ESTIMATION OF SUPPLY LINES IMPEDANCE IN LOW-OHMIC FURNACES USING NUMERICAL METHOD OF ELEMENTARY CONDUCTORS

Oszacowanie impedancji przewodów zasilających w piecach o niskiej impedancji przy zastosowaniu numerycznej metody przewodników elementarnych

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Summary: **This article deals with another exhibition of possible using numerical method of elementary conductors. It is applied in the course of analyze impedance relations of one and three phases supply lines to low-ohmic furnaces, in configurations of single and bundled lines. Results of analysis can be used for cross section form optimalisation and spatial configuration of objective supply lines. Optimalisation of particular conductors leads to reduction of electric loss and to improvement of some process properties of electrical furnaces working in low ohmic mode.**

Streszczenie: **W artykule przedstawiono kolejny przypadek możliwego wykorzystania numerycznej metody przewodników elementarnych. Zastosowano ją w trakcie analizy zależności impedancyjnych jedno- i trójfazowych przewodów zasilających piece o niskiej impedancji, w układzie przewodów pojedynczych i przewodów wiązkowych. Wyniki analizy mogą być wykorzystane do optymalizacji przekrojów i konfiguracji przestrzennej omawianych przewodów zasilających. Optymalizacja poszczególnych przewodników prowadzi do zmniejszenia strat elektrycznych i do poprawy niektórych własności technologicznych pieców elektrycznych pracujących w stanie niskiej impedancji.**

Keywords: skin effect, proximity effect, surface effect, resistance, reactance and complex reactance of conductor, impedance asymmetry of lines
Słowa kluczowe: azjawisko naskórkowości, zjawisko zbliżenia, zjawisko powierzchniowe, rezystancja, reaktancja i reaktancja zespolona przewodnika, asymetria impedacyjna przewodów

1. INTRODUCTION

In journal EPQU we have already concerned of surface events problematics in supply lines of electric energy to low ohmic furnaces. Their existence is conditional of presence of powerful electromagnetic fields, generated by currents order of kA in their magnitudes. Specifically, in issue 2 (vol. 7/2001) in this sequence we have presented the numerical method of elementary conductors as physically demonstrated and sufficiently objective, when the required criteria of real conductor partitioning into elementary is kept [1]. In issue 1 (vol. 9/2003) we have presented some results of analyze field influence to real component of conduction impedance by form of skin effect and proximity effect formulation as functions of geometrical parameters single conductors as well as bundle conductors. There has been exploited the method of physical similarity for electromagnetic event in construction characteristics [2].

In projection practice is required to know both impedance components and expressed in absolute values in specific projection supply lines. Besides of depth of penetration electromagnetic wave they are dependent on type of conductors' cross-section and their spatial configuration, changing theirs geometrical parameters can optimalize them.

In this contribution thus we introduce surface effect influence into conductor impedance, respectively bundled conductors in one and three phase arrangement complexly, that is exactly by estimation of their resistances and reactances for various geometric configurations. Presented results are

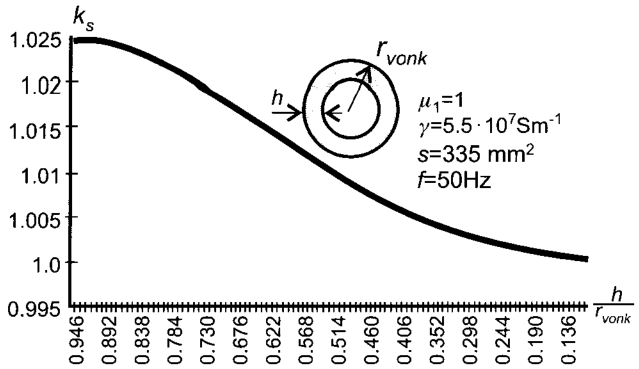

Fig. 1. Skin effect coefficient dependence on specific thickness of cylinder conductor h / r_{ext}

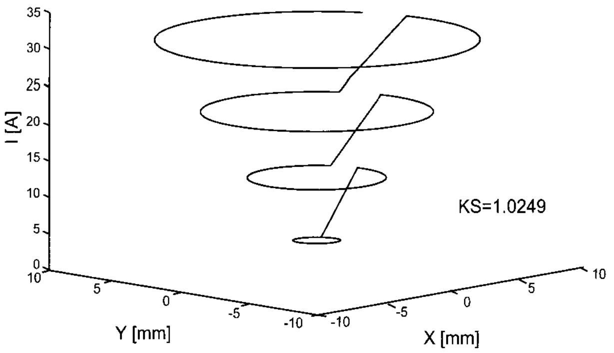

Fig. 2. Elementary currents of elementary conductors net for copper conductor r_{ext} = 10,33 mm, $n_r = 4$, $n_\varphi = 16$ at frequency of 50 Hz

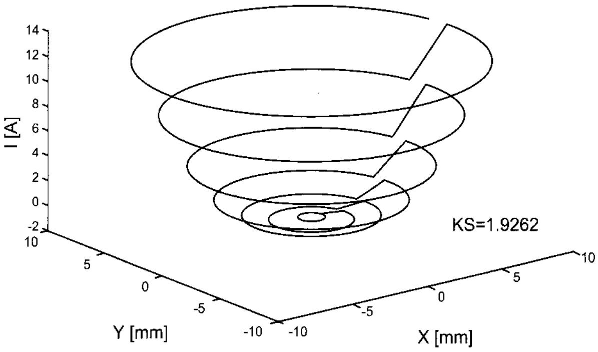

Fig. 3. Elementary currents of elementary conductors net for copper conductor r_{ext} = 10.33 mm, $n_r = 7$, $n_\varphi = 43$ at frequency of 500 Hz

content of solving part of research project VEGA SR No. 1/ 10063/04 with the name "Raising of reliability and transmission efficiency of power lines."

2. ADDITIONAL NOTES TO APPLICATION OF METHOD OF ELEMENTARY CONDUCTORS

The principle of numerical method of elementary conductors and its possible application for analysis of surface events in the conductor were published in literature [1,2]. Considering of estimate precision of appropriate coefficients the essential requirement of its application is partitioning the real conductor onto elementary with the rate, that current density on their cross section was constant. Smaller dimensions, than the depth of penetration of electromagnetic wave is equivalent satisfy this requirement.

For schematic sample of conductor partitioning let us chose the copper hollow pipe, which is supplied by load current I = 1 kA. Current density 3 A.mm^{-2} (for water cooled conductor) is allowed for corresponding active cross section of S = 335 mm^2. For chosen external radius of copper pipe, for example r_{ext} = 12 mm is corresponding to r_{int} = 6.1 mm. Depth of penetration at frequency of f = 50 Hz is ($\mu_r = 1, \gamma = 5.5.10^7$ S.m^{-1}):

$$a_{50} = \sqrt{\frac{2}{\mu_0.\mu_r.\gamma.\omega}} = 9.602 \text{ mm}$$

Its responsible number of elementary conductors [2]:

— In direction of r — coordinate with the introduced radii r_{ext} and r_{int}:

$$n_r \geq 2 \cdot \frac{r_{ext} - r_{int}}{a} = 1.249$$

— In direction of φ-axis:

$$n_\varphi \geq 2 \cdot \frac{2\pi.r_{ext}}{a} = 15.69$$

By approximating of number of conductors in direction of r – coordinate to $n_r = 4$ (what is the minimal count in direction of r – coordinate) and in direction of φ – axis to $n_\varphi = 16$, is the real conductor divided into $n_r .n_\varphi = 64$ of elementary conductors. This number of conductors is sufficient condition of stable and thus enough accurate enumeration.

Applying the objective method to estimation of skin effect coefficient of chosen conductor we obtain for example the dependence, represented at Fig. 1 [2].

It represents the change of conductor resistance flown by alternating current, because direct current is constant rated by reason of uniform cross section. If there are satisfied conditions on the mechanical hardness it confirms the benefit regarding of electrical loss amount. Application of elementary conductor method in Matlab program environment besides enumeration accuracy provides also the conception of current arrangement by affecting surface effect. On the next Fig. 2, there are plotted particular elementary currents of solid cylindrical conductor divided to 4 x 16 elementary. To cross section 335 mm^2 corresponds the radius r_{ext} = 10,33 mm. Although the graph is not faithful for reading of currents sizes (it is necessary to rotate it in the space, what Matlab provides), it is sufficiently physically visual and representing essence of skin effect [3].

In order to show you also the influence of penetration depth for partitioning of conductor, let us consider that the conductor is flowed by current of constant magnitude, but with the frequency of 500 Hz. At this frequency the penetration depth is:

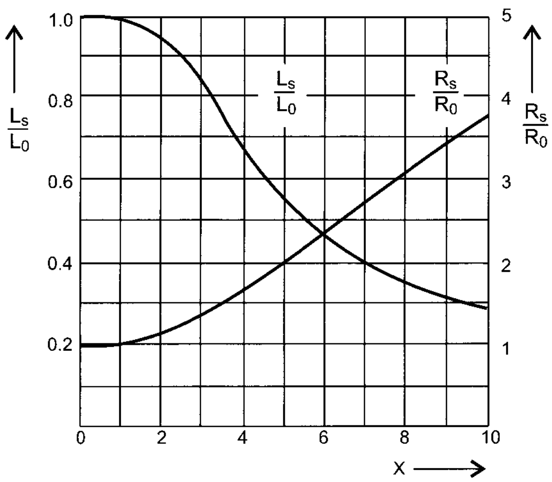

Fig. 4. The relative change of effective resistance and internal inductance of cylinder conductor

$$a_{500} = 3.036 \text{ mm},$$

corresponding to partitioning the conductor with the following number of elementary:

— in direction of r – coordinate: $n_r^{/} \geq 6.805$

— in direction of φ – axis: $n_\varphi^{/} \geq 42.76$

Let us approximate it to $n^{/}_r = 7$ and $n^{/}_\varphi = 43$, i.e. the overall number of elementary conductors will be 301.

At this frequency the arrangement of elementary currents is depicted on Fig. 3 [3].

Comment: We alert the readers of EPQU to mistake in article [2]. Expressions (2) and (3) are exchanged. The correct expression (2) is valid for conductor partitioning in direction of φ – axis, expression (3) for partitioning in direction of r – coordinate. Authors of the article apologize for incurred mistake.

3. IMPEDANCE OF CONDUCTORS IN ONE-PHASE SYSTEMS

We know, from the theory of electromagnetic field that, when the single conductor is flowed by alternating current, the inherent activity of magnetic field express not only by increasing of resistance (decreasing of active conductor cross section – that is the skin effect), but also by decreasing of conductor self inductance (magnetic field inside the conductor is weaken). Thus, both components of impedance are changed with the intensity depending upon penetration depth of electromagnetic wave and specific conductor dimension. On the Fig. 4, there are represented these changes for cylinder form of conductor with the radius of r in relative values (R_S and L_S are resistance and inductance of conductor flowed by alternating current, R_0 and L_0 are resistance and inductance of the same conductor flowed by direct current).

Physically similar effects are indeed applied in system of several conductors. In n – conductor pack, for example to i – th conductor valid for $i \in \langle 1,n \rangle$, besides of intrinsic field, there are affecting also the fields from the rest of adjacent conductors, as well involving changes of both components of impedance. The overall resistance of solid i–th conductor will be

$$R_{ci} = R_{0i}.k_{si}.k_{bi} \quad (1)$$

where:
k_{si} is the coefficient of skin effect
k_{bi} is the coefficient of proximity effect

$$k_{bi} = \prod_{j \neq i}^{n} k_{bi,j} \quad (2)$$

which can be negatively or positively influenced to transmission ability of conductor, dependent upon current directions in particular conductors.

The overall inductance of i–th conductor is affected besides of self inductance also with mutual inductances of adjacent ones.

$$L_{ci} = L_{vi} + \sum_{j \neq i}^{n} M_{ij} \quad (3)$$

It characterizes reactive losses of solid conductor coupled with the energy transmission.

Because both components of impedance, besides of electrical (ω, also f) and material parameters (μ, γ, also ρ), are also depended on the form of conductors, their correlation space configuration and direction of currents flow in conductors, they can be properly manipulated with them. These possibilities represent following examples, in which we will consider copper conductors in form of hollow pipes ($\gamma = 5{,}5.10^7$ S.m^{-1}, $\mu_r = 1$), flowed by currents with frequency of 50 Hz.

3.1. Impedance change of simple one phase input line

Input line parameters:

2x copper pipe of $l = 1$ m, radii: $r_{ext} = 60$ mm, $r_{int} = 50$ mm, pipe wall width: $h = 10$ mm, active cross section of pipe: $S = 3456$ mm^2.

On Fig. 5 there is represented change of both components of pipes impedance in dependence on mutual distance d. The effective resistances both of pipes decrease with distance, because the influence of proximity effect is decreasing. On the other hand the overall inductances increase, because the mutual inductances contribution decreases.

3.2. Impedance change of bundled one phase conductor

Solid system (Fig. 6) consists of 4 pipes, normalized radii $r_{ext} = 30$ mm, $r_{int} = 17{,}5$ mm ($h = 12{,}5$ mm), of the same length $l = 1$ m. Radii are chosen in order to active cross section could be comparable to example in section 3.1 (2x1865 3456 mm^2).

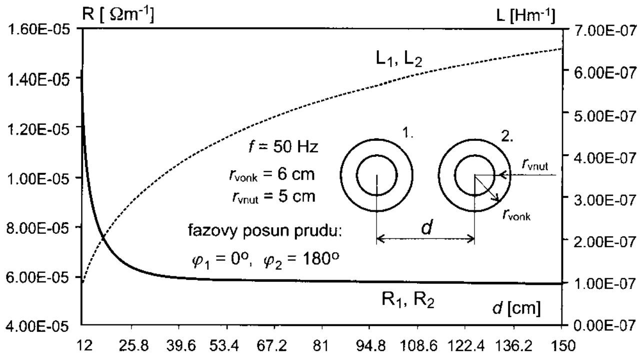

Fig. 5. Resistance and inductance dependency of pipes on mutual distance

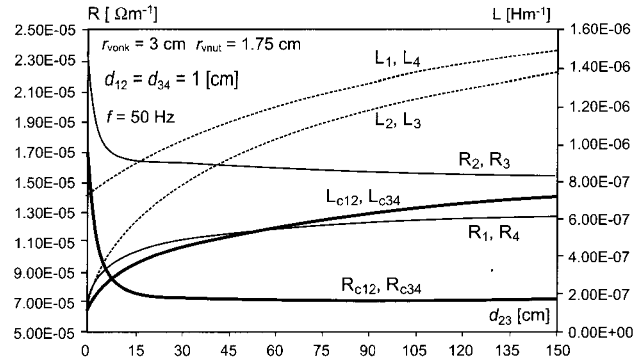

Fig. 7. Resistance and inductance dependency of pipes and bundle of pipes on mutual distance

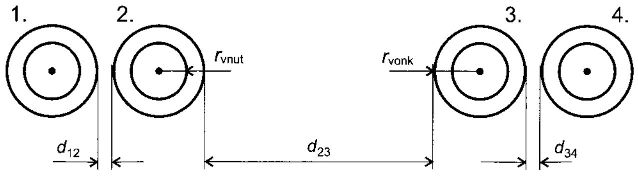

Fig. 6. Two wire bundle of hollow pipes

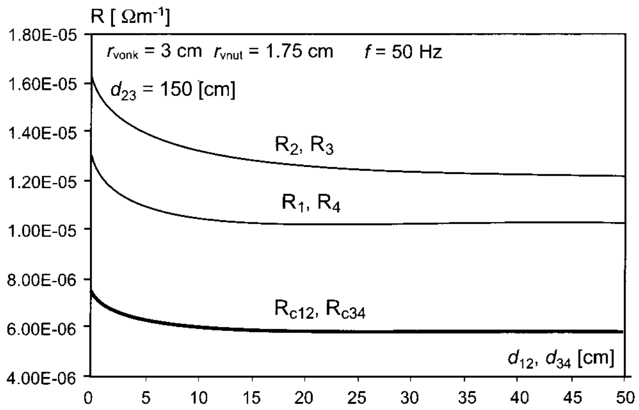

Fig. 8. Resistance and inductance dependency of pipes on their internal distances $d_{12} = d_{34}$

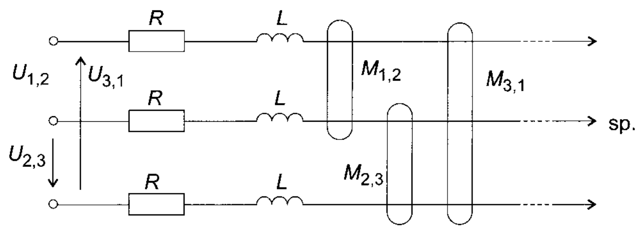

Fig. 9. Simple three-phase system of conductors

Equivalent resistance and inductance change of particular pipes and bundle in dependence on mutual distance d_{23} is represented on Fig. 7.

Characteristics are corresponding to dependencies on Fig. 5; therefore they don't involve detailed commentary. Concerning of bundle projecting it is interesting to observe the influence of pipes distance in bundle (d_{12}, also d_{34}) upon both components of impedance. This dependence represents Fig. 8, separately for resistance change and for inductance change.

Physical interpretation of characteristics is simple:

Increasing of internal distances d_{12}, also d_{34} causes decreasing of proximity effect influence and decreasing of mutual inductances M_{12}, also M_{34}. Therefore the resistances and overall inductances decrease (pipe pairs are flowed by currents of the same direction).

Analogical results were by authors obtained also for other conductor forms, for example for copper stripes.

4. CONDUCTOR REACTANCE IN THREE PHASE SYSTEMS

The influence of powerful electromagnetic fields through the surface events to three-phase line impedance is more complicated. In active component of impedance is not applied only the skin effect and proximity effect, but also well known effect of living and non-living phase, as well as interphase transmission power effect. Their source is complex line reactance, which is caused by generally different mutual inductances among the phases in consequence of their space asymmetry. This three phase system than behaves like impedance asymmetric also with symmetric voltage source and symmetric flowing currents in particular phases. The result of impedance asymmetry is especially unstable transmission of active power in particular phases, following technological or process problems of three phase lowohmic furnaces **[4]**. Later presented results were obtained just using the method of elementary conductors, considering of phase currents twisting in three-phase system.

4.1. Simplified mathematical model of three-phase conductors system

For creating a model let us consider at first simple three-phase, three-conductor system of input lines with identical phase resistances and self-inductances according to Fig. 9.

If we consider, that system is connected to the symmetrical source of voltages and ideally is flowed by symmetrical currents, than with using of twisting operators among the current phasors for these is valid:

$$I_{L2} = a^2.I_{L1} = \left(-\frac{1}{2} - j.\frac{\sqrt{3}}{2}\right).I_{L1}$$

$$I_{L3} = a\ I_{L2} = \left(-\frac{1}{2} + j.\frac{\sqrt{3}}{2}\right).I_{L1} \qquad (4)$$

Applying system (4) for solving of circuit on Fig. 9, we determine by simply method for example the phase voltages drop, which are in the matrix form [4, 5]:

$$\begin{bmatrix} \Delta U_{L1,j} \\ \Delta U_{L2,j} \\ \Delta U_{L3,j} \end{bmatrix} = \begin{bmatrix} R + j.\omega.L + j.\omega.\left(a^2.M_{12} + a.M_{13}\right);\ 0;\ 0 \\ 0;\ R + j.\omega.L + j.\omega.\left(a^2.M_{23} + a.M_{21}\right);\ 0 \\ 0;\ 0;\ R + j.\omega.L + j.\omega.\left(a^2.M_{31} + a.M_{32}\right) \end{bmatrix} \times$$

$$\times \begin{bmatrix} I_{L1} \\ I_{L2} \\ I_{L3} \end{bmatrix} \qquad (5)$$

From the matrix (5) we can get several preliminary conclusions:

1. Phase drops consist of two components:
   — from components in self phase impedances, i.e.

$$\Delta U_i' = \left(R + \ j\omega L\right) I_i \qquad (6)$$

which are the same and constant at symmetrical currents in each phases

— from components of drops from mutual impedances

$$\Delta U_i'' = j.\omega.\left(a^2.M_{i,i+1} + a.M_{i,i+2}\right).I_i \qquad (7)$$

These drops are generally divided, because $M_{12} \neq M_{23} = M_{31}$.

2. Expression below the bracket in equation (7) is complex number, with using system (4) and simplifying angular velocity in form of:

$$X_p = -\tfrac{1}{2}.\omega.\left(M_{i,i+1} + M_{i,i+2}\right) - j.\tfrac{\sqrt{3}}{2}.\omega\cdot\cdot\left(M_{i,i+1} - M_{i,i+2}\right) \qquad (8)$$

It physically denotes the additional reactances in particular phases.

Thus, the overall phase impedances are:

$$Z_i = R_i + j.X_i = R + \tfrac{\sqrt{3}}{2}.\omega.\left(M_{i,i+1} - M_{i,i+2}\right) + j.\omega.\left[L - \tfrac{1}{2}\left(M_{i,i+1} + M_{i,i+2}\right)\right] \qquad (9)$$

Real impedance part excepting of self-resistances *R* contains also different components

$$R_{pi} = \tfrac{\sqrt{3}}{2}.\omega.\left(M_{i,i+1} - M_{i,i+2}\right) \qquad (10)$$

generating additional phase resistances. Whereas they are generally different, their presence negatively affects the transmission of active energy to three phase furnace. It is well known effect of living and non-living phase or regarding of active losses the effect of inter-phase transmission power. Because the sum of additional resistances is always equal to zero, these don't cause increasing of overall active losses with symmetrical currents, only their redistribution among the phases. Therefore, neither with the change of space phase configuration these losses size is not changed.

Reactive component of impedances in expression (9) contains elements:

$$X_{pi} = \frac{1}{2}.\omega.\left(M_{i,i+1} + M_{i,i+2}\right) \qquad (11)$$

with the characteristics of additional reactances in particular phases, which influence the reactive losses. Because the sum of additional reactances is not equal to zero, it influences on the overall reactive loses, which vary with the change of space phases configuration.

Estimation of additional resistances and reactances in the sense of equations (10) and (11) and in agreement with Neumann's integral is not complicated. Issuing of this, for mutual induction of two parallel non-magnetic conductors of length *l*, generally deals [6]:

$$M_{i,k} = 2.l.\left(ln\frac{2.l}{x_{i,k}} - 1\right).10^{-7}\ [\mathrm{H;\ m}] \qquad (12)$$

where $x_{i,k}$ is medial geometric conductance (m.g.c.) between *i* - th and *k*-th conductor, where $e >> x_{i,k}$.

Using equation (12) we subsequently determine:

— according to equation (10) is size of additional resistances:

$$R_{p1} = k_1.ln\frac{x_{13}}{x_{12}},\quad R_{p2} = k_1.ln\frac{x_{21}}{x_{23}},\quad R_{p3} = k_1.ln\frac{x_{32}}{x_{31}} \qquad (13)$$

where $k_1 = \sqrt{3}.\omega.l.10^{-7}$ [Ω;m] and $x_{12} = x_{21}$, $x_{23} = x_{32}$, $x_{13} = x_{31}$ [m]. Equation (13) confirms that sum of additional resistances in three-phase conductors system is equal to zero.

— according to equation (11) is size of additional reactances. It is preferable to calculate directly the overall reactances, i.e. component of equation (9). Necessary self-inductance we calculate by (12) substituting (m.g.c.) among the conductors, conductor's m.g.c. by itself x_{ii}. Following this we obtain:

$$X_{C1} = k_2.ln\frac{\sqrt{x_{12}.x_{13}}}{x_{11}},\quad X_{C2} = k_2.ln\frac{\sqrt{x_{23}.x_{21}}}{x_{22}}$$

$$X_{C3} = k_2.ln\frac{\sqrt{x_{31}.x_{32}}}{x_{33}} \qquad (14)$$

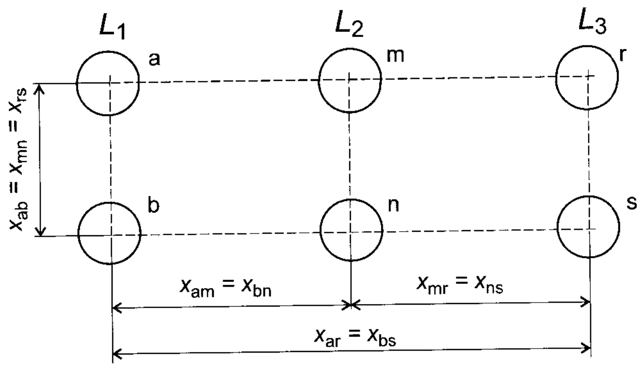

Fig. 10. Two-conductor three-phase system

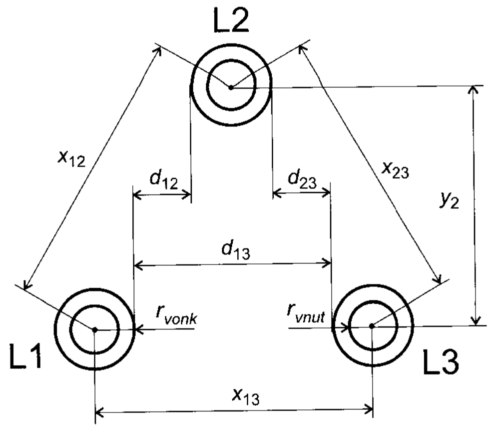

Fig. 11. Triangular three-phase conductors system

where $k_2 = \omega.2.l.10^{-7}$ [Ω; m] and for conductor of the same cross section $x_{11} = x_{22} = x_{33} = x_0$.

The results in form of equations (13) and (14) represent the mathematical model of impedance asymmetric three phase conductors system. It is necessary to note, that enumeration of solid parameters considering of accepted symmetrical currents assumption in not accurate. Presented model can be expanded also to three-phase system of bundled conductors. Let us choose example of two-conductor bundle, according to Fig. 10, let the conductors be circular cross section.

Supposing of symmetrical phase currents and their uniform distribution to conductors of bundle ($I_a = I_b$, $I_m = I_n$, $I_r = I_s$), with the same proceeding as for simple system we establish [4, 6].

— additional resistances of particular conductors

$$R_{pa} = k_1.ln\frac{x_{ar}.x_{as}}{x_{am}.x_{an}}; \quad R_{pb} = k_1.ln\frac{x_{br}.x_{bs}}{x_{bm}.x_{bn}}$$

$$R_{pm} = k_1.ln\frac{x_{ma}.x_{mb}}{x_{mr}.x_{ms}}; \quad R_{pn} = k_1.ln\frac{x_{na}.x_{nb}}{x_{nr}.x_{ns}} \qquad (15)$$

$$R_{pr} = k_1.ln\frac{x_{rm}.x_{rn}}{x_{ra}.x_{rb}}; \quad R_{ps} = k_1.ln\frac{x_{sm}.x_{sn}}{x_{sa}.x_{sb}}$$

with the same constant value k_1 as in (13)

— the overall reactances of particular conductors

$$X_{ca} = k_2.ln\frac{\sqrt{x_{am}.x_{an}.x_{ar}.x_{as}}}{x_0.x_{ab}}$$

$$X_{cm} = k_2.ln\frac{\sqrt{x_{mr}.x_{ms}.x_{ma}.x_{mb}}}{x_0.x_{mn}}$$

$$X_{cn} = k_2.ln\frac{\sqrt{x_{nr}.x_{ns}.x_{na}.x_{nb}}}{x_0.x_{nm}} \qquad (16)$$

$$X_{cr} = k_2.ln\frac{\sqrt{x_{na}.x_{rb}.x_{rm}.x_{rn}}}{x_0.x_{rs}}$$

$$X_{cs} = k_2.ln\frac{\sqrt{x_{sa}.x_{sb}.x_{sm}.x_{sn}}}{x_0.x_{sr}}$$

where k_2 is of the same value as in (14) and $x_0 = x_{aa} = x_{bb} = = x_{mm} = x_{nn} = x_{rr} = x_{ss}$.

The equations (15) and (16) are of the analogical sense and application as the equations (13) and (14).

Also by lower precision of derivate models (13) to the (16) are acceptable especially for two reasons:

— visually they represent impedance asymmetry as the result of space conductors asymmetry of three phase system

— they are initial solution for suppression of impedance system asymmetry in the way of changing conductors form (x_{ii}), changing space conductors configuration in the bundle (x_{ab}, x_{mn}, x_{rs}) or changing of particular phases configuration (x_{ik})

4.2. Simple options of impedance symmetrisation

Like an example of option impedancely to symmetrisate furnace circuit, let us choose simple three phase conductors system, according to Fig. 11.

If we place phase conductors, mutually parallel to the angles of equilateral triangle, i.e. for m.g.c. among the phases deal $x_{12} = x_{23} = x_{31} = x$, then naturally deals:

— for additional resistances (according to equation 13)

$$R_{p1} = R_{p2} = R_{p3} = 0 \qquad (17)$$

— for overall reactances (according to equation 14)

$$X_{C1} = X_{C2} = X_{C3} = k_2.ln\frac{x}{x_0} \neq 0 \qquad (18)$$

By space configuration becomes then system impedancely symmetrical, phases transfers uniform power at minimal active losses, which are depended only upon effective resistance R. Reactive losses depend on side lengths of triangle. According the fact that mutual inductances increase with decreasing of m.g.c. among the phases, the overall reactance and reactive losses decrease.

Applying the method of elementary conductors for resistances and reactances enumeration of triangular system we obtain their necessary dependencies on geometric parame-

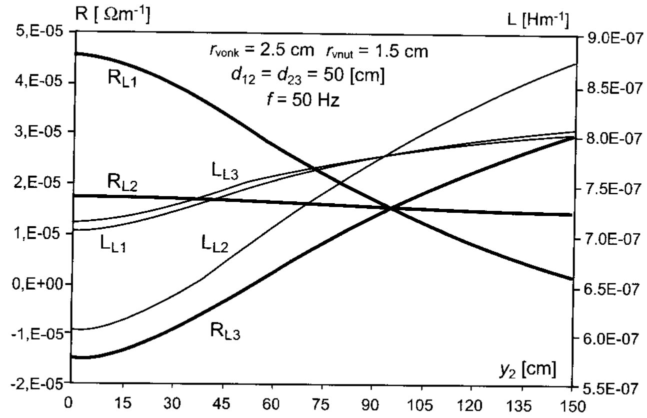

Fig. 12. Dependencies $R_{Li} = f(y_2)$ a $L_{Li} = f'(y_2)$ for i = 1, 2, 3

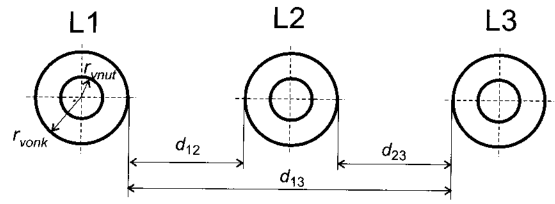

Fig. 13. Coplanar three-phase conductors system

ters. On Fig. 12 is plotted dependency R_{ci} and L_{ci} on triangle height y_2. From dependencies we clearly see, that the equalization of phase resistances and inductances reaches at height of y_2, responding to equilateral triangle.

For $y_2 = 0$ in previous example, triangular phase configuration transforms to coplanar, represented on Fig. 13.

This system is characterized by substantial asymmetry of both impedance components. Because the configuration is symmetrical in plane, according to middle phase axis, from the equation $d_{12} = d_{23}$ results also the equation $x_{12} = x_{23} = {}^1\!/_2.x_{31} = x$. For this condition deals:

— for additional resistances following the relation (13)

$$R_{p1} = k_1.ln2, \ R_{p2} = 0, \ R_{p3} = -k_1.ln2 \qquad (19)$$

— for overall reactances following the relation (14)

$$X_{Ci} = X_{C3} = k_2.ln\frac{\sqrt{2}.x}{x_0}, \ X_{C2} = k_2.ln\frac{x}{x_0} \qquad (20)$$

where $x_0 = x_{11} = x_{22} = x_{33}$.

There are several facts resulting from equations (19) and (20):

— system is fairly asymmetrical, where for the overall resistances and reactances deals:

$$R_{C1} > R_{C2} > R_{C3}, \ X_{C1} = X_{C3} > X_{C2} \qquad (21)$$

— the overall phase resistances in coplanar system cannot be symmetrized. System causes expressive effect of living (R_{C3}) and non-living phase (R_{C1}). The overall active losses are independent from additional resistances, these entail only their redistribution in three phase system (effect of inter phase transmission power)

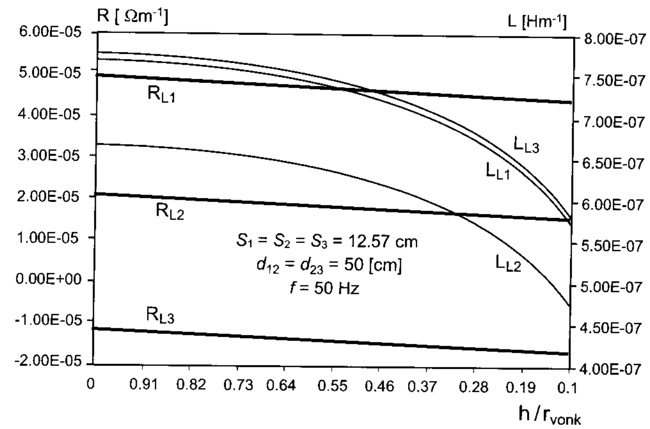

Fig. 14. Dependencies $R_{Li} = f(h/r_{ext})$ and $L_{Li} = f'(h/r_{int})$ for i = 1, 2, 3 of coplanar system

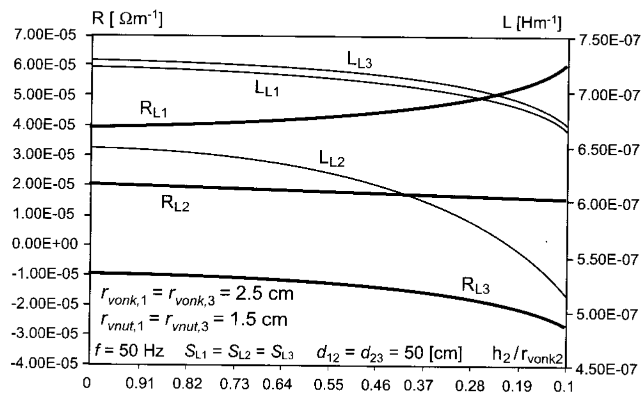

Fig. 15. Dependencies $R_{Li} = f(h_2/r_{ext})$ and $L_{Li} = f'(h_2/r_{int})$ for i = 1, 2, 3 of coplanar modified system

— the overall phase reactances in agreement with equation (20) is possible to symmetrize by decreasing of m.g.c. of middle phase from value of x_0 to value $x_0^{/} = \frac{x_0}{\sqrt{2}}$, i.e. by increasing of self phase inductance. This system is coplanar modified and solves reactance system symmetrisation. Of course, we obtain the same effect by increasing of m.g.c. of marginal phases, from the value x_0 to value $x_0^{//} = x_0.\sqrt{2}$.

For comparison, there are represented on the following figures resistances and reactances changes of original coplanar (Fig. 14) and coplanar modified system (Fig. 15) from relative hollow copper pipes depth.

All the presented examples are naturally referred to three-phase input wires, electrically connected to simple star. It is structurally not difficult, with the low consumption of copper material. From electrical aspect it is more profitable structurally more complicated scheme to triangle, especially when it is solved bifilarly. It is suggested bifilarly connected system on Fig. 16 and on Fig. 17 corresponding dependencies of resistances and reactance changes on actual inter phases distances.

From Fig. 17 we can see the positive bifilarity influence to equalization of phase resistances, as well as inductances and to significant decreasing of overall inductances.

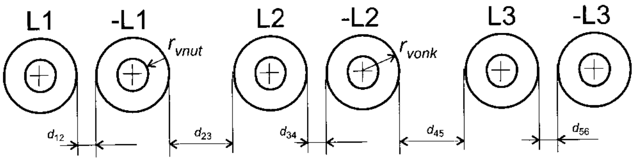

Fig. 16. Bifilar three-phase conductors system

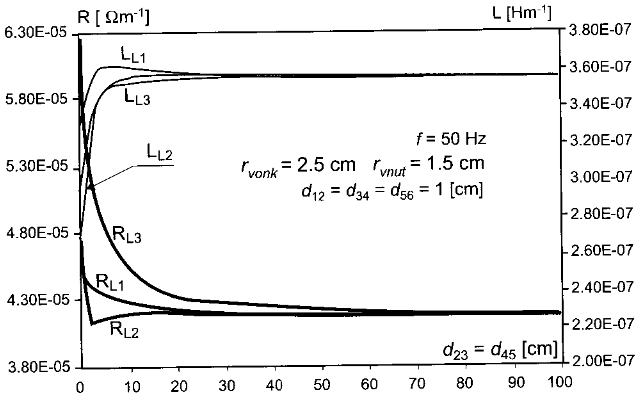

Fig. 17. Dependencies $R_{Li} = f(d_{23} = d_{45})$ and $L_{Li} = f(d_{23} = d_{45})$ for $i = 1, 2, 3$ of bifilar system

5. CONCLUSION

Intention of authors was to mention some options of numerical method of elementary conductors, by means of solving the surface events on supplying systems of low-ohmic furnaces. Even though the presented results are only sectional, restricted with contribution range, they sufficiently document three facts:

— suitability of numerical method of elementary conductors for surface effects solving

— expressive influence of shape and space conductors configuration on their impedance and moreover size of electrical losses, which are not negligible in operation of low-ohmic furnaces

— ability to symetrizate three phase input supply, which improve the transmission quality of electric energy on solid furnaces

On the basis of obtained experiences, objective method of solving and ability of impedance symmetrization can be advised to projection of input supply circuits in low-ohmic furnaces.

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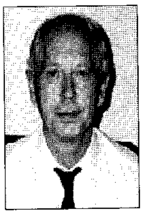

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