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A multiphysics analysis of coupled electromagnetic-thermal phenomena in cable lines

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Abstract: The paper is focused on numerical modeling of multi-strand cable lines placed in free air. Modeling is carried out within the framework of the so-called multi-physics approach using commercial software. The paper describes in detail the steps undertaken to develop realistic, reliable numerical models of power engineering cables, taking into account their geometries and heat exchange conditions. The results might be of interest to the designers of multi-strand cable systems.

Keywords: multi-strand cable lines; ampacity; coupled electromagnetic and thermal phenomena

1. Introduction

Energy transfer in low voltage networks and installations is in many cases related to flow of currents with significant values. This issue occurs e.g. in the lines connecting medium voltage (MV) transformers to main switchgears of industrial entities as well as in the installations of high storey buildings. The necessity to deliver high amounts of energy requires that current-leading tracks with significant ampacities (current carrying capacities) are used. Usually such connections are made of bare bars or insulated bus-bars. The design of these components has been described in detail in several publications, cf. e.g. [1,2]. In some cases due to economical reasons (this is true in particular in the case of insulated bus-bars) or technical limitations, resulting from the geometry of the devices) it is not possible to consider connections made of bare bars. An alternative solution might be the design of the current track made of several single strand cables per phase, connected in parallel, cf. Figure 1. This solutions is simpler to be implemented, more flexible, moreover it is much cheaper than the use of insulated bus-bars. Unfortunately, this solution is not devoid of deficiencies. In many cases it can happen that the individual strands connected in parallel in order to make up a single phase are subject to non-uniform current distribution. This effect may lead to a significant temperature increase in the overloaded strands, sometimes exceeding the long-lasting admissible values, which may lead to shortening of cable insulation service "life" [3] and under certain unfavorable conditions it may lead to cable malfunction or insulation breakdown.

The non-uniform current distribution in individual strands depends on their spatial configuration as well as on other phenomena. On the other hand spatial configuration affects the mutual coupling between conductors leading currents (skin and proximity phenomena related to the flow of eddy currents generated in the strands) [4]. Analytical handling of these effects is rather difficult even for simple geometries. Quite recently Jabłoński *et al.* presented an analytical-numerical method for the skin and proximity effects in a system of two parallel conductors of circular cross section using the method of successive reactions [5]. The approach was extended to take into account the couplings in three phase lines with round conductors in Ref. [6].

De León presented a parametric study of the effects of conductor size, cable grouping, heat exchange conditions, that affect cable ampacity (current carrying capability) both for cables laid in free air and for buried ones [7]. Sedaghat and de León [8] have carried out computations of steady-state temperature of power cables in free air for the most common spatial configurations and compared their results to those resulting from the IEC-60287-2-1 standard [9]. The books [10, 11] are comprehensive sources of information on the issues related to power cable rating and design.

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Figure 1. Multi-strand cable line in a car factory. Source: own work, A. Cywiński.

The paper is complementary to the previous work [12]. The aforementioned publication introduced a simplified approach to assess the current distribution in low-voltage multi-strand cable lines placed in free air, whereas the present contribution focuses on coupled electromagnetic-thermal modeling using commercial software. Both papers have been compiled from PhD Thesis [13]. The following modeling aspects are covered in this contribution:

- description of a laboratory stand for examination of current distribution in multi-strand lines,
- development of a numerical model taking into account coupled electromagnetic-thermal phenomena,
- comparison of computation results from ICEPACK and MAXWELL-MECHANICAL codes for chosen geometries,
- variations of temperature and RMS current values during successive iterations using the coupled electromagnetic-thermal model.

2. Materials and Methods

In the paper [12] a brief description of a laboratory stand used for practical experiments with chosen single-phase systems was given. For physical modeling single-stranded YAKXS-type cables were used (diameters 70mm^2 and 240mm^2). The strand was made of aluminum, insulation – of cross-linked polyethylene (XLPE) and the coating – of polyvinyl chloride, cf. Fig. 2.

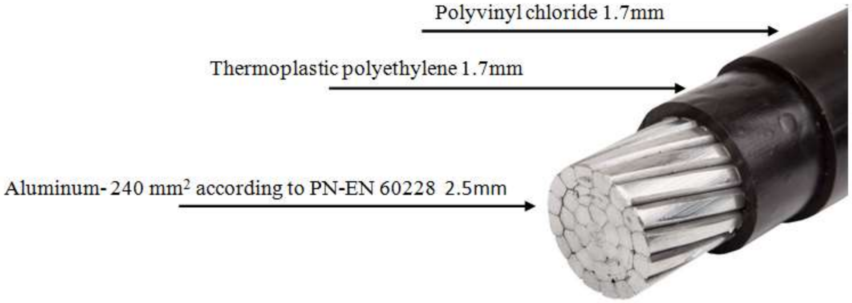

Figure 2. Construction of the YAKXS 1 x 240 cable.

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Table 1 includes the basic data concerning the parameters of the examined cables.

Table 1. Parameters of the examined cables

	YAKXS 1x240	YAKXS 1x70
Working aluminum strand - RMC	240 mm²	70 mm²
Insulation – cross-linked polyethylene	1.7 mm	1.1 mm
Coating – polyvinyl chloride	1.7 mm	1.4 mm
Outer diameter	24.8 mm	14.7 mm
Maximum resistance at 20°C	0.125 Ω/km	0.443 Ω/km
Maximum working temperature	90°C	90°C

The value of the outer diameter was verified experimentally. For chosen sections 15 measurements were made with a digital slide caliper (resolution 0.03 mm) in different points. The following results were obtained for the YAKXS 1x240 cable: 25.71; 26.23; 25.51; 25.61; 25.52; 25.74; 26.11; 25.83; 25.71; 26.23; 25.51; 25.61; 26.12; 25.54; 25.65 mm. The average outer diameter was 25.77 ± 0.03mm.

A fragment of YAKXS 1x240 cable, 138.4cm long (the terminals not taken into account), with resistance 176.75μΩ, was excited with the 608A current (Root Mean Square). This current value was the maximum long-lasting admissible one for this type of cable, according to the producer data. Resistance measurements were carried out using the technical method, using a DC supply source (EMEX 400 DC), with the nominal current equal to 400A. Voltage measurements were made with a digital voltmeter Fluke 177 using the range 0.1-600mV. The accuracy of the measurement: 0.09% + 2 digits. The excitation was achieved using the transformer TW1a (220V, 1 kVA) and the coil DTR4a used for adjusting the current value. The current values were recorded with the PQM-701Z analyzer from Sonel with the use of Rogowski's coils (nominal current 1000 A, minimal fundamental accuracy 1%, according to the producer).

The electrical connection scheme is depicted in Fig. 3. At this point it can be remarked that a similar circuit was used by the authors of Ref. [14].

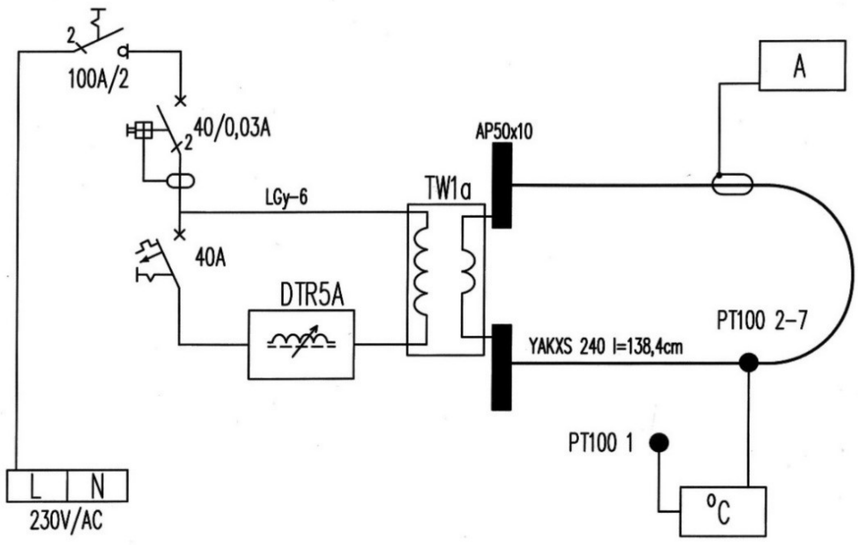

Figure 3. The electrical connection scheme.

3. Numerical model

3.1. Introductory remarks

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In engineering practice the Finite Element Method (FEM) is the prevailing numerical technique to solve partial differential equations that describe phenomena occurring in power cables. Analytical approaches aimed at determination of cable ampacities have a limited application scope, since they may be applied in homogeneous ambient conditions and for simple geometries only [15]. From the literature review it follows that the analysis of coupled electromagnetic and thermal fields for simpler geometries at in-door conditions has been considered by several authors. It should however be remarked that in practice much more attention is paid to the analysis of buried cables [3, 7, 10, 16].

Recently special attention of researchers is focused on the analysis of simultaneous processes within the framework of the so-called multiphysics modeling. An increase in computational capabilities of state-of-the-art computers as well as advanced possibilities of available software make it possible to carry out sophisticated calculations using even desktop computers. There are some good hands-on textbooks on the subject [17-19].

The term "multiphysics" implies an emerging interdisciplinary study area, involving more than one simultaneously occurring physical field and the studies of and knowledge about these processes and systems [20, 21]. Multiphysics approach to modeling means that several phenomena like heat transfer, electromagnetic and mechanical effects are taken into account for the considered material or device. Modeling is carried out using different time and spatial scales and the examined structure might be considerably complex [22-24]. In the context of cable modeling the paper by Chávez *et al.* [25] might be a good example of multiphysics approach. In the aforementioned paper the authors have developed a theoretical model to examine the combined effects of electromagnetic and thermal fields on cable ampacity, taking into account the dependence of resistivity on temperature.

For ampacity calculations in multi-strand cable lines placed in free air at indoor conditions (when it is possible to neglect e.g. the fluid flow affecting heat transfer conditions) the mutual coupling between electromagnetic and thermal fields is of paramount importance. Goga *et al.* carried out numerical computations concerning cooling of a single electrical conductor with insulation [26]. Li and coworkers computed temperature distribution and power losses for typical (flat and trefoil) three phase single strand cable configurations using a simplified 2D FEM cable model [27]. Cirino *et al.* focused on the problem how the cable parameters used in FEM calculations are affected by skin and proximity effects [28]. Korovkin *et al.* presented several possible modeling strategies regarding ampacity modeling using FEM for buried cables [29]. The conclusions drawn by the authors are consistent with the general statements on coupled problems made earlier by Hameyer *et al.* [30], namely for the considered problem the thermal and electromagnetic time scales differ significantly. The electromagnetic part may be coupled to the heat transfer part either by a one-way link, when the generated Ohmic losses are transferred as the input to the thermal model or by two-way links, if subsequently the effect of temperature on conductivity is accounted. For the case of buried cables there are additional problems related to the presence of the grounding circuit.

In the present work electromagnetic and thermal phenomena are coupled using the two-way method, the computations were repeated in a loop until transient phenomena faded away. At least three iterations were needed for this purpose. A representative example depicting variation of temperature distribution over iterations for a flat three phase system is shown in the last part of the subsequent section.

3.2. Modeling

For computations the commercial ANSYS Maxwell software [31] was used. The piece of software makes it possible to model low frequency electromagnetic field phenomena using FEM for solving Maxwell equations. The design of two- and three dimensional systems, taking into account skin and proximity effects is possible. Thanks to integration in the ANSYS Workbench it is also possible to carry out coupled analyses with the use of appropriate mechanical and flow modules. The coupled analyses allow one to describe more precisely such phenomena as e.g. the change in conductivity of the working strand upon temperature increase or cable heating being the result of induced eddy currents.

Model assumptions were as follows:

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- modeling was carried out for 2D geometry. The full 3D modeling is possible in ANSYS, yet it is very time-demanding; some tests carried out by the first author have shown that it may last for several hours even for relatively simple geometries using a state-of-the-art desktop computer;
- individual strands twisted together to form a cable line (cf. Fig. 2) are treated as a whole. This simplification may be called a geometric homogenization on the local scale. The proximity effects are accounted only between „clusters" of strands from the macroscopic standpoint. It can be remarked that this approach is a typical one; yet a recent publication on the wiring system for electrical vehicles focused on a more detailed scale [32].

The geometry for the analysis was prepared directly in ANSYS Maxwell on the basis of real-life dimensions and materials used in the analyzed cables. Figure 5 depicts the geometrical model of a single strand made of aluminum, XLPE insulation and outer coating made of polyvinyl chloride in a six stranded cable. The second part of the Figure illustrates the considered setup. The values for conductivity and resistance temperature coefficient assumed in computations for aluminum were assumed as 34.8 MS/m and 0.0041 deg^{-1}, respectively.

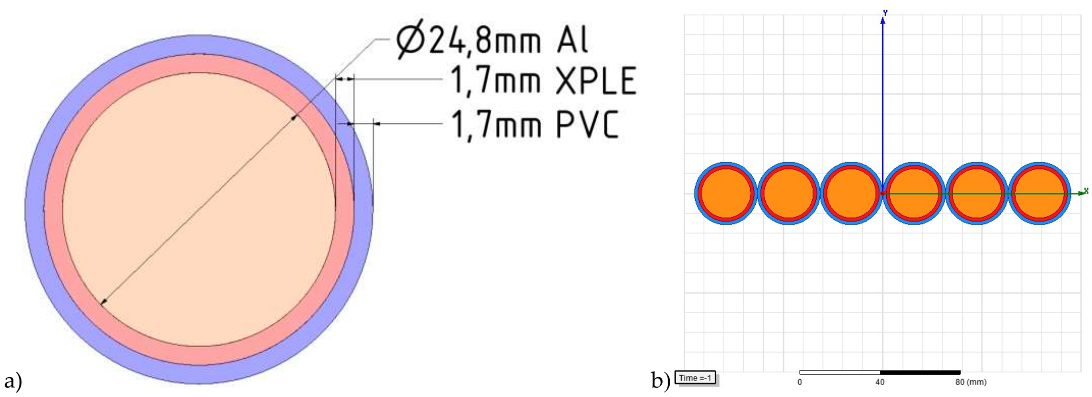

Figure 4. An exemplary model of a six stranded YAKXS 1x240 cable a) a single strand b) the whole setup.

Taking into account the boundary conditions and requirements concerning field analysis, the cables were encompassed with the air domain, as shown in Fig. 5. The domain was prepared in such a way, so that it did not influence the values of magnetic field strength. On its outer boundaries the *Baloon* boundary condition was preset.

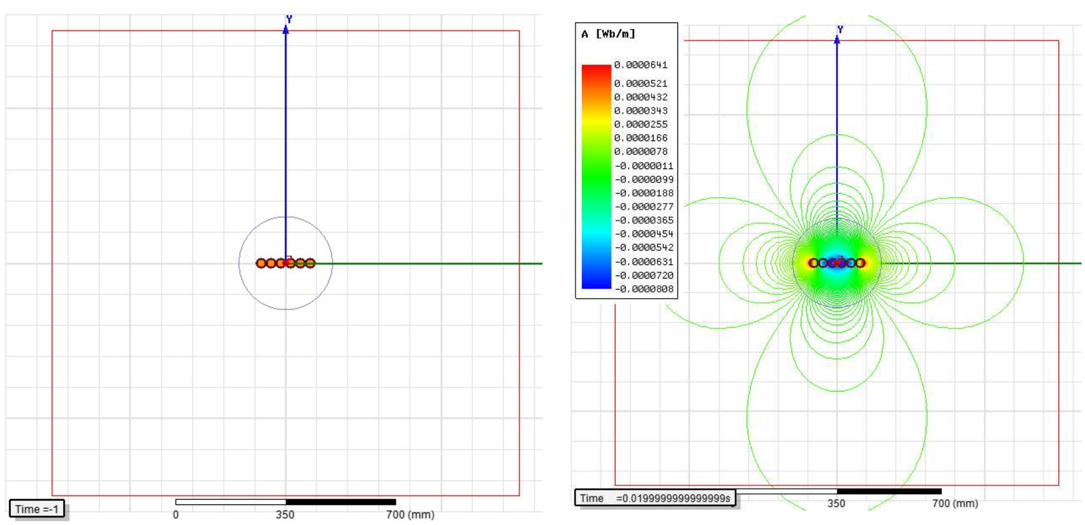

Figure 5. The full computational model

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The analysis was carried out using the Magnetic Transient solver, which makes it possible to monitor instant values of magnetic field intensity taking into account skin and proximity phenomena. In order to obtain more realistic results the contact resistances for cable terminals were included in the equivalent connection diagram, cf. Fig. 5 (the word "zaciski" in Polish stands for "terminals"). It seems important to stress that Maxwell Circuit Editor presented in the Figure allows one to consider different excitation scenarios in a straightforward way, for example if one is interested in the FEM analysis for excitation currents with significant harmonic contents, one has to add additional branches containing sources with appropriately chosen amplitudes and frequencies in parallel to the fundamental supply branch denoted as I0. It is important to stress that in real life conditions the dependencies $i(t)$ might indeed be distorted [33].

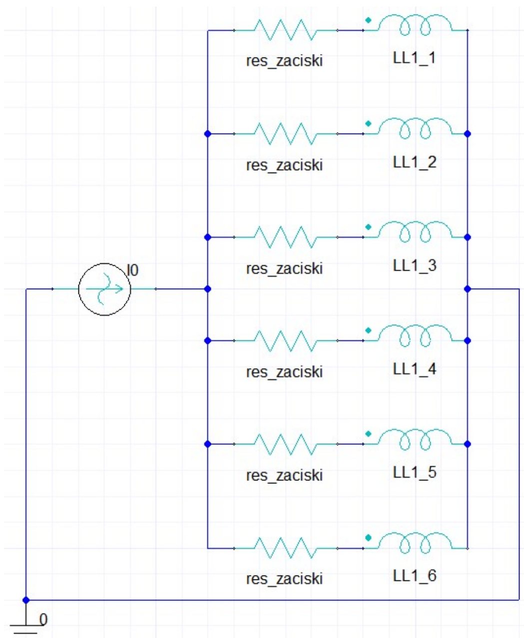

Figure 6. The supply system developed in Maxwell Circuit Editor.

Determination of free convection coefficient, modeling

In order to determine the maximum temperature achieved by the cable with current as well as the temperature distribution inside the cable it is necessary to determine the value of free convection coefficient. It is also necessary to determine the correct values of thermal conductivity for individual layers (insulation and coating), as well as to assume the correct value of radiation coefficient.

For a single strand the heating tests with the maximal long-lasting admissible current were carried out. On their basis the value of free convection coefficient was determined from Newton law. The obtained results were compared to the values from simulations from the ICEPACK module from the ANSYS suite. The estimated values of free convection coefficient, thermal conductivities of outer cable layers and radiation coefficient were introduced into the coupled Maxwell-Mechanical module in order to carry out a verification and a comparison with experimental results from the laboratory stand.

Ambient and strand temperatures were recorded using an eight-channel temperature recorder (AR208 from Apar), equipped with platinum temperature sensors (PT100). These sensors feature high stability of physical properties. In order to increase the measurement sensitivity, the connection of sensor to the examined cable fragment was made using a silver-based conductive paste Zalman STG-2, whereas the attachment to cable surface was made using a silicon tape. Figure 7 depicts the location of temperature measurement points.

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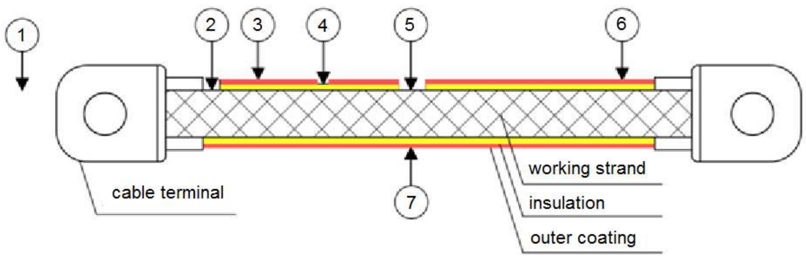

Figure 7. The location of temperature measurement points

Temperature measurements were carried out every 30s. 377 data samples were recorded until the strand and coating temperatures achieved the steady state. The tests lasted 188 minutes. The obtained heating curves for the YAKXS 1x240 cable is depicted in Figure 8. Similar heating tests for a single bare aluminum cable were reported recently by Kasaš-Lažetić et al. [34].

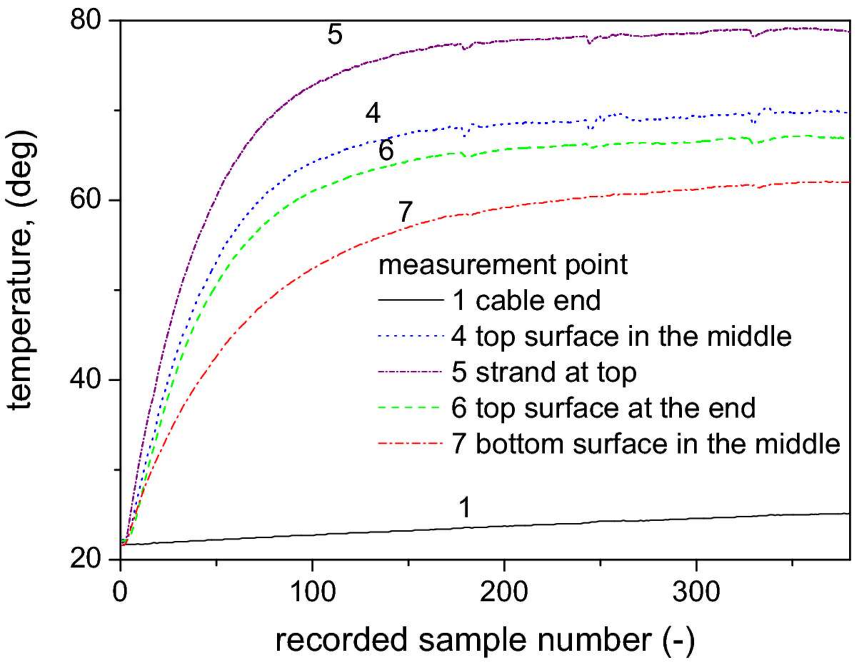

Figure 8. Measured heating curves for chosen locations indicated in Figure 7.

During the measurements the ambient temperature changed from 22.1 up to 24.1^{o}C. The following temperature values were achieved in the steady state:

the working strand	79.0^{o}C
insulation	69.8^{o}C
outer coating (measurement point below the strand)	62.0^{o}C
outer coating (measurement point above the strand)	67.1^{o}C

The value of natural convection coefficient was determined using the Neher-McGrath method [10,35]. The measurements were carried out in a closed room, therefore the effects of heating from solar rays as well as from forced air flow were neglected. Taking into account the measured cable length and strand diameter the surface area was calculated. It was equal to 0.112m^2. Because the strand temperature varied from 62.0 to 67.1^{o}C along the perimeter, the average value 64.55^{o}C was assumed for further calculations. The computed value of natural convection coefficient was equal to h = 10.5 W/(m^2 K).

The following values were assumed for the model developed in the ICEPACK module:

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- unit loss per 1cm length was calculated in Maxwell using the 3D model, it was equal to 0.557W;

- the values of thermal conductivity coefficients were taken from relevant materials science publications. They were as follows: PVC = 0.17W/(m K), XPLE = 0.52W/(m K), ALU = 237W/(m K). The radiation coefficient was 0.94. The ambient temperature was assumed as 26.1^{o}C.

The dependencies temperature vs. iteration number for the working strand (red) and for the outer coating (upper part – blue, lower part – green) are depicted in Fig. 8.

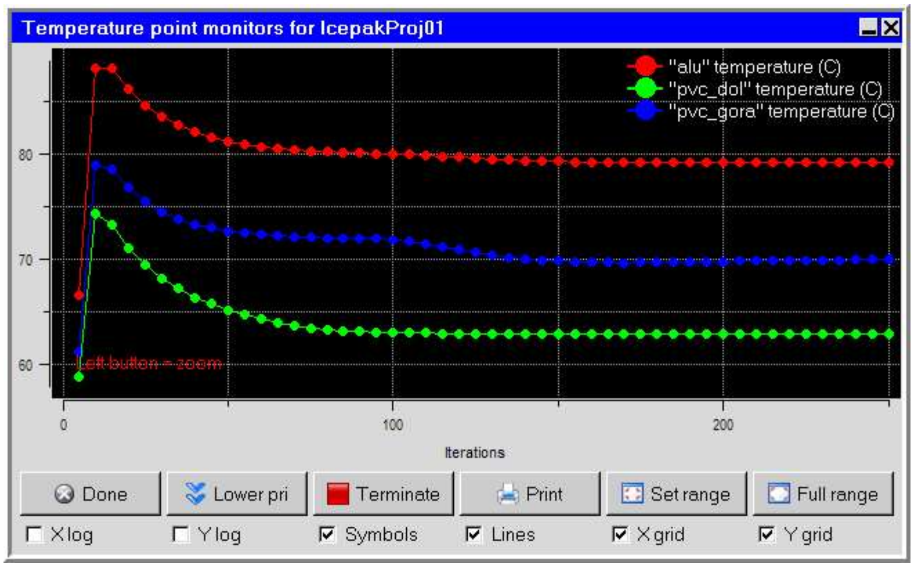


Figure 9. The dependencies temperature vs. iteration number for a single strand from Icepack

Temperature distribution across the cable cross-section, taking into account the individual layers is depicted in Fig. 11. The steady-state temperature values are as follows: for the working strand 79.2^{o}C, for outer coating (measurement point below the strand) – 61.6^{o}C, for outer coating (measurement point above the strand) – 67.9^{o}C, for insulation – 76.2^{o}C. On the basis of carried out measurements the value of free convection coefficient was determined. It was equal to 10.2 W/(m^{2}K).

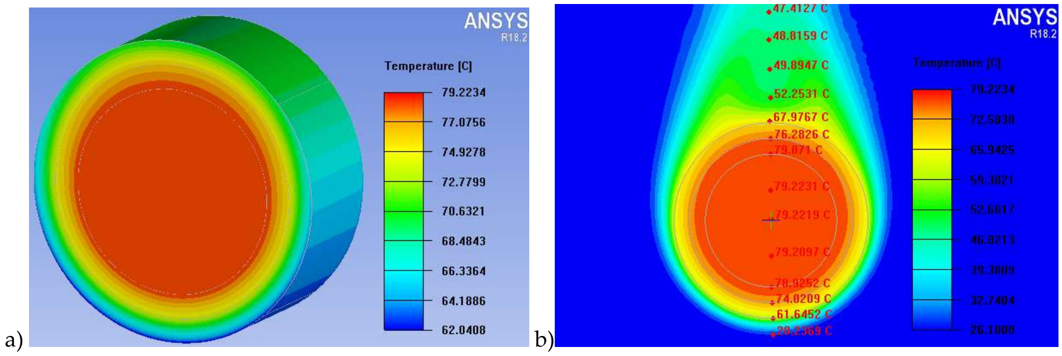


Figure 10. Temperature distribution for a single strand from ANSYS-MECHANICAL: a) computations for the strand itself, ICEPACK b) local temperature distribution of surrounding free air is also shown

The computed value of free convection coefficient and the confirmed experimentally values of thermal conductivity and radiation were subsequently assumed for computations carried out in the MAXWELL-MECHANICAL module for coupled computations. The results of coupled computations for current value 608 A (RMS) and initial ambient temperature 24^{o}C are depicted in Figure 11.

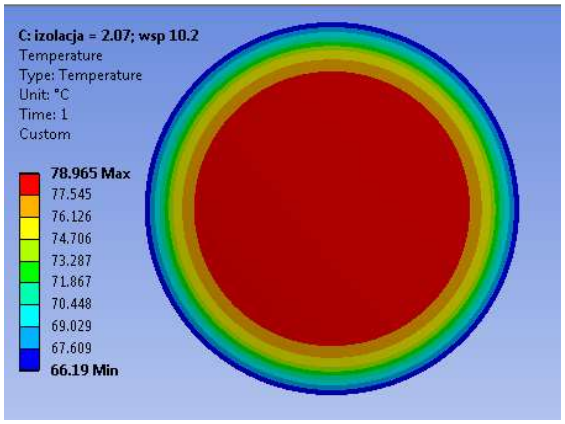


Figure 11. Temperature distribution for the single strand from the coupled electromagnetic-thermal computations using ANSYS-MECHANICAL module

Comparing the results obtained from developed models to those from real-life measurements it can be stated that a reasonable accuracy of the models has been achieved. For subsequent analysis of more complicated spatial configurations the coefficient values describing material properties for the single strand are assumed. In Figures 12-13 the FEM computation results are shown for the trefoil configuration, which is quite commonly found in practice. In Figure 12 the results for congested configuration are depicted, whereas in Figure 13 the cables are set apart, the distance between individual strands is equal to the outer cable diameter. Temperature values computed with both approaches for the strand centers are quite similar (the discrepancies are below 1%), yet it should be remarked that FEM computations made with the ANSYS-MECHANICAL coupled module last significantly longer. On the other hand, the graphics obtained with ICEPACK provide more information, since one can read out local ambient temperature values.

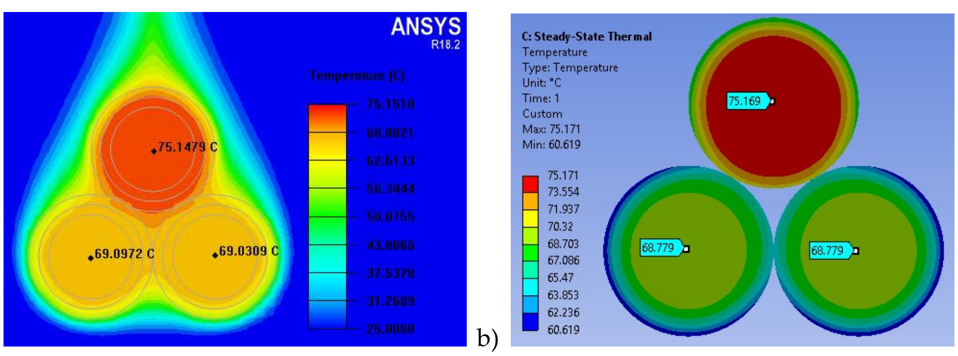
a) b)


Figure 12. Computed temperature profiles for the congested trefoil configuration a) with ICEPACK b) with ANSYS-MECHANICAL coupled module

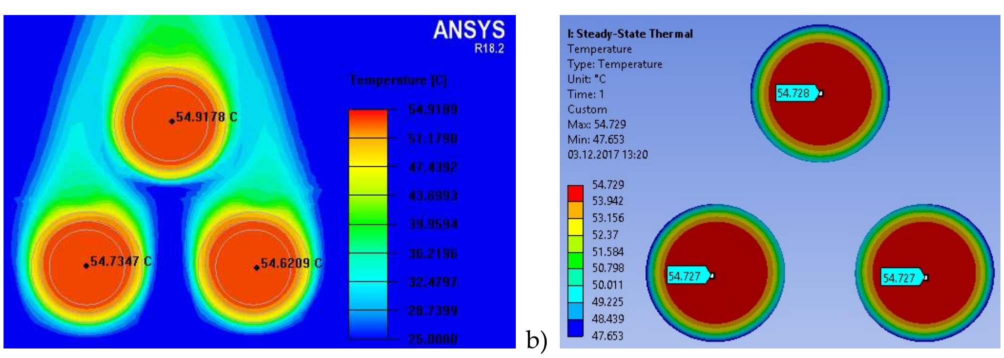
a) b)


Figure 13. Computed temperature profiles for the distant trefoil configuration a) with ICEPACK b) with ANSYS-MECHANICAL coupled module

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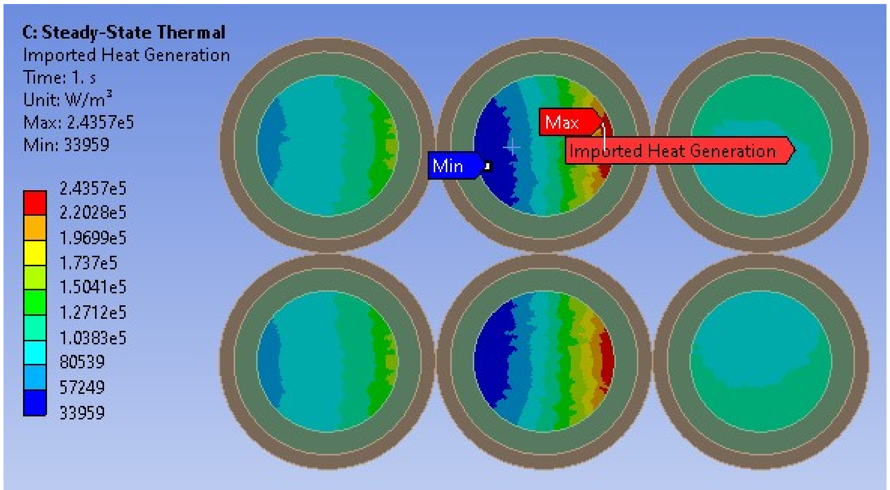
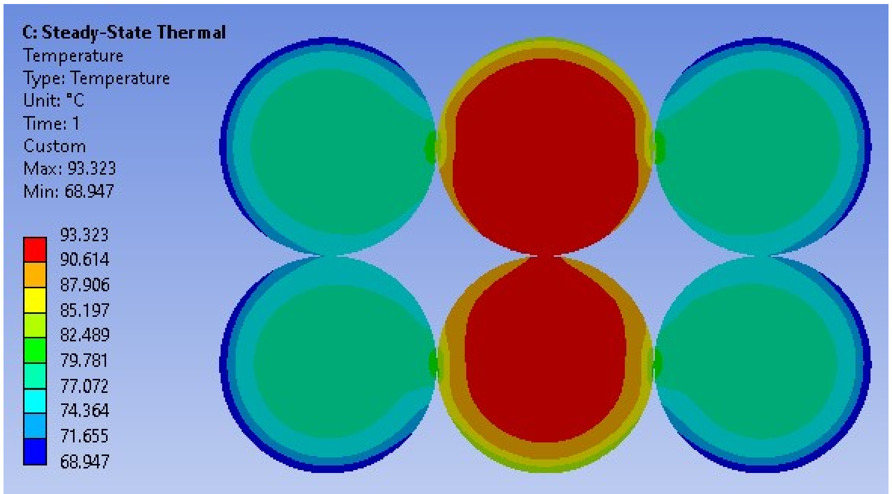
It can be noticed that for the trefoil geometry when the cables are set apart all strands attain practically the same maximal temperature (around 54 deg), which means that favorable heat exchange conditions were achieved. However in practice due to space limitations it is sometimes necessary to use the congested geometry (Fig. 12), which may lead to excessive heating of the upmost strand resulting from convection.

As a representative example for the practical application of the presented method the results of coupled computations are provided for three spatial configurations (two cables per phase) considered previously in Ref. [12]. Some configurations (e.g. the two-row setup ABC/ABC) are not favorable, since they violate the barycenter criterion for uniform current distribution provided in the aforementioned paper. In fact, the computation results indicate that in this case the maximum temperature in the system (obtained for phase B) may indeed exceed the admissible value and thus the system malfunction may occur. Figure 14 depicts the computed distributions of a) power density and b) temperature in the considered setup, whereas Table 2 summarizes the computation results for three chosen configurations.



a)



b)

Figure 14. Computed distributions of a) power density b) temperature for the configuration ABC/ABC

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Table 2. Computation results for chosen configurations

	A1B1C1A2B2C2		A1B1C1/C2B2A2		A1B1C1/A2B2C2	
	P [W]	Tmax [deg]	P [W]	Tmax [deg]	P [W]	Tmax [deg]
A1	22.91		24.73		24.48	
B1	24.61		25.19	90.85	26.87	93.3
C1	24.27	74.1	24.40		24.52	
A2	22.91		24.37		24.53	
B2	24.61		25.21	90.85	26.89	93.3
C2	24.26	74.1	24.40		24.49	
ΣP [W]		143.57		148.3		151.78

In order to illustrate the necessity to carry out iterative computations of coupled electromagnetic-thermal phenomena for practical scenarios we focus on temperature distribution in a single phase system consisting of six strands in flat configuration, cf. Fig. 15.

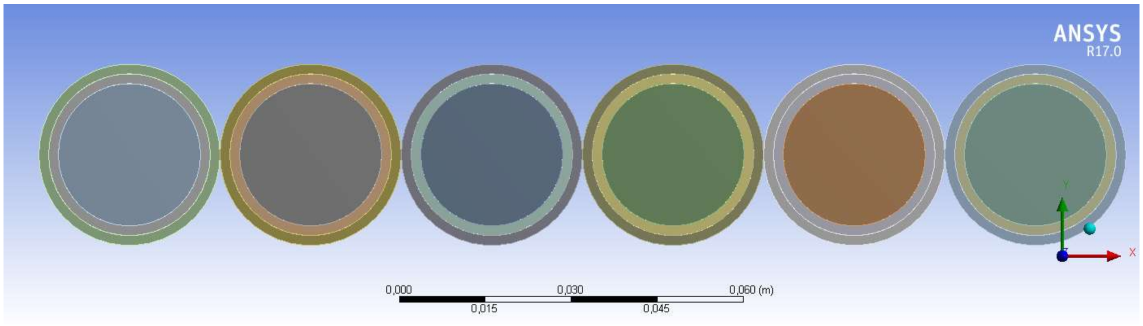

Figure 15. Cable layout for the flat configuration

For computations the value of ambient temperature T_{amb} = 25°C was used as the starting value for computation of aluminum conductivity in the MAXWELL module. In accordance with the assumed algorithm the computed current values after the first iteration were imported to the thermal module and subsequently the temperature attained by individual strands was computed. The highest temperature values (90.3°C) were obtained for the strands at the edges (I_{RMS} = 722 A), the lowest ones (52.1°C) – for the strands in the middle (I_{RMS} = 329 A). The temperature distribution after the first iteration is shown in Figure 16.

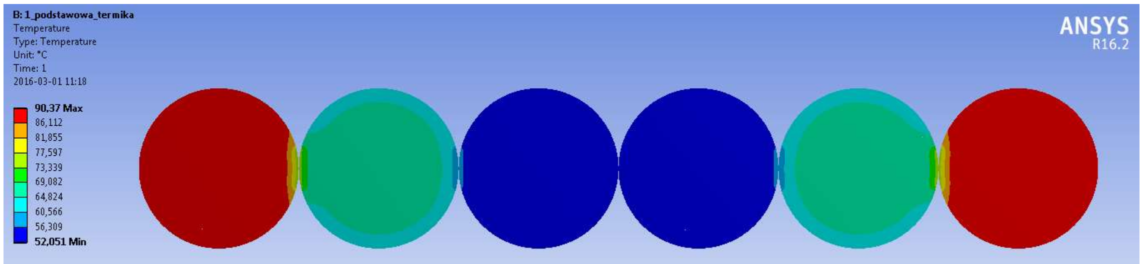

Figure 16. Temperature distribution after the first iteration

For the computed temperature values, new instant values of conductivity for each strand was determined and the computations were repeated iteratively (three iterations) until the temperature values attained steady state. Figure 17 depicts the final temperature distribution. It can be noticed that the maximal temperature for the strands at the edges raised up to the value 103°C. This is an important remark since for the YAKXS cables with cross-linked polyethylene (XLPE) insulation the

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maximal long-lasting admissible temperature is 90°C. Therefore it can be remarked that these strands might be destroyed during operation due to excessive heating.

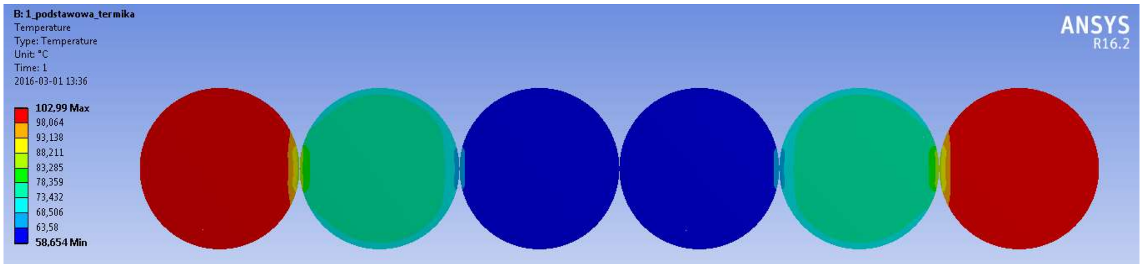

Figure 17. Final temperature distribution

Table 3 lists the RMS current values in individual strands after the first iteration and in the steady state.

Table 2. Computed RMS current values

Strand No.	RMS current after the first iteration [A]	Final RMS current [A]
1	722	687
2	411	437
3	329	348
4	329	348
5	411	437
6	722	687

Conclusions

The paper describes a FEM-based multiphysics approach to model temperature distribution in power engineering cable systems. The conditions of heat exchange are significantly affected by the uneven current distribution in the cable strands caused – among others – by proximity and skin effects. Measurements of relevant physical quantities were carried out and used in subsequent modeling with the commercial ANSYS software suite. The paper describes in detail the steps undertaken to develop realistic, reliable numerical models of power engineering cables, taking into account their geometries and heat exchange conditions.

The modeling results for steady state are compared in the simplest case (a single strand) with the real-life measurement results. It can be stated that considerable agreement was met. The last part of the paper is devoted to modeling of more complex geometries. Two numerical models are compared. One of them is based on the ICEPACK module of the ANSYS suite, the other relies on coupled electromagnetic-thermal FEM computations carried out with the MAXWELL and the MECHANICAL modules, respectively. It is shown that both approaches yield comparable results.

In order to convince the Readers that despite much heavier computation burden it is reasonable to carry out coupled computations, temperature distribution for the single phase flat configuration was computed. Significant discrepancies between the values obtained after the first iteration and in the steady state were shown both for temperature and RMS currents, in particular for the strands at the edges.

As a general remark it can be stated that the quality of the obtained modeling results depends on the skills of the person who prepares the input data, on their accuracy as well as on the simplifying assumptions when the model is formulated. The readers are warned against non-critical trust in the modeling results also in the case of FEM computations.

Author Contributions:

Conceptualization, A.C. and K.C.; methodology, K.C.; validation, A.C., K.C., formal analysis, A.C.; investigation, A.C.; resources, A.C.; data curation, K.C.; writing—original draft preparation, A.C.; writing—review and editing, K.C.; visualization, A.C; supervision, K.C.; project administration, K.C.; funding acquisition, K.C. Both authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

Acknowledgements: A. Cywiński is grateful to Mr. Tomasz Kądziołka from MESco Poland, a distributor of ANSYS software for Poland, for granting access to full version of ANSYS software.

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