IMPROVEMENT OF CALCULATION METHOD FOR ELECTRICAL PARAMETERS OF SHORT NETWORK OF ORE-THERMAL FURNACES

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Abstract ***- The paper describes new method of calculation for active and inductive resistance of split interleaved current leads packages in ore-thermal electric furnaces. The method is developed on basis of regression analysis of dependencies of active and inductive resistances of the packages upon their geometrical parameters, mutual disposition and interleaving pattern. These multi-parametric calculations are performed with ANSYS software. Proposed method allows solving problems of minimization and balancing of electrical parameters of split current lead in ore-thermal furnaces..***

Keywords ***- ore-thermal electric furnace, active and inductive resistance, split interleaved package, current lead system.***

I.INTRODUCTION

Products made in ferroalloy furnaces are needed for steel production, therefore the amount of ferroalloy production tends to grow constantly. Important requirements that have to be fulfilled in an ore-thermal furnace's short current lead are: minimal active and inductive resistances in phases and their symmetry. Modern powerful ore-thermal furnaces contain in their secondary current lead a rigid immovable part (Fig. 1) made up of a package of water-cooled bus tubes. Oftentimes it is the longest part of the short current lead.

Parameters of the short current lead have big impact on technical and economical aspects of the furnace efficiency: total efficiency, symmetry of the loading of phases, specific energy consumption, electrical efficiency, and so on. Conductors of the short network contain high currents up to 150 kA of industrial frequency, which produce strong magnetic fields around these conductors. Consequently electrical parameters of the short network are affected by many phenomena, such as skin-effect, proximity effect, uneven distribution of current between conductors, power transfer between conductors and phases, energy losses through neighboring metal constructions, etc.

Reactive resistance of the short network significantly impairs electrical parameters of the furnace and causes its power sources to be loaded with increased reactive power. Active resistance of the secondary current lead defines the value of electrical efficiency.

Table 1 summarizes inductive resistances of secondary network of ore-thermal furnace RKZ-80 (round, open ore-thermal furnace of 80 kVA capacity) [1].

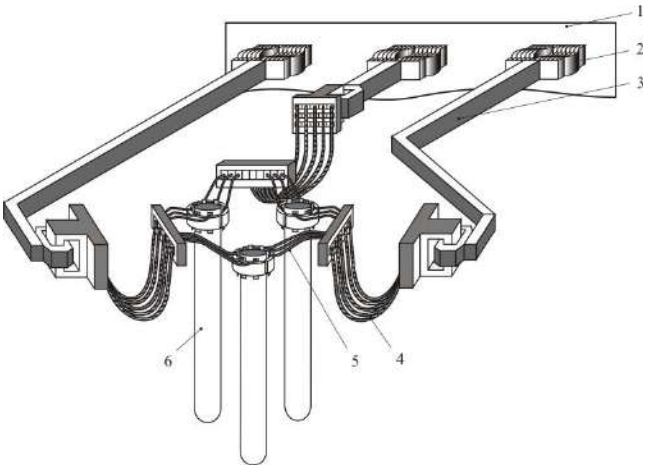

Fig. 1. Scheme of current lead of ore-thermal furnace:
1 – transformer, 2 – compensators, 3 – tubular bus package,
4 – flexible current lead, 5 – tubes of electrode-holder,
6 – electrode.

Table 1 shows that inductive resistance of the short network makes up 32% of total inductive resistance of the furnace, which is a considerable amount. Therefore the task of designing a secondary current lead with rational parameters is of great significance, and consequently effective methods for the calculation of these parameters on that stage are needed.

II.NEW METHOD FOR PURE RESISTANCE AND INDUCTANCE CALCULATION

Important requirements that have to be fulfilled in an ore-thermal furnace's short network are: minimal length and spatial symmetry of phases, minimal surface area covered by one phase, proper choice of conductors (with consideration of their working conditions) and rational usage of their cross-section, most rational interleaving pattern, which enables them to be loaded evenly with current and achieve same electrical parameters in all phases.

Complying with these conditions allows the power delivered from the main network to be used with high effici-

Table 1.

Inductive resistances of secondary network of ore-thermal furnace RKZ-80.

Transformer		Short network		Electrodes and bath		Total per phase	
X, mΩm	%	X, mΩm	%	X, mΩm	%	X, mΩm	%
0.09	7.4	0.39	32.0	0.74	60.6	1.22	100

ency and high power factor, and distributed evenly between phases (or electrodes) in the bath, which is the main and most important requirement of the technology.

The influence of the electrical parameters of short network on the transformer characteristics is as great as the constructional parameters of the working space, and together they determine the range of working voltages. That is why it is necessary to take into account the electrical parameters of the short network while choosing the furnace transformer.

In order to decrease inductive resistance the rigid pars of current lead (article 3 on Fig. 1) are, if possible, made bifilarly. In practice bifilar construction is achieved by splitting and interleaving conductors inside the packages. The employed patterns of interleaving of the conductors in the bus package are presented on Fig. 2 and 3.

Currently there is a generally accepted method of bus-package inductive resistance definition [1]. However, it should be noted that it had been created in times when computer engineering hasn't even one hundredth of its modern possibilities. There is no analytical solution for Maxwell equations for such objects; therefore developmental level of technology defines limitations for numerical solution of the problem.

The existing method [1] contains a number of assumptions. In calculation of active and inductive resistance and the mutual inductance of conductors arbitrarily located in space it doesn’t take into consideration the distribution of current density over the cross-section of the conductor.

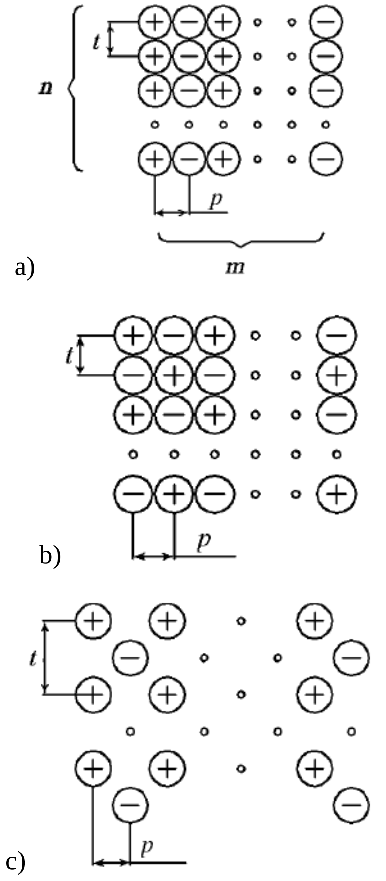

Fig. 2. Interleaving pattern for multi-phase tubular bus packages: a - passage, b - chess, c - passage with vertical shift

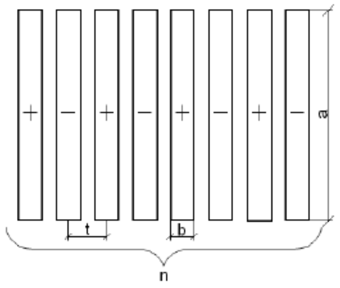

Fig. 3. Interleaving in rectangular bus package.

In calculation of active resistance the influence of electromagnetic field is taken into account by the coefficient of additional losses, which can only be calculated for a limited set of geometrical parameters of the interacting conductors [2].

The practical usage of this method shows that the calculation of inductive resistance through it is carried out with a certain amount of simplification to geometry [3]. Moreover, in calculation of active resistance a substantial inaccuracy takes place in establishing the correctional coefficients, especially for conductors with rectangular cross-section. Furthermore, the redistribution of current in a group of parallel conductors (for instance, in a current lead of an ore-thermal furnace) is impossible to calculate analytically, and the experimental data employed in this method only allows for a very approximate consiredation of it.

Department of automatic electrotechnological installations of Novosibirsk state technical university has carried out the work for development of a new method for calculation of active and reactive resistance of split interleaved packages of tubular and rectangular buses. The method is based on multi-variant calculations bus package parameters under varying geometrical characteristics (diameter and wall thickness of tubular bus, dimensions of the cross-section of rectangular buses *a* and *b*, distances *t* and *p*, presented in Fig. 2, 3) and number of conductors in package (*m* and *n*) [4, 5]. Calculations were performed with ANSYS software [6].

To illustrate obtained results in Fig. 4 dependencies of pure resistance and inductance and conductors' number in the package (variables *n* and *m*) are shown, and in Fig. 5 – the dependencies of spacing between conductors in the package in vertical *t* and horizontal *p* directions. Results for "chess" interleaving are shown because it gives maximal bifilation level.

Fig. 4 shows first of all how tube-bus diameter change affects pure resistance and inductance of the whole package. It's clearly visible that if the tube-bus diameter is increased from 0.05 m to 0.06 m the pure resistance is decreased by 10%. Pure resistance falls due to increase of cross-section area, moreover, cross-section perimeter is enlarged, so self-inductance is decreased. The same phenomenon is observable on Fig. 5.

The bigger number of tub-buses in the package is, the less pure resistance and inductance are, as it should be for a number of parallel connected conductors. Inductive resistance falls even more because of the bigger bifilation level.

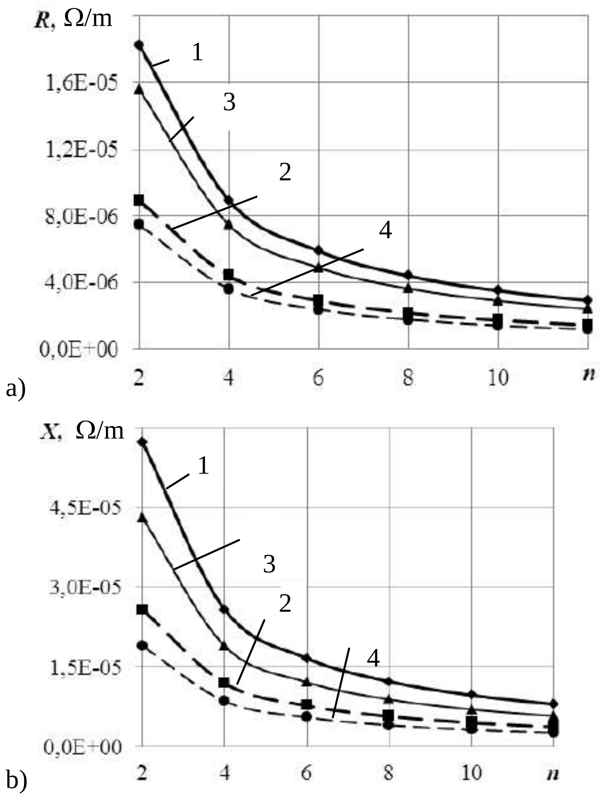

Fig. 4. Dependencies of pure resistance (a) and inductance (b) of chess-interleaved bus package for variation of number of tube buses in vertical line *n*, and constant number of tube-buses in horizontal line *m*, and different outer diameter of a tube-bus *d*: 1 – *d*=0,05 m, *m*=2; 2 – *d*=0,05 m, *m*=4; 3 – *d*=0,06 m, *m*=2; 4 – *d*=0,06 m, *m*=4 (*t* = 0.08 m, *p* =0,08 m)

Fig. 4 shows that pure resistance is comparable to inductive one (it is only 2 times smaller). Formerly pure resistance was believed much less than inductive one, that was the reason for absence of well-defined calculation method for pure resistance. But obtained results lead to opposite conclusion. The obtained results are very important for developers because of the desire to optimize energy consumption of powerful electrotechnological installations.

Fig. 5 b) demonstrates what influence bifilation level has on inductive resistance. Increase of both vertical and horizontal spacing between package's conductors leads to distancing the conductors carrying currents of opposite phases, and consequent to the increase of inductive resistance of the whole package.

The processing of the results with methods of regression analysis gave us empirical formulae of the following form:

$$R\,(or\ X) = b_0 \cdot n^{b_n} \cdot m^{b_m} \cdot p^{b_p} \cdot t^{b_t}\ ,\ \Omega/\mathrm{m}, \qquad (1)$$

for tubular buses and

$$R\,(or\ X) = b_0 \cdot n^{b_n} \cdot a^{b_a} \cdot b^{b_b} \cdot t^{b_t}\ ,\ \Omega/\mathrm{m}, \qquad (2)$$

for rectangular buses, which describe the results of a series of numerical experiments. Quality of the empirical formula is evaluated by coefficient of determination *r*2, lies in the range from 0 to 1, and is defined on the basis of comparison of actual values and values obtained from empiric formula.

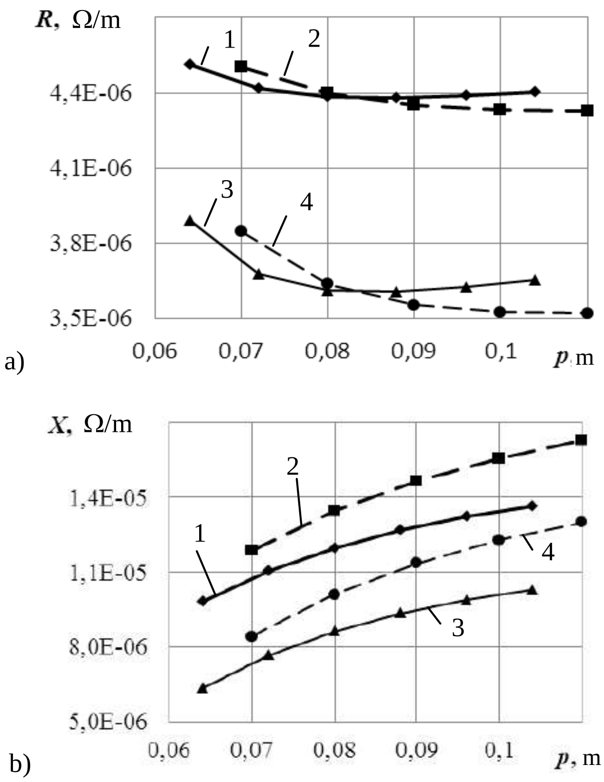

Fig. 5. Dependencies of pure resistance (a) and inductance (b) of chess-interleaved bus-package for variation of spacing between tube-buses in horizontal direction *p*, while outer diameter of a tube-bus *d* and vertical spacing between tube-buses *t* are fixed:
1 – *d*=0,05 m, *t*=0,08 m; 2 – *d*=0,05 m, *t*=0,1 m;
3 – *d*=0,06 m, *t*=0,08 m; 4 – *d*=0,06 m, *t*=0,1 m
(*n* = *m* = 4).

As an example, a set of coefficients for regressions (1, 2) for a package of rectangular buses is presented in Table 2.

The developed method enables easy calculation of active and inductive resistance of split bus packages in ore-thermal furnaces and analysis of influence of the construction decisions of this part of current lead upon the level of asymmetry of its electrical parameters [7, 8]. For example, it is constructively prescribed that the length of bus package of the middle phase is smaller than package length of a side phase, and consequently, this part causes asymmetry of whole current lead (Fig. 1). But inductive resistance depends not only on the length of conductor, but also on the geometry of its cross-section. An increase of the distance between conductors in package *t* is followed by an increase in inductive resistance of the package, which makes it possible to make the resistance of the middle phase package equal to the inductive resistance of a side phase.

In the following example, bus packages of side and middle phases of the furnace RKO-16.5 (round open ore-thermal furnace with power 16.5 MVA) are considered. Table 3 contains the parameters of bus packages of side and middle phases.

Usually, the distance between buses is made minimal, in order for it to provide cooling and isolation of the buses. Maximal distance is limited only by the dimensions of the installation.

Table 2.

Coefficients for calculation of active and reactive resistances of rigid current lead for conductors with rectangular cross-section

R / X	b_0	b_n	b_a	b_b	b_t	r_2
R	$1.55\cdot10^{-7}$	-1.056	0.0124	-0.992	-0.914	0.99
X	$2.44\cdot10^{-4}$	-0.919	-0.319	18.8	2.71	0.99

Table 3.

Bus package parameters of RKO-16.5 installation [1]

Phase	Length, m	Bus weight b, m	Bus height a, m	Inter axis distance t, m	Number of buses m	Package inductive resistance, m Ohm
Side	14.3	0.012	0.3	0.027	6	0.11
Middle	4.6	0.012	0.3	0.027	6	0.05

Calculations have shown that increase of distance between buses to 0.09 m for middle phase makes its inductive resistance equal to inductive resistance of side phase. Thereby, the developed method enables to easily define the geometrical parameters for bus packages which ensure their symmetry.

The developed calculation method has been also employed for balancing of a rigid current lead in an ore-thermal furnace of power of 10 MVA. The rigid current lead consists of bus tubes, 2 to each half-phase, put into a vertical row, with half-phases interlaced. The middle phase is 2.5 m shorter than the side one, which leads to obvious dissymmetry of resistances in this section. The problem in consideration was that of balancing, and therefore of a way to increase inductive resistance of the middle phase or decrease it in the side phases. The first proposal was to increase the length of the middle phase by modifying the trajectory of conductors from rectilinear to loop-like. But inductive resistance is also very sensitive to transposition of conductors in cross-section. Thus the next proposal was to reject the interleaving of conductors in the middle phase, while keeping the interval between half-phases equal to that on the output terminals of the transformer. This has enabled the coefficient of inductive resistance dissymmetry to be diminished from 58% to 27%. The fact that the loop proposal was not reasonable was made obvious. It became possible to further decrease the dissymmetry coefficient to 17% by shortening the interval between the conductors in half-phases of the middle phase by half. Since the portion of this section in the inductive resistance of whole phase is about 10%, and the resistances of all other sections are equal for various phases, the total coefficient of asymmetry became less than 5%, and the problem can be considered to be solved. Notwithstanding, further balancing is possible through shifting of the start of the interlaced section towards the output terminals of the transformer as much as the construction allows it.

III.CONCLUSION

A convenient method of calculation of active and inductive resistances of split interleaved phase bus packages for ore-thermal furnaces has been designed. It enables simple development of construction variants which aid the balancing of short network of electrical furnace.

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