance welding system of reinforced steel bars [11].

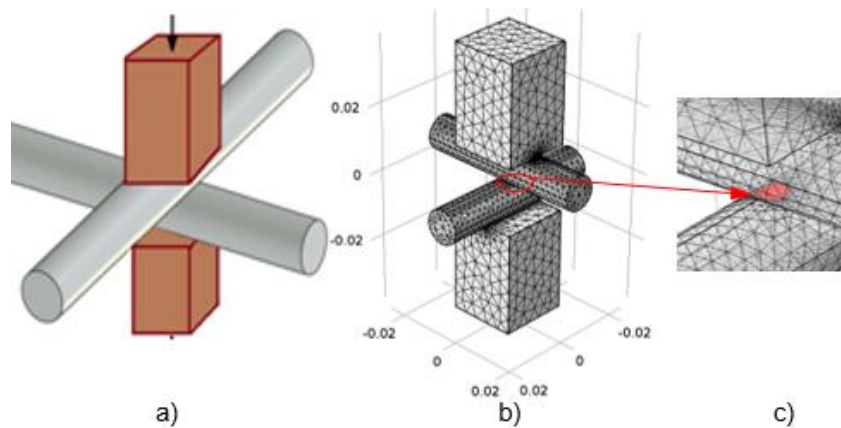


Figure 1: a) Spot resistance welding system; b) FE mesh discretisation; c) contact spot

The system consists of two electrodes and reinforced steel bars (Fig.1) that are to be welded. The two bars are held together under pressure exerted by the electrodes. The welding current is concentrated into a small contact "spot". Forcing a large current through the spot will melt the metal and form the weld. That permits the welding to occur without excessive heating of the remainder of the pieces. The system has been studied when 7kA AC current has been applied for 80 ms and contact area is heated by generated by resistance to flow of electric current. The work process causes significant changes. Because of the material softening, followed by melting and enlarging of the contact zone, the contact resistance changes significantly, as well as the applied power.

In order to account the changes of the contact zone size and contact resistance, three different stages of the welding process are considered in the study. They correspond to the dimensions of the steel bars contact area, contact resistance and time variation of the AC current: I stage: 0 – 0.003s, full power applied; II stage: 0.003 – 0.03s, half power applied; III stage 0.03 – 0.08s, quarter power applied. It should be noted that in the modeling, data obtained during experimental studies of the system were taken for verification.

Some results illustrating the numerical 3D FEM modelling of the time-dependent electric and transient thermal field are presented in Fig.2, Fig.3 and Fig.4. In Figure 2, the electric field is presented when current 7 kA is applied, the overlapping in the welded region reached 0.15mm and contact resistance is taken into account.

Figure 3 and Figure 4 correspond to the thermal state of the studied system during the treatment. As it can be seen the temperature in the contact region changes and at the moment $t = 80ms$ the desired for the welding temperature of $2400^{\circ}C$ has been reached.

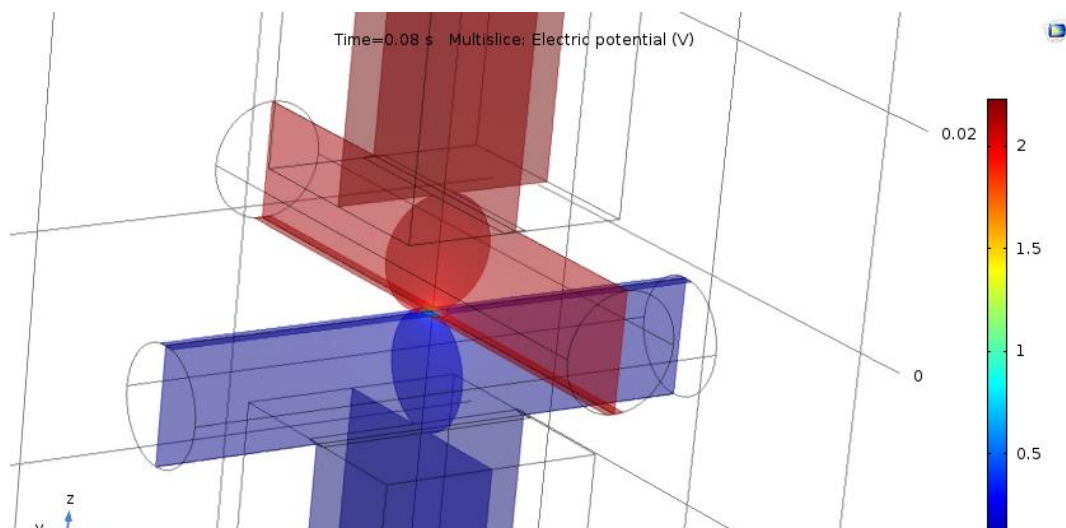


Figure 2. Electric potential distribution, 7 kA, 0.15mm overlapping

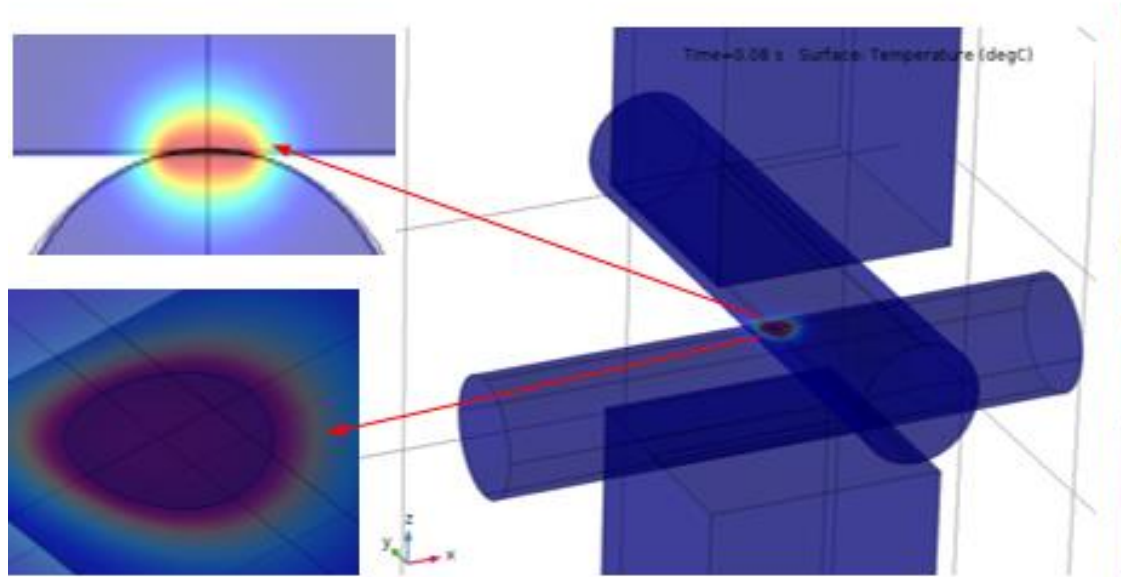


Figure 3. Temperature field distribution, 7 kA, 0.15mm overlapping

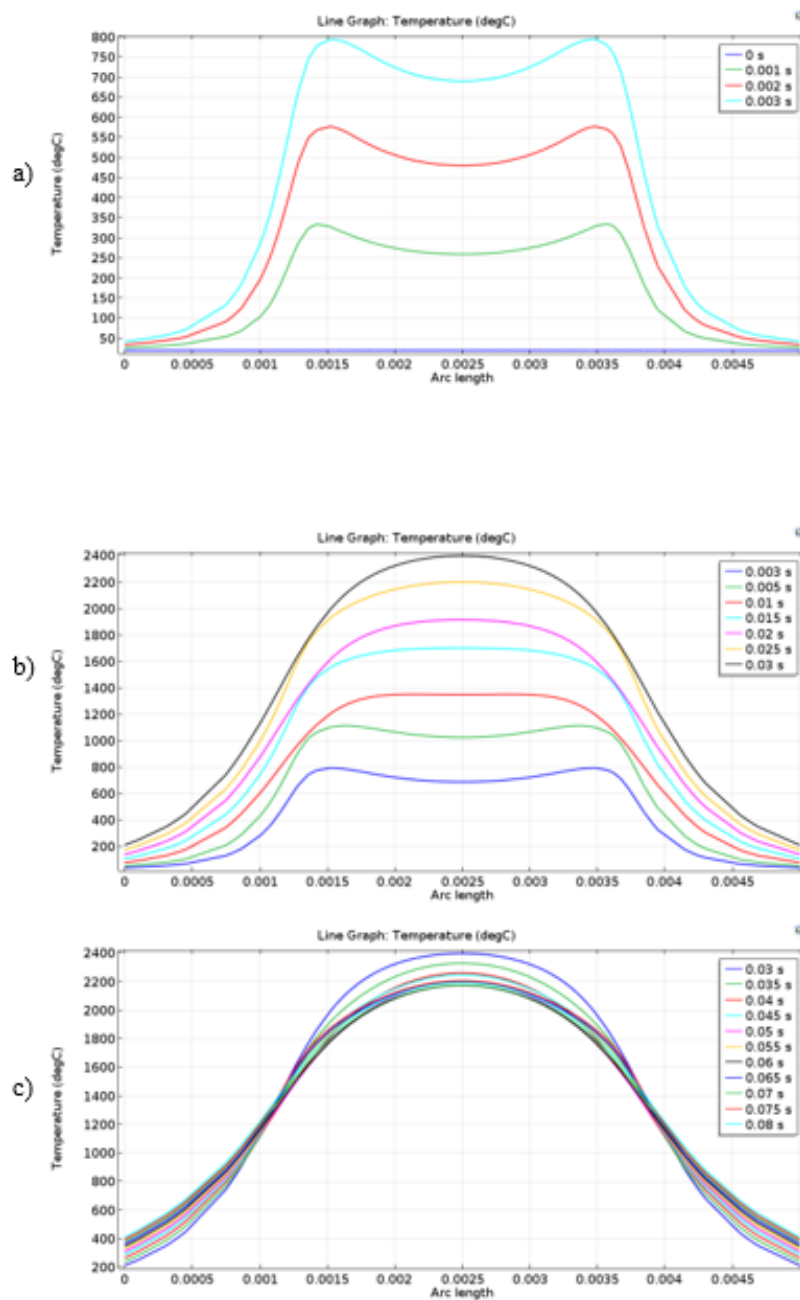


Figure 4. Temperature distribution in the contact spot area: a) I stage; b) II stage; c) III stage.

3.2 Modelling of the processes in electrical isolation

Elements of electrical insulation are subjected to various aggressive influences: strong electrical, thermal and mechanical loads. This causes aging and deterioration of insulation quality due to changes in structure, presence of various inclusions (conductive and non-conductive), partial discharges and change in breakdown dielectric strength, which determines the breakdown voltage.

In the present example, the distribution of the electric field in a simple electrode system, (Fig.5) is modelled and analysed.

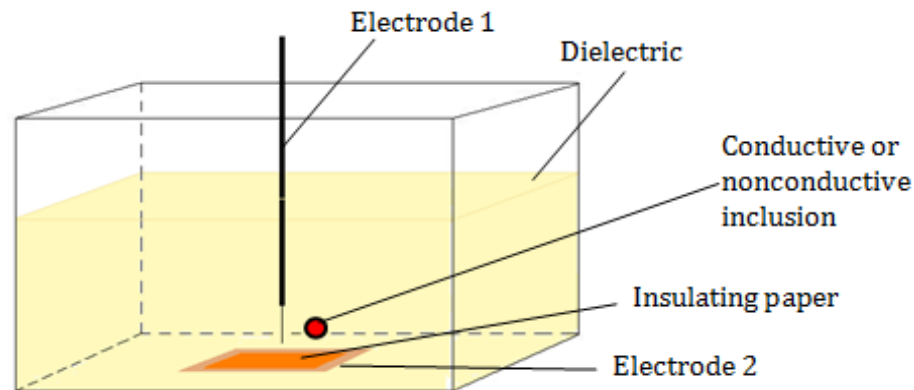


Figure 5. Studied system of electrodes in transformer oil.

The system is suitable for experimental investigations of insulation breakdown voltage [12]. It consists of two electrodes (needle and plate) placed in a transformer oil. It is assumed that the insulation is not uniform but contains single water inclusions in the form of spherical drops. This is one of the worst defects, which significantly affects the quality of the insulation and can cause a breakdown. The problem is that the presence of conductive inclusions significantly affects the electric field. Its distribution becomes highly non-uniform, the water drops line up along the electric field lines and form a conductive chain between the electrodes, in which a breakdown can occur.

The analysis of the electric field distribution is based on 3D field FEM modelling of the processes in studied system in case of insulation with no inclusion, insulation with only one water drop as an inclusion (Fig.6) and insulation with moisture inclusion consisting of several water drops (Fig.7).

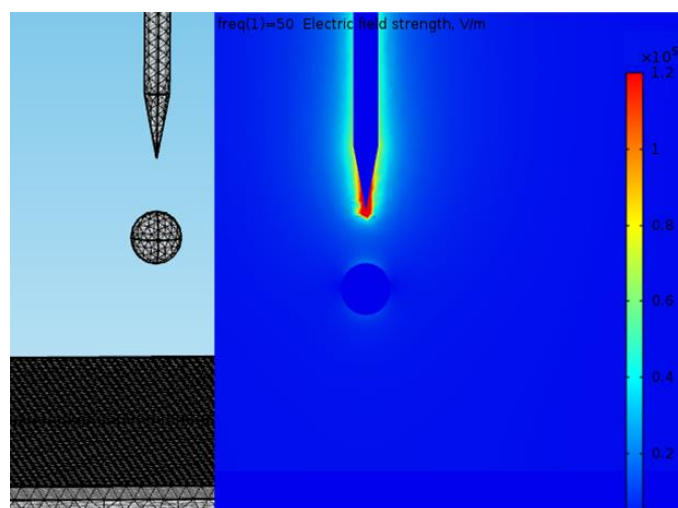


Figure 6. Presence of a single spherical water inclusion: part of the 3D mesh and electric field strength distribution.

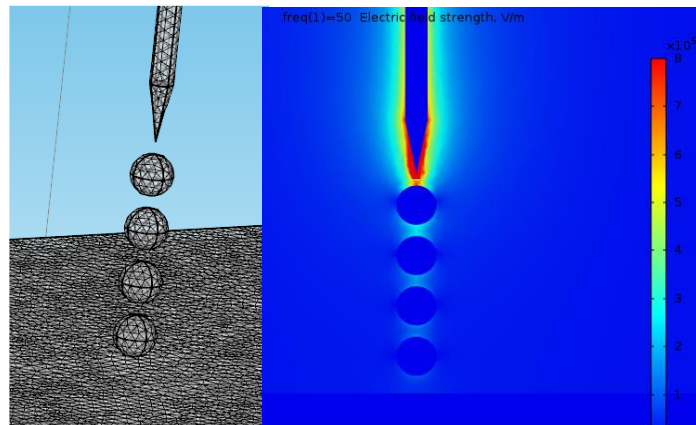


Figure 7. Presence of several water inclusions: part of the 3D mesh and electric field strength distribution.

As it can be seen from the figures illustrating the distribution of the electric field, the maximum value of the electric field intensity increases significantly with increasing water inclusions, exceeds the limit value corresponding to the breakdown intensity, and in this situation a breakdown of the insulation could occur.

4. Conclusions

The paper deals with some specific features and opportunities for numerical modelling of processes related to the application of a time-dependent electric field for the processing of material objects containing conductive zones. Examples are presented illustrating the proposed FEM modelling approach of the electric field distribution and, if necessary, the associated thermal field that appears due to the presence of the currents in the conductive parts.

References

- [1] C. Jörgens and M. Clemens, "Modeling the Electro-Quasistatic Field of Ground Electrodes Under the Influence of Electro-Osmosis," 2020 IEEE 3rd International Conference on Dielectrics (ICD), Valencia, Spain, 2020, pp. 513-516, doi: 10.1109/ICD46958.2020.9341881.
- [2] Böhmelt, S., Kielian, N., Hagel, M., Stierner, M., Henkel, M.-L. and Clemens, M. (2020), "Electro-quasistatic field-simulation of biological cells using balanced domain-decomposition", COMPEL - The international journal for computation and mathematics in electrical and electronic engineering, Vol. 39 No. 3, pp. 739-755. <https://doi.org/10.1108/COMPEL-10-2019-0414>
- [3] F. X. Hart and J. R. Palisano, 'The Application of Electric Fields in Biology and Medicine', Electric Field. InTech, May 23, 2018. doi: 10.5772/intechopen.71683.
- [4] U. Musa, A. A. Mati, A. A. Mas'ud, G. S. Shehu, R. Albarracin-Sanchez and J. M. Rodriguez-Serna, "Modeling and Analysis of Electric Field Variation across Insulation System of a MV power Cable," 2021 International Conference on Electrical, Communication, and Computer Engineering (ICECCE), Kuala Lumpur, Malaysia, 2021, pp. 1-5, doi: 10.1109/ICECCE52056.2021.9514224.
- [5] Novickij, V., Rembialkowska, N., Staigvila, G. et al. Effects of extracellular medium conductivity on cell response in the context of sub-microsecond range calcium electroporation. Sci Rep 10, 3718 (2020). <https://doi.org/10.1038/s41598-020-60789-7>
- [6] S Dastani, K., Moghimi Zand, M., Kavand, H. et al. Effect of input voltage frequency on the distribution of electrical stresses on the cell surface based on single-cell dielectrophoresis analysis. Sci Rep 10, 68 (2020). <https://doi.org/10.1038/s41598-019-56952-4>

- [7] T. Wong, I. Timoshkin, S. MacGregor, M. Wilson and M. Given, "Modeling of the Transient Electric Field in Multilayer Dielectric Composites Under Impulsive HV Energization," in IEEE Transactions on Dielectrics and Electrical Insulation, vol. 30, no. 1, pp. 220-229, Feb. 2023, doi: 10.1109/TDEI.2022.3214180
- [8] Biele, L., Schaaf, P. & Schmid, F. Method for contact resistance determination of copper during fast temperature changes. J Mater Sci 56, 3827–3845 (2021). <https://doi.org/10.1007/s10853-020-05490-w>
- [9] P. Pandey and C. C. Reddy, "Effect of Inhomogeneous Ageing of Insulation on Electric Field Distribution of a 220kV HVAC in-Service Cable," in IEEE Transactions on Dielectrics and Electrical Insulation, doi: 10.1109/TDEI.2024.3383412.
- [10] COMSOL, Inc., COMSOL Multiphysics user's guide, version 5.3
- [11] I. Iatcheva, D. Darzhanova, M. Manilova, Modeling of electric and heat processes in spot resistance welding of cross-wire steel bars. Open Physics, vol. 16, issue 1, pp. 1-8, 2018, doi: 10.1515/phys-2018-0001.
- [12] I. Iatcheva and N. Petkova, "Study of electrical insulation in the presence of heterogeneous inclusions," 2016 19th International Symposium on Electrical Apparatus and Technologies (SIELA), Bourgas, Bulgaria, 2016, pp. 1-6, doi: 10.1109/SIELA.2016.7543012