COMPLEX MODEL OF INDUCTION HEATING – DEMOUNTING OF SHAFT FLANGE

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Summary This paper deals with exemplary solutions of one specifies problem of induction heating. This problem was partly determined by means of numerical method as a light-coupling problem. Numerical solutions were calculated with the help of professional programs (Ansys, Fluent, QuickField). Results of the solution and comparison with measurements are discussed in conclusion

1. INTRODUCTION

The aim of this paper is a description of dismantling of the flange (connector) from the shaft of diesel generator with the output 11,6 MW (Fig. 1).
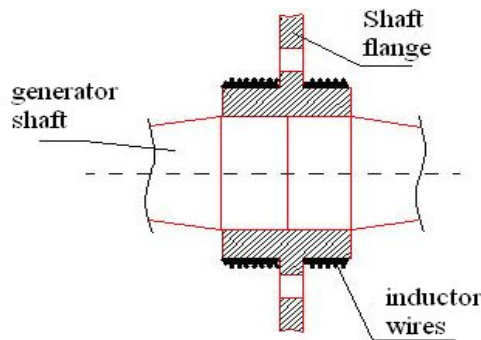

Fig.1. Implementation of inductor for induction heating

During the operation of this equipment a turn occurred of the generator shaft towards the shaft driven by diesel aggregate (about 30°). This turn was intolerable from the viewpoint of the function of the whole machinery and dismantling of the above-mentioned flange (Fig. 2) (connector) was necessary.
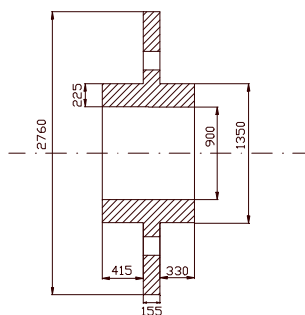

Fig.2. Geometry of the flange

This connector was pressed on the shaft while hot. That is why not only mechanic strength is necessary for the dismantling, but the same technology as for the assembly must be used, it is to bring thermal energy to the dismantled flange and in this way to lower the lubrication powers that are between the inner side of the flange and the outer side of the shaft in the point of contact of both materials.

As these are very large parts (shaft - 20 t (Fig. 3), flange - 10 t (Fig. 2)), that are supposed to be used again, it is impossible, from the economic point of view, to cause a permanent damage to them during the dismantling (through plastic malformation).

 For that reason convention methods were not used for heating, but inductive equipment. The advantage of this equipment designed for heating is the possibility of relatively exact calculation of parameters of heating regarding the permanent damage of the material.

In order to get inductive heating, an inductor was reeled on the flange of the diesel generator. Through this inductor exciting current I_{EXC} of different value and net frequency 50Hz was flowing. Values of exciting current I_{EXC} and time intervals of the influence of exciting current I_{EXC} are given in Tab 1.
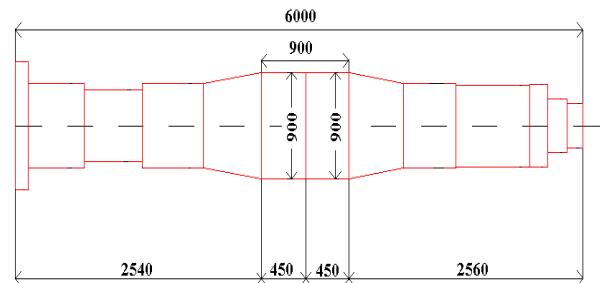

Fig. 3. Geometry of the shaft

Table 1. Exciting current

Nr.	Current in inductor - I_{EXC} [A]	No of turns	Time of warming[min]
1.	1380	28+36	2
2.	1110	28+36	4
3.	1072	28+36	1

2. NUMERICAL SOLUTION OF THE PROBLEM

Numerical solution is done using two various professional programs. The program equipment

QuickField is not able to calculate the non-stationary thermal field that exists in the given application of inductive heating. Electromagnetic field is calculated by the program QuickField and thermal field by the program Fluent. As entering data for the program Fluent for calculation of non-stationary thermal field with inner source of heat the discharge data for electromagnetic field calculated by QuickField are used.

Calculated Joule losses P_{JLOSS} generated by induced currents are used as the inner source of heat of non-stationary thermal field. The problem is approached to as weakly conjugated problem.

Simplified model for solution

Because of a complicated shape of the shaft fledge the authors decided to use, when constructing 2D model, a simplified shape of the fledge (see Fig. 4). The Inductor is considered without insulation materials as joint with diameter that corresponds with the diameter of the real number of turns used for heating.
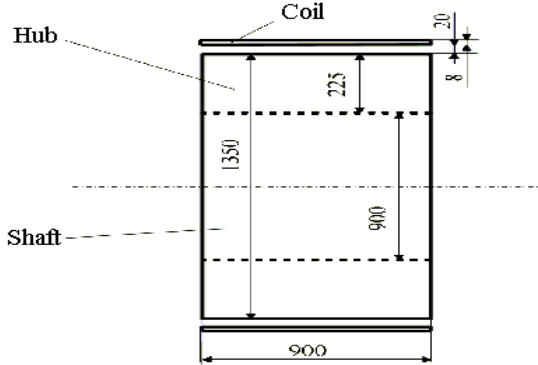

Fig. 4. Simplified model of shaft and fledge

2.1 Numerical model for program QuickField

Because of rotating symmetrical arrangement along axis *z* and axial symmetry of the problem along axis *r* it is possible to solve it only in 1 quarter of model from (Fig.4). For numerical solution of electromagnetic field using QuickField the authors constructed a numerical model (Fig.5). For numerical calculation it is necessary to recalculate the value of the intensity of the exciting current I_{EXC} so that this intensity is in harmony with a numerical model (see Fig.5). Calculated values are given in Table 2, where **I_{EXC}** - exiting current in the inductor of the real arrangement; **$I_{ef-area}$** - effective value of exiting current in the spare inductor from Fig.3; **$I_{max-area}$**- maximal value of exiting current in the spare inductor from Fig. 3; **$I_{max-\Omega 2}$** - maximal value of exiting current in the inductor in area Ω_2 from Fig. 4; **Tu-**number of turns of the real inductor.

Table 2. Calculated values of exciting current

Nr	I_{EXC} [A]	Tu	$I_{ef-area}$ [A]	$I_{max-area}$ [A]	$I_{max-\Omega 2}$ [A]
1.	1 380	64	88 320	124 903	62 451
2.	1 110	64	71 040	100 465	50 232
3.	1 072	64	68 608	97 026	48 513

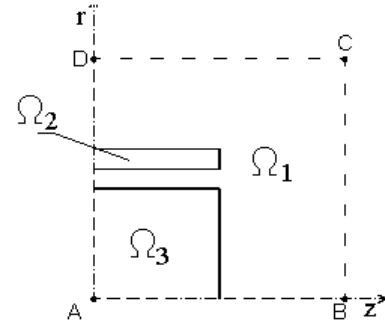*Fig. 5. –Numerical model – QuickField*

In particular areas Ω_1, Ω_2 and Ω_3 these equations are valid [1]:

$$\Omega_1: \quad \mathrm{rot}\ \mathrm{rot}\ \overset{\nu}{\mathbf{A}} = 0 \tag{1}$$

$$\Omega_2: \quad \mathrm{rot}\ \mathrm{rot}\ \overset{\rho}{\mathbf{A}} - \gamma_1 \frac{\partial \overset{\nu}{\mathbf{A}}}{\partial t} = \mu_0 \overset{\rho}{\mathbf{J}}_{EXC}(t) \tag{2}$$

$$\Omega_3: \quad \mathrm{rot}\ \frac{1}{\mu_k}\mathrm{rot}\ \overset{\rho}{\mathbf{A}} = \gamma_2 \frac{\partial \overset{\nu}{\mathbf{A}}}{\partial t} \tag{3}$$

where

γ_1 specific electric conductance of the inductor [S/m];

γ_2 MEDIUM value of specific electric conductance of heated material [S/m];

μ_k medium value of relative permeability of heated material [H/m];

$J_{EXC}(t)$ exiting current density in the inductor [A/m^2];

Ω_1 area of surrounding air;

Ω_2 area of inductor;

Ω_3 area of heated material.

$\overset{\rho}{\mathbf{A}}$ vector magnetic potential [Wb/m];

Boundary conditions [2]:

Considering the symmetry along axis *r*:

$$A - B: \ \mathrm{B}_r = 0 \quad \Rightarrow \quad \frac{\partial \mathrm{A}_\alpha}{\partial z} = 0 \tag{4}$$

In a sufficiently big difference from the inductor:

$$B - C, C - D: \ \mathrm{B}_r, \mathrm{B}_z = 0 \quad \Rightarrow \quad \mathrm{A}_\alpha = 0 \tag{5}$$

Considering the antisymmetry along axis *z*:

$$D - A: \ \mathbf{A}_\alpha = 0 \tag{6}$$

then

$$\vec{B} = \vec{r}B_r + \vec{z}B_z \qquad (7)$$

$$\vec{A} = \vec{r}.0 + \vec{z}.0 + \vec{a}_0 A_\alpha \qquad (8)$$

Conditions for the boundary of two environments inside areas Ω_1, Ω_2 and Ω_3:

$$\frac{1}{\mu_i}\frac{\partial A_{\alpha i}}{\partial n_{ij}} = \frac{1}{\mu_j}\frac{\partial A_{\alpha j}}{\partial n_{ij}} \qquad (9)$$

Joule losses are calculated according to the formula [3]:

$$P_{JLOSS} = \int_V \frac{1}{\gamma_2}\vec{J}_{Eddy}^2\, dV \qquad (10)$$

where

$$\vec{J}_{Eddy} = -\gamma_2\frac{\partial \vec{A}}{\partial t} \qquad (11)$$

where

γ_2 MEDIUM value of specific electric conductance of heated material [S/m];

$\vec{J}_{Eddy}$ current density of induced Eddy currents in heated material (flange) [A/m^2];

$\vec{A}$ vector magnetic potential [Wb/m];

P_{JLOSS} value of Joule losses (induced heat) in a charge [W].

2.2 Numerical calculation of electromagnetic field and its results

Values of Joule losses in a charge calculated using QuickField are given in Table 3, where
P_{JLOSS} - value of Joule losses (induced heat) in a charge [W].

Table 3. Calculated Joule losses using QuickField

Heating Nr.	P_{JLOSS}	heating[min]
1.	2 341 440	2
2.	1 514 840	4
3.	1 412 920	1

2.3 Numerical model for the Fluent program

When creating model for solution of non-stationary thermal field using the Fluent program the author decided to simplify it. For the construction of the model such arrangement shaft – fledge is considered that the length of the shaft is many times longer than the diameter. For the solution of the problem the following numerical model was created.(see Fig.6).

As the internal supply the Joule losses P_{JLOSS} which were calculated with the QuickField program are used. These losses are counted into specific losses for volume unit 1 m^3. It is well known that almost all heat comes

into existence in the charge in a distance smaller than $3a$ [4], where

$$a = \sqrt{\frac{2}{\varpi.\gamma.\mu}}\ [m] \qquad (12)$$

from the surface of the charge. The area (distance $3a$ [m] from the surface), where most heat exists, is divided into three subareas Ω_{Z1}, Ω_{Z2} and Ω_{Z3}. The boundaries are coaxial cylinders. The distance of the walls of these cylinders corresponds with the depth of the origin of induced current a. According to formula (12) is $a=6,2mm$. In these areas three internal supplies of heat are defined Z_a, Z_{2a}, Z_{3a} for more exact simulation of heating. In the subarea Ω_{Z1} originate 86,40 %, in the subarea Ω_{Z2} originate 11,82 % and in the subarea Ω_{Z3} originate 1,538 % from the whole amount of heat (Joule losses) due to induced currents [4].
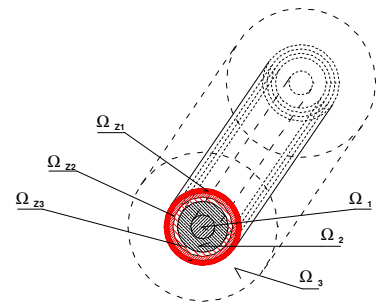

Fig.6 – Numerical model - program Fluent

In particular areas Ω_1, Ω_2, Ω_3, Ω_{Z1}, Ω_{Z2} and Ω_{Z3} these equations are valid [5]:

$$\Omega_1 : \mathrm{div}(\lambda_1\, grad\,T) = c_{p1}\rho_1\frac{\partial T}{\partial t} \qquad (13)$$

$$\Omega_2 : \mathrm{div}(\lambda_2\, grad\,T) = c_{p2}\rho_2\frac{\partial T}{\partial t} \qquad (14)$$

$$\Omega_{Z3} : \mathrm{div}(\lambda_2\, grad\,T) = c_{p2}\rho_2\frac{\partial T}{\partial t} - Z_{3a} \qquad (15)$$

$$\Omega_{Z2} : \mathrm{div}(\lambda_2\, grad\,T) = c_{p2}\rho_2\frac{\partial T}{\partial t} - Z_{2a} \qquad (16)$$

$$\Omega_{Z1} : \mathrm{div}(\lambda_2\, grad\,T) = c_{p2}\rho_2\frac{\partial T}{\partial t} - Z_a \qquad (17)$$

$$\Omega_3 : \frac{dw_i}{dt} = R_i + \frac{1}{\rho_{air}}\frac{\partial(\sigma_{ik})}{\partial k} \qquad (18)$$

where

λ_1 mean value of specific thermal conductance of the shaft material [W/m.K];

λ_2 mean value of specific thermal conductance of the fledge material [W/m.K];

c_{p1} specific thermal capacity of the shaft material[J/kg.K];

c_{p2} specific thermal capacity of the fledge material [J/kg.K];

ρ_1 specific density of the shaft material [kg/m^3];

ρ_2 specific density of the fledge material [kg/m^3];

ρ_{air} specific density of surrounding liquid (air) [kg/m^3];

i   index labelling one of the components (x,y,z), record with index „i" contains three equations;

Ω_1 area of heated shaft material;

Ω_2 area of heated fledge material;

Ω_3 area of surrounding air;

Ω_{Z1} area of heated fledge material + area of internal supply of heat Z_a;

Ω_{Z2} area of heated fledge material + area of internal supply of heat Z_{2a};

Ω_{Z3} area of heated fledge material + area of internal supply of heat Z_{3a};

$$\frac{\partial(\sigma_{ik})}{\partial k} = \frac{\partial(\sigma_{ix})}{\partial x} + \frac{\partial(\sigma_{iy})}{\partial y} + \frac{\partial(\sigma_{iz})}{\partial z}$$

Conditions for the boundary of two environment inside the given areas [6]:

Boundary of two solid substances:

$$-\lambda_i \frac{dT}{dn} = -\lambda_j \frac{dT}{dn} \tag{19}$$

Boundary of solid substance and liquid:

$$-\lambda \frac{dT}{dn}\bigg|_{\delta} = \alpha \left(T|_{\delta} - T_{sor} \right) \tag{20}$$

where

$T|_{\delta}$ temperature of the body in the boundary [K];

T_{sor} temperature of surrounding liquid [K].

Values of specific Joule losses and of internal supplies of heat are given in Table 4, where is **P_{JLOSS}** - value of Joule losses (induced heat) in a charge [W]; **P_{Jspec}**- value of specific Joule losses in the whole area in distance $3a$ from surface [W/m^3]; **Z_a**- value of internal heat supply in subarea Ω_{Z1} [W/m^3]; **Z_{2a}** - value of internal heat supply in subarea Ω_{Z2} [W/m^3]; **Z_{3a}** - value of internal heat supply in subarea Ω_{Z3} [W/m^3].

Table 4 Value of spare heat supplies in subareas

Nr.	P_{JLOSS}	P_{Jspec}	Z_a	Z_{2a}	Z_{3a}
1.	2 341 440	33 440 222	28 892 352	3 952 634	514 310
2.	1 514 840	21 634 800	18 692 467	2 557 233	332 743
3.	1 412 920	20 179 188	17 434 818	2 385 180	310 355

2.4 Numerical calculation of thermal field and its results (prg. Fluent)

Fluent is a modern program enabling complex solution of problems in the area of flow and combustion. It is possible to model laminar and turbulent flow of compressible and incompressible liquids including transfer of heat and chemical reactions. The program enables both stationary and non-stationary analysis of 2D and 3D problems with following high quality visualisation of results.

The Fluent program solves stationary and non-stationary Navier-Stokes equations using the method of finite volumes. When calculating heat transfer energy equations are solved as well.

Similar to QuickField also the Fluent program needs the necessary information that specifies the given problem (Fig.6). The model and the mesh of the model are created using the Gambit program, which is a volume modeller and generator of mesh of finite volumes that is not a part of Fluent. The model created with the Gambit program is then transferred to Fluent. In the Fluent program it is necessary to specify what problem it is and to define the material constants, initial and boundary conditions of the solved problem. The dependence in time of the surface temperature of the fledge is given in the graph Fig. 8-Surface temperatures.

3. MODEL FOR COMPLEX SOLUTION OF INDUCTIVE HEATING

When constructing the numerical model using *Ansys* program it is not necessary to simplify the geometrical shape of the solved object. As a result, it enables to use fully the advantages of numerical simulation of physical processes. The model of geometry of the shaft and fledge of the diesel generator is thus done according to reality. In this model only simplification of the shape of the inductor is used, which does not influence the size and distribution of final Joule losses in effect distribution of thermal and then deformation field in the heated material. As it is an axially symmetrical problem, it is possible to use for its solution a model of one half of the examined device. Detail of the model mentioned above see Fig. 7.
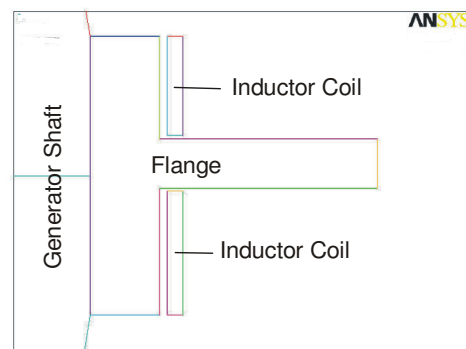

Fig.7 – Model - program Ansys-detail

3.1 Electromagnetic field (solved with the Ansys program)

It is possible to visualize different quantities of the electromagnetic field. For the comparison with QuickField model it is most important to know Joule losses in heated material. The values of these Joule losses are given in Table 5, where is P_{JLOSS} - value of Joule losses (induced heat) [W].

Table 5. Value of Joule losses calculated using Ansys

Heating Nr.	P_{JLOSS}	heating[min]
1.	2 028 614	2
2.	1 311 172	4
3.	1 225 282	1

3.2 Thermal field (solved with the Ansys program)

The dependence in time of the surface temperature of the fledge is given in the graph Fig. 8. - Surface temperatures.

4. DISCUSSION OF THE RESULTS

For comparison of the results of mathematical models calculated using programmes QuickField+Fluent and Ansys with values of surface temperatures on the real electrotechnical device measured values are available. These are given in the graph Fig. 7 Surface temperatures. In the graph, there are also the courses of measured surface temperatures of the shaft of the diesel generator.
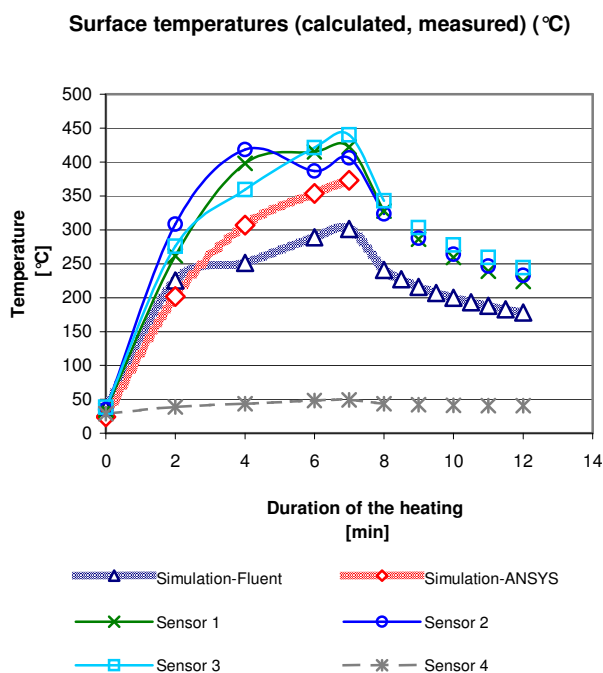
Temperature signed as "Simulation-Fluent" corresponds with the surface temperature of the flange calculated using Fluent with the previous calculation of magnetic field using QuickField.

Temperatures signed as and "Simulation-Ansys)" corresponds with the surface temperatures of the flange calculated using Ansys for initial temperature.

Temperature values signed as "sensor1-3" corresponds with the surface temperatures measured on the flange of the real device. Temperature values signed as "sensor4" corresponds with the surface temperatures measured on the shaft which was not supposed to be heated.

The better results are obtained using Ansys according to graph above. The difference between measured and simulated values of the surface temperatures may be caused by ignored heat insulation which was on the real device used.

As next calculations – thermoelastic displacements can only be calculated using Ansys program.

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Surface temperatures (calculated, measured) (℃)

Fig. 8 –Surface temperatures