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DESIGN STUDY AND PRODUCTION OF THE ROD INDUCTORS FOR BOLTS HEATING

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Abstract: Based on a specific need of ŠKODA ENERGO Ltd., Plzeň, our research programme was focused on the design and manufacturing of water-cooled rod inductors; the appliance should be exploited in a heating procedure of massive ferromagnetic steel bolts. It consists of a copper U-shaped hollow conductor with an inserted ferromagnetic laminated core. Special developed thermal isolations of the copper tube conductor and the ferromagnetic core are based on polyimide and glass materials. Magnetic fields and losses were evaluated by the help of standard Rosemberg method and checked by a 2D numerical calculation. The size and geometry of the ferromagnetic core was calculated to reach the demanded induced losses in the bolt-massive material. The inductor is power supplied from a 4 kHz frequency source. The developed appliance was proved to meet successfully both the demanded induced output and heat resistance of the insulation.

Keywords: Inductive heating. Magnetic field inductor. Polyimide resins and varnishes.

1 Introduction

In collaboration with SKODA ENERGO Ltd., calculations, design and manufacture of water-cooled rod inductors were carried on. The inductors are assigned to a heating of turbine massive steel bolts. A high power loss should be induced in the massive bolt to reach the required heating of about 300 °C in 15

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minutes. For the bolt of 150/32 mm in diameter and 500 mm long the demand corresponds to the induced power loss of 11.6 kW as minimum. At the same time, the inductor has to be inserted into rather small bolt opening of 32 mm. Obviously, in agreement with literature[1], such a fast heating couldn't be reached without a ferromagnetic core, the size and geometry of which was to be optimised. Due to rather high operating temperatures expected, a special thermoelectric insulation based on polyimide and glass materials was developed and used as well.

2 Inductor concept

The rod inductor consists of a copper U-shaped hollow conductor and 500 mm long ferromagnetic laminated core. The inductor will be power supplied from a 2 or 4 kHz frequency source. Consequently, the core was made of oriented 0.35 mm thick transformer sheets glued together by a polyimide varnish. The inner thermoelectric insulation of the copper tube made of the Kapton H polyimide (PI) film and Kerimid 500 PI resin, as well as the outer insulation formed from a glass tape, PI resin and Rhodeftal 200 polyimide varnish, had to be developed and tested - Fig. 1.

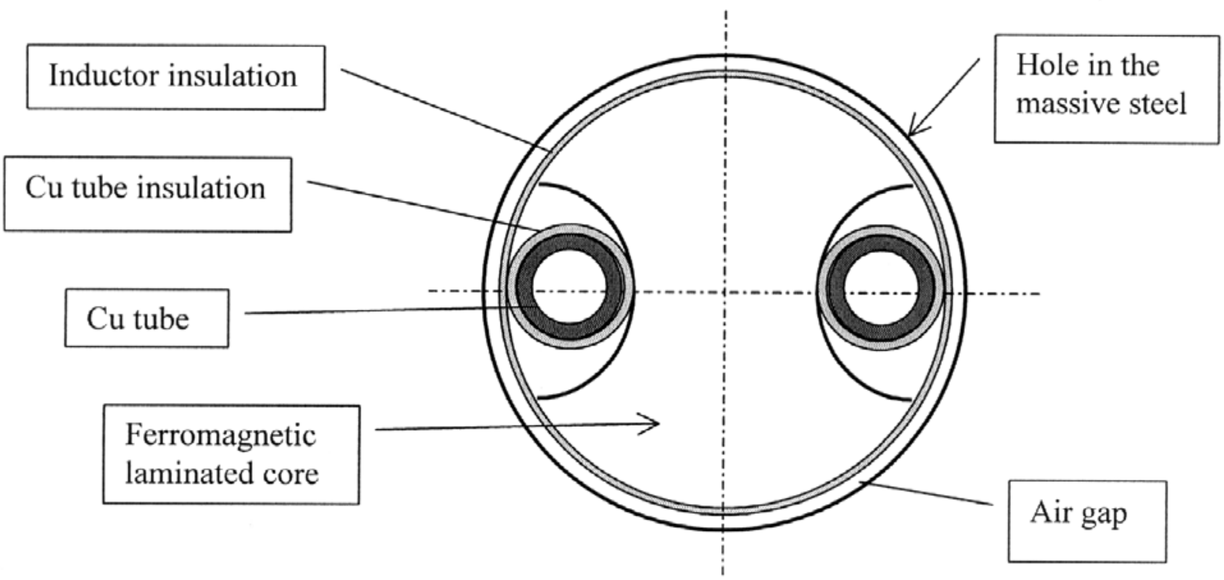

Fig.1. Cross-section layout of the rod inductor

3 Analytical solution

The standard Rosemberg method was used for magnetic field and loss calculations. According to this method it is assumed that the magnetic flux flows only inside a penetration depth in a ferromagnetic solid material and reaches the saturation flux density of B_o there. A current density is changeable. It decreases linearly from J_o in the ferromagnetic material surface to zero in the penetration depth h, which is

$$h = Ø_{Fe}/(B_o\lambda) = Ø/(2B_o\lambda)$$

Individual parts of the magnetic circuit (see Fig.2) can be described by the help of reluctances. Assume that an alternate magnetic flux **$Ø_{Fe}$** of angular frequency ω flows only in a part b of the hole circumference, then the solid steel reluctance can be written

$$R_{Fe} = 2\,KØ$$

where

$$\mathbf{K} = \frac{1}{8}\gamma\omega\frac{b}{B_0\lambda^2}$$

and γ is electric conductivity of the solid steel. In Fig.2 the reluctance of the laminated steel core is neglected and R_v is the air gap reluctance.

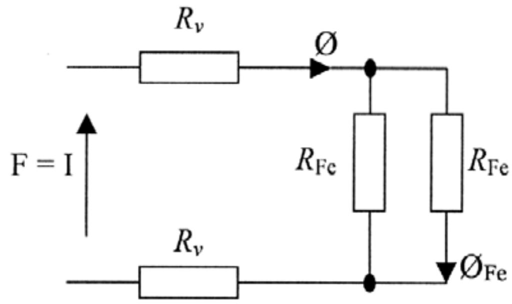

Fig.2. Substitute magnetic circuit

Using above assumptions the following expression for losses in the massive steel bolt can be derived

$$P = \frac{1}{12}\gamma\omega^2\frac{b}{\lambda^2}\frac{Ø^3}{B_0}$$

where magnetic flux is given by formula

$$Ø = \frac{\sqrt{R_v^2 + KI}}{K} - \frac{R_v}{K}$$

Calculation results in Fig.3 show a strong impact of the air gap (1 or 2 mm) and frequency (2 or 4 kHz) on the results. On the other hand, variations of γ, B_o and b have no significant influence on the results. The rod inductor was designed for 1000 A nominal current, 4 kHz frequency, and air gap of 2 mm. In this case, the losses induced in the massive bolt material reach the asked value of 12 kW.

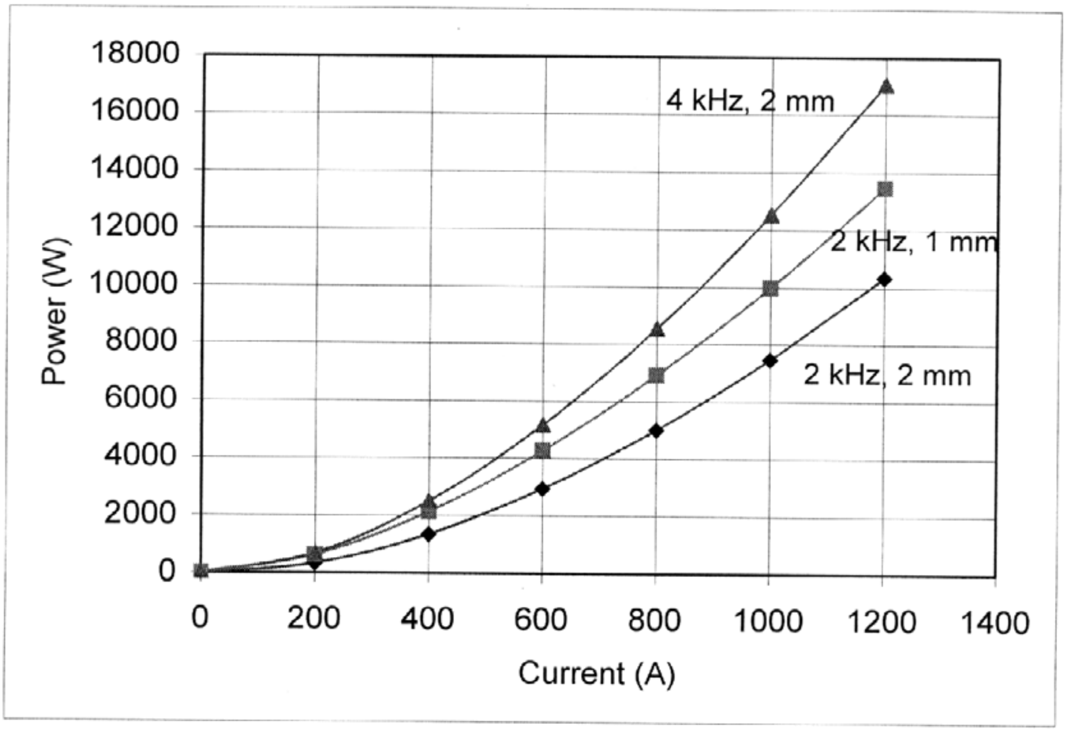

Fig.3. Losses induced in solid steel (2 or 4 kHz frequency, 1 or 2 mm air gap)

4 Numerical solution

The finite element method (software FEMM) was used for numerical calculations. Higher accuracy is principally a basic advantage of the numerical solution. On the other hand, an exact calculation of induced currents in massive ferromagnetic areas is not simple, because only a constant permeability can be prescribed in the massive area. In this case, the massive ferromagnetic area was divided into 2 subregions: the 0.5 mm thick inner surface layer with the relative permeability about 100 and the rest of massive area with a relative permeability several times higher. The result of a calculation for the 2 mm air gap, 800 A current and 4 kHz frequency is illustrated in Fig.4. Corresponding power loss is 5.55 kW, which is 65 % of the analytical calculation.

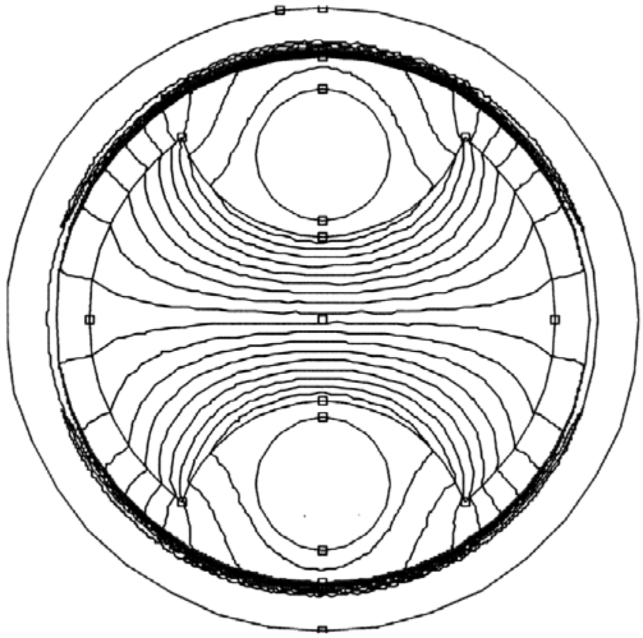

Fig.4. Magnetic lines of forces

5 Insulation technology

The ability of polyimide polymers to maintain their excellent properties over a wide temperature range was exploited in the rod inductor construction – Fig.5. According to the dynamic and isothermal thermogravimetry experiments[2], a substantial degradation of a PI material under a limited oxygen presence can only occur at the temperature exposure to about 580 °C. To our disposal were the Kapton H polyimide films, reportedly useful in field applications up to 400 °C [3]. Polyimide precursor solutions in N-methyl pyrrolidone, Kerimid resins[4] and Rhodeftal varnishes[5], are recommended for the fabrication of high temperature resistant laminates and electric insulating coatings. However, the optimum processing conditions, i.e. drying at 100 °C and curing at 180 to 300 °C, are essential to meet the desirable properties of the products[5]. The preliminary tests in our laboratory proved the following insulating structure reliable enough to meet the operating temperature resistance demand of 350 °C for at least two hours:

★ First ply of Kapton H tape wound around the copper tube (10 mm wide and 0.025 mm thick, half-breadth overlap)
★ First Kerimid 500 coating, drying and curing
★ Second ply of Kapton H tape followed by the second Kerimid 500 coating and curing

★ Ferromagnetic core insertion, Kerimid 500 impregnation coating and glass tape outer winding (15 mm wide and 0.1 mm thick, half-breadth overlap), drying and curing
★ Two consecutive layers of Rhodeftal 200 varnish, drying and curing.

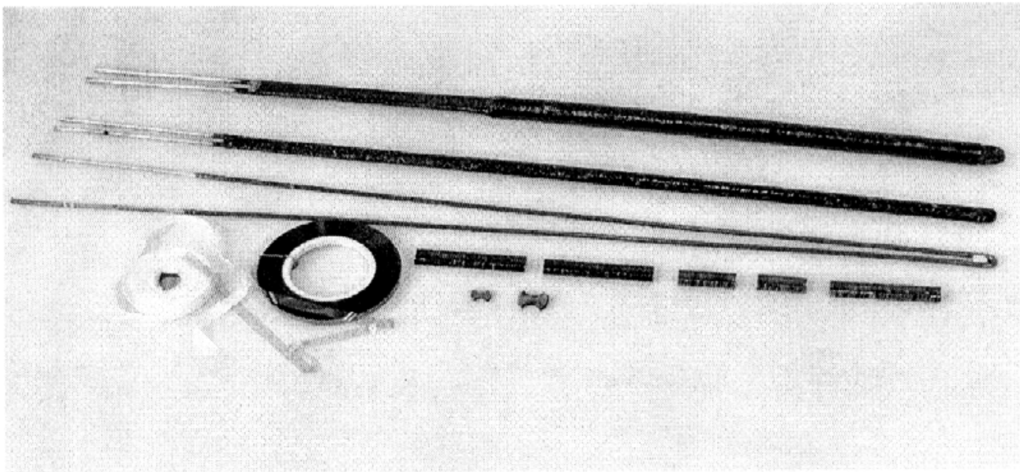

Fig.5. Rod inductors and their components

6 Conclusions

The developed design of the rod inductor based on the induced electric currents and induced losses calculations as well as on the temperature resistance tests of the polyimide/glass insulation resulted in a successful application in the massive steel bolts heating technology. Inductors with the outer diameter of 21 mm and 30 mm, characterized by about 1000 mm total length and a 500 mm long inserted laminated ferromagnetic core, were put to operation in a twin connection series supplied with 80 kW/4 kHz frequency source and secured a demanded bolts heating within a few minutes.

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