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# Low voltage cable lines made of parallel wires – modelling of spatial configuration

***Streszczenie.*** *Orzedstawiono modele linii kablowych wykonanych z żył równoległych w różnych konfiguracjach przestrzennych i ich wpływ na asymetrię obciążenia. Wyniki pomiarów w wykonanych modelach zostały porównane z wartościami zmierzonymi w układach rzeczywistych. Zaproponowano sposoby ułożenia linii wielowiązkowych zapewniające równomierny rozkład obciążenia oraz maksymalną obciążalność długotrwałą.* ***Modele linii kablowych wykonanych z żył równoległych w różnych konfiguracjach przestrzennych***

***Abstract.*** *The paper presents models of cable lines made of parallel wires in different spatial configurations and their impact on load asymmetry. The results of measurements in the developed models have been compared with measurement values in real-life circuits. The methods have been suggested to lay multi-conductor cables which assure a uniform load distribution and maximum long-lasting load-carrying capacity.*

**Słowa kluczowe:** linie kablowe wykonane z żył równoległych, obciążalność długotrwała, zjawisko zbliżenia
**Keywords:** multiconductor parallel cable, current carrying capacities, proximity effects

## Introduction

High current values in supply systems in industry, multi-storey office buildings, electric power plants and distribution network in the case of necessity to carry high power from a transformer, generator or a low voltage switching unit make it necessary to apply current tracks with appropriate long-lasting and short-circuit current carrying capacities. Usually these are made up as bulk busbars or busways. The methods to design and choose the components of these above mention power tracks have been described in great detail in the literature [1,2]. Unfortunately, sometimes due to financial (in the case of busbars) or technical (usually resulting from the design of the object and the location of devices) limitations, it is not always possible to introduce busbars. An alternative solution may be the application of multi-conductor cables lines made of single wire cable set up in parallel way in order to obtain the desired current carrying capacity. Such a solution is easier to use a more flexible and less expensive in comparison to busbars. In many cases, however, it happens that individual wires arranged in parallel connection and making up a single current track (a single phase) are loaded in an uneven manner. This phenomenon may result in a substantial increase in temperature in overloaded wires, which may exceed the admissible values. It is commonly known that excessive temperature above the admissible level leads to a shortened "life" of insulation and in extreme cases may lead to a total break-down of the cable, and result in a fire. Determining the current value, which may flow over a long time in the system of wires and does not result in the temperature increase above the admissible level is thus substantial for safety and reliable operation of the system. The calculation methods concerning current carrying capacity have been described in detail in References [3,4], however the considered examples did not address parallel wires unambiguously. The problem has become so important – in particular in the USA and Canada, that many engineers and scientists working on distribution of electric energy have attempted to describe and solve it.

Some standards concerning the design of low-voltage cable lines such as National Electrical Code [3] or Canadian Electrical Code [4] have tried to introduce solutions how to set cables and to maintain a limited asymmetry of parallel wires. The presented solutions are often not possible to applied in practice due to strong spatial limitations in the area where the line is set up or due to other demands concerning the installation. The researched in to determining the possible current carrying capacity in cables has a long history (since 1890) [5].

The term "Ampacity" defined as admissible long-lasting current carrying capacity was proposed in 1951 by William Del Mar. The first complete study concerning design of cable lines taking into account their current carrying capacity was the work by two American engineers J. H. Neher and M. H. McGrath, „*The Calculation of the Temperature Rise and Load Capability of Cable Systems"* published in October 1957. It was based on experimental attempts to address the complicated Fourier equations, which described the heat flow in the cables.

The fundamental document that regulates the issue of choosing wire diameters concerning long-term current carrying capacity for Polish engineers is the standard PN-IEC 60364-5-523:2001 „Instalacje elektryczne w obiektach budowlanych - Dobór i montaż wyposażenia elektrycznego - Obciążalność prądowa długotrwała przewodów" [6].

The regulations included in it referring to parallel wires (paragraph 523.6) assume that if the conditions such as the same wire length, cross-section area and material are met, the wires which make up a single phase of the current track shall be subject to a uniform loading. For copper wires with cross-section larger than 50mm$^2$ and aluminum ones with cross-section larger than 70mm$^2$ it was just enigmatically mentioned that special configurations are needed for their design. It is worth mentioning at this point that the source European standard IEC 60354-5-52 in the paragraph 523.7 – Appendix H mentions the problem, suggesting at the same time examples of placement of parallel wires [7].

In the present paper the attention is focused on modeling cable lines made of parallel wires. Physical models and CAD simulations have been carried out. The results have been compared to the results obtained in real-life circuits. The methods to design cable lines made of parallel wires have also been proposed.

## A physical model

In order to model cable lines made of parallel wires six physical models have been developed. For five of them the cables YAKXS 1x70 were used for the wires, whereas for the sixth one the cable YAKXS 1x240 was used. Each of the developed models was a single phase circuit. The current excitation was applied using a TW1a (220V, 1kVA) transformer and a DTR5a inductor was used to control the current value. The current values have been recorded using a PQM-701Z analyzer from Sonel with current transformers (Rogowski coils with rated current 1000A and minimum basic accuracy 1 %). The electrical equivalent diagram is depicted in Fig. 1, whereas the spatial configuration of the developed models is shown in Fig. 2. The view of the measurement stand and one of the developed models is shown in the photograph No. 1.

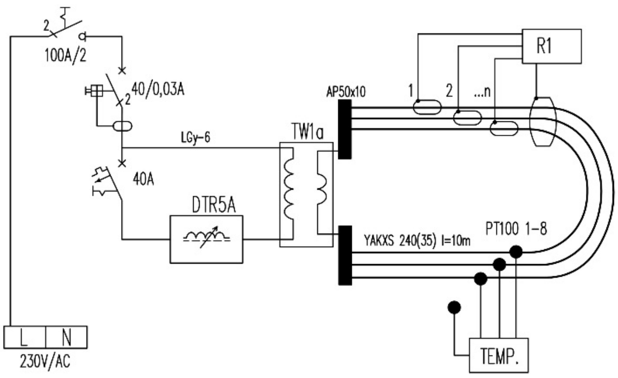



Fig.1. The equivalent diagram of the laboratory stand

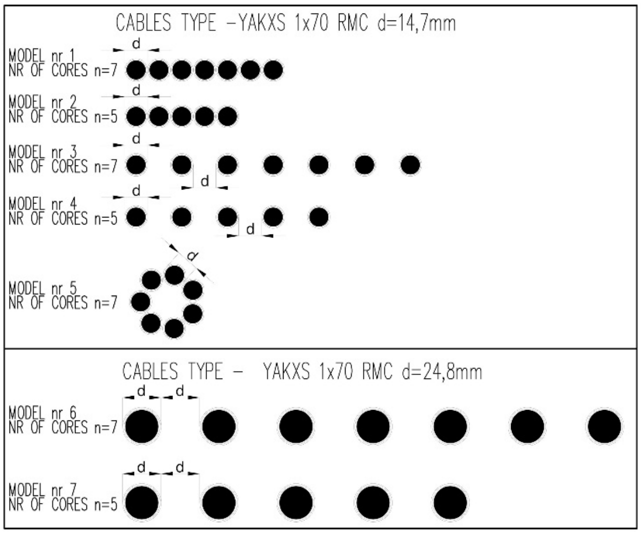
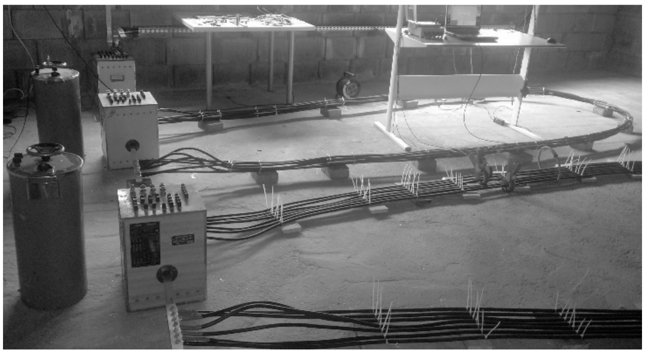



Fig. 2. Spatial configuration of the wires



Phot.1. The view of the measurement stand

For each of the developer models three current values were chosen for excitation i.e. 200A, 300A and the maximum attainable value. For each current value of the secondary winding of the transformer the ratio of load of individual wires was similar, therefore the results for the maximum current value for each model shall be presented. Before the actual measurements were started, the measurements of resistance of individual wires were carried out. The difference between the extreme values was less than 1 %. During tests a Sonel device was used, type MMR-620. The temperature of each wire before the actual measurements was the same and it did not change much during the measurements (taking into account the current values and the time spent on measurements). Recording of the ambient temperature and the temperature of each wire was made using an eight-channel temperature recorder using PT100 probes.

Due to very small values of wire resistances (4,42mΩ – for the YAKXS 70 cable, 1,21mΩ – for the YAKXS 240 cable) it was crucial to prepare the cable connections in a correct way and to minimize the contact resistance. The helical connections were made and the cable endings were pressed from both sides using aluminum bars.

Table 1. A summary of wire loads

| | **YAKY 1x70** | | | | | **YAKY 1x240** | |
|---|---|---|---|---|---|---|---|
| | M1 | M2 | M3 | M4 | M5 | M6 | M7 |
| Z1 | 116A | 138A | 66A | 94A | 104A | 132A | 132A |
| Z2 | 104A | 128A | 66A | 84A | 94A | 86A | 90A |
| Z3 | 98A | 126A | 66A | 76A | 86A | 68A | 78A |
| Z4 | 92A | 128A | 66A | 70A | 92A | 62A | 84A |
| Z5 | 98A | 140A | 66A | 72A | 104A | 58A | 104A |
| Z6 | 102A | | 68A | 84A | | 66A | |
| Z7 | 116A | | 66A | 106A | | 96A | |
| Σ | 726A | 660A | 465A | 586A | 480A | 568A | 488A |

In order to compare the obtained results for all models the ratio of load of the extremely loaded wires was calculated, it was defined as the asymmetry ratio

(1) $$k_{AS}=I_{max}/I_{min},$$

$I_{max}$ – current value for the maximally loaded wire,
$I_{min}$ – current value for the minimally loaded wire,

The obtained results are given in Table 2.

Table 2. Asymmetry coefficient – physical model

| | MODEL | | | | | | |
|---|---|---|---|---|---|---|---|
| | M1 | M2 | M3 | M4 | M5 | M6 | M7 |
| $\mathbf{k_{AS}}$ | 1,26 | 1,11 | 1 | 1,51 | 1,20 | **2,27** | 1,69 |

**A CAD model**

The possibilities to avail of numerical CAD procedures based on the finite element method, concerning the method to calculate characteristic parameters of multi-wire cable lines, which take into account the phenomena of proximity and skin effect, have been described in the publication [10], whereas high accuracy of the method has been confirmed in papers [11], [12]. Until now there has been no analytical method based on field theory, which makes it possible to assess the mutual effects of several wires, which make up a single current track. This phenomenon for the system of two tubular parallel wires was described in the paper [13] and solved analytically using Kaden equations. On the other hand an attempt to calculate the total loss taking into account the proximity and skin effects was presented in a quasi-analytical manner for the system of three wires per phase in the paper [9]. Carrying out the classical calculations for the system of several parallel wires per phase is extremely complex. In order to simulate the behavior of developed physical models the software FEMM was used. FEMM (Finite Element Method Magnetics) is a software package aimed at solving two dimensional flat problems for low frequency electromagnetic field and electrostatics. For the analyzed problem the module for magnetic problems was used, which solves the preset Maxwell equations. For each physical model an equivalent FEM model was developed under the assumptions of the same spatial configuration, wire parameters (length, cross-section and material) as well as the current excitation. The obtained results (coefficient $k_{AS}$) are presented in Table 3. For the most characteristic models i.e. M3 and M6 a comparison of load of individual wires was presented in the form of charts. Moreover, a simulation of the real system using the Ansys platform was made. Two modules – Maxwell and Mechanical were used in order to describe the electromagnetic and thermal phenomena in parallel wires.

ble 3. Asymmetry coefficient - model FEMM

| | MODEL | | | | | | |
|---|---|---|---|---|---|---|---|
| | M1 | M2 | M3 | M4 | M5 | M6 | M7 |
| **$k_{AS}$** | 1,74 | 1,36 | 1 | 1,76 | 1,41 | **2,32** | 2,04 |

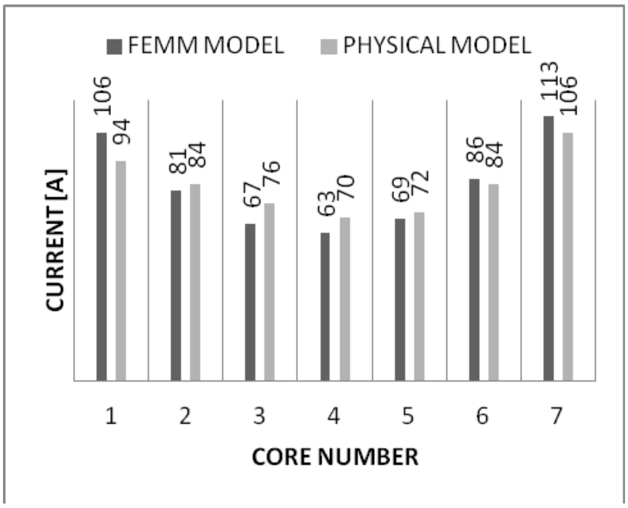



Fig.2. Wire load for the model M3

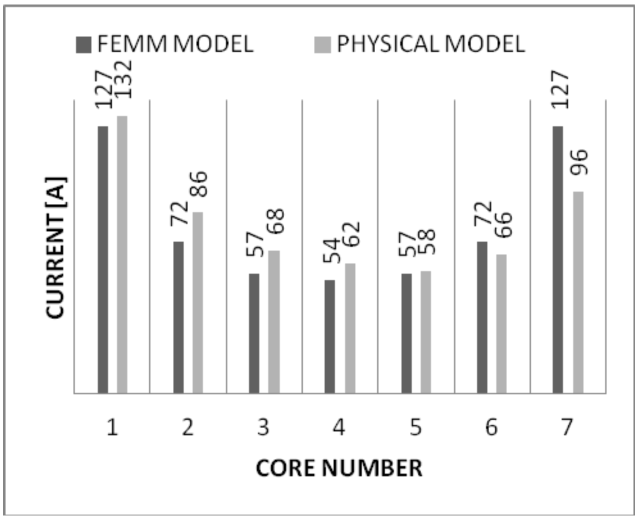



Fig. 3. Wire load for the model M6

The obtained results confirm the possibility of occurrence of non-uniform load in the system of parallel wires. The asymmetry coefficient is dependent mainly on the geometrical configuration of the wires, as well as on the wire cross-section and their number in the bundle (group), which may be confirmed with theoretical considerations. Comparing the results from the physical and CAD models for the flat system (models M1,2,4,5,6,7) it can be stated that the difference in load for the extreme wires is smaller, in particular for the 240mm$^2$ cable. The difference is the most significant for extremely loaded wires, whereas in the minimally loaded wire the current values are comparable. It depends on the parameters of the physical setup, in particular on the contact resistance (connection of cable endings with the transformer bar), which plays an important role regarding the length (10 m) of the used cables, diminishing at the same time the importance of mutual reactance of reacting wires, thus decreasing the current value in the edge wires. For the M3 model, in which the wires of the cable bundle were placed along a circle the results from the physical and the CAD models are the same. The asymmetry coefficient is equal to unity and all wires are loaded uniformly. It proves that the connections of cable endings and transformer bar have the same contact resistance. The cable lines made of parallel wires for large powers are usually made of cables with a diameter of 240mm$^2$. The use of wires with smaller diameters is useless. In the analyzed cases of real-life production plants in which parallel lines were used (11 such plants were considered) in each case the aluminum wires with 240mm$^2$ cross-section were applied. The placement was like the M1 model (four cases) and the M3 model (seven cases). The methods to transter power from the 110/20kV and 110/6kV transformers for the low voltage supply in three stations were also analyzed. In that case five parallel wires per phase were used and in each case the line was placed in accordance with the M3 model.

**A numerical CAD model of a real-life system**

For comparison of the recorded measurements of a real-life system a 2D numerical model were used was developed in the Ansys platform. Two modules namely– Maxwell and Mechanical. For the developed model a single step joining two modules was applied i.e. for the fixed initial temperature of the wires (20$^o$C) the calculations concerning current distribution were carried out and the results were next imported to the Mechanical module in order to carry out thermal calculations. Due to the limitations of the 2D model carrying out subsequent iterations for the current distribution were not possible. For the calculations, the parameters of the real-life system were assumed. The coefficient of heat transfer for the wires was assumed to be equal to 5 W/m$^2$K. The system made of six wires 50 m long, YAKXS1x240mm$^2$ type, was modelled. Theoretical long-term admissible current capacity assuming symmetrical load was assessed as 409A/wire. The calculation results are given below in agraphical and in a tabular form.

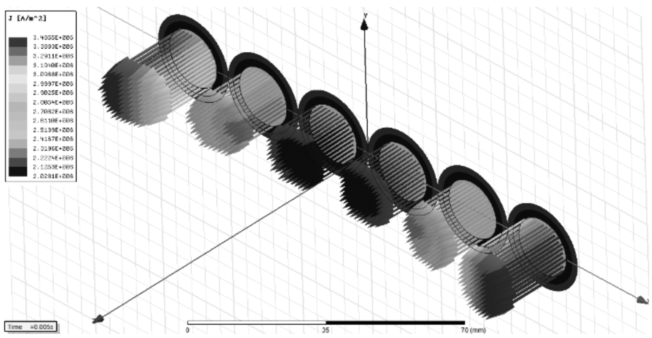


Fig.4. Distribution of current density vector

Table4. A summary of effective value of current and temperature

| | NUMBER OF WIRE | | | | | |
|---|---|---|---|---|---|---|
| | Z1 | Z2 | Z3 | Z4 | Z5 | Z6 |
| I [A] | 543 | 374 | 309 | 309 | 374 | 543 |
| t [$^0$C] | **104** | 88 | 70 | 70 | 88 | 104 |

The calculated value of asymmetry coefficient is equal to $k_{AS}$=1,76.

For comparison the current values recorded in a real life object are given in table below.

Tab.5. A summary concerning the effective value of current

| | NUMER ŻYŁY | | | | | |
|---|---|---|---|---|---|---|
| | Z1 | Z2 | Z3 | Z4 | Z5 | Z6 |
| I [A] | 375 | 292 | 244 | 223 | 278 | 321 |

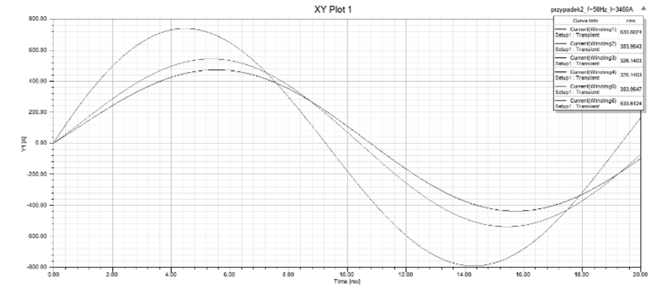



Fig.5. The time dependence of wire load

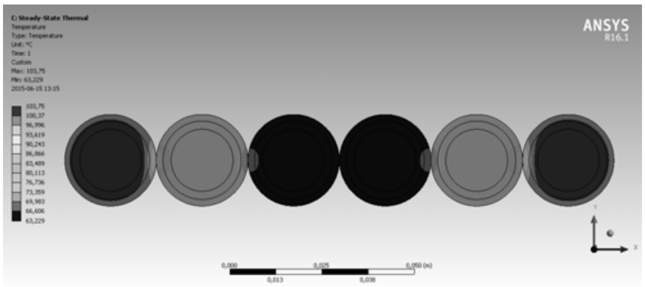



Fig.6. Temperature distribution

The calculated value of asymmetry coefficient is equal to $k_{AS}$=1,76 and is the same as for the numerical model.

## Summary

The paper focuses on the issue of non-uniform current distribution in multi-conductor cable lines. This problem is usually neglected in the international standards The measurements carried out in the developed physical models and numerical CAD model have proven the possibilty of potential dangers related to design and development of low voltage cable lines made of parallel wires due to non-uniform loading of individual wires. The examples of recorded time dependencies from real-life objects and an analysis of faults support the idea that it might be purposeful to introduce corrections to the standard [4], which would point out the possibility of the occurrence of asymmetry in the load of individual wires due to their configuration. Moreover, the amendments could suggest the methods of placement for typical supply systems, providing correction coefficients for the calculation of ampacity of cables made of parallel wires as well as deny the recommendations for the flat system, which is up to date theone most used in practice. The presented methods of placement in the Canadian [6], American [5] or European [9] standards do not address the issue fully. These regulations just present some possible solutions, but they do not provide the methods to calculate the current carrying capacity. Also the preferred system of mixing wires within a single bundle is inconsistent with habits and design experience of generations of Polish electric power engineers. In the future successive studies on physical models are planned. They will be aimed at minimizing additional resistances affecting the conducted measurements, the use of a transformer, which would make it possible to excite currents with substantially higher values, which in turn would make it possible to examine the heating and cooling phenomena, in particular for the spherical configuration as well as the development of a 3D model, which would make it possible to carry out multiple couplings between the Maxwell and Mechanical (or Icepack) modules within the Ansys platform in order to simulate the actual phenomena related to heat transfer in order to determine the admissible current carrying capacity for the proposed configurations of cable lines made of parallel wires. The system preferred by the authors it is the spherical configuration and leading a single phase with a single track.

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