Simulation Problems of Internal Inductors

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***Abstract*—The problems of choosing and calculating the parameters of the internal inductor, the power supply and the necessary matching circuits are considered. A simple analytical method for calculating the electrical parameters of a multi-turn internal inductor with a magnetic core is described. The results of simulating the internal induction heating system are presented, which allow determining the main electrical and heating parameters at the stage of preliminary selection of the design of the induction coil and magnetic concentrator for induction heat treatment.**

Keywords—internal inductors, computer simulation, calculation algorithm, ELTA program

I. Introduction

Some individual induction technologies require the use of internal heating as more efficient than other variants of process. Applications of internal inductors are described by V. Vologdin (1947), F. Kurtis (1950), V. Nemkov et al. (1988) [1-3] and other scientists. Research has also been carried out in recent years by V. Nemkov et al. (2004), V. Bukanin et al. (2005, 2008) [4-6]. They showed an increasing interest in optimizing the parameters of the internal inductor to obtain the maximum efficiency. The developer of the induction installation tries to solve two main problems. The first of them is the choice of the induction system, the parameters of the power supply and the variant of the matching circuit, for example, parallel, series or other compensation circuit, the matching transformer, leads, etc. The second task is to obtain the necessary quality and efficiency of process by optimizing the design of the induction system selected at the first stage. A rational solution can be found using approximate or simple analytical calculation methods at the first design stage and using more accurate numerical methods at the second stage. Induction systems currently in use are discussed below.

A. Hair-pin Internal Inductors

A hairpin inductor (Fig. 1) can heat the hollow part near the coil areas

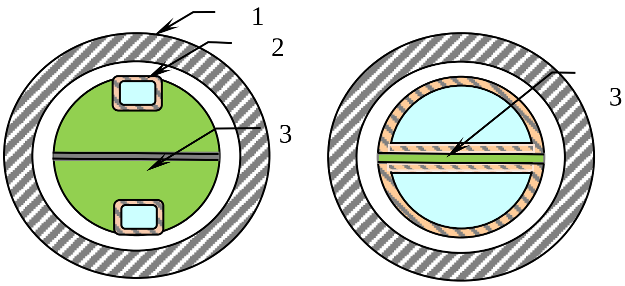

Fig. 1. View of cross-section of a heating system using the hairpin coils (1 – workpiece, 2 – coil, 3 – magnet yoke)

In this case, the inductor or the workpiece should be rotated at a certain speed to ensure uniform heating throughout the surface.

B. Single-turn Internal Inductors

Two types of the single-turn inductors are usually used to heat different workpieces (Fig. 2).

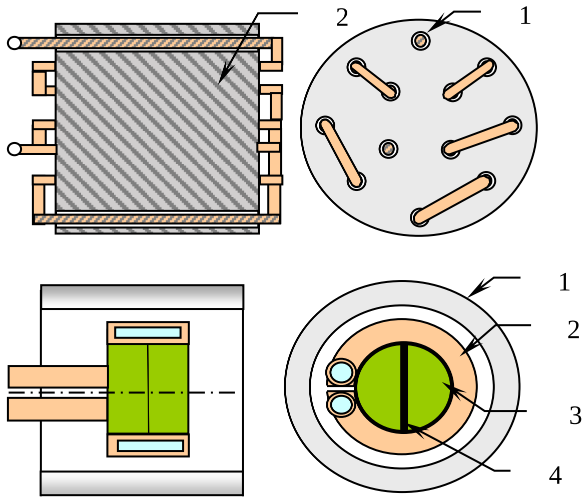

Fig. 2. Examples of single-turn inductors for a forging mold (top) and a hollow cylinder (bottom) (1 – workpiece, 2 – coil, 3 – magnet yoke, 4 – technological gap)

The single-turn cylindrical inductor can realized both simultaneous and continuous technological process.

II. Calculation Algorithm

All variants of internal induction systems can be calculated based on the simplified magnetic substitutional circuits and a Total Flux Method (TFM) proposed by V. Nemkov [3]. The equivalent electrical circuitry of the multi-turn inductor with a magnetic core and a return leg is shown in Fig. 3. The two main views of the system are shown in Fig. 4.

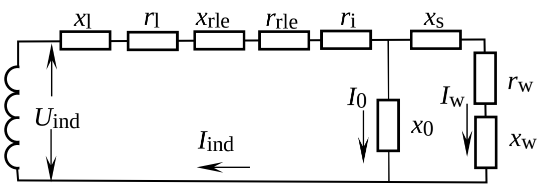

Fig. 3. Electrical schem of the induction system (inductive reactance of leads x_l, return leg x_{rle}, air clearance x_S, reverse closure x_0, workpiece x_w, active resistance of leads r_l , return leg r_{rle} , coil r_i and workpiece r_w)

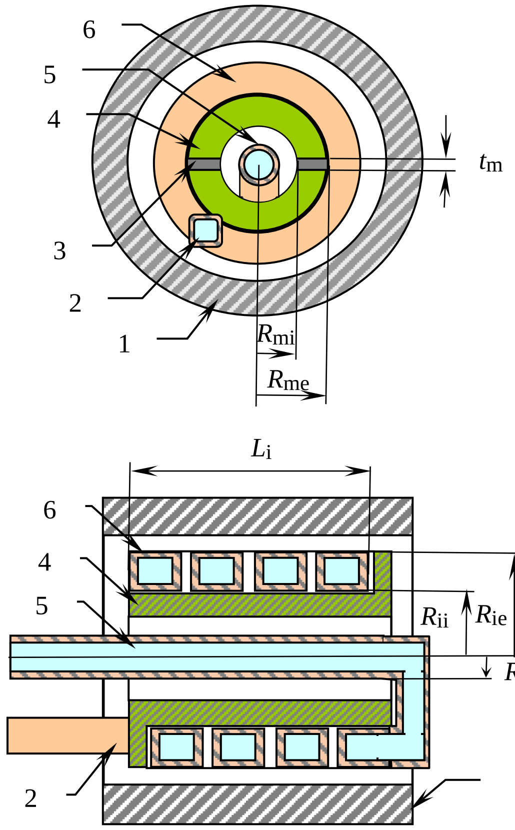

Fig. 4. View of multi-turn induction system (1 – workpiece, 2 – leads, 3 – technological gap, 4 – magnet yoke, 5 – return leg, 6 – coil)

The main problem of calculation in the TFM is the determination of active resistance r_{rle} and inductive reactance x_{rle} of the return leg, as well as reactance of an air clearance x_S and reverse closure x_0.

The resistance of the return leg r_{rle} (Ohm) can be found using the following formula:

$$r_{rle} = \frac{\rho L_{rle}}{2\pi(R_{rle} - \Delta_{rle}/2)\Delta_{rle}}, \qquad (1)$$

where ρ is the resistivity (Ohm·m); L_{rle} is the length (m); R_{rle} is the external radius of the leg (m); Δ_{rle} is the penetration or reference depth (m).

An inductive reactance of the return leg x_{rle} (Ohm) is:

$$x_{rle} = \frac{\omega L_{rle}\mu_0}{2\pi}\left[\ln\frac{R_{ii} + \Delta_{ind}/2}{R_{rle} - \Delta_{rle}/2} + K_m\right], \qquad (2)$$

where R_{ii} is internal radius of the inductor (m); K_m is a coefficient of magnetic core.

Other formulae of resistances, inductive reactance's, impedances, power, efficiency, power factor, the induction in the magnetic core, etc. are described and implemented in ELTA program for further analysis and choosing of rational variant, which can provide heating the inner layer of 0.1 cm to the quenching temperature of about 1000...850 °C (Fig. 5).

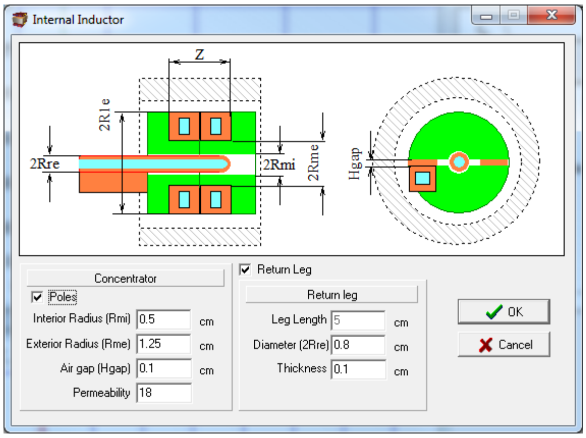

Fig. 5. View of investigated multi-turn induction system

III. Results of Investigation and Discussion

In this section, we will consider two main tasks that need to be solved to optimize the heating by the internal inductor. The first problem is the choice of the concentrator parameters to prevent saturation and overheating of the magnetic material. The second problem is economical, i.e. obtaining minimum energy consumption.

As an example, consider the case of surface hardening of steel 1040 tube to a depth of 0.1 cm. The workpiece has an inner diameter of 4.8 cm, an outer diameter of 5.8 cm and a length of 5.0 cm. The frequency of the power supply is about 70 kHz and varies during the stage. 5 cm long, 4-turn coil is made of copper oval tubing with dimension 1×1 cm and the coil has exterior diameter of 4.5 cm. The return leg is 5 cm long and has an outer diameter of 0.8 cm and a wall thickness of 0.1 cm. There are two sections of leads: 2×12 cm long tube 0.8 cm OD and 20 cm long rectangular busbars 8 cm×0.4 cm. The heating time is 1.0 s. The main electrical parameters of the optimized induction heating are shown in Table I.

TABLE I. Electrical Parameters Depending on the Variant

Variant	**Electrical parameters**					
	U_{ind}	**I_{ind}**	**$\cos\varphi_{ind}$**	**η_{ind}**	**P_{ind}**	**B**
	V	A			kW	T
Core no, poles no, return leg yes	*247.5*	*3010*	*0.170*	*0.613*	*127.5*	–
Core yes, poles yes, return leg yes	*247.1*	*1552*	*0.337*	*0.774*	*127.5*	*1.251*

References

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