The 14th International IGTE Symposium

on Numerical Field Calculation in Electrical Engineering

IGTE '10

Proceedings

Sept. 20 - 22, 2010

Hotel Novapark, Graz, Austria

Institute for Fundamentals and Theory
in Electrical Engineering - IGTE

IGTE

Graz University
of Technology

TU Graz

Oral Session 3: Optimization and Inverse Problems

Tuesday, September 21, 08:30 - 10:10, Plenary Hall: Room Thöny

Invited Lecture

Tuesday, September 21, 10:30 - 11:10, Plenary Hall: Room Thöny

Oral Session 3: Optimization and Inverse Problems

Tuesday, September 21, 11:10 - 12:10, Plenary Hall: Room Thöny

Numerical Based Simulation and Electromagnetic Field Calculation at Metal Induction Heating

*Goce G. Stefanov, †Ljupco V. Karadzinov and *Vasilija J. Sarac
*University Goce Delcev-Stip, Faculty of Electrical Engineering, Radovis, R. Makedonija, goce.stefanov@ugd.edu.mk
†Ss. Cyril and Methodius University, Faculty of Electrical Engineering and IT, Skopje, R.Makedonija
L. Karadzinov@ukim.edu.mk

Abstract— **Paper is presenting results of research on application of simulation software in defining the parameters of the electromagnetic field and temperature distribution in induction heating for metal conductor. Modern simulation programs for calculation of parameters of electromagnetic field and head transfer are based on numerical methods such as Finite Differences Methods (FDM) and Finite Element Method (FEM). In this paper is used ELTA simulation program, based on FDM method, product of the Flux control.**

Index Terms—**temperature distribution, electromagnetic field, parameters, simulation**

I. INTRODUCTION

In general, the transient (time-dependent) heat transfer process in a metal work piece can be described by the Fourier equation, [4] :

$$C\gamma\frac{\partial T}{\partial t} + div(-\lambda gradT) = Q \qquad (1)$$

where T is the temperature, γ is the density of the metal, C is the specific heat, λ is the thermal conductivity of the metal, and Q is the heat source density induced by eddy currents per unit time in a unit volume (so-called heat generation). In general case the calculation of the parameters of the electromagnetic field is based on the calculation of Maxswell's equations for defined medium and geometry. Solving of Maxswell's equations and equation for heat transfer process in general and special case is a complex task. Computer simulation makes the problem of designing the induction device easy and simple, [1], [2], [3], [4]. Computer simulation is based on numerical methods. By using the numerical methods problems of distribution of the electromagnetic field and heat transfer in metals are reduced to finding approximate solutions of partial differential equations (PDE).

II. NUMERICAL METHODS

At present time, Finite Differences Method and Finite Element Method are the most popular, [3], [4]. Method of Finite Differences (FDM) is relatively simple for understanding and realization. It may be used for any media, magnetic or non-magnetic and for any geometry-1,2 and 3 dimensional. A disadvantage of this method is that it does not work very well for complex geometry with sharp angles and curved surfaces. For 1D or rectangular 2D areas it works very well. Finite Element Method (FEM or FEA) is the most universal method for solution of electromagnetic, thermal, mechanical and other problems. It can work for 1,2 and 3D physical problems in systems of complex geometry.

Although the FDM and FEM appear to be different; however, they are closely related. As FDM starts with a differential statement of the problem of interest, and requires that the partial derivative of the governing equation be replaced by a finite-difference stencil to provide point wise approximation. FEM starts with a variational statement and provides an element wise approximation. Both methods discretize a continuous function (e.g., magnetic vector potential or temperature) and the result is a set of simultaneous algebraic equations to be solved with respect to its nodal values. Therefore, the two methods are, in fact, quite similar.

Finite-difference stencils overlap one another, and in the case of complicated work piece geometry they might have nodes outside the boundary of the work piece, coil, or other components of the induction heating system. Finite elements do not overlap one another, do not have nodes outside the boundaries, and fit the complicated shape of the boundary perfectly. As shown above, in electromagnetic field computation finite elements are usually introduced as a way to minimize a functional. In fact, FDM can also be described as a form of functional minimization (so-called finite-difference energy method). Therefore, FDM and FEM are different only in the choice of mesh generation and the way in which the global set of algebraic equations is obtained. They have approximately the same accuracy; however, required computer time and memory are often less when FDM is used. For example, the computer time needed to form global matrices is usually four to nine times greater with FEM than with FDM. As one would expect, a comparison of the efficiency of the two methods depends on the type of problem and program organization. Experience with both methods shows that FDM is not well suited for an induction heating transfer (IHT) system with complicated boundary shapes or in the case of a mixture of materials and forms (e.g., heat treating of camshafts, crankshafts, gears, and other critical components). In this case, FEM has a distinct advantage over FDM.

Both FDM and FEM require a network mesh of the area of modeling. That network includes induction coils, the work piece, flux concentrators, etc. Unfortunately, to suit the condition of smoothness criteria and continuity of the governing differential equation it is also necessary to take into general consideration the airspace regions. Electromagnetic field distribution in the air, in most cases of coil designs, can be considered useless information, of interest only during the final design stage when evaluating electromagnetic field exposure of the induction heater. The need to always compute the electromagnetic field distribution in air can be considered a disadvantage of both the FDM and FEM. Another difficulty, which appears when using FDM or FEM for electromagnetic field computation, is how to treat an exterior region that extends to infinity. This deals with an infinite nature of electromagnetic wave propagation. Several methods have been used taking into account this phenomena of the infinite exterior region. Some of the methods are ballooning method, mapping technique, and combination of finite and infinite elements. However, each of the above-mentioned methods has certain shortcomings.

In many applications it is effective to use a combination of methods. The right choice of method depends on the specific application and features of the induction heat-treating process. The use of modern software does not guarantee correct computational results. It must be used in conjunction with experience in numerical techniques and engineering knowledge to achieve the required accuracy of mathematical modeling. This is especially so because even in modern commercial software, regardless of the amount of testing and verification, a computation program may never have all of its possible errors detected. The engineer must consequently be on guard against various kinds of errors. The more powerful the software, the greater the probability of errors. Common sense and engineering gut feeling are always the analyst's helpful assistants.

Computer modeling provides the ability to predict how different factors may impact the transitional and final heat-treating conditions of the work piece and what must be accomplished in the design of the induction heating system to improve the effectiveness of the process and guarantee the desired heat-treating results.

III. COMPUTER SIMULATION

In this paper ELTA simulation program is used for estimation of the electromagnetic field and head transfer for work piece metal with cylindrical geometry exposed of the induction heating, [2], [3]. In the ELTA simulation program are implemented Finite Differences Method and Method of the Magnetic Circuit.

ELTA was developed to fill the gap between complicated numerical programs and empirical approach. It is based on a combination of FDM for simulation of coupled electromagnetic and thermal fields inside the part and method of magnetic circuits for account of finite lengths of the part (work piece) and inductor. Other methods of account of finite lengths such as use of fixed correction coefficients provide acceptable accuracy only under certain conditions laid on geometry and materials. It is because the magnetic field distribution in the length of the system depends on material properties, dimensions and frequency and varies in the process of heating. Fixed correction coefficients do not take this into account. In this method it is supposed that magnetic flux Φi of the inductor flows around all its turns as one stream (Figure 1). Inside the inductor it consists of a leakage flux Φ_s in the gap between the coil and work piece and flux Φ_w inside of the work piece.

In the Figure 1 is present equivalent electrical circuit.

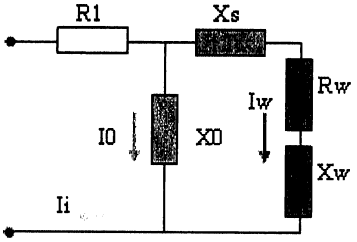

Figure 1: Equivalent electrical circuit

Parameters Xw and Rw of the work piece as well as reactance of the gap Xs are calculated by FDM and multiplied by number of turns of the inductor N^2. A key role in this method plays calculation of mutual reactance X0 between inductor and the work piece . Resistor R1 added to the circuit represents resistance of the coil. Components of external circuit (busswork, transformer and series or parallel capacitors) may be added to the circuit from Figure 1. Using this circuit it is possible to calculate input parameters of the inductor, its active and reactive powers, a part of ampere-turns required to drive magnetic flux through the back path etc. We can evaluate also an influence of coupling gap and magnetic flux controller on the coil parameters. When in the process of heating parameters Rw and Xw change, the program recalculates the whole circuit again and again, correcting operating conditions of the system and power delivery into the work piece.

A scheme of Figure 1 is a simplified substitution scheme of a transformer with all stray inductance transferred to the secondary winding. However calculation of component parameters is different than in traditional transformers. This method was initially used by Baker for a simple case of a cylindrical system with equal lengths of the coil and work piece. An induction coil was considered as a thin multi-turn winding and Nagaoka coefficient is used for calculation of reactance X0.

A. Accuracy of ELTA simulations

Accuracy of the method depends on many factors (geometry, material properties, frequency, operating conditions) and also on selected criteria of evaluation. Typically design of induction heating system may be broken in two stages: process design and induction coil design.

A goal of the first stage is to define what combination of power, frequency and time (or power and frequency versus time) can provide the result – desired temperature distribution in the part. This stage may be called process design. ELTA is an excellent tool for design of heating process for relatively simple parts, such as rods (shafts), tubes, strips etc.

We can apply specific power density to the work piece surface at a given frequency and analyze temperature distribution in time. ELTA provides a wide range of thermal conditions on the surface or on both surfaces in the case of tubes or flat bodies. With correct physical description of the system numerical simulation of coupled electromagnetic and thermal processes is quite accurate. Inaccuracy due to numerical mesh building and equation solution is usually negligible. Errors may be caused by uncertainty or inaccuracy of physical properties of materials, axial heat transfer or complex geometry of part (other than round, flat or rectangular). ELTA uses a reliable algorithm for automatic selection of calculation process parameters (steps in time, space, magnetic field strength and temperature). Electromagnetic and thermal equations are solved using a special fast and stable algorithm. An operator can use a default Normal Precision mode for almost all calculations. Only in very special cases of severe quenching, some oscillations in temperature curve may occur and another mode of calculation (High Precision or Custom) must be used.

The second stage of design procedure is induction coil (or coils) design. At this stage the problem becomes eventually 2D or even 3D and some inaccuracy are inevitable. Due to a big variety of tasks it is impossible to evaluate these inaccuracies in general form. However an operator well familiar with induction technique and algorithm of calculation can easily define a level of possible errors.

It is reasonable to select achievement of required temperature under the coil at a given time as a main criterion of accuracy. Factors favorable for good accuracy of calculations are:

1. "long" induction system; the length here isn't always physical length but ratio of the coil length to a coupling gap for high frequency or to a coil radius for relatively low frequency (such as in the case of mass heating);
2. high or optimal frequency; at optimal or higher frequency electromagnetic field in the part is close to one-dimensional;
3. high work piece material conductivity, i.e. high skin effect;
4. fast heating; fast heating reduces influence of losses or axial/longitudinal heat transfer;
5. application of concentrators; concentrators "organize" magnetic flux flow and calculation of reluctances is more accurate, plus power distribution under the coil is more uniform;
6. work piece equal in length or slightly shorter than the coil; in this case current and power distributions in the work piece length are more uniform;
7. small gap between the coil and the work piece ("coupling gap"); with small gap the system becomes "longer";
8. selection of power or voltage supply options for coil energizing in calculations; it follows from electric circuit (Figure 1) that with these options the work piece heating less depends on inaccuracy in calculation of X0; calculation using current supply mode is less accurate for a given heating cycle.

It is clear from the above considerations that for induction systems with high efficiency ("good" systems) an accuracy is higher that for "bad" systems with big coupling gap.

In general errors in calculation of power and voltage is usually less than 10% while calculated current may be 15-20% inaccurate. These numbers refer to heat treating induction coil heads. Calculation of bussbars and other components of power supplying circuitry is much more accurate. For forging coils calculation of power and voltage has usually 5% inaccuracy and error in current calculation does not exceed 10%.

B. Calculation of the heat losses and specific surface heat

In the simulation program is defined working piece of metal with its dimensions. This dimension defines the geometry of the inductor. Process of work piece heating presented in this paper is defined with following operating conditions: work piece consisted of metal copper with cylindrical shape and length of 0.13m, internal diameter of 0m, external diameter of 0.0525m. Maximum temperature is 1120°C while time cycle is 3600s. Switching frequency of 6 kHz was assumed for the calculation of maximum power. Also is selected serial resonant converter for the power supply of the induction device with 75 V.

In conventional induction heating, all three modes of heat transfer—conduction, convection, and radiation—are present, [4]. Heat is transferred by conduction from the high-temperature region of the work piece toward the low-temperature region. The basic law that describes heat transfer by conduction is Fourier's law,

$$q_{cond} = -\lambda grat(T) \tag{2}$$

where q_{cond} is the heat flux by conduction, λ is the thermal conductivity, and T the temperature.

In contrast to conduction, heat transfer by convection is carried out by fluid, gas or air (i.e., from the surface of the heated work piece to the ambient area). Convection heat transfer can be described by the well-known Newton's law. This law states that the heat transfer rate is directly proportional to the temperature difference between the work piece surface and the ambient area,

$$q_{conv} = \alpha(T_s - T_a) \tag{3}$$

where q_{conv} is the heat flux density by convection, W/m^2 or W/in.^{2}; α a is the convection surface heat transfer coefficient, W/(m^2 °C) or W/(in.^{2} °F); T_s is the surface temperature, °C or °F; and T_a is the ambient temperature, °C or °F.

In the third mode of heat transfer, which is heat radiation, the heat may be transferred from the hot work piece into a nonmaterial region (vacuum). The effect of heat transfer by radiation can be introduced as a phenomenon of the electromagnetic energy propagating due to a temperature difference. This phenomenon is governed by the Stefan–Boltzmann law of thermal radiation, which states that the heat transfer rate by radiation is proportional to a radiation loss coefficient Cs and the value of T_s^4 and T_a^4.

$$q_{rad} = C_s(T_s^4 - T_a^4) \qquad (4)$$

Due to the fact that radiation losses are proportional to the fourth degree of the temperature, these losses are significant part of the total heat losses in high-temperature applications.

In a typical induction heating and heat treatment applications, heat transfer by convection and radiation reflects the value of heat losses. A high value of heat losses reduces the total efficiency of the induction heater.

Analyze of the distribution of the surface specific losses, specific thermal losses and efficiency of the induction system is made by the aid of diagrams, obtained from simulation.

In Figure 2 is given the distribution of the specific surface power on the work piece.

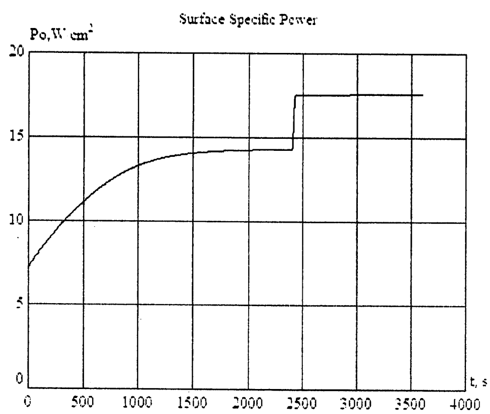

Figure 2: Distribution of the specific surface power

In the Figure 3 is presented the distribution of the specific thermal losses in the induction system. Internal power losses- P_{int} are zero since there are no thermal losses in the work piece. P_{ext} are thermal losses outside of the work piece.

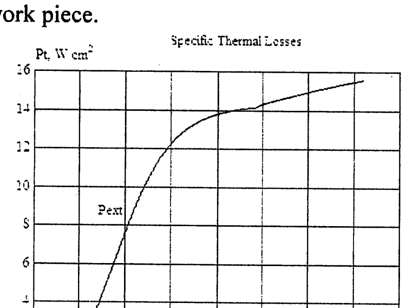

Figure 3: Specific thermal losses

In Figure 4 is present efficiency of the induction heating system consisted of metal work piece and inductor and no thermal insulator between the work piece and the inductor.

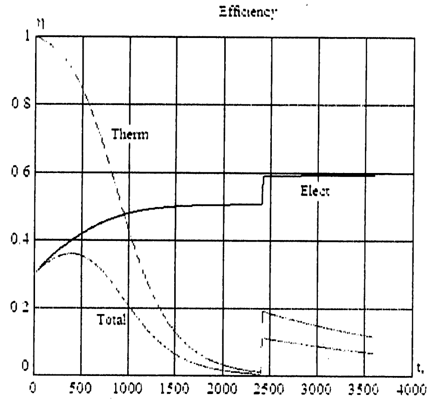

Figure 4: Efficiency of the induction system

From the results presented in Figure 4 it can be concluded that thermal efficiency is not good. The reason for poor thermal efficiency is inductor which is used without a thermal insulator. After installing the thermal refractor in the induction system obtained efficiency of the system is presented in Figure 5.

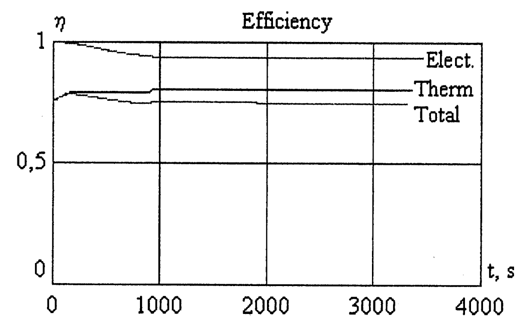

Figure 5: Efficiency with thermal refractor

The analysis of the Figures 3, 4 and 5 shows that without thermal refractor losses of the induction system are high and efficiency is bad. With the installation of the thermal refractor efficiency of the system is considerably improved.

This is an example how by using simulation software, it can be quickly concluded that the induction system is not satisfactorily working. The proper choice of the thermal refractor allows the heating only of the selected areas of the work piece.

C. Affect on the geometry on the power factor

According to the above mentioned, one of the assumptions for the good design is the ratio of length of the induction system to the size of the air gap between the inductor and the work piece to be relatively large. In this section is analyzed how this geometry affects the power factor. The analysis is made for two combinations of dimensions of the system inductor-work piece. In first case following dimensions of inductor and work piece are taken into consideration:

a.) Inductor: radius 5.75cm, length 16.5cm
Work piece: radius 3.75cm, length 13 cm

In Figure 6 is present power factor for this combination of dimensions.

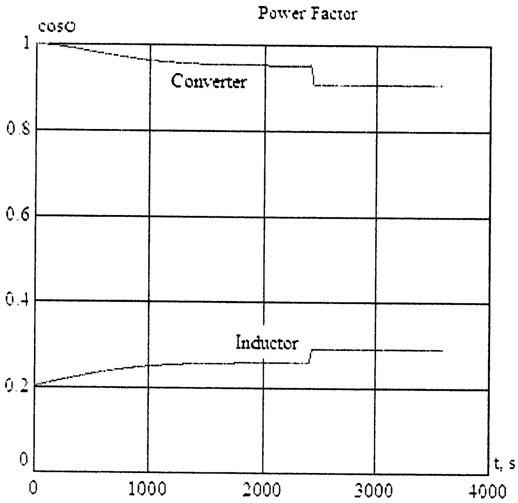

Figure 6: Power factor for first set of dimension inductor-work piece

In second case dimensions of the system inductor-work piece are considered to be following:

b.) Inductor: radius 5.75cm, length 16.5cm
Work piece: radius 5.25cm, length 15 cm

In Figure 7 is present power factor for this combination of dimensions while in Table I are given data of the power factor from the above analysis.

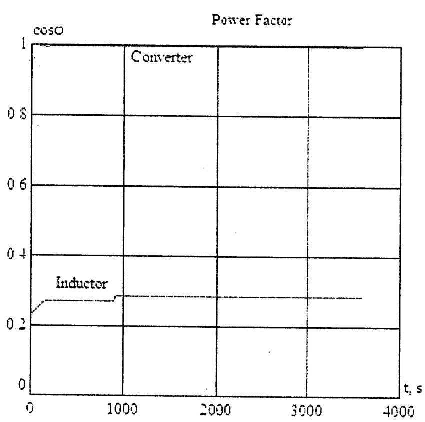

Figure 7: Power factor for second set of dimension inductor-work piece

From Figure 7 it can be concluded that for the second set of dimensions where air gap between the inductor and work piece is considerably reduced and the work piece is slightly shorter than the inductor the power factor of converter is considerably improved as well as of the inductor. This is verified by presented results in Table I.

TABLE I
Values of power factor for different dimensions of inductor-work piece

Inductor		Work piece		$\cos\varphi_{induct}$ (min value)	$\cos\varphi_{conv}$ (min value)
radius	lengt h	radius	lengt h		
5.75	16.5	3.75	15	0.2	0.91
5.75	16.5	5.25	13	0.25	1

Variations of the dimensions of work piece and inductor have a considerable influence on the efficiency of the inductor but as well as on the efficiency of the power converter which is supplying the process of induction heating. Therefore special attention should be put on proper choice of the dimensions of inductor-work piece since it influences the efficiency of the whole process of induction heating.

D. Distribution of the magnetic field and the density current

Not linear dependence of the properties of the metallic materials: specific heat, thermal conductivity, magnetic permeability, specific resistance causes the distribution of the magnetic field, the current density and temperature along the cross-section of conductor exposed to induction heating to be non uniform. In Figure 8 is presented the distribution of the magnetic field strength along the cross-section (radius-r) of the work piece.

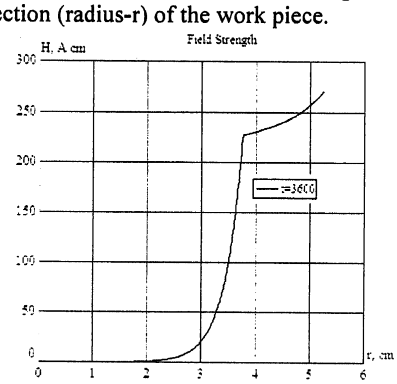

Figure 8: Distribution of the magnetic field in the work piece

In the Figure 9 is present the distribution of the current density.

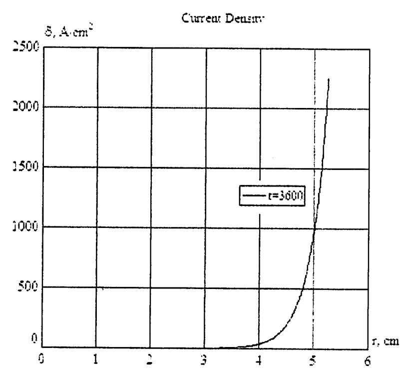

Figure 9: Distribution on the current density

In Figure 10 is presented the distribution of the temperature in the work piece.

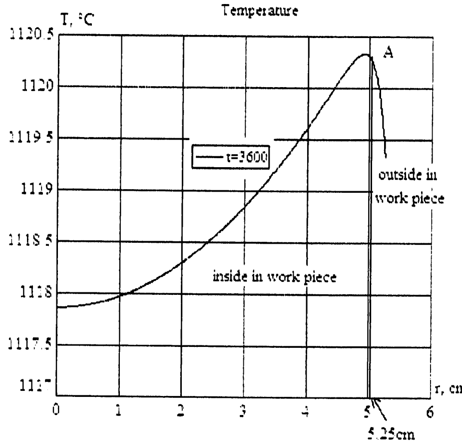

Figure 10: The temperature distribution

From the Figures 8, 9 and 10 it can be concluded that:

- The distribution of the field, the current density and temperature is not uniform in the work piece.
- They are the largest on the surface of work piece and they are decreasing in the direction to the center of the work piece.
- The distribution of temperature on the right side from point A is experiencing the rapid decline which is understandable as we are entering the area of the air gap.
- Non uniform distribution of the field and the current density is a reason why the inductance of the induction system is not constant.

This is comprehensible from the presented distribution of inductance in Figure 11.

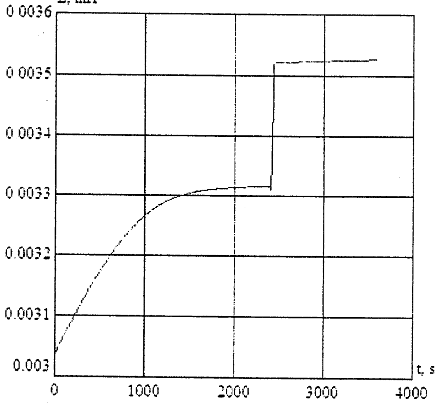

Figure 11: Distribution on the inductance

The change of the inductance causes for change of the output power, which is presented in Figure 12.

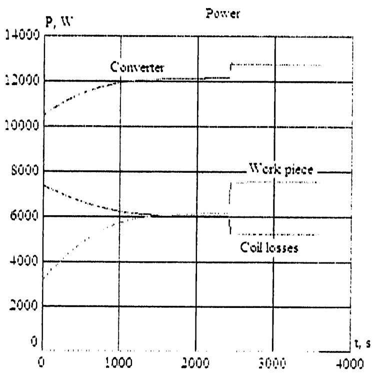

Figure 12: Distribution of output power caused by change of the inductance

IV. Conclusion

In this paper dynamic change of parameters of electromagnetic field and heat transfer for work piece of metal used in the process of the induction heating are analyzed. Influence of these changes on the magnitudes of power, current and voltage of the power converter are evaluated. It can be concluded that:

1. The process of induction heating of metals is a dynamic one and its dynamic changes the inductance of the output circuit of the converter.

2.The current density is the largest at the surface of the work piece.

3. The efficiency of the system inductor and work piece depends from their geometry. The smaller the air gap between work piece and inductor is and the larger the length of the induction system is, the efficiency of the converter and the inductor is larger as well.

4. The change of inductance causes the change of the current and the power of the converter. In some application maintenance of the constant power output of the power converter is an imperative therefore system for automatic regulation of converter power should be implemented. Since the process of the induction heating is a transient process where all parameters are time and spatial variables, empirical calculations of the process parameters are implemented as well as simulation programs. Therefore the simulation program ELTA for the object of investigation work piece metal-inductor is implemented, and transient characteristics of electromagnetic field strength, current density, inductance, cosφ and efficiency factor are obtained on fast and effective way.

References

[1] G.Stefanov, Computer simulation on the topologies of resonant converters used in induction cookers, CONFERENG 2009" Tg-Jiu, Romania, ISSUE 2/2009, pp.161-170, 13-14.10.2009.

[2] G.Stefanov, L.Karadzinov, D.Karanfilov, Design of Power Converter for Induction Furnaces with Computer Simulation, MIPRO 2010, Opatia, Croatia, 33 International Convention, pp.164-169, 24-28.05.2010.

[3] ELTA simulation program, www.Fluxcontrol.com.

[4] G.E.Totten, Steel Heat Treatment, Equipment and Process Design, Portland,University, USA, 2007

[5] G.Stefanov, L.Karadzinov, V.Sarac, Analysis of Power Converter with Computer Simulation, MMT 2010, Sanny Beach, Bulgaria, Volume 4, Part 2, pp.30-47, 11-14.06.2010.